ISSN 0236-2945

LIGHT & ENGINEERING

Volume 27, Number 1, 2019

Editorial of Journal
"Light & Engineering" (Svetotekhnika), Moscow

Journal "Light & Engineering" had been founded by Prof. Julian B. Aizenberg in 1993

LIGHT & ENGINEERING

СВЕТОТЕХНИКА

Moscow, 2019

Light & Engineering / Svetotekhnika Journal Country Correspondents:

Editorial Office:

Russia, VNISI, Rooms 327 and 334
106 Prospekt Mira, Moscow 129626

Tel: +7.495.682.26.54
Tel./Fax: +7.495.682.58.46
E-mail: lights-nr@inbox.ru
http://www.l-e-journal.com

Scientific Editors:

Light & Engineering" is an international scientific Journal subscribed to by readers in many different countries. It is the English edition of the journal "Svetotekhnika" the oldest scientific publication in Russia, established in 1932.

Establishing the English edition "Light and Engineering" in 1993 allowed Russian illumination science to be presented the colleagues abroad. It attracted the attention of experts and a new generation of scientists from different countries to Russian domestic achievements in light and engineering science. It also introduced the results of international research and their industrial application on the Russian lighting market.

The scope of our publication is to present the most current results of fundamental research in the field of illumination science. This includes theoretical bases of light source development, physiological optics, lighting technology, photometry, colorimetry, radiometry and metrology, visual perception, health and hazard, energy efficiency, semiconductor sources of light and many others related directions. The journal also aims to cover the application illumination science in technology of light sources, lighting devices, lighting installations, control systems, standards, lighting art and design, and so on.

"Light & Engineering" is well known by its brand and design in the field of light and illumination. Each annual volume has four issues, with about 80–140 pages per issue. Each paper is reviewed by recognized world experts.

To promote the work of the Journal, the editorial staff is in active communication with Thomson Scientific (Citation index) and other international publishing houses and agencies, such as Elsevier and EBSCO Publishing.

CONTENTS

VOLUME 27 **NUMBER 1** **2019**

LIGHT & ENGINEERING

Light & Engineering
Vol. 27, No. 1, pp. 4–14, 2019

EFFECTIVE ELECTRODYNAMIC PARAMETERS OF NANO-COMPOSITE MEDIA AND THE THEORY OF HOMOGENISATION

Leon A. Apresyan

Prokhorov General Physics Institute of the Russian Academy of Sciences
E-mail: leon_apresyan@mail.ru

ABSTRACT

When creating new lighting and optoelectronic devices, great attention in recent years is paid to use nano-composite materials, i.e. the media containing impregnations of nanometre size, such as nano-particles of metals, quantum points, carbon nanotubes, graphenes, etc. This allows obtaining media with new, formerly unattainable characteristics. An initial point when describing properties of such medias is usually evaluation of their effective parameters (dielectric permeability, conductivity, heat conduction and of other similar transport coefficients) in the model of macroscopically heterogeneous media, in other words, media containing macroscopic impregnations with known or determined from experiments characteristics. Main approaches used in such cases are known Maxwell Garnett and Bruggeman approximations. In this review, methodical questions connected with various approaches to obtain these approximations and of their generalisations are discussed. Also some new results are given, which connected with evaluations of percolation thresholds within generalised Bruggeman approximations in the event of multi-component media.

Keywords: nano-composite media, effective parameters, quasistatic approximation, Maxwell Garnett approximation, Bruggeman approximation, percolation threshold, multi-component composites

1. INTRODUCTION

A constant improvement of lighting devices connected with development of modern technology applications, such as photovoltaic [1, 2] and optoelectronics [3–6], brings to the forefront the problem of creating new optical materials with unattainable formerly properties. This problem is solved in particular by obtaining new composite materials. If it comes to the purely optical aspect of the problem abstracting from numerous applications of composites, such as power mechanical, heat-conducting, etc. structures, then first it is about nano-composites, i.e. about the composites with non-uniformity size of tens nanometres. Such inclusions are various carbon structures (nano-tubes, graphenes, fullerenes), quantum dots, as well as metal nano-particles, which are used long since from the historical point of view. Study of such objects has led to creation of a new science direction known as nano-photonics, or otherwise as nano-optics [5, 6] being a subsection of general photonics, which is a science about transformation and propogation of photons within the interval from IR to ultraviolet.

Nano-photonics studies behaviour of light "compressed" to nanometre sizes, as well as its interaction with the nanometre objects. Both of these directions are interconnected. The first part is focused on overcoming the Rayleigh limit (i.e. impossibility of photon localisation in normal conditions on scales smaller than the wavelength) due to plasmon effects in metal nano-particles, nano-sized apertures or spires used in the near-field scanning microscopy. The second encloses study both of purely quantum features of light interaction with single nano-objects, and of properties of ensembles with large number of N >> 1 particles, which is typical for the case of composite media. The prospective nano-photonics application field is extremely wide and includes both already quoted applications in solar photovoltaic and optoelectronics, and many other fields: lighting engineering, electrical engineering, biophysics and biochemistry, medicine, etc. Large lists of references are available in monographs [2–6].

Nano-sized particles with a good approximation can be considered as purely classical macro-objects with their macro-characteristics (dielectric and magnetic permeability, conductivity, heat conduction, etc.). Besides, they can be "corrected" if necessary to account micro-effects (such as limitation of electron free path length by the particle size [7]). If such inclusions are distributed in a composite spatially uniformly, then as the first step, the composite can be characterised using some averaged "effective parameters", which are closely connected with specific measurements and are often sufficient for the composite description corresponding to practical applications. In doing so, it is considered that the composite volume under study can be replaced when calculating with the same volume of a homogeneous medium described using effective parameters. A creation of models and calculation of such parameters is called homogenisation. And in materials science, "mixing formulas" (mixing rules) name is widely used instead of this term [8, 9]).

This review considers methodical questions of creating the main models used during homogenisation, as well as some new results connected with evaluation of percolation thresholds. The review is first of all intended for students and graduate students who are interested, how to obtain effective parameters and to use practically homogenisation methods. The reference list is very limited and mainly contains references to the last monographs and reviews, as well as to some very instructive classical works, which became available in Internet. Useful discussions of similar questions in reviews should be also noticed [10, 11]. The problems connected with description of single diffusers with plasmonics and quantum effects, as well as with optics of meta-materials [12, 13] and meta-surfaces [14] obtained by artificial of ordering nano-particles are not considered here. We will refer in this regard to the recently appeared monographs [14–19] describing electrodynamics of nano-particles. These monographs are suitable for a deeper study of the specified problems.

Methodical questions connected with a possibility of introduction of effective parameters are discussed in Section 2 (where, when, why). Approaches used to obtain most widespread approximations of homogenisation, namely: Maxwell Garnett (MG) approximation and of Bruggeman effective medium (Effective Medium Approximation, EMA) in the simplest model of spherical "effective cells" are discussed in Section 3. Generalisations of these approximations for the case of elliptic cells are described in Sections 4 and 5. Expressions for percolation thresholds in the generalised Bruggeman approximations are considered in Section 6. Main conclusions are briefly formulated in Section 7.

2. GENERAL REASONS

On the face of it, the "optics of composites" concept usually is at once associated with the need of the attraction of the multiple scattering theory, as composites inherently contain many of statistically distributed scattering non-uniformities. This is really so in case of a complete wave description of the problem.

Fortunately, it turns out that for composites with small-scale non-uniformities relative to the wavelength, simple heuristic models suitable both for description of experiments and for creation of composites with required properties are often rather well usable. Good results can be obtained when using even very rough characteristics of real composites, such as volumetric relations of the components. However, as inner structure of various composites with a set volume of the components can differ essentially, one cannot recon to obtain "universal" dependences of effective parameters on limited number of the composite characteristics equally suitable for a wide range of problems. When changing inner parameters of a composite, which control is usually difficult, or when changing the measurement method, or the used radiation wavelengths, different models of effective parameters can be claimed.

This explains a wide use in applications of various homogenisation models. So, the model choice to a large extent depends on intuition of the experimenter and on quality of the results obtained when customising free parameters.

A possibility of introduction of effective parameters is not obvious; it can be implemented not in all cases and depends not only on structure of the composite but also on the measurement method (see, e.g., an old review [20], where former and often unsuccessful attempts to replace insular films with equivalent uniform layers are discussed). A wide class of the problems, for which effective parameters are especially useful, is enclosed by the quasistatic approximation, when wavelength of the used radiation is big in comparison with the composite non-uniformities, and not precise characteristics of the field are measured but only averaged by space size, which is much more than the non-uniformity size. One can say that in doing so neither the wave, nor the observer "notice" small-scale fluctuations, which always take place, when the space size is of the medium non-uniformities size order. A strict description of such fluctuations is outside the effective parameters theory.

For small-scale composites, a close analogy of homogenisation with the classical fundamental problem of statistical substantiation of macroscopic electrodynamics exists. This analogy concerns the transition from micro- to macro-description of the observed values. Really, this transition means a possibility to use macroscopic, i.e. averaged by physically infinitely small environment volume characteristics to create electrodynamics of macroscopic bodies of any configuration. The difference is that if in statistical physics, atoms and molecules appear as primary micro-objects, which differ from each other not too essentially (except for the case of macromolecules), then in the event of composites they are replaced with macroscopic non-uniformities, which configuration can change in a random way within rather wide limits. In other words, a variety of inner structures for composites is much wider than for macroscopically uniform bodies usually considered in statistical physics. Therefore if to distract from quantum effects and from difference in freedom degree number, in some specified sense, a strict calculation of effective parameters gives much more many-sided problem than calculation of macro-characteristics of molecular objects.

The simplest composite version is a two-component mixture with volume component parts f_0 and f_1 (so that $f_0 + f_1 = 1$). For a more distinctness, we primarily consider a mixture of two dielectrics with dielectric permeability ε_0 and ε_1, though similar reasoning are also applicable for many other kinetic coefficients: electrical conductivity, heat conduction, diffusion coefficient, etc. [8]. Inherently, in each point of a composite, induction $\mathbf{D}(\mathbf{r})$ is expressed using dielectric permeability ε(r) and electric field strength $\mathbf{E(r)}$ as $\mathbf{D}$ (r) = ε(r)$\mathbf{E(r)}$. In this connection, effective permeability ε^* is determined by the following relation:

$$\langle \mathbf{D}(\mathbf{r}) \rangle_v = \varepsilon^* \langle \mathbf{E}(\mathbf{r}) \rangle_v , \tag{1}$$

where angular brackets mean averaging over volume *V*,

$$\langle \ \rangle_v = \frac{1}{V} \int_V \ldots dr , \tag{2}$$

and instead of points there can be an arbitrary function **r**. As *V*, "physically infinitely small volume" is selected. This volume contains many (N >>1) non-uniformities, but it is small in comparison with the composite size. And it is supposed that statistical uniformity of a composite, as well as choice of the electromagnetic field source, allow considering averaged values of $\langle \mathbf{D}(\mathbf{r}) \rangle_v$ and $\langle \mathbf{E}(\mathbf{r}) \rangle_v$ to be constant, i.e. not dependent on the choice of point **r**.

Effective dielectric permeability of a composite as function of volume parts should meet obvious "boundary conditions" (for clearness, it is written down as ε^* (f_0, f_1)):

$$\varepsilon^*(1,0) = \varepsilon_0 , \ \ \varepsilon^*(0,1) = \varepsilon_1 . \tag{3}$$

These conditions correspond to the full filling environment of one component. As a matter of fact, strictly speaking, condition (3) is not necessary for practical applicability of ε^* various models as suitability of most of them even for composite narrow classes is usually limited to some field of values of f_0 and f_1 only. Nevertheless, conditions (3) are performed in many empirical and simulation approximations for ε^* mentioned in the publications. But this fact should not mislead concerning their applicability with any relations of f_0 and f_1. Generally accomplishment of conditions (3) can be only considered as a courageous extrapolation of the considered model for the whole interval of f_0 and f_1 concentrations. The perturbation theory by concentration of one of the components, such as f_1, requires a smallness of this concentration in comparison with 1 and naturally is unsuitable with f_1 ~ 1, though effective value ε^* calculated according to this theory sometimes can be also applied with f_1 concentration being not too small.

To obtain an expression for effective permittivity ε^* automatically meeting conditions (3), they often use a formal trick already going from classical works of Maxwell [21]: they empirically select function $F(\varepsilon(\mathbf{r}))$ so that ε^* is determined from equation:

$$F(\varepsilon^*) = \langle F(\varepsilon(r)) \rangle_v = f_0 F(\varepsilon_0) + f_1 F(\varepsilon_1).$$

In [22] this property is called additivity of $F(\varepsilon(\mathbf{r}))$. In this case, at uniform filling of a composite using dielectric with ε_0 or ε_1, fluctuations disappear and, averaging symbol can be omitted, which at once gives $\varepsilon^* = \varepsilon$, provided that F- is an unambiguously reversible function. In the referenced publications, for different problems, most different choices of the $F(x)$ function were used and are widely used up to now, namely: $F = x$, 1/x, $x^{1/3}$, log x, ½(x+1/x), etc. (see, e.g. the report of various approximations in [23]). It should be noticed that the MG approximation considered below can also be referred to this class, if to consider F to be depended on the dielectric permeability matrix.

By nature (or more precisely, by topology) of the spatial structure, composites can be usually separated into aggregates (statistically symmetric, like powder mixtures), and cermets (asymmetric), in which spatial distribution statistics of a matrix is other than statistics of fillers as it is in the event of environments with random impregnations (Fig. 1, [24]). In the first case, if consider topological aspects only, i.e. connectivity of a composite component, it is impossible to divide formally the matrix and the inclusions. Below we will mainly describe the cermet case, or otherwise media with random impregnations, when statistical properties of the components are various, and matrix can be separated from them (for definiteness, it will be the first component, i.e. f_0) and impregnations (it will be the second component, i.e. f_1).

Fig. 1. Topology of composites: (a) cermets: discrete impregnations into a matrix (b); aggregates: symmetric filling of a composite without selected matrix [23]

Most widespread approximations meeting these two topologies are Maxwell Garnett approximations [25][1], which in an elementary form are often written as the equation:

$$\frac{\varepsilon^* - \varepsilon_0}{\varepsilon^* + 2\varepsilon_0} = f_1 \frac{\varepsilon_1 - \varepsilon_0}{\varepsilon_1 + 2\varepsilon_0}, \quad (4)$$

and symmetrical Bruggeman approximation of an effective medium [27].

$$f_0 \frac{\varepsilon_0 - \varepsilon^*}{\varepsilon_0 + 2\varepsilon^*} + f_1 \frac{\varepsilon_1 - \varepsilon^*}{\varepsilon_1 + 2\varepsilon^*} = 0, \quad (5)$$

Another asymmetric Bruggeman approximation is also known but we don't consider it here.

Approximations (4) and (5) are based on use of the spherical particle model. When generalising these relations for the case of non-spherical particles, ellipsoid model is usually initial. It also is widely used in the referenced publications. In the elementary case of identical and equally oriented (mono-directed) ellipsoids, the medium becomes anisotropic, and relation (5) is transformed to the following:

$$f_0 \frac{\varepsilon_0 - \varepsilon^*}{\varepsilon^* + L_i(\varepsilon_0 - \varepsilon^*)} + f_1 \frac{\varepsilon_1 - \varepsilon^*}{\varepsilon^* + L_i(\varepsilon_1 - \varepsilon^*)} = 0, \quad (6)$$

where L_i is depolarisation factor along the axis under consideration (see below). Relation (6) is correct for three orthogonal axes $i = x, y, z$ coinciding with main axes of the ellipsoid. If as L_i, normal depolarisation factors are used, which are determined for an isotropic medium, then (6) gives three independent equations for each of axes. This approximation is known as "traditional" [28, 29], and has

[1] Relation (4) is often called "Maxwell Garnett formula" connecting it by that with J. C. M Garnett [25], (one of his names was Maxwell). A more correct is "Maxwell-Garnett formula", which takes into consideration thereby the fundamental contribution of Maxwell who had obtained an equivalent result for conductivity long before Garnett [21]. An addition here of Rayleigh name who obtained this formula also before Garnett together with correction terms [26], would make it somewhat awkward, though more informative.

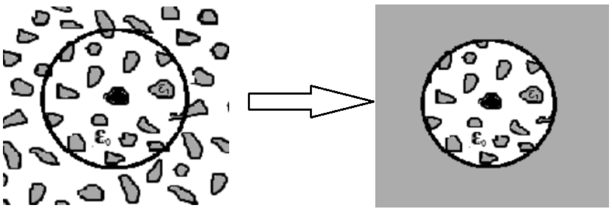


Fig. 2. Lorentz's sphere

been widely used in applications. In case of a more sequential approach [30], depolarisation factors as L_i in anisotropic medium differ from normal depolarisation factors [31]. And then (6) appears to be a more complex system of three connected equations (a comparison of these approaches is available in [29]). A successful use of equation (6) with "incorrect" depolarisation factors in some applications should not be surprising, if to take into account that all considered models are a consequence of use of a less exact approximation using L_i as adjustable parameters. It should be noticed that in the model of chaotically oriented ellipsoids, medium again becomes statistically isotropic, so even formal necessity to use depolarisation factors in anisotropic medium in this case is eliminated.

Any macroscopic composite is a particular case of non-uniform dielectrics with dielectric permeability $\varepsilon(\mathbf{r})$, which is a complex function of spatial co-ordinate **r**. As in practical situations, $\varepsilon(\mathbf{r})$ distribution in each point is not measured and some external parameter values are only recorded (like components relation) and $\varepsilon(\mathbf{r})$. As a result, ***E(r)*** can be considered as some random fields [32]. In case when their spatial correlations quickly decrease (a spatial ergodicity takes place), averaging with respect to volume can be replaced by statistical averaging [32]. Such replacement of volumetric averaging by averaging over a statistical ensemble will be used below.

Equations (4) – (6) can be solved easily, if explicit dependences $\varepsilon^*(f_0, f_1, \varepsilon_1, \varepsilon_2)$, are obtained. However, generally accepted configurations of equations (4) – (6) are convenient first to compare with other versions of these theories, and secondly as observance of boundary conditions (3) follows from them with evidence. Though formally approximation (4) is derived for the case of cermet topology, and (5) and (6) are for aggregates, both these approximations are often used independently from the composite expected topology. Let's consider the main approaches to obtain these approximations.

3. HOMOGENISATION METHODS

In the referenced publications, many various approaches to obtain approximations (4) – (6) and their generalisations are described. We give briefly most widespread of them. As these approaches are multiply repeated in the publications, we don't give numerous references to the sources (see, e.g., [8–11]).

Lorentz sphere method is most widespread when obtaining the considered approximations. Each diffuser is mentally surrounded with a big sphere (Fig. 2), and it is considered that effective field E_L near it is composed from averaged $\langle E \rangle$ plus Lorentz field $\langle P \rangle / 3\varepsilon_0$ (in the CGS system $4\pi \langle P \rangle / 3$) from diffusers out of the sphere, which are considered as point dipoles with polarizability α_1 "smeared out" into continuous environment $E_L = \langle E \rangle + \langle P \rangle / 3\varepsilon_0$, where $\langle P \rangle$is average polarization. And field of particles inside the sphere is considered on average to be equal to zero in the centre of the sphere, which is correct not in all cases (see, e.g., discussion in the classical textbook [33]. Supposing that average polarization $\langle P \rangle = n\alpha_1 E_L$, where $n = N/V$ is average number of particles in the volume unit, it is easy to obtain the known Clausius-Mossotti formula (it is also named Lorentz-Lorentz formula, if it is written down for particles in vacuum refraction index $\sqrt{\varepsilon^*}$).

$$\frac{\varepsilon^* - \varepsilon_0}{\varepsilon^* + 2\varepsilon_0} = \frac{n\alpha_1}{3\varepsilon_0}. \tag{7}$$

Replacement of polarizability of dot dipoles $\alpha_1$with the well-known polarizability of volume v_1 sphere with dielectric constant ε_1 (see, e.g., [9])[2],

$$\alpha_1 = 3v_1 \frac{\varepsilon_1 - \varepsilon_0}{\varepsilon_1 + 2\varepsilon_0} \varepsilon_0, \tag{8}$$

[2] It should be noticed that different authors determine polarizability of a particle in dielectric medium with ε_0 differently: either as in (6): $\alpha = P/E$ [9], or as $P/(\varepsilon_0 E)$ [7], where P is particle dipolar moment, which should not lead to misunderstanding.

transforms (7) into MG formula (4). The same relation (7) is often used to generalise MG approximation to more complex particle sets, for which it is enough to substitute the sum of the correspondent polarizabilities in (7) instead of $n\ \alpha_1$. So for example, for a set of n_i spherical particles with different dielectric permeability ε_i, i = 1.2,…, we have from (7):

$$\frac{\varepsilon^* - \varepsilon_0}{\varepsilon^* + 2\varepsilon_0} = \sum_{i\geq 1} \frac{n_i \alpha_i}{3\varepsilon_0}. \qquad (9)$$

Equivalent scatterer method originates from classical studies of Maxwell [21]. Spherical volume V of a composite is selected with non-uniformities interpreted as spherical impregnations of dielectric permeability ε_i in matrix ε_m, where ε_m is a heuristically selected free parameter (Fig. 3). Effective permittivity ε^* is selected from the requirement that scattered field far from V coincides with a scattered field with uniform filling of volume V by medium with dielectric permeability ε^* provided that the particles are sufficiently rarefied and that they scatter independently from each other. For this purpose, it is enough to equate polarizability of a uniform sphere to the sum of the polarizabilities of the particles of the composite sphere, which gives as follows:

$$V\frac{\varepsilon^* - \varepsilon_m}{\varepsilon^* + 2\varepsilon_{m1}} = v_0\frac{\varepsilon_0 - \varepsilon_m}{\varepsilon_0 + 2\varepsilon_m} + v_1\frac{\varepsilon_1 - \varepsilon_m}{\varepsilon_1 + 2\varepsilon_m},$$

or as $f_i = v_i/V$,

$$\frac{\varepsilon^* - \varepsilon_m}{\varepsilon^* + 2\varepsilon_m} = f_0\frac{\varepsilon_0 - \varepsilon_m}{\varepsilon_0 + 2\varepsilon_m} + f_1\frac{\varepsilon_1 - \varepsilon_m}{\varepsilon_1 + 2\varepsilon_m}. \qquad (10)$$

Believing here $\varepsilon_m = \varepsilon_0$, we obtain MG approximation (4), and with $\varepsilon_m = \varepsilon^*$ it is Bruggeman approximation (5). It should be noticed that in work [34], the considered condition was extended to the general case as a requirement of absence of scattering towards "forward" in the effective medium. Having replaced spherical objects with ellipsoids everywhere, it is easy to obtain by the same generalisation method these approximations for the case of anisotropic particles, as well as for the case of anisotropic composites (if such particles are fractionally or completely ordered).

Macroscopic averaging method uses a direct averaging **D**(**r**) and **E(r)** over volume with the ε^* determination (1). An advantage of this approach

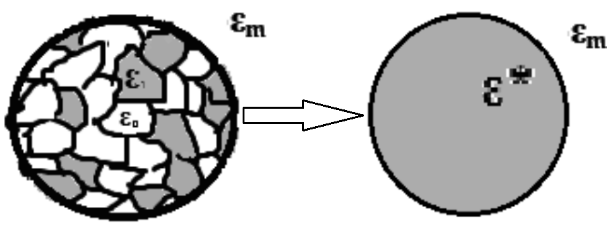


Fig. 3. Equivalent scatterer method

is more obvious description of the accepted approximations, which allows estimating at least qualitatively, conditions of applicability of final results. Let's turn our attention to it in more detail based on our work [35].

Let's consider the general case of medium with random (generally non-uniform) impregnations (cermet), divide the whole considered volume V into two parts, $V = V_0 + V_1$ so that V_0 corresponds to points of matrix **r**, and that $V_1 = \sum_{i=1}^{N} v_i$ corresponds to points of particles with volumes v_i.

Dividing the full integral when averaging over volume V into sum of integrals by partial volumes, it is easy to obtain in accordance with (1):

$$\varepsilon^* = \frac{\langle \mathbf{D(r)} \rangle_v}{\langle \mathbf{E(r)} \rangle_v} = \frac{f_0 \langle \varepsilon(\mathbf{r})\mathbf{E(r)} \rangle_{v_0} + f_1 \langle \varepsilon(\mathbf{r})\mathbf{E(r)} \rangle_p}{f_0 \langle \mathbf{E(r)} \rangle_{v_0} + f_1 \langle \mathbf{E(r)} \rangle_p}. \qquad (11)$$

Here $f_i = V_i/V$ is the matrix material volume fraction (i = 0), or particles fraction (i = 1), $f_0 + f_1 = 1$, (substantiation of formal operation of division by vector (9) can be found in [35]). Brackets with index p mean averaging with respect to particle ensemble of the following type:

$$\langle \ldots \rangle_p \equiv \sum_{i=1}^{N} P_i \langle \ldots \rangle_{v_i}, \qquad (12)$$

and $P_i = v_i/V_1$ is ratio of i particle within volume of all particles, which can be interpreted as a conventional probability "to meet" this particle among all particles, so $\sum_{i=1}^{N} P_i = 1$.

Relation (11) is exact formally, if to consider distributions of $\varepsilon(\mathbf{r})$ and of $E(\mathbf{r})$ field in the composite as known. Though at present, computing abilities allow carrying out computer simulations with simultaneous estimation of **E(r)** and of applicability of different models [36], in most of practical situations, these distributions can be considered as stochastic functions, which exact values are not recorded in experiments. But to obtain approximations (4) – (6), as well as their generalizations, it is enough to use simple statistical hypotheses about particle typical configuration and on "typical values" of the field inside and out of them. Thereby averaging with respect to volumes of medium and particles is heuristically replaced with a statistical averaging over volumes of some "effective cells". Selecting such cells of different structures and setting field distribution **E(r)** out and inside them, one can obtain different approximations for ε^*.

4. MAXWELL-GARNETT APPROXIMATION

The main assumption necessary to obtain MG approximation from (11) is that particles on average can be considered as being in the uniform external field. To obtain MG approximation (4) from (11), it is enough to consider that all particles are uniform, have identical dielectric permeability ε_1, as well as identical spherical shape, and the field out of the particles is accepted to be equal to the uniform field E_0 without particles. Instead we will at once consider generalisation (4) for a case of chaotically oriented elliptic particles with random distribution of depolarisation factors L_i. The field within such a particle in the uniform external field $\mathbf{E_0}$ is also uniform and expressed using the known relation:

$$\mathbf{E}_{in} = \Lambda \mathbf{E}_0, \tag{13}$$

where tensor Λ is expressed by means of a depolarisation tensor being diagonal in the ellipsoid main axes $L = \mathrm{diag}(L_1, L_2, L_3)$ as

$$\Lambda = \frac{1}{1 + L\left(\dfrac{\varepsilon_1}{\varepsilon_0} - 1\right)}. \tag{14}$$

Here and below we don't add special designations for tensor values considering that their nature is clear from the context. The division in (14) is understood as a matrix inversion, and explicit expressions for depolarisation factors Li are well-known [3] and are not written here (see e.g. Section 4 [22]; (1 in (14) is the symbol of unit matrix). With due regard to (13), formula (11) can be written as

$$\frac{\varepsilon^*}{\varepsilon_0} = 1 + \frac{f_1\langle\alpha\rangle}{1 - f_1\langle L\alpha\rangle}, \tag{15}$$

where

$$\alpha = \frac{\alpha_1}{\varepsilon_0 v_1} = (\varepsilon_1 - \varepsilon_0)\Lambda \tag{16}$$

is the tensor of specific polarizability of the ellipsoid, and symbol of full statistical averaging $\langle\ldots\rangle$ includes both averaging with respect to orientation, which is limited to calculating 1/3 of tensor trace, and averaging with respect to random distribution of depolarization factors connected with the particle configuration. So

$$\langle\ldots\rangle = \frac{1}{3}\mathrm{Sp}\Lambda\langle\ldots\rangle_L, \tag{17}$$

where $\mathrm{Sp}\Lambda = \Lambda_1+\Lambda_2+\Lambda_3$, $\Lambda_i = (1+L_i(\frac{\varepsilon_1}{\varepsilon_0}-1))^{-1}$.

To implement averaging over L, one should set a model of random distribution for depolarization factors L_i. For particles of identical configuration with prescribed L_i, averaging with respect to L in (17) can be omitted. We will not fix on it here in more detail (see, e.g., [7], section 12.2.5). A similar expression (15) can be also obtained in the event of partially ordered orientations of ellipsoids, when the composite becomes anisotropic, and ε^* becomes tensor.

If particles have a different nature, besides with random dielectric permeability ε_i, then averaging over L in (17) should be added with a statistical averaging over ε_i, which expands the class of the permissible composites with multi-component fillers.

The considered method to obtain MG allows at least a qualitative estimating applicability condi-

[3] Nevertheless, there are various readings in the referenced publications: so for example, in known monograph [7] when determining ellipsoid depolarization factors, polarizability relative to vacuum but not to medium is considered, which forces to add new depolarization factors depending on dielectric permeability of the medium and on the ellipsoid besides normal depolarization factors named in [7] as geometrical factors.

tions for this approximation. Indeed, each particle is considered on average as distant enough from its neighbours, and this requires a smallness of the effects connected with fields scattered by particles, as well as with "adhesion" of particles. This places upper limit for particle relative volume f_1 (so as such limitation, condition $f_1 < 0.4$ is considered in [37]).

Applications of MG approximation are extremely broad. It should be noticed as examples only, interesting evaluations of composites with refractive indices both high [38], and close to zero [39], as well as antiglare optical composite coatings [40].

As in the event of dielectric matrices in MG approximation, each particle is considered to be surrounded with non-conducting dielectric, for metal (well conducting) particles, this approximation allows describing the so-called conductivity resonance connected with electron movement limitation by particle volume [41]. One can find a more detailed discussion of this question for example in [37]. From the other side, for the same reason MG approximation does not describe emergence of percolation threshold (or otherwise, percolation phenomenon [42]), because it excludes a possibility of particle contact. This phenomenon consists in emergence a dielectric-metal junction in the specified composite with increase of the conducting phase concentration f_1 not beginning from $f_1 = 0$ but after some threshold value f_{1c} is only achieved [42]. This disadvantage can be eliminated in the self-coordinated Bruggeman approximation, which even in the elementary form (5) allows qualitative describing emergence of percolation threshold.

5. BRUGGEMAN APPROXIMATION IN MODELS OF ELLIPTIC CELLS

To obtain this approximation from (11), it is enough to accept the following "effective cells" model: effective cells are ellipsoids filled with the correspondent material (with ε_0 for environment points and with ε_1 for particles). The self-coordination condition consists in that each such cell is considered to be placed into an "effective medium" with dielectric permeability ε^*, in which field is regarded as uniform and equal to an average field $\langle \mathbf{E} \rangle$ (Fig. 4).

In an elementary model leading to (5), instead of ellipsoids a sphere is used, for which $L_1 = L_2 = L_3 = 1/3$.

Now let's consider a more general model of chaotically oriented ellipsoids, for which medium is statistically isotropic with scalar effective dielectric permeability ε^*. In this approximation, the field both in medium points, and in particles is expressed using relation (13), where an average field $\langle \mathbf{E} \rangle$ appears as an external field $\mathbf{E}_0$, and tensor corresponding to ellipsoids Λ is presented as expression (14) with different depolarization tensors $L^{(0)}$ for medium points and $L^{(1)}$ for particles (we will further designate these tensors as $\Lambda^{(i)}$). In this model of "effective cells", configuration of ellipsoids for particle and medium points can be various and generally this configuration is random.

Taking into account this difference allows first introducing additional free parameters into the model and secondly, corresponds to physical intuition. Indeed, "particle cell" structure is determined by choice of their typical configuration, whereas "medium cell" configuration is connected with particle relative positions. Taking into consideration the all said and using (11), after simple transformations we obtain the following:

$$f_0 \left\langle \left(\frac{\varepsilon_0}{\varepsilon^*} - 1\right) \frac{1 - L^{(0)}}{1 + L^{(0)}\left(\frac{\varepsilon_0}{\varepsilon^*} - 1\right)} \right\rangle + f_1 \left\langle \left(\frac{\varepsilon_1}{\varepsilon^*} - 1\right) \times \frac{1 - L^{(1)}}{1 + L^{(1)}\left(\frac{\varepsilon_1}{\varepsilon^*} - 1\right)} \right\rangle = 0 . \qquad (18)$$

Here statistical averaging is still understood as (17), and if necessary it can be added with averaging over random dielectric permeability ensuring description of multi-component fillers.

If as an initial approximation, expression (6) is accepted, then after setting different depolarization factors for environment and for particles, after averaging we have:

$$f_0 \left\langle \left(\frac{\varepsilon_0}{\varepsilon^*} - 1\right) \frac{1}{1 + L^{(0)}\left(\frac{\varepsilon_0}{\varepsilon^*} - 1\right)} \right\rangle + f_1 \left\langle \left(\frac{\varepsilon_1}{\varepsilon^*} - 1\right) \times \frac{1}{1 + L^{(1)}\left(\frac{\varepsilon_1}{\varepsilon^*} - 1\right)} \right\rangle = 0. \qquad (19)$$

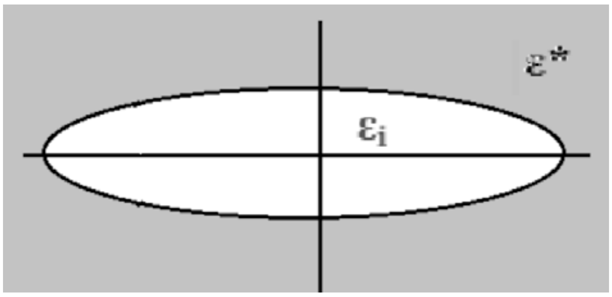


Fig. 4. Effective cell in approximation of the self-consisted Bruggeman field: ellipsoid in effective medium with ε^*

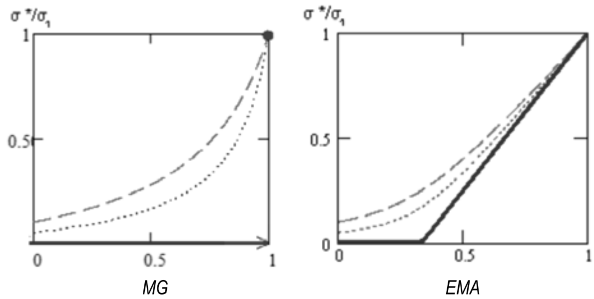


Fig. 5. Dependences of effective conductivity on filling factor f_1 in approximations MG (4) and EMA (5); – – –σ_2/σ_1= 0,1; – - -σ_2/σ_1 = 0,05; —— $\sigma_2/\sigma_1 \to 0$

Such configuration of EMA (Effective medium approximation) was widely used in different works (see, e.g., [43, 44])

Equation (18) differs from (19) by presence of multiplier factors 1-$L^{(i)}$ in each summand numerator. For identical and mono-directed ellipsoids, these common multiplier factors can be omitted, so (18) and (19) are transformed into (6), however generally such simplification does not happen. Thus (18) and (19) correspond to different models of effective medium.

6. GENERALIZED BRUGGEMAN APPROXIMATION AND PERCOLATION THRESHOLD

Equations (18) and (19) are generally rather complex and can be solved numerically. In this regard, the known problem of choice of a "correct" branch of the EMA equation solution, which generally is many-valued, should be noticed [45]). However, without solving these equations, one can at once find expressions from them for correspondent percolation thresholds. With that end in view, we will pass from consideration of dielectric permeability ε to conductivity σ, for which all relations are retained in quasistatic approximation as it was specified above. To find percolation threshold, we will consider the case of dielectric matrix $\sigma_0 = 0$ with conducting particles $\sigma_1 \neq 0$. Having replaced ε with σ everywhere and considering in (18) and (19) first $\sigma_0 = 0$, and then $\sigma^* = 0$ (order of these substitutions is important!), it is easy to obtain the following expressions for threshold value of volume particles part. In case of (18):

$$f_{1c} = 1\Big/\left\langle \frac{1}{L^{(1)}} \right\rangle, \tag{18}$$

and in case of (19):

$$f_{1c}^* = \frac{1}{1 + \dfrac{\left\langle 1/L^{(1)} \right\rangle}{\left\langle 1/(1-L^{(0)}) \right\rangle}}. \tag{19}$$

We will not further discuss these expressions, which for the model of spherical cells are both reduced to the well-known evaluation for the Bruggeman approximations f_{1c} = 1/3 (5). For an illustration, we are limited to comparison of MG and EMA approximations in simplest models (4) and (5). Fig. 5 shows effective dependences of conductivity σ^* in these models on volume part of conducting component for different relations σ_0/σ_1. One can see from these figures that MG approximation (4) gives dependence σ^* converging in limit $\sigma_0/\sigma_1 \to 0$ to a discontinuous function $\sigma^* = 0$ at $0 \leq f_1 < 1$ and $\sigma^* = 1$ at $f_1 = 1$, which corresponds to absence of the percolation threshold, whereas for EMA in this limit there are two sections of right lines with threshold value f_{1c} = 1/3 (Fig. 5).

7. CONCLUSIONS

In this review, we have briefly considered various methodical approaches to obtain MGA and EMA as most widespread homogenisation approximations, i.e. to replace a strongly non-uniform composite with a homogeneous medium so that to save invariable the measured averaged electro-dynamic characteristics of the composite. Such a procedure even for composites with non-uniformities being small in comparison with the wavelength, is feasible not always and practically leads to neglect of possible strong small-scale field fluctuations in the composite. Due to a big variety of composite inner structures, one cannot expect a creation of formulas for effective medium parameters suitable in all cases, and this explains presence of many various models in the publications. Nevertheless, MGA, EMA and their generalisations remain basic approximations when describing many nano-composite media. In this review, we have not touched on many questions connected with taking into account in MGA and EMA various complicating factors, which description can be found in the quoted references.

At present, a rapid development of nano-photonics continues, and homogenisation theory occupies a useful niche in this development, which often allows obtaining uncommon results using simple facilities.

REFERENCES

1. Milichko V. A., Shalin A.S., Mukhin I.S., Kovrov A.E., Krasilin A.A., Vinogradov A.V., Belov P.A., Simovsky K.R. Solar photovoltaics: current state and trends of development //Achievements of physical sciences, 2016, V.186, pp. 801–852. DOI:10.3367/UFNr.2016.02.037703

2. Valenta J., Mirabella S. (Eds.) Nanotechnology and Photovoltaic Devices: Light Energy Harvesting with Group IV Nanostructures.Taylor & Francis Group, 2015, 441p.

3. Lourtioz J.-M. et al., eds. Nanosciences and Nanotechnology: Evolution or Revolution? – Springer, 2016, 438 p. DOI:10.1007/978–3–319–19360–1

4. Di Bartolo B., Collins J., Silvestri L. (eds.) Nano-Structures for Optics and Photonics: Optical Strategies for Enhancing Sensing, Imaging, Communication and Energy Conversion. Springer, 2015, 586p.

5. Novotny L., Hekht B. foundations of nanooptics, Moscow: Fizmatlit, 2009, 484 p.

6. Quinten M. Optical properties of nanoparticle systems: Mie and beyond. Weinheim: Wiley-VCH, 2011, 488p. DOI:10.1016/j.jqsrt.2011.10.001

7. Boren K., Hafman D. Absorption and scattering of light by small particles. Moscow: Mir, 1986, 660 p.

8. Milton G.W. The Theory of Composites. Cambridge Univ. Press, 2004, 749 p.

9. Sihvola A. Electromagnetic Mixing Formulas and Applications, Electromagnetic Wave Series 47, London: IEE Publishing, 1999, 284p.

10. Markel V.A. Introduction to the Maxwell Garnett approximation: tutorial// J. Opt. Soc. Amer. 2016, A 33, No.7, pp.1244–1256. DOI:1084–7529/16/071244–13

11. Markel V.A. Maxwell Garnett approximation (advanced topics): tutorial // J. Opt.Soc.Amer.-2016, A 33, № . 11, pp.2237–2255. DOI:1084–7529/16/112237–19

12. Sarychev A. K., Shalaev V.M. Electrodynamics of metamaterials. Moscow: Naychny Mir, 2011, 224 p.

13. Cai W., Shalaev V. Optical Metamaterials. Springer, 2009, 200 p. DOI: 10.1007/978–1–4419–1151–3

14. Remnev M. A., Klimov V.V. Metasurfaces: a new view on Maxwell's equations and new methods of light control // Achievements of physically sciences. 2018, V.188, pp. 169–205.

15. Andrianov E. S., et al. Quantum nanoplasmonics. Dolgoprudny: Intellect Publiching house, 2015, 368 p.

16. Pal R. Electromagnetic, Mechanical, and Transport Properties of Composite Materials, 2015, CRC Press, 400p.

17. Aliofkhazraei M., ed., Handbook of Nanoparticles. Springer, 2015, 1439 p. DOI 10.1007/978–3–319–15338–4

18. Kong E. S.W. K., ed. Nanomaterials, polymers, and devices. Wiley, 2015, 584p.

19. Stenzel O. The physics of thin films. Optical spectra. An Introduction. 2nd Edition. Springer, 2016, 352 p. DOI: 10.1007/978–3–319–21602–7

20. Rosenberg G.V. Current state of the theory of optical properties of translucent metal coatings // Achievements of physically sciences, 1956, V.58, pp. 487–518. DOI:10.3367/UFNr.0058.195603d.0487

21. Maxwell J.C. Treatise on electricity and magnetism. V.1. Moscow: Nauka, 1989, 415 p.

22. Landau L. D., Lifshits E.M. Electrodynamics of solid environments. The 4th, stereotypic edition. Moscow: Fizmatlit, 2003, 656 p.

23. Taherian R. Experimental and analytical model for the electrical conductivity of polymer-based nanocomposites // Composites Science and Technology.2015. DOI: 10.1016/j.compscitech.2015.11.029

24. Lamb W., Wood D.M. and Ashcroft N.W. Long-wavelength electromagnetic propagation in heterogeneous media // Phys. Rev.1980, B21, № 6, pp.2248–2266. DOI: 10.1103/PhysRevB.21.2248

25. Maxwell Garnet J.C. Colours in metal glasses and in metallic films // Phil. Trans.R.Soc.London. 1904, A203, pp.385–420; Colours in metal glasses, in metallic films, and in metallic solutions, II., ibid. 1906, A 205, pp.237–288.

26. Strutt J. (Lord Rayleigh). On the influence of obstacles arranged in rectangular order upon the properties of a medium// Phil. Mag.1892, V. 34, 481p. DOI:10.1080/14786449208620364

27. Bruggeman D.A.G. Calculation of various physics constants in heterogeneous substances. I. Dielectric constants and conductivity of mixed bodies from isotropic substances //Ann. Phys. 1935, V.23, pp.636–664. DOI:10.1002/andp.19354160705

28. Smith G.B. Effective medium theory and angular dispersion of optical constants in films with oblique columnar structure// Opt. Commun. 1989, V.71, № 5, pp.279–284. DOI:10.1016/0030–4018(89)90008–4

29. Schmidt D., Schubert M. Anisotropic Bruggeman effective medium approaches for slanted columnar thin films //J. of Applied Physics. 2013, V.114, № 8, 083510. DOI: 10.1063/1.4819240

30. Mackay T.G., and A. Lakhtakia A. Bruggeman formalism versus "Bruggeman formalism": particulate composite materials comprising oriented ellipsoidal particles // J.of Nanophotonics. 2012, V.6, № 1, 0695012. DOI:10.1117/1.JNP.6.069501

31. Apresyan L. A., Vlasov D.V. On factors of depolarisation of anisotropic ellipsoids // Journal of technical physics. 2014, V. 84, #12, pp. 23–28.

32. Rytov S. M., Kravtsov Yu. A., Tatarsky V.I. Introduction in statistical radiophysics. V.1.2. Moscow: Nauka, 1978.

33. Tamm I.E. Fundamentals of theory of electricity: Textbook for high education institutions. Revised 11th edition, Moscow: Fizmatlit, 2003, 616 p, ISBN5–9221–0313-X.

34. Stroud D., Pan F.P. Self-consistent approach to electromagnetic wave propagation in composite media: Application to model granular metals// Phys.Rev. 1988, B37, № 15, pp.8719–8724.

35. L. A. Apresyan, D.V. Vlasov, D.A. Zadorin, V.I. Krasovsky. On a model of effective environment for particles with complex structure // Journal of technical physics. 2017, V.87, № 1, pp. 10–17. DOI: 10.21883/JTF.2017.01.44011.1841

36. Brosseau C. Modelling and simulation of dielectric heterostructures: a physical survey from an historical perspective // J. Phys. D: Appl. Phys.– 2006. – V. 39. – P. 1277–1294. DOI:10.1088/0022–3727/39/7/S02

37. Petrov Yu.I. Physics of small particles. Moscow: Nauka, 1982, 359 p.

38. Orayevsky A.N., Protsenko I.E. A high refraction factor and other features of optical properties of heterogeneous environments // Letters to JETP. 2000, V.72, pp. 641–646.

39. Liznev E. O., Dorofeenko A.V., Vinogradov A.P. Creation of environments with dielectric permeability close to zero in a wide frequency interval // Optical journal. 2010, V.77, pp. 11–12.

40. Moiseev S.G. Composite medium with silver nanoparticles as an anti-reflection optical coating//Applied Physics A. 2011, V.103, pp. 619–622.

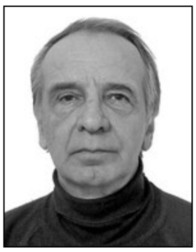
41. Marton J.P., Lemon J.R. Optical properties of aggregated metal systems. 1.Theory // Phys.Rev.– 1971, V.B4, № 2, pp.271–280.

42. Bergman D.J., Stroud D. Physical properties of macroscopically inhomogeneous media // Solid State Physics Phys, 1992, V. 46, pp.148–269.

43. Wang Y. and Weng G.J. Electrical conductivity of carbon nanotube and graphen -based nanocomposites, Ch. 4 in: S.A. Meguid, G.J. Weng (eds.), Micromechanics and Nanomechanics of Composite Solids, Springer International Publishing AG 2018. DOI 10.1007/978–3–319–52794–9_4123

44. Liang D., Schmid D., Wang H. et al. Generalized ellipsometry effective medium approximation analysis approach for porous slanted columnar thin films infiltrated with polymer // Applied Physics Letters, 2013, V. 103, № 11, 111906 (1). DOI: 10.1063/1.4821159

45. Vinogradov A. P., Dorofeenko A.V., Zukhdi S. Concerning the question of effective parameters of metamaterials // Achievements of physical sciences. 2008, V. 178, #5, pp. 511–518.



Leon A. Apresyan,
Ph.D. (Phys.-math. sciences, 1978), graduated from Moscow Physical-Technical Institute (MPhTI) in 1972. At present, he is the Senior Researcher in Prokhorov General Physics Institute of the Russian Academy of Sciences. His fields of interest are statistical radio-physics and electrodynamics of randomly inhomogeneous media

Light & Engineering
Vol. 27, No. 1, pp. 15–24, 2019

OPTICAL COMMUNICATION ON SCATTERED OR REFLECTED LASER RADIATION

Vladimir V. Belov

V.E. Zuev Institute of Atmospheric Optics
Russian Academy of Sciences, Siberian Branch, Tomsk
E-mail: belov@iao.ru

ABSTRACT

Results of theoretical and experimental research of NLOS (Non-Line of Sight) communication systems in the atmosphere, under water, and in mixed media based on publications of authors from China, Canada, Greece, the USA, Great Britain, Russia, and other countries are discussed in the present work. The theory of radiation transfer and the linear systems theory provide the basis for theoretical research. The radiation transfer equation is solved by the Monte–Carlo method in the single-scattering approximation. It is demonstrated that approximate methods are applicable when the average scattering multiplicity in open communication channels does not exceed 1.

The Monte Carlo method is used to study the influence of optical-geometric parameters of schemes of communication channels on the probabilities of communication errors, signal/noise ratios, limiting base lengths, attenuation of information-carrying signals, and their superposition leading to communication errors.

Examples of communications in the atmosphere in the UV range at distances up to 1300 m, in the visible range up to70 km, and under water up to 20 m are given.

Search for optimal methods of signal modulation, development of software and hardware complexes for numerical simulation of the transfer properties of communication channels, refinement of analytical models of impulse transfer characteristics of non-coplanar schemes of bistatic optoelectronic communication systems (OECS), and research of the effect of wind-driven sea waves and processes of radiation scattering in water are planned to study the efficiency of operation of the communication systems and to expand ranges of variations of the input NLOS and OECS parameters in the experiments carried out in natural water reservoirs.

Keywords: optical communication systems in the atmosphere and under water, Monte Carlo method, single scattering

1. INTRODUCTION

Essential progress in the development of modern high-quality communication and control systems through atmospheric channels is connected with application of radio waves for these purposes. Communication in radio range is all-weather and accessible practically to everyone.

Historically, the optical range was first used for high-rate message transfer. Though the exact date of the beginning of optical communication is unknown, it is possible to suggest that it goes in depth of centuries, when alarm fires, torches, and so forth were used for message transfer. Nowadays this communication technology is used to transmit signs of the telegraph Morse code using directional devices (for example, ISNP-250M).

Centuries later, new technologies based on applications of laser radiation sources and fibre optic channels have replaced these simplest methods of information transfer. Integration of possibilities of radio and optical communication systems of this type has culminated, in particular, in the development of the worldwide communication network – the Internet.

Does it make sense to create new optical communication systems and whether the conditions exist at which control signals or information flows cannot be transferred in radio range through the air or in acoustic range through water? Yes, because there is the impossibility or undesirability of application of radio-waves or low rates of data transfer by low rate of data transmission by acoustic devices underwater.

Therefore, the next branch of optical communication systems based on application of open communication channels in vacuum, atmospheric, and water media has been developed that allows line-of-sight information flows to be transmitted and received. Communication systems of this type are more often called *LOS* (*Line-of-Sight*) systems abroad. The useful signal in them is unscattered optical radiation. Extensive theoretical investigations devoted to the feasibility of realization of the LOS systems, estimation of their range of action in air, water, and mixed (water-air or air-water) media are performed. Results of these and experimental investigations have already been published in numerous works and continue to be published intensively (for example, see [1–10]). There are commercially available optoelectronic communication systems (OECS). A PAVLight ET-4000 optical modem can serve as an example.

This review presents results of theoretical and experimental investigations of the OECS, in which useful signal is scattered or reflected optical radiation. These OECS in Russia are called over-the-horizon or bistatic communication systems and abroad they are more often called *Non-Line-of-Sight (NLOS*) communication systems. Despite that the feasibility of realization of such communication was reported in scientific publications in the last century (for example, see [11]), intensive theoretical and then experimental studies in this direction have been started more than 15 years ago and remain relevant nowadays.

The main advantage of line-of-sight communication is high rate of data transfer. However, it can be interrupted because of interference on the radiation propagation path and beam wandering over the receiver aperture plane caused by turbulent pulsations of optical characteristics in open communication channels. Non-line-of-site optical communication has no such disadvantages. Advantages of the *NLOS* communication in comparison with *LOS* communication are that it can be realized at much larger distances when there are barriers between the receiver and the transmitter and that it is multiuser one.

Below we limit our consideration by the communication systems based on pulsed radiation sources considering that they have essential advantages at least in the range of action (and we are interested in over-the-horizon communication) over the systems with cw radiation sources.

In the review we do not consider all results of investigations in this scientific and technical area. This does not mean that the works that are not included in References of the present review have contained no new results by the moment of their

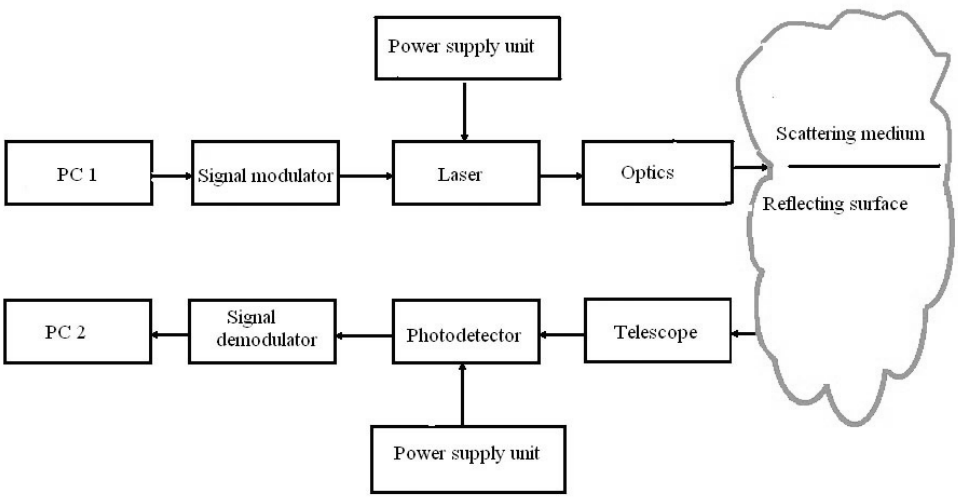


Fig. 1. General block diagram of an over-the-horizon OECS

publication; this is due to the fact that hundreds of works have already been published in reviewed journals, proceedings, and materials of conferences and symposiums.

2. PURPOSES OF RESEARCH AND PROBLEM FORMULATION

Let us describe the bistatic OECS by a set of the following parameters (we call them input ones). The radiation source: wavelength λ, polarization type, angular beam divergence ν_s, outer radius of the initial beam cross section r_s, orientation of the optical axis $\boldsymbol{\omega}_s(\theta_s, \varphi_s)$, and average power P_s. Receiving optoelectronic system: field-of-view angle ν_d, radius of the entrance pupil r_d, orientation of the optical axis $\boldsymbol{\omega}_d(\theta_d, \varphi_d)$, spectral sensitivity of the photodetector and level of its noise N. The blocks of electronic modulation and demodulation of transmitted and received radiation are compound multi-component elements of any communication system, including bistatic one. The base distance between the source and the receiver L_d is the main external OECS parameter. Fig. 1 shows the block diagram of the bistatic OECS.

In Fig. 1 we have used the following designations: PC1 denotes the control computer, PC2 denotes the receiving computer to record the obtained information and, for example, to estimate the quality characteristics of the communication channel, etc. Modulator is intended for input of information into the laser beam, and Demodulator is intended for decoding of the received scattered or reflected laser radiation. In the unit Optics, laser radiation with required divergence is formed; radiation with wavelength λ_1 can be converted into radiation with wavelength λ_2, etc. We note that in literature, bistatic OECS are sometimes called Direct NLOS if the useful signal is reflected from a surface (a building, an aircraft, a ship bottom, an air-water interface, etc.) and Non-Direct NLOS if radiation is scattered in water or in air medium.

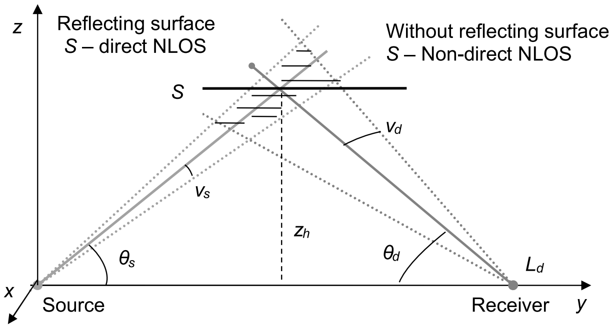


Fig. 2. Geometrical scheme of forming external channels of over-the-horizon communications

The general geometrical scheme of forming a bistatic communication channel is illustrated in Fig. 2. To simplify the figure, a coplanar OECS is shown with optical axes of the laser beam and receiving optical system located in the *XoY* plane and orientation of the axes determined by the elevation angles θ_s and θ_d.

To the main (called *output*) OECS characteristics as a whole, we refer the error probabilities p, their standard deviation (SD) σ, and the rate of symbol transfer s. Each of these characteristics depends on the parameters of transceiving systems and geometrical parameters of the schemes of external channels of the bistatic OECS.

Therefore, the main goals of theoretical and experimental investigations of the bistatic communication or control systems consist in the determination of these characteristics depending on the entire set of the parameters determining the concrete OECS type or on some part of these parameters as well as on the optical conditions in the external channels of radiation propagation from the source to the receiver. In addition, experimental investigations can be aimed at confirmation or disapproval of theoretical conclusions on the feasibility of realization and characteristics of these or other OECS. Thus, for example, in [11] the feasibility of realization of over-the-horizon communication in the UV wavelength range was predicted in 1997 at base distances up to 200 km. So far, this conclusion has neither been confirmed, nor denied.

3. ATMOSPHERIC OVER-THE-HORIZON COMMUNICATION SYSTEMS

From the viewpoint of the system analysis, any of the OECS shown in Fig. 1 can be subdivided into two parts: transceiving system and external communication channel. For fixed characteristics of optoelectronic blocks in Fig. 2, the output OECS characteristics will depend on the optical state of the channel of radiation propagation from the source to the receiver. Both in the atmosphere and in the water medium these conditions can greatly change [12–15]. Therefore, attention in [16–40] was focused on an analysis of the influence of the input OECS parameters, including the optical properties of the atmosphere, on the communication quality.

For all other conditions remaining the same, the optical properties of the communication channel can limit the working range of the OECS, increase the probability of errors, and, as for one of the means of overcoming these limitations, to a forced decrease in the rate of information signal transfer.

Theoretical research of the transfer properties of the bistatic OESS channels are carried out within in the context of the theory of short-wave radiation transfer in scattering and absorbing media (namely, in the atmosphere and water media) and of the theory of analysis of linear systems.

The radiation transfer equation (RTE) establishes a relationship between the light field intensity at the given point in a preset direction in the medium and its optical characteristics. In the integro-differential form, it is written as

$$\frac{1}{c}\frac{\partial I}{\partial t}+(\boldsymbol{\omega}, grad\ I)=-\beta_{ext}I+\beta_{sc}\times$$
$$\times\int_{\Omega} I(\boldsymbol{r},\boldsymbol{\omega}')g(\boldsymbol{r},\boldsymbol{\omega},\boldsymbol{\omega}')d\boldsymbol{\omega}'+\Phi_o(\boldsymbol{r},\boldsymbol{\omega}), \qquad (1)$$

where $I = I(\lambda\boldsymbol{r}, \omega)$ is the radiation intensity at the point $\boldsymbol{r}$ in the direction ω, c is the velocity of light, $\beta_{ext}(\lambda\boldsymbol{r})$ is the extinction coefficient at the point $\boldsymbol{r}$, $\beta_{sc}(\lambda\boldsymbol{r})$ is the scattering coefficient at the point $\boldsymbol{r}$, $g(\lambda\boldsymbol{r}, \omega\omega')$ is the normalized scattering phase function at the point $\boldsymbol{r}$ in the direction ω, ω' specifies the direction of radiation propagation before scattering, and Φ_0 is the source function at the point $\boldsymbol{r}$ in the direction ω.

Equation (1) is linear for the intensity; therefore, it is expedient to analyze the transfer properties of the bistatic communication channel in the context of the linear systems theory, that is, to investigate the channel response $h(t)$ to the input $\delta(t)$ pulse depending on the input OECS parameters.

Equation (1) has no general analytical solution. For communication with the NLOS systems, different algorithms of the Monte Carlo method (from direct simulation algorithms [19] to double local estimate modifications [20]) are often used. The single scattering approximation for the determination of impulse response h (t), pulse broadening, etc. has obvious limitations of its application field. This is illustrated in Fig. 3.

The time interval [t_1, t_2] indicated in Fig. 3 corresponds to the intersection of the laser beam divergence angle with the field-of-view angle of the receiving system in Fig. 2 (hatched region). The

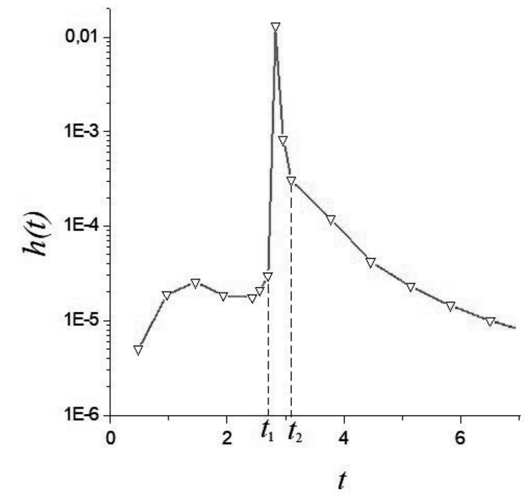


Fig. 3. Example of the impulse response simulated in [18] by the Monte Carlo method

function h (t) for t lying beyond this interval is determined by radiation with scattering multiplicity higher than 1. This means that the leading and trailing edges of the impulse response $h(t)$ in Fig 3 can be determined by solving RTE (1) taking into account scattering multiplicity no lower than 2.

The atmospheric OECS have a wider spectral range of characteristics of laser sources – from UV to IR ranges; for the underwater systems, this choice is limited by the visible range (*green* and *dark blue* ranges).

What are reasons for interruptions or infeasibility of bistatic communication? Obviously, to record informative signal, its power must be greater than the power P_f of the intrinsic photodetector noise. Communication errors arise if this condition is not satisfied from time to time. This can be caused by the presence of turbulent fluctuations of the optical characteristics in the communication channel or when local scattering or absorbing optically denser formations (fragments of smoke plumes, cloudy media, etc.) fall within the receiver field-of-view. The power of the received informative signal can exceed that of noise, but nevertheless, communication can be impossible. This occurs when the impulse response at $t < t_1$ and $t \to t_1$ or at $t < t_2$ and $t \to t_2$ becomes close or equal to max h (t) in its central part.

Let us try, proceeding from this general knowledge of interaction of optical radiation with scattering and absorbing media, to estimate the influence of some optical-geometrical parameters of bistatic OECS, for example, on the range of action. We now perform a number of the following thought experiments. We fix all geometrical and optical parameters and the photodetector characteristics. Let the laser radiation beam divergence v_s be zero. And let the range of action reaches L_d. We will increase v_s to π/2. It is obvious that L_d will monotonically decrease since the radiation flux density in the region of intersection of cones of the beam divergence and of the field of view of the receiving optical system will monotonically decrease (Fig. 2). The increase in v_s will also result in the increased impulse response at $t < t_1$ and $t \to t_1$ or at $t < t_2$ and $t \to t_2$, thereby increasing the probability of errors, which can be decreased by decreasing the pulse transfer rate.

Let all optical-geometrical parameters of the OECS scheme be fixed (Fig. 2), except the field-of-view angle of the receiving optical system v_d, which we will monotonically increase starting from zero value. We assume that at $v_d = 0$ the range of OECS action is equal to L_d. It can be easily demonstrated that with increasing v_d, the power of the fronts of the impulse response $h(t)$ will increase together with the interval $[t_1, t_2]$, but max $h(t)$ will not increase. Both these factors can lead to an increase in the communication errors, that is starting from some critical v_d values the maximum base L_d will decrease.

It is sufficiently simply to predict the dependence of L_d on the variations of some optical properties of the medium in which the external channel of the OESS in Fig. 2 is formed. Let the optical characteristics of the medium be homogeneous. We fix values of the remaining OECS parameters. Let the scattering properties of the medium be absent. Then obviously, the base $L_d = 0$, the probabilities of errors $p = 0$, and the rate of symbol transfer $s = 0$. Let the scattering coefficient $\beta_{sc} \to \infty$; then it is obvious that $L_d \to 0$, the probabilities of errors $p \to 0$, and the rate of symbol transfer $s \to 0$. Hence, for each concrete β_{sc} value, there exist nonzero values L_d, p and s. This means that for each set of the input OECS parameters, there exists such optical state of the medium at which a maximum L_d value can be realized.

This suggests that optimal conditions for communication (at least, from the viewpoint of max $h(t)$) can be obtained by variations of the orientation angles θ_s and θ_d of the transmitter and receiver axes (given that all other OECS parameters remain the same), when θ_s and $\theta_d \to 0°$. This conclusion remains the same if vertical optical inhomogeneity of the atmosphere is considered with its scattering properties decreasing with increasing altitude above the Earth surface. In this case, exotic cases when the scattering properties near the Earth surface $\beta_{sc} \to \infty$ were disregarded. It is obvious that an increase in the average or peak laser radiation power will lead to the increase of the maximum L_d values.

As to the atmospheric OECS, much greater number of theoretical and experimental works was devoted to the UV NLOS systems. A fairly good review on the history of the development of UV signal transmission and registration is suggested in [16]. The lamps and flash lamps mentioned in this work were previously used as light sources in communication systems. All these devices, as a rule, are bulky, and consume significant power. Semiconductor optical sources have low cost, small size, low power consumption, and high reliability. Therefore, modern commercial light-emitting diodes and photodetectors (including avalanche ones) are accessible and are widely used in the bistatic UV communication systems. Nevertheless, there are examples of application of solid-state UV lasers [21] and of transformation of output radiation of the visible range lasers into the UV range [56].

The overwhelming majority of experimental investigations in [16–40] consider UV OECS with application to small bases L_d. In [56] a bistatic communication was operated in this spectral range in the daytime at the base distance equal to 1300 m.

We emphasize that the number of works on the OECS in the visible and IR spectral ranges is significantly less than of works on the OESC in the UV range. Works [2] (an infrared LOS OECS) and [53] (a visible range NLOS OECS) can be mentioned here as examples. Interest to the UV communication systems is understandable. In the solar-blind range they can be employed round the clock in the absence of artificial UV noise sources.

The main methods of research of the transmission properties of NLOS channels are the Monte Carlo method [18–20,23,29,30,32,33,34,39,50–52] and the single scattering approximation [11,17,22,38]. In [17–19] results of theoretical and experimental investigations of the influence of the geometrical parameters on the probabilities of errors and range of action of the bistatic OECS were presented. In [30] it was shown that the single scattering approximation cannot be used to solve the RTE to explain exhaustively the results obtained in experiments. In [30] the widths of the impulse response determined for concrete input parameters of the OECS schemes by the Monte Carlo method and in the single scattering approximation were compared. It was shown that the single scattering approximation is applicable to estimate *h* (*t*) if the medium is transparent and the multiplicity of scattering in the atmospheric channel does not exceed 1. In model experiment with the average number of collisions in the channel equal to 3.85, the duration of *h* (*t*) was 8 μs, whereas in the single scattering approximation it was practically absent.

The common feature of [16,17,19,21–36,38,39] was that they presented results of theoretical and-or experimental investigations devoted in some extent to an analysis of the influence of the input OECS parameters on the communication quality (probability of errors) and range of action (not exceeding 100 m in the experiments) on the rate of data transfer and the protection against noise.

In [54] an example of simulation by the Monte Carlo method of the impulse response was given, and with its help ranges of action and data transfer rates were estimated taking into account the characteristics of a FEU-17a photodetector. Statistical experiments were performed for the OECS comprising the laser radiation source at a wavelength λ = 0.5 μm. A dependence of the communication quality on the temperature regime of the receiver operation was considered in [6, 57].

An important place in theoretical and experimental investigations of experts on the bistatic OECS was occupied by the methods of increasing the stability of their operation. The choice of the methods of radiation modulation and their comparison was considered, for example, in [26]. In [23, 25] different types of the OESS radiation receivers were discussed.

4. UNDERWATER BISTATIC COMMUNICATION SYSTEMS

Works [41–51, 55] were devoted to theoretical and experimental investigations of underwater communication systems. Among them, attention is drawn to work [44] in which extensive review of studies was presented devoted to the LOS systems, but including some aspects of the communication NLOS Systems. It contains 232 references to publications of authors from the USA, Canada, China etc. Let us complement it by a short analysis of other works.

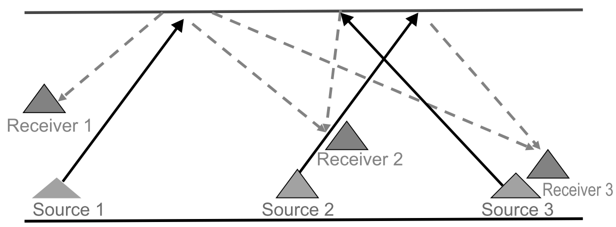


Fig. 4. Geometrical scheme of underwater communication based on radiation reflection from the water-atmosphere interface

In Fig. 4, one of such problem formulations considered in [46, 51] is shown. This communication scheme was called Direct NLOS (see Fig. 2). Interest in these investigations is caused by the application of networks of intellectual robots for solving problems of monitoring of states of underwater objects, exploration of natural resources, etc. In [46, 51] numerical experiments were performed, and not only flat, but also wavy water surface was considered; however, radiation scattering in water was not taken into account.

In publication [42], results of experimental laboratory research performed for small base distances not exceeding several meters were discussed. Conclusions from these experiments are reduced to that the range of action of LOS and Direct and Non Direct NLOS communication systems depends on the water turbidity whose increase leads to the decrease of their range of action and data transmission rate.

The overwhelming number of publications of the results of theoretical investigations of the bistatic underwater OECS are based on the application of the Monte Carlo method for solving the radiation transfer equation. Here we refer only to [43,47–51] publications. The transfer properties of the underwater bistatic communication channels were described in the context of the linear systems theory using the influence functions *h* (*t*) ([47] reference can serve as an example). In [48], possibilities of the LOS and NLOS systems were compared. Numerical experiments demonstrated that the rate of symbol transfer in the LOS communication systems can reach 100 MHz in a turbid medium and is much greater in a clear medium. For NLOS systems, this rate is limited by 20 MHz in clear water. These results were obtained by numerical experiments with base distances up to 20 m. For simulation by the Monte Carlo method of the process of optical radiation propagation in a water medium, the Henyey–Greenstein model of the scattering phase function was used in [48]. The probabilities of communication errors caused by the pulse interference, that is, superposition of the leading edge of the current pulse on the trailing edge of the previous pulse (see Fig. 3) were estimated in [48].

Let us pay attention to papers [45, 55] in which results of experiments on optical communication through mixed media were presented. In [45], results of laboratory experiments were discussed with the LOS scheme of communication on air-water paths (the receiver was placed in water) and on water-air paths (the receiver was placed in air). In [55], results of field experiments in a natural water reservoir were presented. In particular, the probabilities of communication and their standard deviations were given for communication through ice.

5. CONCLUSIONS

The urgency of research on the problems of optical communication based on scattered or reflected radiation is confirmed by abundance of previous and continuing publications (there are examples of works published in 2018). The countries in which scientific groups carrying out study in this direction are sufficiently widespread all over the world: China (the greatest number of publications), Canada, the USA, Greece, Great Britain etc. There are some examples of international teams.

The main conclusions based on the above-discussed publications can be formulated as follows. Results of simulations by the Monte Carlo method of the informative signal transfer through atmospheric bistatic channels [54] in the visible wavelength range have allowed us to conclude that at small base distances (2–3 km), the power of the received informative pulse is maximum for radiation in the UV range ($\lambda \approx 0.3$ μm) given that the remaining conditions remain the same. For large base distances and low turbidity of the medium (meteorological visibility range $S_M \approx 50$ km), it is observed at $\lambda \approx 0.5$ μm. At high atmospheric turbidity ($S_M \approx 10$ km), depending on the base distances and the orientation of the receiving plane, it can be obtained at $\lambda \approx 0.5$ μm and $\lambda \approx 0.9$ μm. In the same work, it was also shown that the limiting frequencies of pulses transmission in a bistatic optoelectronic communication system, depending on the optical conditions in the atmosphere and geometrical parameters of the schemes of communication channels, lie within the limits from 4×10^3 to 2×10^7 Hz (for ideal characteristics of the receiving and transmitting systems).

The implementation of the bistatic communication in the atmosphere in the visible wavelength range for base distances up to 70 km was reported in [53]; in [56] the communication in the UV range was realized for base distances up to 1300 m; and the underwater communication in a natural water reservoir for base distances up to 40 m was reported in [58].

In [28] based on investigations on the network applications of the NLOS systems, it was established that the optical communication systems intended for short (up to 100 m) base distances with semiconductor sources are significantly cheaper and have smaller overall dimensions. Experiments in [28] were carried out at a radiation wavelength of 0.34 μm.

Software for investigation of the transfer properties of non-coplanar communication systems (for example, see [23, 33]) has been developed. Theoretical results obtained in [24] were confirmed by experiments.

In [31] the possibility of application of network technologies for monitoring of biosystems, detection of fires, control of atmospheric pollution, and communication in the UV range of wavelengths 0.200–0.280 μm was analyzed. On the basis of analytical relationships derived in the single scattering approximation for small base distances, the influence of optical-geometric conditions of observations and radiation power on the probability of errors, the signal/noise ratio, and some other characteristics of the examined OECS was investigated.

In publications, different types of laser sources used in bistatic OECS were reported. There are examples of application of CW (continuous wave) radiation with its subsequent transformation into pulsed radiation [40]. The OESS can include solid-state lasers in the UV range and gas-discharge lasers with radiation in the visible range that can be transformed, if necessary, into UV radiation using nonlinear BBO crystals.

Attention of researchers was also focused on the problem of application of polarization properties of light to improve the noise protection of the OECS operating on scattered laser radiation. In [34], the development of the Monte Carlo program-algorithmic complex was reported intended for simulation of propagation and reception of polarized radiation in the NLOS communication channels. It was shown that the reception of the polarized signal makes it possible to decrease the probability of errors by decreasing the influence of multiple scattering on the formation of the leading and trailing pulse edges.

One of the factors that influence the quality of bistatic OECS performance is turbulence. It can decrease the useful signal power and interrupt the communication. In [35], the influence of the number of receivers on the communication errors was analyzed.

The important OECS components are photodetectors. In the literature discussed above, Hamamatsu solid-state photodetectors, avalanche photodiodes, domestic FEU142 and 17a, and modern photoelectronic multipliers UFK-4G-4, UFK-4G-3, and UFK-4G-2 (manufactured by the "KATOD" LLC) were used.

In [52, 53], the procedure of estimating in real time of the probabilities of communication errors and their SD was described for OECS testing in the atmosphere, water, and mixed media.

In [51], the Monte Carlo method was used to perform numerical experiments on underwater communication taking into account the wavy water surface for schemes of Direct NLOS, and the rate of data transmission in clear and turbid water was estimated.

Future investigations will be aimed at the search for optimal methods of signal modulation, the development of means for numerical simulations of transfer properties of the NLOS communication channels, the development of analytical models of the impulse response in non-coplanar schemes of the bistatic OECS, the study of the influence of waves on the water surface and scattering processes in water on the overall performance of the communication systems on scattered laser radiation, and expansion of the range of variations of the input parameters of NLOS OECS for carrying out experiments in natural water reservoirs.

The author is grateful to his colleagues M.V. Tarasenkov, V.N. Abramochkin, A.V. Fedosov, A.N. Kudryavtsev, V.V. Ivanov, and Yu.V. Gridnev for their collaboration in the research, creation, and testing of the atmospheric and underwater bistatic OECS.

REFERENCES

1. Lee I.E., Ghassemlooy Z., Ng W.P., Khalighi M-A., and Liaw S-K. Effects of aperture averaging and beam width on a partially coherent Gaussian beam over free-space optical links with turbulence and pointing errors//Applied Optics. 2016. Vol. 55, No. 1, pp. 1–9.

2. Amr S. El-Wakeel, Nazmi A. Mohammed, and Moustafa H. Aly. Free space optical communications system performance under atmospheric scattering and turbulence for 850 and 1550 nm operation//Applied Optics. 2016. Vol. 55, No. 26, pp. 7276–7286.

3. Zhengguang Gao, Hongzhan Liu, Xiaoping Ma, and Wei Lu. Performance of multi-hop parallel free-space optical communication over gamma–gamma fading channel with pointing errors//Applied Optics. 2016. Vol. 55, No. 32, pp. 9178–9184.

4. Zina Abu-Almaalie, Zabih Ghassemlooy, Manav R. Bhatnagar, Hoa Le-Minh, Nauman Aslam, Shien-Kuei Liaw, and It Ee Lee. Investigation on iterative multiuser detection physical layer network coding in two-way relay free-space optical links with turbulences and pointing errors//Applied Optics. 2016. Vol. 55, No. 33, pp. 9396–9406.

5. Xin Zhao, YunQing Liu, and Yansong Song. Line of sight pointing technology for laser communication system between aircrafts//Optical Engineering. 2017. Vol. 56, No. 12, p. 126107.

6. Huihua Fu, Ping Wang, Tao Liu, Tian Cao, Lixin Guo, and Jiao Qin. Performance analysis of a PPM-FSO communication system with an avalanche photodiode receiver over atmospheric turbulence channels with aperture averaging//Applied Optics. 2017. Vol. 56, No. 23, pp. 6432–6439.

7. Bykova N.G., Gochelashvily K.S., Karfidov D.M., Makarenko G.F., Senatorov A.K., Sergeichev K.F., Shatalov O.P., and Zabelinskii I.E. Experimental demonstration of feasibility of laser communication with the reentry spacecraft at 1.55 μm//Applied Optics. 2017. Vol. 56, No. 10, pp. 2597–2603.

8. Jing Ma, Jiajie Wu, Liying Tan, and Siyuan Yu. Polarization properties of Gaussian–Schell model beams propagating in a space-to-ground optical communication downlink//Applied Optics. 2017. Vol. 56, No. 6, pp. 1781–1787.

9. Ming Li, Wenbo Gao, and Milorad Cvijetic. Slant-path coherent free space optical communications over the maritime and terrestrial atmospheres with the use of adaptive optics for beam wavefront correction//Applied Optics. 2017. Vol. 56, No. 2, pp. 284–297.

10. Vorontsov M.A, Dudorov V.V., Zyryanov M.O., Kolosov V.V., and Filimonov G.A. Frequency of occurrence of erroneous bits in systems of wireless optical communication with partially coherent transmitting beam//Atmosphere and Oceanic Optics. 2012. Vol. 25, No. 11, pp. 936–940.

11. Pozhidaev V.N. Practicability of communication lines of the ultraviolet range based on molecular and aerosol scattering in the atmosphere//Radiotekh. Elektr. 1977. Vol. 22, No. 10, pp. 2190–2192.

12. Zuev V.E. and Krekov G.M. Modern Problems of Atmospheric Optics. Vol. 2/Optical Models of the Atmosphere. Leningrad: Gidrometeoizdat, 1986. 256p.

13. Zuev V.E., Belan B.D., and Zadde G.O. Optical Weather//Publishing House "Nauka" Siberian Branch of the Russian Academy of Sciences. Novosibirsk, 1990, 192 p.

14. Ocean and Atmosphere Optics/under the editorship of K.S. Shifrin. Moscow: Nauka, 1981, 231 p.

15. Ocean Optics. Vol. 2. Applied Optics of the Ocean/under the editorship of A.S. Monin. Moscow: Nauka, 1983, 236 p.

16. Chen G., Abou-Galala F., Xu Z., and Sadler B.M. Experimental evaluation of LED-based solar blind NLOS communication links//Optics Express. 2008. Vol. 16, No. 19, pp. 15059–15068.

17. Chen G., Xu Z., Ding H., and Sadler B.M. Path loss modeling and performance trade-off study for short-range non-line-of-sight ultraviolet communications//Optics Express. 2009. Vol. 17, No. 5, pp. 3929–3940.

18. Belov V.V., Tarasenkov M.V., Abramochkin V.N., Ivanov V.V., Fedosov A.V., Troitskii V.O., and Shiyanov D.V. Atmospheric bistatic communication channels with scattering. Part 1. Methods of Research//Atmospheric and Oceanic Optics. 2013. Vol. 26, No. 4, pp. 261–267.

19. Ding H., Chen G., Majumdar A.K., Sadler B.M., and Xu Z. Modeling of Non-Line-of-Sight Ultraviolet Scattering Channels for Communication//IEEE Journal on Selected Areas in Communications. 2009. Vol. 27, No. 9, pp. 1535–1541.

20. Belov V.V. and Tarasenkov M.V. Three algorithms of statistical simulation in problems of optical communication on scattered radiation and bistatic sensing//Atmospheric and Oceanic Optics. 2016. Vol. 29, No. 05, pp. 397–403.

21. Chen G., Xu Z., and Sadler B.M. Experimental demonstration of ultraviolet pulse broadening in short-range non-line-of-sight communication channels//Optics Express. 2010. Vol. 18, No. 10, pp. 10500–10509.

22. Bifeng Li, Hongxing Wang, Min Liu, Hao Hu, Zhongyang Mao. Applicability of non-line-of-sight ultraviolet single-scatter approximation model// Photon. Netw. Commun. 2016. Vol. 31, No. 1, pp. 147–154.

23. Dahai Han, Xing Fan, Kai Zhang, and Rui Zhu. Research on multiple-scattering channel with Monte Carlo model in UV atmosphere communication//Applied Optics. 2013. Vol. 52, No. 22, pp. 5516–5522.

24. Hailiang Zhang, Hongwei Yin, Honghui Jia, Shengli Chang, and Juncai Yang. Characteristics of non-line-of-sight polarization ultraviolet communication channels//Applied Optics. 2012. Vol. 51, No. 35, pp. 8366–8372.

25. Dahai Han, Yile Liu, Kai Zhang, Pengfei Luo, and Min Zhang. Theoretical and experimental research on diversity reception technology in NLOS UV communication system//Optics Express. 2012. Vol. 20, No. 14, pp. 15833–15843.

26. Menglong Wu, Dahai Han, Xiang Zhang, Feng Zhang, Min Zhang, and Guangxin Yue. Experimental research and comparison of LDPC and RS channel coding in ultraviolet communication systems//Optics Express. 2014. Vol. 22, No. 5, pp. 5422–5430.

27. Petr Chvojka, Stanislav Vitek, Stanislav Zvanovec, Zabih Ghassemlooy, and Sujan Rajbhandari. Analysis of nonline-of-sight visible light communications//Optical Engineering. 2017. Vol. 56, No. 11: 116116. DOI.org/10.1117/1.OE.56.11.116116.

28. Gary A. Shaw, Andrew M. Siegel, Melissa L. Nischan. Demonstration system and applications for compact wireless ultraviolet communications//Proc. SPIE. 2003. Vol. 5071. Doi.org/10.1117/12.500861.

29. Peng Song, Xianli Zhou, Fei Song, Caixia Su, and Anxiang Wang. Performance analysis of UV multiple-scatter communication system with height difference//Applied Optics. 2017. Vol. 56, No. 32, pp. 8908–8916.

30. Yin H., Chang S., Jia H., Yang J., and Yang J. Non-line-of-sight multiscatter propagation model//J. Opt. Soc. Am. A. 2009. Vol. 26, No. 11, pp. 2466–2469.

31. Debbie Kedar. Multiaccess interference in a non-line-of-sight ultraviolet optical wireless sensor network//Applied Optics. 2007. Vol. 46, No. 23, pp. 5895–5901.

32. Hongwei Yin, Shengli Chang, Xiaofeng Wang, Jiankun Yang, Juncai Yang, and Jichun Tan. Non-line-of-sight multiscatter propagation model//J. Opt. Soc. Am. A. 2009. Vol. 26, No. 11, pp. 2466–2069.

33. Mohamed A. Elshimy and Steve Hranilovic. Non-line-of-sight single-scatter propagation model for non-coplanar geometries//J. Opt. Soc. Am. A. 2011. Vol. 28, No. 3, pp. 420–428.

34. Hongwei Yin, Honghui Jia, Hailiang Zhang, Xiaofeng Wang, Shengli Chang, and Juncai Yang. Vectorized polarization-sensitive model of non-line-of-sight multiple-scatter propagation//J. Opt. Soc. Am. A. 2011. Vol. 28, No. 10, pp. 2082–2085.

35. Houfei Xiao, Yong Zuo, Jian Wu, Yan Li, and Jintong Lin. Bit-error-rate performance of non-line-of-sight UV transmission with spatial diversity reception//Optics Letters. 2012. Vol. 37, No. 19, pp. 4143–4145.

36. Robert J. Drost, Terrence J. Moore, and Brian M. Sadler. Ultraviolet scattering propagation modeling: analysis of path loss versus range//J. Opt. Soc. Am. A. 2013. Vol. 30, No. 11, pp. 2259–2265.

37. Peng Wang and Zhengyuan Xu. Characteristics of ultraviolet scattering and turbulent channels//Optics Letters. 2013. Vol. 38, No. 15, pp. 2773–2775.

38. Houfei Xiao, Yong Zuo, Jian Wu, Yan Li, and Jintong Lin. Non-line-of-sight ultraviolet single-scatter propagation model in random turbulent medium//Optics Letters. 2013. Vol. 38, No. 17, pp. 3366–3369.

39. Siqi Hu, Le Mi, Tianhua Zhou, and Weibiao Chen. Viterbi equalization for long-distance, high-speed under-

water laser communication//Optical Engineering. 2017. Vol. 56, No. 7, p. 076101.

40. Hongwei Yin, Shengli Chang, Xiaofeng Wang, Jiankun Yang, Juncai Yang, and Jichun Tan. Analytical model of non-line-of-sight single-scatter propagation//JOSA A. 2010. Vol. 27, No. 7, pp. 1505–1509.

41. Kuznetsov C., Ognev B., and Polyakov S. System of optical communication in water//Pervaya Milya. 2014, No. 2, pp. 46–51.

42. Hanson F. and Radic S. High bandwidth underwater optical communication//Appl. Opt. 2008. Vol. 47, No. 2, pp. 277–283.

43. Jaruwatanadilok S. Underwater wireless optical communication channel modeling and performance evaluation using vector radiative transfer theory//IEEE J. on Selected Areas in Communications. 2008. Vol. 26, No. 9, pp. 1620–1627.

44. Hemani Kaushal1 and Georges Kaddoum. Underwater optical wireless communication//IEEE Access. 2016, Vol. 4, pp. 1518–1547.

45. Majumdar A.K., Siegenthaler J., and Land P. Analysis of optical communications through the random air-water interface: feasibility for under-water Communications//Proc. SPIE. 2012. Vol. 8517, 85170T. DOI: 10.1117/12.928999.

46. Arnon S. and Kedar D. Non-line-of-sight underwater optical wireless communication network//J. Opt. Soc. Am. A. 2009. Vol. 26, No. 3, pp. 530–539.

47. Gabriel C., Khalighi M.-A., Bourennane S., Leon P., and Rigaud V. Channel modeling for underwater optical communication//2011 IEEE GLOBECOM Workshops (GC Wkshps). 2nd International Workshop in Optical Wireless Communications. 2011, pp. 833–837. DOI: 10.1109/GLOCOMW.2011.6162571.

48. Choudhary A., Jagadeesh V.K., and Muthuchidambaranathan P. Path loss analysis of NLOS underwater wireless optical communication channel//2014, International Conference on Electronics and Communication System (ICECS-2014). DOI: 10.1109/ECS.2014.6892620.

49. Jagadeesh V.K., Choudhary A., Bui F.M., and Muthuchidambaranathan P. Characterization of channel impulse responses for NLOS underwater wireless optical communications//2014, Fourth International Conference on Advances in Computing and Communications (ICACC). DOI: 10.1109/ICACC.2014.24

50. Chadi Gabriel, Mohammad-Ali Khalighi, Salah Bourennane, Pierre Léon, and Vincent Rigaud. Monte-Carlo-based channel characterization for underwater optical communication systems//IEEE/OSA Journal of Optical Communications and Networking. 2013. Vol. 5, No. 1, pp. 1–12

51. Shijian Tang, Yuhan Dong, and Xuedan Zhang. On Path loss of NLOS underwater wireless optical communication links//2013 MTS/IEEE OCEANS. DOI: 10.1109/OCEANS-Bergen.2013.6608002

52. Belov V.V., Tarasenkov M.V., Abramochkin V.N., Troitskii V.O. Over-the-horizon optoelectronic communication systems//Russian Physics Journal. 2014 Vol. 57, No. 7, pp. 202–208.

53. Abramochkin V.N., Belov V.V., Gridnev Yu.V., Kudrjavtsev A.N., Tarasenkov M.V., and Fedosov A.V. Optoelectronic communication in the atmosphere on scattered laser radiation. Field experiments//Light engineering. 2017. No. 4, pp. 24–30.

54. Tarasenkov M.V., Poznakharev E.S., and Belov V.V. Statistical estimations of transfer characteristics, limiting ranges, and rates of information transfer in pulsed atmospheric bistatic optical communication channels// Svetotekhnika, 2018, No. 4, pp. 37–43.

55. Belov V.V., Abramochkin V.N., Gridnev Yu. V., Kudryavtsev A.N., Tarasenkov M.V., and Fedosov A.V. Bistatic optoelectronic communication systems: Field experiments in artificial and natural water reservoirs//Atmospheric and Oceanic Optics. 2017 Vol. 30, No. 4, pp. 366–371.

56. Belov V.V., Gridnev Yu.V., Kudryavtsev A.N., Tarasenkov M.V., and Fedosov A.V. Optoelectronic communication in the UV wavelength range on scattered laser radiation//Atmospheric and Oceanic Optics. 2018. Vol. 31, No. 07, pp. 559–562.

57. Belov V.V., Tarasenkov M.V., Abramochkin V.N., Ivanov V.V., Fedosov A.V., Gridnev Yu.V., Troitskii V.O., Dimaki V.A. Atmospheric bistatic communication channels with scattering. Part 2. Field experiments of 2013//Atmospheric and Oceanic Optics. 2014. Vol. 27, No. 08, pp. 659–664.

58. Belov V.V. Optical communication on scattered laser radiation // Proceedings of SPIE. 2017. V. 10466. CID:10466 0H. [10466–24].

Vladimir V. Belov,
Prof., Dr. of Phys.-math. Sciences, graduated from Tomsk State University in 1971. At present, he is the Head of laboratory of V.E. Zuev Institute of Atmospheric Optics of Russian Academy of Sciences (SB), Honoured Scientist of the Russian Federation, his research interests: the theory of optical radiation transfer in scattering and absorbing media, the theory of laser sensing, the theory of vision, atmospheric correction of aerospace images of the earth's surface, the Monte Carlo method, multiple scattering

Light & Engineering
Vol. 27, No. 1, pp. 25–32, 2019

A BIDIRECTIONAL SCATTERING FUNCTION RECONSTRUCTION METHOD BASED ON OPTIMIZATION OF THE DISTRIBUTION OF MICRORELIEF NORMALS

Nicolai N. Bogdanov [1], Andrew D. Zhdanov [1], Dmitriy D. Zhdanov [1], Igor S. Potyomin [1],
Vadim G. Sokolov [2], and Eugene Y. Denisov [2]

[1] ITMO University, Saint-Petersburg, Russia
[2] Keldysh Institute of Applied Mathematics (RAS), Moscow, Russia
E-mails: nnbogdanov@corp.ifmo.ru; eed@gin.keldysh.ru; adzhdanov@corp.ifmo.ru; ddzhdanov@mail.ru; ipotemin@yandex.ru; sokolovv1969@gmail.com

ABSTRACT

The paper is devoted to the development of a method for reconstructing the scattering properties of a rough surface. The rough surface, in this case, is the dielectric-air interface. Typically, these properties are described by the bidirectional scattering distribution function. Direct measuring of such functions is either impossible, or its cost is very high. The method of reconstructing the bidirectional scattering distribution function, based on the distribution of the elevations of the microrelief, requires a complicated fitting procedure and often yields not very good results. In the proposed solution, the rough surface is modelled by a parametric function that simulates the density distribution of the normals to the faces of the surface microrelief. The result of optimizing the density distribution of the normals to the faces of the surface microrelief is in good agreement with the expected one.

Keywords: microrelief, bidirectional scattering distribution function, rough surface, diffusion, rendering, photoconductive systems, total internal reflection, wave optics, ray optics

1. INTRODUCTION

Photoconductive optical elements with rough surfaces, Fig.1, are widely used in devices with complex light distribution. As a rule, rough surfaces are used in two cases: either to form a special goniometric light scattering diagram or to create the required spatial luminance distribution in various photoconductive devices, such as liquid crystal display illumination systems, car dashboards, LED luminaires, etc. When modelling the propagation of light inside the material of a photoconductive element, it is necessary to take into account the optical properties of a rough interface between two media, whereas the optical properties of the entire element are meaningless. Moreover, these properties differ depending on whether the light falls on the interface from the side of the material of the photoconductive element or whether light falls on the surface from the air. Therefore, for physically-correct modelling of such devices, the optical properties of

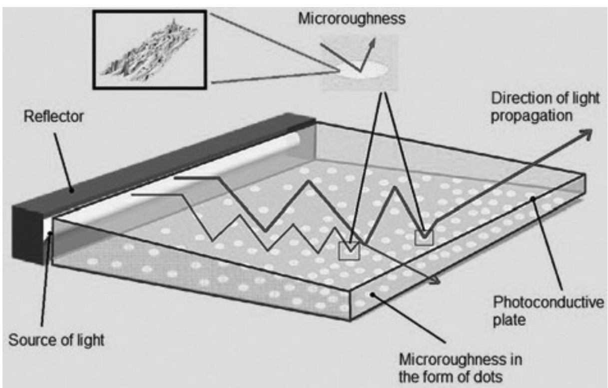


Fig. 1. An example of the use of a rough surface

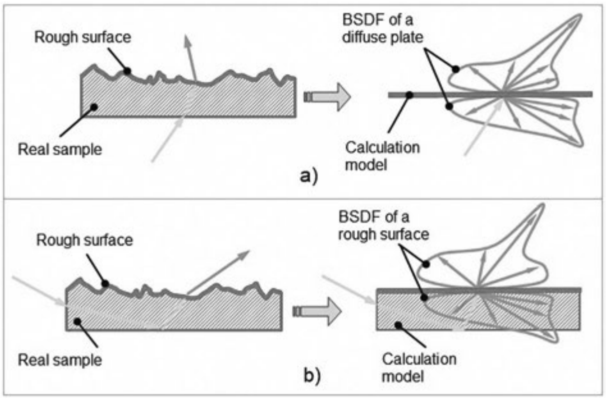


Fig. 2. "Surface" model pf a diffuse plate (a), "solid-state" model of a PCP

a rough surface must be taken into account individually for each side.

Fig. 1 shows an example of the use of a rough surface. On the lower surface of the photoconductive plate (PCP) stains with microrelief are applied. These stains are scattering surfaces. They have a relatively small size, and therefore they are sometimes called diffuse points. Inside the PCP, the light beam spreads according to the law of total internal reflection. After scattering at diffuse points, the beam deviates from the direction of specula reflection and can leave the PCP. The diffuse point's density distribution that varies along the surface of the PCP makes it possible to obtain uniform radiation over the entire area of the external surface.

The light scattering parameters of a rough surface are described by the bidirectional scattering distribution function (BSDF). The function has a complex multidimensional representation and depends on a number of parameters, such as the direction of incident light, the observation direction of light and the spectral composition (colour) of the radiation. The BSDF is a superposition of two functions: the bidirectional reflectance distribution function (BRDF) and the bidirectional transmittance distribution function (BTDF). For flat thin samples, the BSDF can be measured using a goniophotometer. In cases where the thickness of a sample with a microrelief can be neglected, its physically correct model can be represented as a single surface, on which the properties of the BSDF obtained as a result of measurements are assigned. Such a "surface" model, shown schematically in Fig. 2a, can be used to simulate various diffuse films or filters. Unfortunately, this model is not applicable if the thickness of a sample with a microrelief is important for the propagation of light inside a transparent material of the NGN. In this case, the "solid-state" model should be used, shown in Fig. 2b. This means that for correct modelling it is necessary to have two BSDFs of a rough surface, one of which describes the scattering properties when radiation passes from the air into the glass, and the other describes the scattering properties when radiation passes from the glass into the air.

The main problem is that the BSDF of a rough surface of a PCP cannot be measured directly. There are several reasons for this. First, it is the presence of multireflections between the rough surface and other surfaces of the sample being measured. Secondly, it is impossible to illuminate the sample or detect light at glancing angles to a rough surface. Solving problems is expensive and requires special equipment to eliminate multireflections between surfaces and refraction on the side opposite to the measured rough surface.

Many researchers are dealing with the complex problem of the reconstruction of the BSDF [1–8]. A number of works [1–5, 7] are devoted to accurate and physically correct reconstruction by comparison with the database of MERL BSDF measurements [9]. This database contains reflection functions for 100 kinds of materials. The authors of this database describe their method of obtaining a BSDF [10], but the question arises about the correctness of the measurements. It is difficult to say how accurate the BSDF measurements are in the MERL database due to the lack of information on certified measuring equipment. That is why the question arises about the reliability of measurements.

It should also be noted that in most papers the authors consider the problem of reconstruction only the bidirectional reflectance function (BRDF), and not in general the two-beam scattering function (BSDF). As a rule, BRDF is applied only to surfaces, but this is not enough for accurate modelling, for example, frosted glass.

One of the alternative methods of BSDF reconstruction is computer modelling of light scattering at the boundary of the microrelief of the sample medium [11]. Such an indirect method also has a number of drawbacks. In particular, the deviation of the surface profile can be comparable with the wavelength of the incident light. This means that the calculations must be carried out taking into account the aspects of wave optics, which, first, are very complex, and secondly, they may not be reliable because of insufficient accuracy in measuring the surface profile.

This article presents a combined approach. It uses the BSDF optimization, based on the approximation of the form to the Gaussian and Cauchy functions, with a limited number of parameters. This approach ensures a more correct reconstruction of the BSDF than the method proposed in [11].

The authors propose a method for reconstructing the BSDF, which allows modelling of physically correct complex scenes with frosted glass. For the experiments, GCMS-4 certified measuring equipment [12] was used, which made it possible to conduct physically accurate measurements of the BSDF. In this study, the BSDF was reconstructed and the results were compared with measurements on GCMS-4 equipment, so we can be sure that the results obtained are physically correct.

2. NUMERICAL METHODS OF BSDF RECONSTRUCTION

There are several numerical approaches to the calculation of the BSDF of rough surfaces both on the basis of wave optics and on the basis of the ray approximation. In the previous study, a solution was described, in which the surface microrelief is represented as a height distribution within the representative region of the sample [11].

The reconstruction of the BSDF of the plate with a rough surface was based on the use of two sets of measured data: the distribution of microrelief heights and the total BSDF of the sample (BTDF and-or BRDF). The reconstruction results were often not very good and required a comprehensive optimization of the microrelief (scale and profile filtering). However, filtering cannot guarantee a successful solution to the problem.

The new approach is based on using only one type of data, namely BSDR (BTDF and/or BRDF) measured for the entire sample. Despite the difference with the previous algorithm, the basic model of the new approach is the same. The initial information for the reconstruction of the BRDF is the angular distribution of the luminous intensity, calculated after the transformation of the rays at the boundary of two media, represented in the form of microgranules. The only difference is that micro boundaries are defined as the density of the distribution of the normals to the surfaces of these microgranules. The OPTOS MicroRelief tool [13], integrated into the Lumicept software package [14], provides correct calculations for the distribution of the light intensity scattered on the microrelief.

The initial distribution of the normals to the relief microfaces, necessary for simulating the propagation of light, can be reconstructed from the measured BRDF of the sample. In the absence of shadowing of neighbouring microgranules, the angular distribution of the normals is approximately 2 times greater than that of the BRDF. Of course, this is a rough approximation, but it can be used as an initial step for the whole procedure for the reconstruction of the BSDF.

To restore the BSDF, we used a real sample in the form of a plane-parallel plate, in which one surface is polished and the other is rough (matted). The plate was illuminated by a collimated light

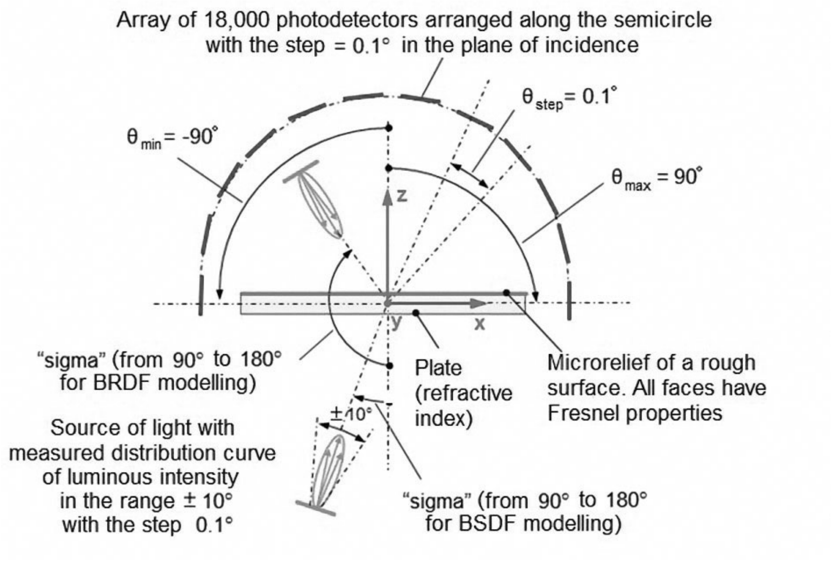


Fig. 3. Schematic model of a goniophotometer for measuring the BSDF of a diffuse plate

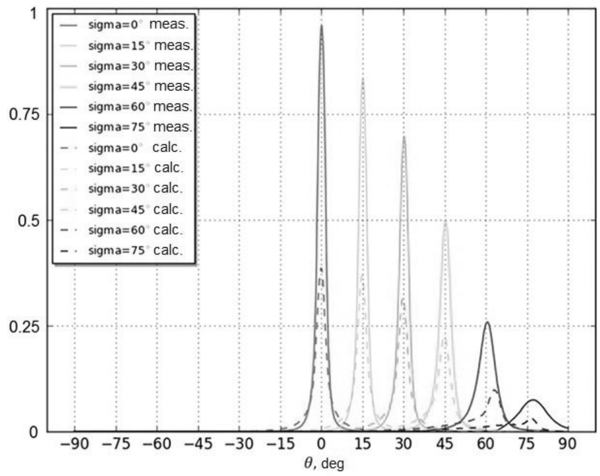


Fig. 4. Results of measurements and calculations of BTDF

beam. The intensity of reflected and transmitted light was measured for each direction of incidence. For simplicity, the measurements were carried out in the same plane – in the plane of incidence. The simulation scheme (Fig.3) is very close to the measurement circuit. A collimated beam of light with a corresponding aperture and angular divergence illuminates the plate. The rough surface of the sample was modelled by the BRDF calculated using the BSDF generation module included in the Lumicept software package [15], using the density of the angular distribution of normals. The light scattered by the plate was accumulated by round virtual detectors located along a predetermined angular grid. The distances between the detectors and the measured sample and the radius of the detectors correspond to the characteristics of the measuring device: the relative position of the measured sample and the photodetector, the angular and spatial resolution of the goniophotometer.

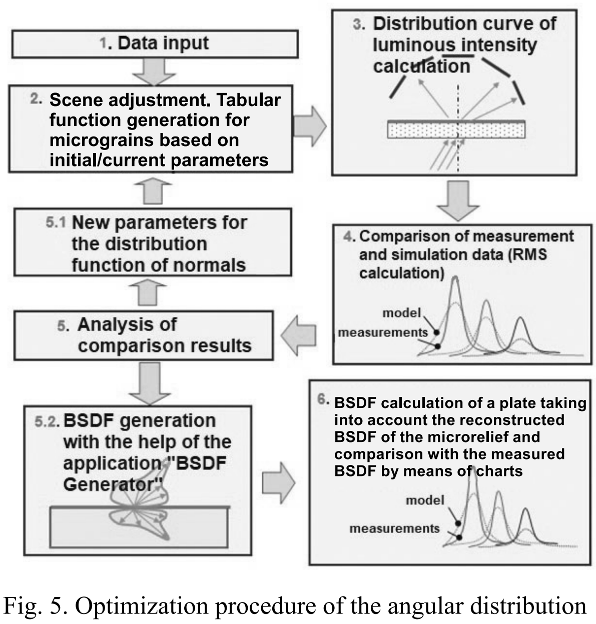


Fig. 5. Optimization procedure of the angular distribution of normal to the micrograins of a rough surface relief

Fig. 4 shows the charts of the measured and calculated BTDF in the form of the relative angular distribution of the light intensity transmitted through a sample with one rough surface. The combined graph contains the BTDF for all measured directions of the incident light: 0º, 15º, 30º, 45º, 60º, 75º (sigma is the angle between the normal to the sample surface and the direction of incident light). Note that all measurements and calculations are carried out in the plane of incidence. Solid lines indicate the results of measurements of a real sample. The dashed lines correspond to the results of modelling a sample with a reconstructed BSDF. It can be seen that there is a significant difference between simulation and measurement results. A similar trend can be observed on the chart with the results on the light reflection (not presented in the article).

3. THE OPTIMIZATION ALGORITHM OF BSDF RECONSTRUCTION, BASED ON THE DISTRIBUTION OF NORMALS

The main reason for the differences between the measurement and calculation results shown in Fig. 4 is that the initial reconstructed deviation of the normals is not suitable for the real model of light scattering on the sample. On the other hand, the angular distribution of normals is an indirect way of determining the BSDF. Thus, it is reasonable to assume that optimizing the angular distribution of the normals to the microfaces of the relief of the rough surface will yield the target BSDF of the sample.

The main idea of the proposed optimization method is that to restore the desired BSDF of a rough surface it is sufficient to use only one set of measured data, for example, the transmission characteristics of the entire sample or, in other words, its BTDF. Fig. 5 shows the optimization procedure. The rough surface is determined by the density of the angular distribution of the normals to the surface microfaces. The optimization algorithm contains the following steps:

1. In the first step, information is entered on the sample size, the refractive index, the BTDF of the sample, the initial parameters for describing the density function of the normal distribution.

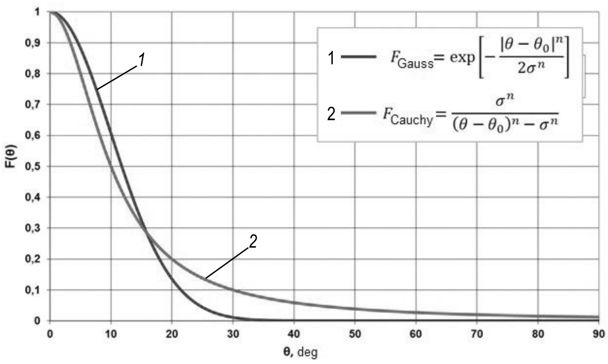


Fig. 6. General form of the Gaussian and Cauchy functions

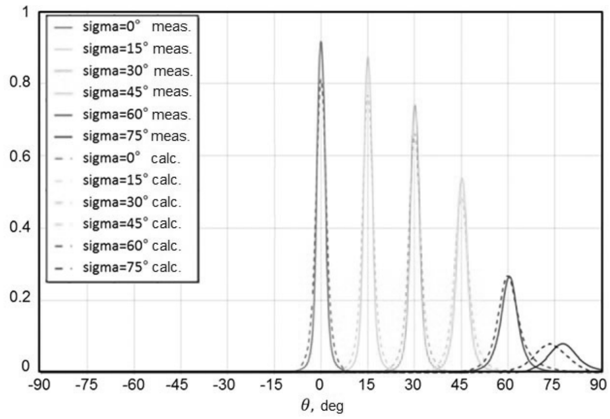


Fig. 7. Previously achieved results of BSDF reconstruction

2. The second step involves setting up the test scene, generating a table function for the microfaces based on the initial parameters. After that, the distribution of microfaces is added to the optional OPTOS MicroRelief application [13], which generates the corresponding BSDF.

3. In the third step, the angular distribution of the light intensity for the prepared sample is calculated.

4. Next, the optimizer compares the results of the calculation with the results of the measurements and calculates the root-mean-square deviation (RMS).

5. The next step is to analyze the deviation between the optimized and measured results in order to decide whether to continue or stop the optimization process.

5.1. If the desired deviation is not achieved, then the optimizer changes the density distribution parameters of the normals and returns to step 2 to continue the process.

5.2. Subsequently, if the deviation is acceptable, the final BSDF is generated using the "BSDF Generator" tool of the Lumicept software package [14].

6. Finally, the optimizer constructs the charts of the measured BSDF of the sample and the calculated BSDF of the sample, taking into account the reconstructed BSDF of the rough surface of the sample.

An important feature of this method is that when the BSDF is reconstructed, the optimization parameter is the distribution of the density of the normals to the surface microfaces. However, tabular determination of the density distribution of normals is not suitable for most optimization tools, since multi-parameter procedures require a lot of time for calculation. The most convenient representation of the distribution law is an analytic function with a minimum number of parameters. The experiments carried out by the authors made it possible to determine the two most suitable in this case types of basic functions: Gauss-shaped and Cauchy-shaped. For most cases, the Cauchy distribution gives a better result, although for some microreliefs the Gaussian approximation seems to be the best. In the authors' opinion, the Gaussian approximation gives good agreement with the BTDF measurements in zones with high transparency (at least from the point of view of the standard deviation between simulation and measurement results). Therefore, it is reasonable to use both types of functions in the optimization process. The general form of the Gaussian and Cauchy functions is shown in Fig. 6. It is clearly seen that the Cauchy distribution is wider in the zones of distant angles. The parameter θ_0, which determines the shift of the peak of the distribution along the axis of the angles, is rather formal, since in most cases the density distribution of the normals has a maximum at $\theta_0 = 0$. But this parameter is reserved for improved optimization.

Considering that the general tabular representation of the normal distribution density function is not a good optimization solution, an alternative "hybrid" solution was chosen. The base density function of the distribution of normals can be given by Gauss-form or Cauchy-form, while some regions of the function can be replaced by a locally tabular function. A brief description of the algorithm can be presented as follows:

1. Suppose that the optimization procedure with an analytic function of the density distribution of the normals can not correspond to the BSDF in a region close to the zero angle θ. This means that the density distribution of the normals in the region of

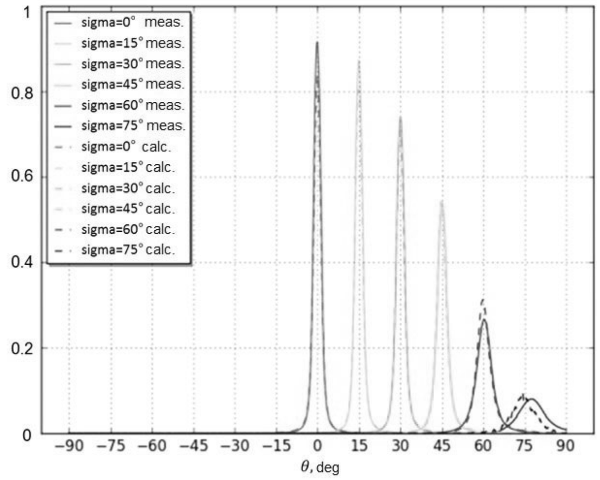


Fig. 8. The results of the BSDF reconstruction based on the Cauchy function

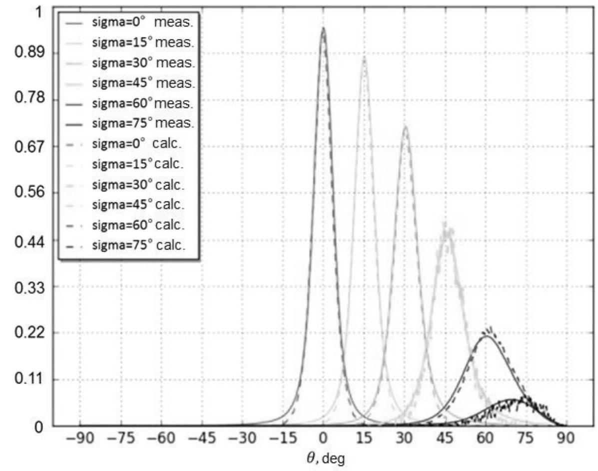


Fig. 9. The results of the BSDF reconstruction based on the Gauss function

zero angular deviation should be represented by a tabular function.

2. Then the optimizer adds several points to the tabular representation of the density of the distribution of normals in this region and continues optimizing the mixed function. If the number of points added is not high, the optimization procedure can find a solution.

4. COMPARISON OF BSDF RECONSTRUCTION METHODS BASED ON THE DISTRIBUTION OF HEIGHTS AND BASED ON THE ANGULAR DISTRIBUTION OF THE NORMALS

To test the new method, several problematic samples were selected, presented in [15]. These samples required a complicated tuning procedure based on the filtration and scaling of the measured microreliefs, for some samples an artificially created relief was used. Previously achieved results are shown in Fig. 7.

The results of the BSDF reconstruction based on the Cauchy function are shown in Fig. 8.

The results of the BSDF reconstruction based on the Gaussian function are shown in Fig. 9.

The results of optimizing the density distribution of the normals are in good agreement with the desired result (at least for the samples under study). In most cases, the Cauchy-form function gives acceptable results, at least not worse than in the case of the measured microrelief [16]. The Gaussian distribution function is also useful in some cases. All this allows us to conclude that accurate measurements of the microrelief, in general, are not required to reconstruct the BSDF of a rough surface.

Using the OPTOS MicroRelief plug-in [13] allows us to exclude the BSDF Generator Lumicept [14] from the optimization procedure. It accelerates the optimization process since it does not require the generation of a BSDF at each optimization step, which requires considerable time for calculations.

An attempt to apply the tabular density function of the angular distribution of normals as an optimization parameter failed. Optimization of the multi-parameter function is a very time-consuming task and all the advantages caused by the free form of specifying the density of the distribution of normals are nullified by the slowing down and the general divergence of the optimization procedure.

It is possible to observe a good agreement between the results of measurements and modelling for directions of incidence close to the normal ($\theta = 0$), and an acceptable agreement of the results for other directions of incidence. In this paper, the results were shown only for BTDF. However, the optimization procedure can also be applied for reflection. Usually, the optimization of the results of BTDF improves the results of the BRDF.

In addition, we simulated the construction of a photorealistic image of a plate with a rough surface. The appearance of the plate with the BSDF of a rough surface before optimization (i.e. when the measured profile was initially used) is shown in Fig. 10a. The shape of the plate with an optimized BSDF is shown in Fig. 10b.

The images shown in Fig. 10 were synthesized using a physically correct rendering based on the ray tracing method implemented in the Lumicept

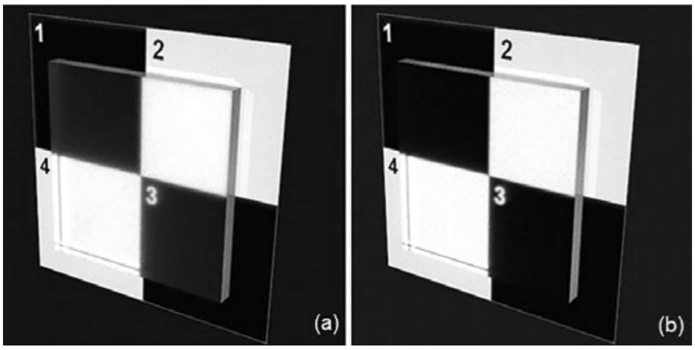


Fig. 10. The appearance of the plate with the BSDF of a rough surface before (a) and after (b) optimization

software package [14]. The scene consists of a plate, on the outer surface of which is assigned a BSDF. The plate is placed above the chess substrate and is illuminated by a set of light sources, creating a complex diffuse illumination.

5. CONCLUSION

In conclusion, it can be noted that the method for optimizing the density of the angular distribution of the normals for the reconstruction of the BSDF shows good agreement with the desired result (at least within the framework of the samples under study). In most cases, the use of the Cauchy function as the basic function for optimizing the BSDF is more preferable and in some cases shows much better results of the BSDF reconstruction than the BSDF reconstruction method from the measured microrelief. In addition, an alternative function of optimizing the BSDF can be the Gaussian-shaped function, which in some cases can provide a higher rate of convergence of the optimized BSDF to the target value. This allows us to conclude that it is possible to exclude measurements of the micro-profile in general for the exact reconstruction of the BSDF.

ACKNOWLEDGEMENT

This study was conducted with partial support of RFBR grants № 16–01–00552 and № 17–01–00363, financial support of leading universities of Russia (subsidy 074-U01), as well as by Integra Inc.

REFERENCES

1. Seylan, N., Ergun S., Öztürk A. BRDF Reconstruction Using Compressive Sensing// 21st International Conference on Computer Graphics, Visualization and Computer Vision 2013, pp. 88–94.

2. Nielsen, J.B., Jensen, H.W., Ramamoorthi, R. On Optimal, Minimal BRDF Sampling for Reflectance Acquisition// ACM TOG 34(6), 2015, pp.1–11.

3. Doris Antensteiner, D., Ŝtolc, S. Full BRDF Reconstruction Using CNNs from Partial Photometric Stereo-Light Field Data// Workshop on Light Fields for Computer Vision at ECCV-2017, pp. 13–21.

4. Lu, F., Chen, X., Sato, I., Sato, Y. SymPS: BRDF Symmetry Guided Photometric Stereo for Shape and Light Source Estimation // IEEE Transactions on Pattern Analysis and Machine Intelligence, Issue 99, pp.1–14.

5. Manmohan Chandraker, M., Bai, J., Ramamoorthi, R. On Differential Photometric Reconstruction for Unknown, Isotropic BRDFs"/ IEEE Transactions on Pattern Analysis and Machine Intelligence, 2013, Vol. 35, #12, pp.2941–2954.

6. Chuaa, S.Y., Wanga, X., Guoa, N., Tan, C.S. Performance of Range Gated Reconstruction: A Theoretical Analysis// Proc. of SPIE, Vol. 10250, pp.1–5.

7. Filip, J., Havlí, M., Vávra, R. Adaptive highlights stencils for modelling of multi-axial BRDF anisotropy// The Visual Computer, 2017, Vol. 33, Issue 1, pp. 5–15.

8. Chen, C., Dong, Y., Peers, P., Zhang, J., Tong., X. Reflectance Scanning: Estimating Shading Frame and BRDF with Generalized Linear Light Sources// OOPSLA '94.Vol. 5, Issue 4, Oct. 1994, pp. 67–71.

9. MERL BRDF database http://people.csail.mit.edu/wojciech/BRDFDatabase/

10. Matusik, W., Pfister, H., Brand, M., McMillan, L. A Data-Driven Reflectance model"// ACM Transactions on Graphics 22, 3(2003), pp.759–769.

11. Letunov, A.A., Barladian, B., Galaktionov, V.A., Ershov, S.V., Voloboy, A., Zueva, E.// Proc. 22nd Int. DAAAM Symp., pp. 1459 (2011).

12. Muracami Color Research Laboratory, http://www.mcrl.co.jp/english/index.html

13. Voloboy, A.G., Galaktionov, V.A., Zhdanov, D. Technology of optical elements in computer mode-

ling of optoelectronic devices // Information technology of CAD/CAM/CAE, № 3, 2006, pp.46–56.

14. Lumicept – Hybrid Light Simulation Software, http://www.integra.jp/en

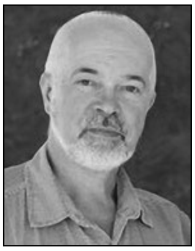
15. Zhdanov, D., Sokolov, V., Potemin, I., Voloboy, A., Galaktionov, V., Kirilov, N.// Opt. Rev. 2014, 21(5), p. 642.

16. Sokolov, V.G., Zhdanov D.D., Potemin, I.S., Garbul, A.A., Voloboy, A.G., Galaktionov, V.A., Kirilov N. Reconstruction of scattering properties of rough air-dielectric boundary // Optical Review.2016, 23(5), pp. 834–841.

Nikolai N. Bogdanov, an engineer. At present, he is a senior engineer of Inter RAO LED Systems JSC, a postgraduate student of the Chair "Technology of visualisation" of the ITMO University (St. Petersburg State University of Information Technologies, Mechanics and Optics). His scientific interest field is illumination design

Andrei D. Zhdanov, an engineer, junior research worker of Scientific and Technical Computer Centre of IPM LLC, a postgraduate student of the Chair "Technology of visualisation" of the ITMO University. His scientific interest fields are computer graphics and virtual prototyping

Dmitriy D. Zhdanov, Ph.D., graduated from the Leningrad Institute of Precise Mechanics and Optics in 1984. At present, he is a Head of the Chair "Technology of visualisation" of the ITMO University. His scientific interests are: applied optics, computer graphics, lighting engineering



Igor S. Potyomin, Ph.D. graduated from the Leningrad Institute of Precise Mechanics and Optics in 1984. At present, he is a senior research associate of LLC Scientific and Technical Computer Centre IPM and Associate Professor of the chair "Technology of visualisation" of the ITMO University. His scientific interests are applied optics, computer graphics, lighting engineering

Vadim G. Sokolov, Graduated from LITMO in 1994. At present, he is the research assistant of "STCC IPM" LLC. Research interests: computer graphics, applied optics, lighting engineering

Eugene Y. Denisov, Graduated from the Faculty of Computational Mathematics and Cybernetics of Lomonosov Moscow State University in 1995. At present, he is the research assistant of Keldysh Institute of Applied Mathematics (RAS)

Light & Engineering
Vol. 27, No. 1, pp. 33–37, 2019

LIGHT DESIGN AND TEXTILES

Juri V. Nazarov and Violet V. Popova

National Institute of Design, Autonomous non-commercial organisation,
Moscow, Russian Federation
E-mails: nazaret48@yandex.ru; violetta.pvv@mail.ru

ABSTRACT

Innovation textile is a new and unusual product type combining information technologies with wide art opportunities. The article considers three types of innovation textiles selected using the functional purpose principle: materials radiating light (electro-fluorescence, light emitting diodes, including organic and fibre optics), materials forming an image (LC screens, OLED, LCD) and materials with fluorescence effect.

A new cloth type named electronic textiles is a material, which conducts and at the same time consumes electric energy. It combined three formerly independent spheres: textiles, electrical engineering and electronic engineering. Textile materials are the base, on which various electronic devices are mounted.

Keywords: electronic textiles, light, light emitting diodes, *OLED*, innovation textiles, luminescence, electroluminescence

1. LIGHT EMMITING MATERIALS ON BASIS OF ELECTROLUMINESCENCE, LEDS, OLEDS, AND FIBRE OPTICS

In development and use of light emitting materials, their own priorities and leaders exist. One of the most widespread integral technologies is use of light emitting diodes. Attempts to use this technology in producing “smart” textiles were made from the beginning of the 21st century. The most outstanding work in this format was carried out in 2009 by well-known British designers *Francesca Rosella* and *Ryan Genz* of the *GuteCircute* London studio (2004). As a futuristic development, they created the well-known *Galaxy Dress* (Fig. 1).

An idea of English designers was to place 24 thousand light emitting diodes on the surface of a silk dress. Each flexible emitting element was manually sewed on the textile warp. As a matter of fact, the dress was turned into a suit display. In order to scatter light uniformly, the designers used four layers of cloth consisting of chiffon and organza. A significant amount of light sources required a large number of special compact *iPod* batteries placed under the crinoline.

Another technological branch of light design is production of materials based on optical fibres. In 2008, in France near Paris, one more leading company in the field of development of fluorescent materials and clothes was established. Beginning from the establishment date, it was named

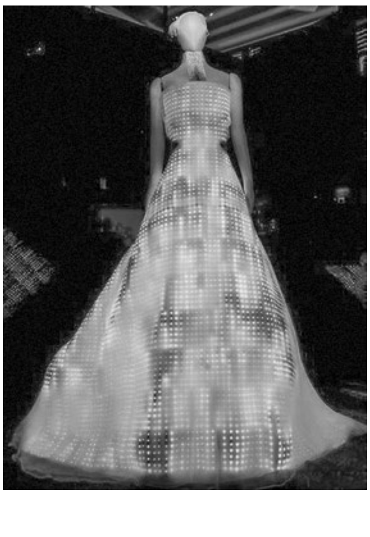


Fig. 1. Galaxy Dress

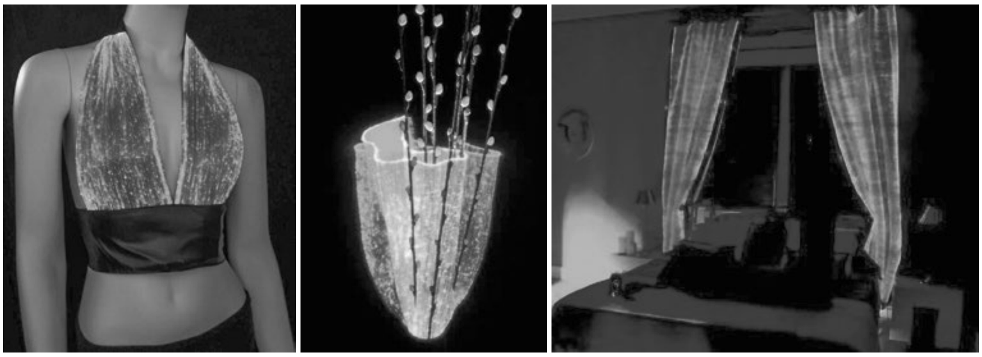


Fig. 2. Textiles of *LumiGram* Company

LumiGram. The range of the products manufactured by the company is very wide: there are dresses, house textiles, decorative clothes to decorate interiors, etc. A source of pride of this French company is a cloth, which is produced according to an original *luminous fabric* technology (fluorescence cloth). At the daytime illumination, *luminous fabric* has a standard image. At the moment, when illumination level decreases, decorative properties of this unusual cloth are fully shown. This effect is based on a combination of standard threads and of optical fibres. The light effects are implemented using light emitting diodes operating by means of tiny controllers and chips. An adjusting system switches on and off the glow mode, as well as changes its intensity and colour. The cloth obtains electric energy due to replaceable compact U-3–5B batteries, which capacity is sufficient at least for 12 hours of continuous operation. The manufacturers ensure consumers a continuous LED operation during 50 thousand hours. The *luminous fabric* technology allows the cloth uniform and soft glowing in the darkness, which makes the material attractive for fashion designers and for developers of interiors (Fig. 2).

The products can be entirely cut off of the fluorescence cloth, or light fibres can be mounted as fragments. In doing so, the composite materials are easily washed and cleaned, which is important in case of their intensive operation.

Prof. Ying Gao, creator of dresses and professor of design at the University of Province of Quebec (*UQAM,* Montreal, Canada), has developed two unique dresses rotating around the figures and shining when someone looks at them. The developers used a sensor system responding to human eyes and at the same time controlling the dress illuminance level. A complex cut off of the products made of organza makes it possible to place behind the cloth top layer compact electric motors, which change geometry of the dresses when supplying a correspondent signal from the sensor. One dress is covered with fibres of a photo fluorescent thread bringing to mind a cloth of ruche type. From the other side of the products are fluorescence threads forming a basic layer divided into separate tapes meeting at the top part of the dresses (Fig. 3).

2. MATERIALS FORMING AN IMAGE: LC SCREENS, OLED, LCD, ELECTROLUMINESCENT MATERIALS

Royal Philips Electronics concern is an undisputed leader on innovation developments in its field. The concern has established a profile compa-

Fig. 3. A "catching sights" dress

Fig. 4. The *Bubble* dress

Fig. 5.The *Twitter* dress

ny *Philips Design* directly connected with art-and-design developments. In 2009, specialists of *Philips Design* developed an original *Lumalive* technology, which makes it possible to bring various luminescent images to the cloth surface. This effect is reached due to flexible LED displays integrated into the textiles structure. Materials created according to the *Lumalive* technology allow applying them to manufacture dresses, furniture, house textiles and accessories. Due to connection with microprocessors, the cloth surface becomes dynamic, changes image intensity and colour saturation.

Developers of *Philips Design* Company in 2007 under the leadership of *Clive van Heerden*, being the *Skin* project manager and senior innovation chief officer of *Philips Design* in Eindhoven, developed a conceptual project of an "emotional" dress (Fig. 4).

The material, of which a prototype was manufactured, was a two-layer cloth. The inside product layer was filled with special controllers tracking emotional state of the user. A fluorescence dynamic image was brought to the second layer surface using flexible LED displays. The projection nature changed according to the dress owner's mood fluctuations.

In order to give a concert dress not only representative but also information properties, *Cute Circuit* British company specialising in creation of futuristic electronic dresses, developed in 2012 a unique dress under the *Twitter* brand for a North American singer Nichole Sherzinger (Fig. 5).

Again, as well as in the *Galaxy Dress* case, the designers built in a set of light emitting diodes into the French chiffon cloth scenic suit. In doing so, they connected light devices with the *Swarovski* crystals. By means of the Bluetooth technology, greetings from Nicole addressed to admirers of her art of any part of the world were brought to the dress surface. Then the cloth was turned into a media screen again, creating an additional spectacular effect during the singer's shows.

Besides the *Cute Circuit* London studio and the well-known *Philips Design,* several progressive creative groups engaged in digital design operate in the world. A British designer Nancy Tilbury being the

Fig.6. A fragment of the designer *Rami Kadi* collection

Fig.7.The fluorescent silk dresses

founder of *Studio XO* and Ben Males, a programmer are among them.

3. MATERIALS WITH PHOSPHOR EFFECT

Rami Kadi is a modern couturier captured by innovation ideas. Using his unique products, he constructs bridges between cultures so that the East and the West would meet. Due to his collections, he pays a tribute of respect to the "handwork", which he especially likes. His another success is connected with a demonstration of his original collection of evening women's dresses "Autumn/winter of 2015–2016" at the *Haute Couture* week in Paris. The cloth of the products was covered from top with a phosphor layer, which allowed a distinct glowing in the darkness of the amazing pattern applied on the dress surface under the influence of ultraviolet lamps (Fig. 6).

When commenting his own products, designer noticed that in this collection he tried to overcome his children's fear of darkness and importunate insects. As a result, the author managed to achieve an art effect comparable with bio-fluorescence of glow-worms.

Professors of the leading Japanese university of Kyoto city *(Kyoto University)* were also interested in the studies in the phosphor material field. *Tetsuya Iizuka and Tosika Tamura*, who were scientists of the Technology Institute being a part of the *Kyoto University* educational holding, have bred an unusual class of silkworm larva generating a special silk thread glowing as a phosphor in the darkness (Fig. 7).

The glow shades are various: orange, green, blue, violet and white. This effect was obtained due to an upgrade of individuals of mulberry silkworm, which were implanted with special genes excreting fluorescent components. According to some forecasts, such silk clothes will be capable to keep their fluorescent properties up to three years. The problem of the scientists for the next period is to give the silk cloth a saturated shade at the day-time light and to increase heat resistance of the natural cloth after a special treatment. This innovation tends to an expansion of the sphere of its practical use.

The *Stone Island,* which is an Italian brand being a leader in the innovation technology market, has manufactured jackets glowing in the darkness (Fig. 8).

For the first time, such products were made in 2013, and they are manufactured until now. For their production, membrane clothes are used, which accumulate light energy at the day time and glow in the darkness. Technologists have laminated the material from within and connected it with a nylon mesh.

Fig.8. A fluorescent demi-season jacket

A specific technology under the *Teflon* brand allows treating the cloth cotton warp using a special method. After that, it becomes air-tight, water-repellent and highly resistant to mechanical loads. Due to a light warp, the product has a small mass and is almost indestructible.

Technological innovations connected with lighting engineering and electronics became a noticeable phenomenon in development of design and production of textile products at the end of the 20th and at the beginning of the 21st centuries. By efforts of some designers and design companies, topical technology developments and technologies are successfully integrated with modern products of consumer industry and generate profit for the companies producing attractive innovation products.

REFERENCES

1. Braddock S. E. O'Mahony M. Techno Textiles: Revolutionary Fabrics for Fashion and Design / Thames & Hudson, 1999, 192 p.: il.

2. Clarke S. Textile Design / Laurence King Publishers, 2011, 224 p.: il.

3. McQuaid M. Extreme Textiles: Designing for High Performance / Thames & Hudson, 2005, 224 p.: il.

4. Philips [official site]. URL: http://www.philips.com (Date of the application: 9.01.2011).

5. Luminex [official site]. URL: http://www.luminex.ru.

Juri V. Nazarov,
Prof., Dr. of arts, graduated from Moscow State Stroganov School of Design and Applied Arts in 1972. At present, he is the President of National Design Institute, corresponding member of Russian Academy of Arts, Honorary President of Russia Designers Association, Laureate of the Russian Federation State Prize, Distinguished art worker of Russian Federation

***Violet V. Popova*,**
Ph.D. in Art History, Master Degree in design, at present, she is a teacher at the A.N. Kosygin RSU college, Moscow

Light & Engineering
Vol. 27, No. 1, pp. 38–45, 2019

A PILOT STUDY ASSESSING SHORT-TERM CHROMATIC ADAPTATION PREFERENCES FOR CORRELATED COLOUR TEMPERATURE IN INDIA

Amardeep M. Dugar[1] and Dashak Agarwal [2]

[1]Lighting Research & Design, Chennai, India
[2]Thea Light Works, Hyderabad, India
Email: amdugar@lighting-rnd.in

ABSTRACT

This small-scale pilot study investigates peoples' short-term chromatic adaptation preferences for correlated colour temperature (CCT) within the cultural context of India. White tone CCT preferences were investigated using a spectrally tuneable LED lighting system. A mock-up room was built and illuminated with two LED luminaires. Each LED luminaire has 216 clusters and each cluster comprising three LED with CCT equal respectively to 3000 K, 4000 K and 6500 K (total 648 LEDs per luminaire). User preference studies in a generic environment were conducted with 50 Indian subjects, where each subject performed generic everyday activities, such as reading, watching TV, eating and relaxing, while being totally immersed in three different scenes of 3000 K, 4000 K and 6500 K. The study shows 6500 K is the least preferred CCT, and 4000 K is preferred for task-oriented activities such as reading and eating. Furthermore, subjects are unable to differentiate between 3000 K and 4000 K while performing non-task-oriented activities such as relaxing and watching TV.

Keywords: correlated colour temperature (CCT), LED lighting, short-term adaptation, culture

1. INTRODUCTION

This small-scale pilot study aims to provide guidance for improved user acceptance of LED products by researching peoples' short-term chromatic adaptation preferences for the correlated colour temperature of illumination. CCT is defined as the temperature of the Planck's radiator having the chromaticity nearest the chromaticity associated with the spectral power distribution (SPD) of the light source in a specific colour space, and describes the appearance of illumination along a reddish-yellowish-white to bluish-white dimension [1]. Chromatic adaptation is defined as the human visual system's ability to adjust to changes in illumination to preserve the colour appearance of objects, and is responsible for the stable appearance of object colours against the spectral changes of the illuminant [2]. Short-term chromatic adaptation results from an exposure of 15 minutes or less to a chromatic light, with the adaptation effect decaying within seconds or minutes [3]. Research [4] reveals that chromatic adaptation at constant luminance is 90 % complete after approximately 60 seconds of exposure. The present study focuses on the perceived white tone CCT preferences of the illumination itself for performing generic everyday activities: reading, watching TV, eating and relaxing, instead of the colour appearances of objects under the illumination.

The objective of this study is to assess whether culture plays a role in people's short-term chromatic adaptation preferences for CCT. Cross-culture studies [5–7] indicate the need for light sources that have the ability to dynamically tune their colour quality of illumination as they can facilitate well-being of people, both within a single cultural group and within different cultural groups. As one of the determinants for the colour quality of illumination, the CCT of light sources plays an imperative role in addressing both psychological and physiological functions [8]. Short-term chromatic adaptation preferences for CCT are emphasised in this study because research [9–11] reveals that once people are fully adapted to the illumination conditions, CCT in the range (2500–6500) K has little effect on people's subjective preferences of illumination.

Current developments in LED-based lighting systems have enabled the CCTs of illumination to be adapted to suit people's different needs [12]. India is poised to emerge as the largest market for LED-based lighting systems with its government-led schemes for replacing all inefficient lamps by LEDs [13]. Its state-run nodal agency Energy Efficient Service Ltd (EESL) responsible for conversion from older technology (compact fluorescent or incandescent) to LED is committed to its target of selling 770 million LED lamps by 2018. The EESL's distribution scheme titled Unnat Jyoti by Affordable Lamps for All (UJALA) played an important role in lowering the retail price of 9 watt LED lamps to as low as US $1.00 per unit to encourage consumers to opt for these energy efficient lamps. Considering the fact that the UJALA scheme doles out LED lamps with a static CCT of 6500 K, the study uses India as the cross-cultural test-bed for sampling population to determine, whether 6500 K is the actual preference of Indian population. The present study, however, limits its scope to 3000 K, 4000 K and 6500 K, as these are the three most readily available CCTs at the Indian market.

2. METHODS

The overall research strategy follows a repeated-measures experimental study design, with a cross-sectional design format where the sample population is tested only once to gather and compare responses. A total of 50 subjects in smaller groups of three or four were presented with an experimental set-up and expected to complete a questionnaire. While 50 subjects is too small a sample size to be representative of the entire Indian population, this pilot study first aims to understand its impact by conducting it with a population of a singular Indian city, before conducting similar studies in other cities. The experiment was conducted in the south Indian city of Hyderabad, with subjects sampled from this city.

Literature [11] reveals that specification of CCT alone does not pinpoint the precise SPD used in a study as many different SPDs can have the same CCT. Therefore, colour rendering index (CRI) was also considered along with CCT for specifying the test luminaires in this study, as there are only two widely used metrics in India for differentiating the colour quality of illumination. CRI is defined as the effect of a light source on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference light source, and is determined by the SPDs of the respective light sources [14]. The physical set-up consisted of an experimental room illuminated by a tuneable LED lighting system generating three scenes of 3000 K, 4000 K and 6500 K at a CRI of 80 and average illuminance of 300 lx at the table-top level as depicted in Fig. 1. The CCT and CRI ratings are based on the manufacturers' data available for the LED lighting system. The entire experiment lasted for approximately 9 hours spanning over two days with each group being allotted approximately 40 minutes for the experiment.

2.1. Physical Set-Up

The experiment was conducted in a confined room without a window as external source of light inside the office of *Thea Light Works* in Hyderabad. The dimension of the room was 3.0×2.9 ×3.0 m (l × b × h) where the room was being illuminated by two LED luminaires (L) installed in the grid ceiling as per the layout depicted in Fig. 2. The room

Fig.1. Experimental room with tuneable LED lighting system generating three scenes of CCTs 3000 K, 4000 K and 6500 K respectively at an average constant illuminance of 300 lx at the table-top

Table 1. Surfaces Reflectance of the Room

Room surface	Material	Colour	Reflectance
Ceiling	Acoustic tile	Matt black	0.05
Wall 1	Plaster	Painter's grey	0.28
Walls 2, 3	Chip board	Painter's white	0.82
Floor	Local stone	Matt black	0.05
Table	Wooden	Pine	0.45
Shelf	Wooden	Matt white	0.85
Chairs (4 Nos.)	Plastic	White/Black/Blue	0.85/0.10/0.50
LCD screen (off)	Liquid crystal	Black	0.12

temperature was maintained at 24 °C with the help of a wall-mounted air-conditioning unit. The room was equipped and furnished to provide a space that allows subjects to read, watch TV, eat and relax. A rectangular light pine-coloured table was placed adjoining the wall opposite the entrance door along with four office chairs. The table height was 0.7 m. A wall-mounted flat 24" LCD TV screen was also set on the adjoining wall, directly above the table. The monitor's settings (brightness, colour temperature, gamma, saturation, hue and grain) were maintained constant throughout the experiment. There was also a bookshelf integrated with the wall adjacent to the door for storing all the experiment-related materials such as coloured magazines and eatables. During the experiment, printed questionnaires and pens were placed on the table. The room surfaces reflectance are presented in Table 1.

2.2. Luminaires

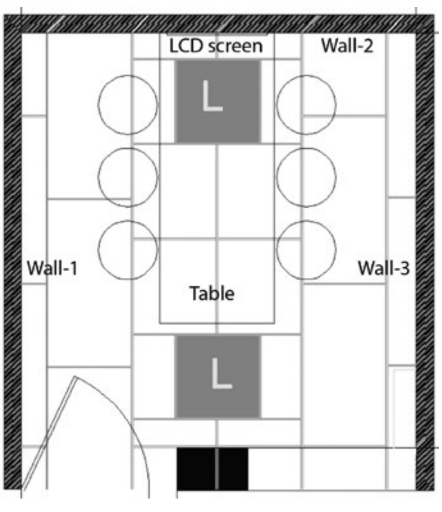


Fig.2. Experimental room layout where "L" represents the LED panel integrated within the grid ceiling

Two ceiling-recessed LED luminaires with dimensions 598 mm × 598 mm × 86 mm each, were custom-designed to illuminate the room. The luminaires and its compatible control system were built with the help of an LED luminaire manufacturer, using four main components:

- LED Panels – 3-channel Panels fitted with Edison LEDs [PLCC2835 0.2W LC CRI80];
- Driver – Osram Optotronic Constant Voltage DALI Dimmable Driver [OTi DALI75/220–240/24 1–4 CH];
- Controller – Philips LightMaster Modular 4-Channel Controller [PDLPC416FR-KNX];
- IR Receiver – Busch-Jaeger Triton 3/6-fach MF/IR [320/30–24G].

Each luminaire comprised six LED panels; each LED panel comprised 36 LED clusters; each LED cluster comprised three different LED types of CCTs 3000 K, 4000 K and 6500 K with a constant 80 CRI as per the LED manufacturer's data i.e. 648 LEDs in total as depicted in Fig. 3. A plexiglas diffuser, which blended the light to provide homogeneous luminance of the luminaire opening, covered the LED panels. The variations in CCT and CRI occurring due to inter-reflections within the luminaire and diffusion through the plexiglas were not taken into consideration for this study. Three drivers drove each luminaire where LEDs of identical CCT were on a single channel thereby enabling each CCT in the luminaire to be controlled by one driver. The two luminaires and its six drivers were connected to a controller, thus making it possible to control the CCT and illuminance of the luminaires with an IR receiver.

2.3. Sampling Population

Table 2. Demographic Analysis of the 50 Subjects from Hyderabad

Age Group	**16–24**	**25–34**	**35–44**	**45–54**	**55 & above**
	7	**25**	**8**	**4**	**6**
Monthly Income [INR]	*Below 5,000*	*5,000–24,000*	*25,000–49,000*	*50,000–74,000*	*75,000 & above*
	02	21	11	7	9
Religion	*Christian*	*Hindu*	*Muslim*	*Jain*	*Sikh*
	4	42	2	1	1
Travel – Inside India	*Bangalore*	*Chennai*	*Delhi*	*Kolkata*	*Mumbai*
	33	27	30	20	36
Travel – Outside India	0 visits	1 visits	2 visits	3 visits	4 visits
	23	7	4	3	13
Gender	*Male*			*Female*	
	35			15	
Area of Residence	*Urban*			*Suburban*	
	41			9	
Education	*High school or below*			*Graduate or above*	
	11			39	

As the intention of this experiment was to obtain feedback from a wide range of subjects from India with different ages, gender and socio-economic backgrounds, a simple random sampling method was used where a generic invitation applicable to a general population was prepared. Additionally, by ensuring that all participants were selected in a random fashion and given an identical treatment, the influence of any form of individual characteristics was eliminated. The 50 subjects who agreed to participate in the experiments included members of the general public as well as staff from the commercial building premises where the experiment was conducted. Table 2 lists a brief demographic analysis of the 50 subjects. Majority of the subjects are between the age group of 25–34 (50 %), have a monthly income between INR 5,000–24,000 (42 %), follow Hinduism (84 %), have visited Mumbai (72 %) in comparison to all the other major cities in India, have travelled outside India (54 %), live in urban areas [82 %], and have completed graduation (78 %).

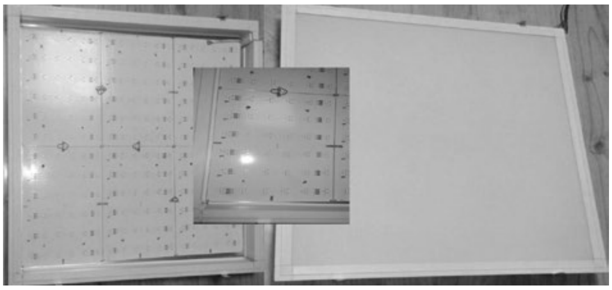


Fig.3. Ceiling-recessed luminaire with six LED panels covered by a Plexiglas diffuser for homogenous luminance

2.4. Experimental Procedure

A questionnaire was designed, which first asked the subjects to visually experience the three scenes with 3000 K, 4000 K and 6500 K by being completely immersed in them, before identifying any variability in the scenes. The scenes with the different CCTs were presented to the subjects in various different orders in order to counterbalance any carry-over or ordering effects by slowly interchanging them a couple of times. As the intention was to obtain short-term chromatic adaptation preferences, the time allotted to experience each scene was short, approximately 90 seconds, to ensure that subjects' eyes are not fully adapted to each CCT. In case of any perceptible variability in the three scenes, the subjects were asked to name this difference. Subjects were then asked which of these CCTs were they previously aware of in terms of their availability in the local market: '1 – Not aware' and '2 –

Fig.4. Subjects performing the different activities of reading, watching TV, eating and relaxing while being completely immersed in the three different CCT

Aware.' Subjects were finally asked to list areas, buildings or localities, which according to them were the most suitable applications for these CCTs.

Subjects were then asked to perform four activities of reading, watching TV, eating and relaxing in the three scenes, and rate their preference of each CCT for performing these activities under the categories: '1 – Not Appropriate', '2 – Somewhat Appropriate' and '3 – Appropriate'. The time allotted for each activity was approximately ten minutes with each of the three CCTs being interchanged after approximately 90 seconds. Subjects were also given the freedom to rate their preferences from the questionnaire at any time during these ten minutes allotted for each activity. For reading, subjects were provided with magazines. Magazines were the preferred reading material considering their variety in content presentation through font sizes, coloured pictures, etc. For watching TV, a video clip from the national geography channel was played for the subjects. For eating, subjects were offered fruits and snacks. For relaxing, subjects had the free will to relax in whichever manner that suits their comfort. The subjects performing various activities in the experimental room are presented in Fig. 4.

3. RESULTS AND ANALYSIS

Statistical Package for Social Sciences (SPSS) for Windows was used to perform nonparametric tests to calculate the percentages of responses, the mean ranks, p-values and significance levels. Cochran's Q test and percentages of responses were used for calculating the statistical significance of tests that involved binary response variables. Friedman's test and mean ranks were used for all other tests, which involved more than two response variables. Wilcoxon's test was used for a pairwise comparison of the three CCTs. The qualitative data was coded by the method of systematic observation, where careful observation of one or more specific behaviours in a particular setting was recorded.

All 50 subjects perceived a difference in the three scenes; 30 related this difference to colour and 20 related it to brightness. Majority (90 %) of the 20 subjects who related the perceived difference in the scenes to brightness were from the income groups of INR 24,000 and below or an education level of high school and below. Tables 3 and 4 list the descriptive and inferential statistics respectively obtained from the sample population. Table 5 lists the pairwise comparisons of the three CCTs to assess which CCTs are different from each other. Sub-

Table 3. Summary of Means, Standard Deviations and Minimum-Maximum Range for the Three CCTs

Activity	3000 K			4000 K			6500 K		
	M	*SD*	*Min-Max*	*M*	*SD*	*Min-Max*	*M*	*SD*	*Min-Max*
Awareness	1.18	0.388	1–2	1.22	0.418	1–2	1.26	0.443	1–2
Reading	1.80	0.756	1–3	2.48	0.677	1–3	2.22	0.815	1–3
Watching TV	2.26	0.828	1–3	2.24	0.657	1–3	1.78	0.815	1–3
Eating	2.16	0.817	1–3	2.34	0.745	1–3	1.86	0.833	1–3
Relaxing	2.44	0.861	1–3	1.84	0.734	1–3	1.66	0.848	1–3

Table 4. Percentages of Responses and Mean Ranks for the Three CCT

Activity	3000 K	4000 K	6500 K	P	Cochran's Q [df=2]
	Aware % [Not Aware %]				
Awareness	82 % [18 %]	78 % [22 %]	74 % [26 %]	0.050	6.00
	Mean Ranks				*X^2 [df=2]*
Reading	1.45	2.47	2.08	<0.001	51.94
Watching TV	2.25	2.22	1.53	<0.001	36.87
Eating	2.06	2.33	1.61	<0.001	36.75
Relaxing	2.25	2.22	1.53	<0.001	36.87

jects were more aware about the availability of 3000 K in the market as it received the highest percentage of favourable response. Subjects preferred 4000 K for reading and eating as it received the highest mean rank. Although subjects did not perceive any difference between 3000 K and 4000 K while watching TV and relaxing as $p > 0.05$ for their respective pairwise comparisons, both CCTs received similarly high mean ranks for these two activities. Table 6 lists the subjects' preferences of these CCTs for possible real-life applications in different areas, buildings or localities. All 50 subjects have travelled to at least one other city in India, while 27 of them have travelled outside India. The sample size was not large enough to draw any other relationship of statistical significance with respect to age, gender or socio-economic backgrounds.

While majority of the subjects are aware about the availability of the three different CCTs for LED luminaires in India, 40 % of the subjects were not able to relate this difference to the colour quality of illumination. For task-oriented activities such as reading and eating, 4000 K is considered the most appropriate. Maximum numbers of subjects associate 4000 K for task-oriented applications such as classrooms, offices, workspaces and kitchens. However, 3000 K is considered the least appropriate for reading, and 6500 K is considered the least appropriate for eating. Maximum numbers of subjects associate 3000 K for applications such as restaurants, bars or hotels; and 6500 K with applications such as hospitals and supermarkets as shown in the application survey. For non-task-oriented activities such as watching TV and relaxing both 3000 K and 4000 K are considered almost equally more appropriate than 6500 K. Overall, the study reveals that 4000 K and 6500 K are the most and least preferred CCTs respectively.

4. DISCUSSIONS

Literature reviews of previous cross-cultural studies on the preference of the colour appearance of objects under LED illumination of different CCT reveal mixed results. A study [6] on Chinese and American observers living in the US reports that: for very familiar objects (fruits and vegetables) and paintings, no cultural differences were found; for less familiar or unfamiliar paintings, cultural differences were found depending on the content; American observers exhibited noticeably wider differences. A similar study [7] on Chinese and European observers living in Germany reports that: Chinese women prefer warm white CCT (2700–3500) K for

Table 5. Pairwise Comparisons of Preferences in the Three CCTs

Activity	(3000–4000) K		(3000–6500) K		(4000–6500) K	
	Z	*p*	*Z*	*p*	*Z*	*p*
Reading	–5.831	<0.001	–4.583	<0.001	–3.606	<0.001
Watching TV	–0.277	0.782	–4.899	<0.001	–4.796	<0.001
Eating	–3.000	0.003	–3.873	<0.001	–4.899	<0.001
Relaxing	–0.277	0.782	–4.899	<0.001	–4.796	<0.001

Table 6. CCT Preferences for Different Applications

	Area/Building/Locality											
	Classroom	Garden	Hospital	Industrial Workshop/ Warehouse	Kitchen	Office/ Workspace	Place of Worship	Playground/ Stadium	Restaurant/ Bar/Hotel	Retail Store/ Showroom	Street/Path-way	Supermarket
3000K	4	23	5	7	9	5	20	6	33	18	20	6
4000K	26	3	19	14	19	20	6	6	6	12	3	12
6500K	11	9	25	14	11	14	7	18	5	13	11	21

reddish objects in contrast to Chinese men and Europeans; a general preference of 4000 K (in certain cases up to 5000 K) could be observed for the bluish and colourful combination than for the reddish objects; Europeans do not prefer warm white (2700–3500) K for bluish and colourful objects. Four studies that have independently experimented with interchangeable CCT in office lighting environments for workers in Asia [8,15,16] and Europe [12] report a similar result that 4000 K is the most comfortable and most preferred CCT than 3000 K and 6500 K. A study [17] on LED office lighting that experimented with Africans, Asians and Europeans living in Finland reports that Europeans prefer a lit environment under CCT 4000 K, while Africans and Asians preference between 4000 K and 5000 K depends upon illuminance levels.

Relating the results of these previous cross-cultural studies with this study has led to the following observations:

- Educational and economic backgrounds might play a role in relating the perceived chromatic differences in illumination to colour quality or more precisely to CCT. Majority of the subjects who related the perceived differences between the three scenes to brightness instead of colour were either from a lower income group or lower educational background.
- Travelling and exposure to different cultures might play a role in influencing people's preferences and associations with a particular CCT. The preference of 4000 K for eating, while an association of 3000 K with eating places like restaurants and hotels can be accounted to the subjects' travel experiences and exposure to fine dining places illuminated with warmer CCTs.
- A CCT of 4000 K seems to be universally acceptable across most cultures for familiar office-oriented activities. The preference of 4000 K for a task-oriented activity like reading supports to a certain extent the results of the previous studies [8,12,15–17] on office lighting. This may also explain why a CCT of 3000K is considered unsuitable for an office-oriented activity like reading as people relate it more to an environment conducive for non-task-oriented activities like watching TV or relaxing.
- Differences of up to 1000 K at the reddish-yellowish-white dimension of the CCT are not noticeable while performing non-task-oriented activities. The subjects' inability to report any difference between 3000 K and 4000 K was only while performing the non-task-oriented activities like relaxing or watching TV.
- While the present study did not consider the impact of different skin tones on CCT preferences, it certainly is a case in point for future research considering the various differences in skin tones within the Indian population. Research reveals [18] that people are very sensitive to CCT preferences when their skin is used as a target of observation.

5. CONCLUSIONS

Two broad conclusions can be drawn from the results of this study. First, the people of Hyderabad have a general preference for 4000K while performing most activities and tasks. Second, the government-led UJALA scheme for distributing LED lamps at subsidized rates needs to establish people's preferences for CCT before implementation. The fact that people of Hyderabad do not have much of a preference for 6500 K provides sufficient evidence to disagree with the UJALA scheme. The practical applications of this study include areas where the choice of CCT has an impact on the immediate entry to buildings is important, such as in retail and hospitality lighting. The results of this study can also be practically used by the UJALA scheme to reassess their decision of doling out 6500 K lamps. The answer to the overarching question whether culture plays any significant role in people's preferences for CCT requires further investigation and validation with similar experiments conducted across different cities in India using larger samples sizes.

REFERENCES

1. CIE. 17–258 correlated colour temperature [Tcp] [Internet]. e-ILV. [cited 2017 Jul 26]. Available from: http://eilv.cie.co.at/term/258
2. CIE. 17–140 chromatic adaptation. e-ILV.
3. Belmore SC, Shevell SK. Very-long-term and short-term chromatic adaptation: Are their influences cumulative? Vision Res [Internet]. 2011;51(3):362–266. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3025050/pdf/nihms262722.pdf
4. Fairchild MD, Reniff L. Time course of chromatic adaptation for color appearance judgements. J Opt Soc Am A. 1995;12:824–33.
5. Kuller R, Ballal S, Laike T, Mikellides B, Tonello G. The impact of light and colour on psychological mood: a cross-cultural study of indoor work environments. Ergonomics. 2006;49:1496–507.
6. Liu A, Tuzikas A, Žukauskas A, Vaicekauskas R, Vitta P, Shur M. Cultural Preferences to Color Quality of Illumination of Different Objects. IEEE Photonics J [Internet]. 2013;5(4). Available from: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6583259
7. Bodrogi P, Khanh TQ, Stojanovic D, Lin Y. Intercultural colour temperature preference of Chinese and European subjects living in Germany. Light & Engineering. Moscow, RUSSIA; 2016;24(1):8–11.
8. Shamsul BMT, Sia CC, Ng YG, Karmegan K. Effects of light's colour temperatures on visual comfort level, task performances, and alertness among students. Am J Public Heal Res. 2013;1(7):159–165.
9. Davis RG, Ginthner DN. Correlated color temperature, illuminance level and the Kruithof curve. J Illum Eng Soc. 1990;27–38.
10. Boyce PR, Cuttle C. Effect of correlated colour temperature on the perception of interiors and colour discrimination. Light Res Technol. 1990;22(1):19–36.
11. Fotios S. A Revised Kruithof Graph Based on Empirical Data. LEUKOS. 2017;13(1):3–17.
12. Dangol R, Islam M, Hyvarinen M, Bhushal P, Puolakka M, Halonen L. User acceptance studies for LED office lighting: Preference, naturalness and colourfulness. Light Res Technol. 2015;47:36–53.
13. Dutta S. India headed for top slot in global LED bulb market. The Times of India [Internet]. 2016 Apr 21; Available from: http://timesofindia.indiatimes.com/business/india-business/India-headed-for-top-slot-in-global-LED-bulb-market/articleshow/51918389.cms
14. CIE. 17–222 colour rendering index [R] [Internet]. e-ILV. [cited 2017 Jul 26]. Available from: http://eilv.cie.co.at/term/222
15. Lin RF, Chou C, Wang YT, Tu HW. Effects of LED color temperature on office workers. In: 2nd Southeast Asian Network of Ergonomics Societies Conference. Langkawi, MALAYSIA; 2012.
16. Kang M, Chang JD, Yoon Y, Kim S. Determining occupant-friendly lighting environments for the improvement of visual perception. In: ICSDEC2012: Developing the Frontier of Sustainable Design, Engineering, and Construction. Fort Worth, TX, USA; 2013. p. 937–944.
17. Baniya RR, Tetri E, Halonen L. A study of preferred illuminance and correlated colour temperature for LED office lighting. Light & Eng. 2015; V.23, #3, pp. 39–47.
18. Quellman EM, Boyce PR. The light source color preferences of people of different skin tones. J Illum Eng Soc. 2002;31:109–18.

Amardeep M. Dugar, Ph.D**.,** is a trained architect and founding principal of Lighting Research & Design. After completing a Masters degree in Architectural Lighting from University of Wismar/Germany, he pursued a Ph.D. from Victoria University of Wellington/New Zealand to solidify his academic and professional leadership role into a career at a higher level

Dashak Agarwal, M.D. is a founding partner of *Thea Light Works*, a total enterprise architectural lighting company in India. He completed his Bachelors degree in Logistics Management from Fisher College of Business at The Ohio State University/USA and Masters Degree in Architectural Lighting from the University of Wismar/Germany

Light & Engineering
Vol. 27, No. 1, pp. 46–50, 2019

DEVELOPMENT OF A MICROCONTROLLER BASED EMERGENCY LIGHTING SYSTEM WITH SMOKE DETECTION AND MOBILE COMMUNICATION FACILITIES

Shibabrata Mukherjee[1], Parthasarathi Satvaya[2], and Saswati Mazumdar[3]

[1] *Jadavpur University, Kolkata, India*
[2] *School of Illumination Science Engineering & Design, Jadavpur University, Kolkata, India*
[3]*Electrical Engineering Department, Jadavpur University, Kolkata, India*
E-mail: smshibabrata@gmail.com

ABSTRACT

This paper describes a microcontroller based emergency lighting system, which can early detect fire and send the alarm message through a mobile network. This is achieved via smoke and gas detector technology added with integrated microcontroller, mobile communication and a LED emergency light. First five Minutes of fire is more important than last five hours [1]. Hence, it is important to have early detection of fire and start fire fighting in its inception. In many hazardous areas where flammable materials are handled, any leak or spillage may give rise to an explosive atmosphere. In this situation, early detection of leaking gas or smoke plays an important role in reducing fire deaths and injuries. In fact, immediately after detection of fire, fire fighting should be started by means of portable fire extinguishers or by informing the fire brigade. This developed system can initiate these functions by detecting the fire hazard, establishing the communication to dwellers and turning on the emergency light to show the exit route.

Keywords: **e**mergency light, **e**scape route, gas and smoke sensor, hazardous area, mobile communication

1. INTRODUCTION

The combined smoke detector system with emergency lighting and communication system can save lives if there is a fire at home or any official building or cinema hall. Smoke spreads very fast and power cuts out immediately; this needs a smoke alarm, and an emergency light to show the exit route. Primary purpose of detection system is to respond as quickly as possible and transform the responses into an automatic alarm, SMS alert and immediately turn on the emergency light to evacuate the premises, moving people to a place safely or allowing important documents to be moved to a safety zone [2]. Installation of a battery backed emergency light with relay technology is used here to switch on the emergency light. This system can detect smoke and different gas leakage like LPG, methane, butane or any such petroleum based gaseous substance. It sends the SMS alert in hazardous situation, so that people can evacuate easily with the help of emergency light. This system is easy to install and very simple to operation. Its longer life makes the system relatively more reliable and compact. This system has been developed in Illumination Engineering Laboratory of Jadavpur University.

2. HARDWARE COMPONENTS REQUIRED

In this system, the following components are mainly required:

a) Gas and smoke sensor (MQ2) is used for detection of smoke and gas; b) Microcontroller board is used for controlling the whole system; c) GSM

Module is used for mobile communication; d) 5V Relay is used for switching the emergency light;

e) LED Emergency light is used to show the exit route;

f) DC power Supply is used to turn on the emergency light in emergency situation;

g) LCD Module is used to display whether the gas or smoke is present or not;

h) Transistor is used for switching purpose;

i) Adapter 12 V is used to supply the GSM Module;

j) Buzzer is used to alert;

k) Small LED is used to check the relay circuit is properly working or not.

3. WORKING PRINCIPLE OF GAS AND SMOKE SENSOR MODULE

Fig. 1 shows the block diagram of functioning of gas and smoke sensor module. In this system, mainly semiconductor type smoke & gas sensor module is used. Sensitive material of smoke & gas sensor is SnO_2. Initially, when the air is clean, the conductivity between the electrodes of sensor is less as the resistance is in order of 50 kΩ and electrodes are keeping at constant distance. The inverting terminal input of comparator is higher than the non-inverting terminal input. The indicator Buzzer and LED is off. In the event of fire, when the sensor gets filled with smoke, the resistance of the sensor falls to 5 kΩ and the conductivity between the electrodes increases [3]. This provides a higher input at the non-inverting terminal of comparator than the inverting terminal and the output of the comparator becomes high. The alarming LED and Buzzer are turned on as indication of presence of smoke. The sensitivity of the gas & smoke sensor can be adjusted by the potentiometer.

4. MICROCONTROLLER USED IN THE SYSTEM

In this system ARDUINO UNO is used, which is a microcontroller board based on the ATmega328P. It has 14 digital input/output pins of which 6 can be used as PWM outputs, input voltage (7–12) V of direct current (DC), 5V DC operating voltage, 40 mA on input or output pin and 50 mA on 3.3 V-pin, 6 analogue inputs, a 16 MHz quartz crystal, a USB connection, a power jack, an ICSP header and a reset button [4].

5. BRIEF DESCRIPTION HOW GAS & SMOKE SENSOR COMMUNICATE WITH MICROCONTROLLER & EMERGENCY LIGHTING

In this system, a smoke detector with emergency lighting for safety purpose in any indoor area is introduced. This is achieved via smoke and gas detector technology and added intelligence utilizing integrated microcontroller, mobile communication and a LED emergency light. Here a LED emergency light is used, this light is operated at 3V DC, 0.25A battery source. Fig. 2 shows the circuit diagram of using Microcontroller to interface of Gas and smoke sensor with emergency light.

When developing a smoke and gas detector system, there is a need to monitor the gas and smoke sensor parameters continuously. This combined smoke detector system with emergency lighting and communication system can monitor the smoke from the fire or gas leakage continuously. This is achieved by scanning the digital output (D_0) of the sensor continuously. When the air is clean that is there is no smoke or gas leakage, the D_0 of the sensor is high as well as the conductivity between the electrodes of the sensor is less. If there occurs a smoke or gas leakage at any time, the conductivity between the electrode of the sensor is high as well as the digital output D_0 of the sensor will change to low status and that time SMS alert, buzzer and emergency light will be activated [5].

When the emergency situation arises, SMS is sent by using AT commands. The SMS alert set in the programme and the base of the transistor *Q1* gets the high pulse due to detection of smoke or gas, the transistor is turned on or forward biased and turns on the buzzer, which is connected to the specified pin of the microcontroller. Once smoke or gas

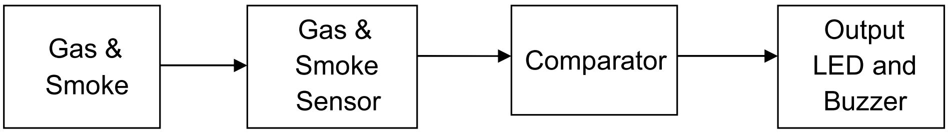


Fig. 1. Block diagram of gas & smoke sensor module

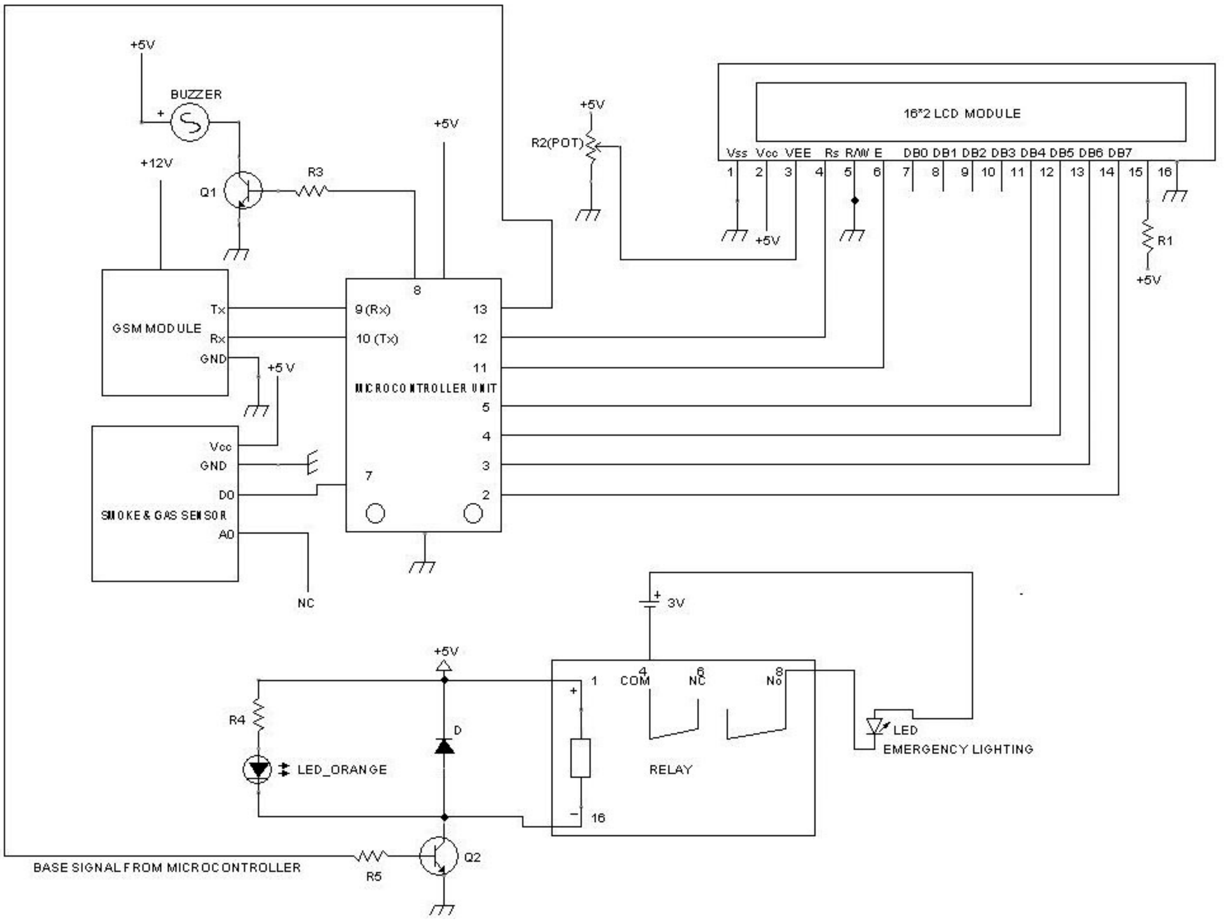


Fig. 2. Circuit diagram of using microcontroller to interface gas and smoke sensor with emergency light

leakage is detected by the system, the set numbers of SMS alert are sent. When this situation arises, humans should take proper action to stop the gas or smoke problem.

After sending the SMS alerts, the system will activate the emergency light. When the smoke or gas leakage has been stopped and system will automatically reactivate its SMS alert setting by resetting SMS counting variable back to zero. Fig. 3 shows the flow chart to interface gas and smoke sensor with emergency light.

When the base of the transistor *Q2* gets the high pulse due to detection of smoke or gas, the transistor is turned on or forward biased. The relay also gets energized and 'NC' (Normally Closed) terminal of the relay changes to 'NO' (Normally Open) terminal, the relay circuit is completed. The emergency light is turned on.

In this circuit an orange colour small LED is used. This LED is used to check the relay circuit is properly working or not that is relay circuit is properly energized during the presence of smoke or gas or not. When there is no gas leakage or smoke, the

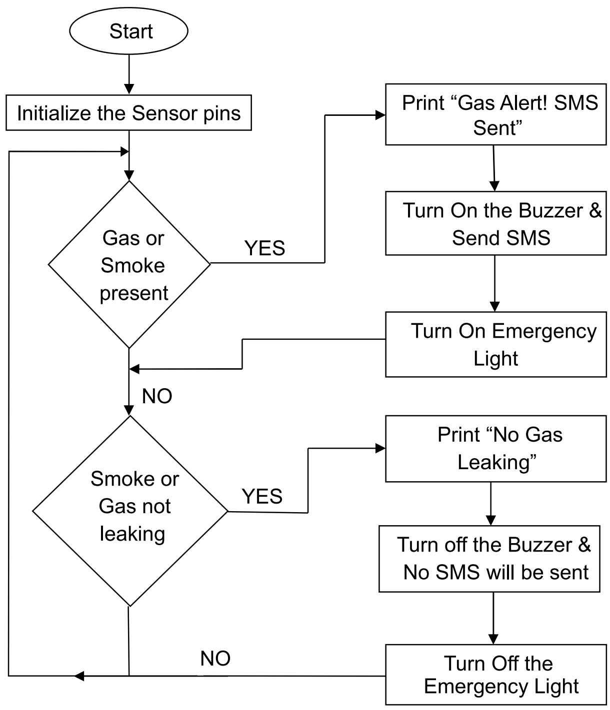


Fig 3. Flow chart to interface gas and smoke sensor with emergency light

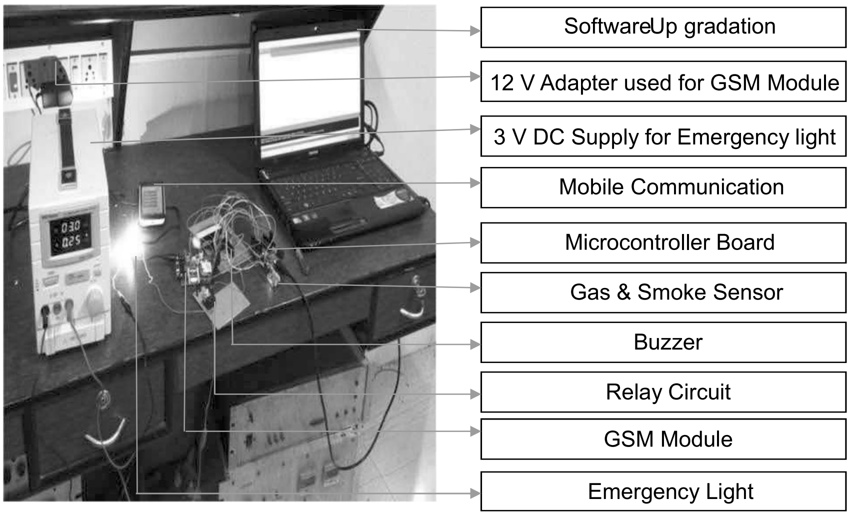


Fig. 4. Experimental setup using microcontroller to interface gas and smoke sensor with emergency light

base of the transistor gets low pulse, the transistor is reverse biased, and the relay also gets de-energized, and in such case the 'NO' terminal of the relay changes to 'NC' terminal. Fig. 4 shows the experimental setup using microcontroller to interface gas and smoke sensor with emergency light.

6. ADVANTAGE OF THE SYSTEM

The developed combined smoke detector with emergency lighting system has the following specifications:

– The LED emergency light has long life, small size, good efficacy and good visibility having monochromatic yellow LED light. The whole system requires proper maintenance and can be sustained for a long period of time.

– This system is easy to install and very simple to operation.

– This system is more reliable in domestic, industrial and commercial interiors.

– This system detects the different gas leakage like LPG leak, methane leak, butane leak, or any such petroleum based gaseous substance and smoke that can be detected using smoke and gas sensor.

7. DISADVANTAGE OF THE SYSTEM

The developed combined smoke detector with emergency lighting system has the following disadvantages:

– The smoke and gas sensor with emergency light is driven by battery power. So, regular checking, maintenance and replacement of the battery system is necessary. A smoke detector and emergency light with dead battery saves no live.

– Water steam is very harmful for smoke and gas sensor. Smoke detector should not be installed in bathroom, steam rooms or over ovens of kitchens. If sensors are installed in such a place, this will be get damaged or create malfunctioning.

– The smoke and gas sensor should not install near gas ovens, stoves. If sensors are installed in such a place, this will give the false alarm. But this areas are the most important areas where need of careful monitoring for fire hazards, installation of the system in a proper wall or ceiling is very much necessary [6].

8. CONCLUSION

In this system, the gas and smoke detector system with an emergency light is provided with a microcontroller system. In this troublesome world, risks are increasing due to human faults and failure. Automation and security is the most important factor in our day to day life. This system approaches to home and industrial automation and security system design which is almost standardized now to day. Everyone wants to be as much as secured as possible. This developed system, if installed in large scale, may save lives of many people by giving early warning and showing the escape route.

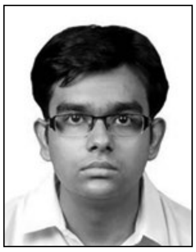
In case of emergency situation in future, laser light may be used to get more sensitivity in the smoky and hazardous situation than LED. Laser achieves the goals of high sensitivity and high stability by its monochromatic nature.

This combined smoke detector system with emergency lighting and communication system may be used outside of official building or heritage building etc. At night, when the density of people of any area is very low, if fire hazard occurs outside, the fire may spread rapidly and may affect the inside of the building and damage various important documents, instruments or artefacts. This developed smoke detector system with emergency lighting and communication system may protect this hazardous situation.

This combined smoke detector system may be effective in wildfire. Wildfire may occur all over the world except Antarctica continent. The wildfire spreads very fast and come to the local premises what may cause extensive damage to property, human life, wild life etc. This developed smoke detector with SMS alarm system may save extensive damage of property, human life, wildlife, forest etc. from the wildfire.

REFERENCES

1. People of Planet Earth and Fire by Debabrata Biswas, B.E Mining, Calcutta University, Life Member: M.G.M.I & loss prevention Association of India.
2. The society of Light and Lighting Hand Book by Peter Boyce PhD, FSLL, FIESNA & Peter Raynham BSc MSc CEng FSLL MCIBSE MILE.
3. MQ-2 Semiconductor Sensor for Combustible Gas available at https://www.pololu.com/file/download/MQ2.pdf?file_id=0J309.
4. www.arduino.org/products/boards/arduino-uno.
5. Gas Leakage Detector using Arduino and GSM Module with SMS Alert and Sound Alarm, http://www.circuitstoday.com/gas-leakage-detector-using-arduino-with-sms-alert.
6. The Disadvantages of Smoke Alarms by Marc Chase, available at www.hunker.com/13419400/the-disadvantages-of-smoke-alarm.



Shibabrata Mukherjee,
received his B. Tech. Degree in Electrical Engineering from St. Thomas College of Engineering & Technology, Kolkata, India in 2013 and M. Tech. Degree in Illumination Technology & Design from Jadavpur University, Kolkata, India in 2017. His research interest includes non-conventional energy sources and optical communications

Parthasarathi Satvaya,
Assistant Professor, School of Illumination Science Engineering & Design Jadavpur University, Kolkata, India. He has received his B. Tech. Degree in Electronics & Instrumentation Engineering and M.E. Degree in Illumination Engineering in 2006 and 2008 respectively. His research interests includes smart lighting and electronic instrumentation

Saswati Mazumdar,
Ph.D., Professor in field of Electrical Engineering at Jadavpur University (JU, Kolkata, India). She has 30 years of experience in lighting research and teaching. She was a developer of a modernized Illumination Engineering Laboratory in Electrical Engineering Department of Jadavpur University, have founded two Masters' Courses on Illumination Engineering (Daytime) and Illumination Technology & Design (Evening) in JU, executer of a large number of R&D and consultancy of projects on illumination and allied fields

Light & Engineering
Vol. 27, No. 1, pp. 51–60, 2019

A NOVEL FRAMEWORK TO EVALUATE THE PERFORMANCE OF RESPONSIVE KINETIC SHADING DEVICES

Mustafa Teksoy[1] and Onur Dursun[2, 3]

[1] *Teksoy Yapi Mimarlik Ltd.*
[2] *Yasar University, Izmir, Turkey*
[3] *Liverpool John Moores University*
E-mails: O.Dursun@ljmu.ac.uk; mustafateksoy@teksoyyapi.com

ABSTRACT

Determining control parameters of kinetic shading devices introduces a dynamic problem to designers, which can best be tackled by computational tools. Yet, excessive computational cost inherits in reaching near optimum solutions led to exclusion of many design alternatives and weather conditions. Addressing the issue, the current study aims to explore the design space adequately and evaluate the performance of responsive-kinetic shading devices (RKSD) by proposing a novel framework. Current framework adopts a surrogate-based technique for multi-objective optimization of control parameters of a RKSD on randomly sampled daylight hours. To test the plausibility of any results obtained by the proposed framework, a controlled experiment is designed. Empirical evidences suggest RKSD outperforms the static one in daylighting and view performance metrics. However, considering indoor temperature no significant differences observed.

Keywords: responsive, kinetic, shading, daylight, temperature, view, simulation, surrogate, optimization

1. INTRODUCTION

Solar control has been historically a vital consideration in architectural design, since it is highly relevant with the concepts of energy and comfort. A proper control strategy by means of shading devices has dramatic influence on room temperature and natural lighting, accordingly, contributes to energy savings while providing comfort for the occupants [1]. Regulating the sunlight on the exterior of a facade, before solar beams enter the room and radiate its energy inside, is a much efficient strategy for sun control [1–3]. Conventionally, static shading devices are integrated to facades to perform this task. However, static devices fail in responding to fluctuating environmental and comfort demands. Lechner [4] put forward a critical question:

"Is it logical that a static system can respond to a dynamic problem?"

To tackle with the issue, responsive kinetic shading devices (RKSD), which forms the focus of the current research, were introduced. RKSD are defined as active shading systems. They consist of components with the ability to change themselves due to the change in the environment with help of kinetic movement in an automated manner. To be responsive, a shading device must possess moving parts, actuators, a control system, sensors and be programmed to respond in a certain way due to the sensor data. When designing a kinetic system, which accounts for change in time, the complexity of the design problem increases substantially. On the other hand, the developments in the computer technology along with new computational approaches, researchers gained the ability to deal with such complexity.

As a specific domain of computer aided design – performance integrated parametric design and performance optimization help making well-informed design decisions. However, information feedback in the design process comes at a price, which is computation time. Most of the simulation engines that generate such design information are computationally expensive. In the study of solar control with help of kinetic shading devices that respond to its environment, the problem of high computational times is even more significant. Because the determination of the values for the shading control parameters requires to be based on minor fractions of time.

A critical review of the literature on responsive kinetic shading devices revealed that most of the studies over-simplified the design problems due to the high levels of complexity and computational costs (i.e. [5–9]). Such simplifications may lead to deficiency in the exploration of the design space. For instance, El Sheikh & Gerber [10] and Sharaidin, Burry, & Salim [11] employed a meta-heuristic search method, namely genetic algorithm, towards exploration of design alternatives that have better daylight performance. Excessive number of simulations is required to converge to optimum design alternatives. Therefore, computational cost was extremely high as each population member for the given number of generations must be simulated in simulation-based optimization. In response, Wortmann et al. [12] argued that surrogate model based optimization outperforms simulation-based optimization in solving architectural design problems, both at computational cost and finding better solutions. For instance, Kazanasmaz et. al. [13] developed a predictive model by using artificial neural networks in order to predict daylight intensity for the office buildings in Izmir, Turkey. Parallel, Hu and Olbina [14] utilized surrogate models for predicting the influence interior split-blinds on illuminance levels and achieved very low prediction errors. Both works [13,14] focused only to daylight performance, by neglecting thermal and other visual comfort aspects such as view to the outside environment. In another instance, Skavara [15] implemented artificial neural networks for controlling the emergent behaviour of an exterior shading system that is driven by cellular automata for daylight performance. However, her focus was more on the training techniques of the neural networks, than the comfort and energy related influence of the responsive-kinetic shading device that she proposed.

Not only performance assessment using computational tools but also comparison between static and responsive-kinetic shading devices, have been considered by previous studies (i.e. [7,9,16,17]). In all cited studies, researchers concluded that kinetic shading devices outperform static ones. However, the static shading systems that they examined were not optimized for better performance. Additionally, in none of the works cited, view – one of the most important consideration in architectural design – has been considered as a performance objective, along with thermal and daylight objectives in the same problem. Finally, a single point in time was considered as a basis for comparison. Specifically, only a time-point in a year i.e. July at 11:00 a.m. was studied for comparison aims. Therefore, any results obtained by such limitations can reach to restricted conclusions.

To address the gap in the literature, the current study aims to explore the design space and evaluate the performance of RKSD adequately by proposing a novel framework. Current framework adopts a surrogate-based technique for multi-objective optimization of control parameters of a RKSD on randomly sampled daylight hours. To test the plausibility of any results obtained by the proposed framework, a controlled experiment is designed, which is detailed profoundly in Methodology section. Empirical evidences suggest RKSD outperforms the static one in daylighting and view performance metrics. However, considering indoor temperature no significant differences observed.

2. METHODOLOGY

The current research employed a quantitative approach for assessing the performance of shading devices. To achieve, a novel computational framework was proposed, Fig. 1. Next, the framework was tested in a comparative study between annually optimized-static and hourly optimized responsive-kinetic shading devices. It was hypothesized that responsive-kinetic shading devices would outperform optimized-static shading devices on the given performance metrics. To test the hypothesis, a controlled experiment was designed using the computational tools, which aims at measuring the influence of quantitative independent variables on selected performance metrics.

The current work considered three performance metrics. The first one is denoted by $|\Delta T|$ which is defined as the absolute value of the difference between the air temperature simulated inside the hypothetical box model and 23 °C threshold. The second

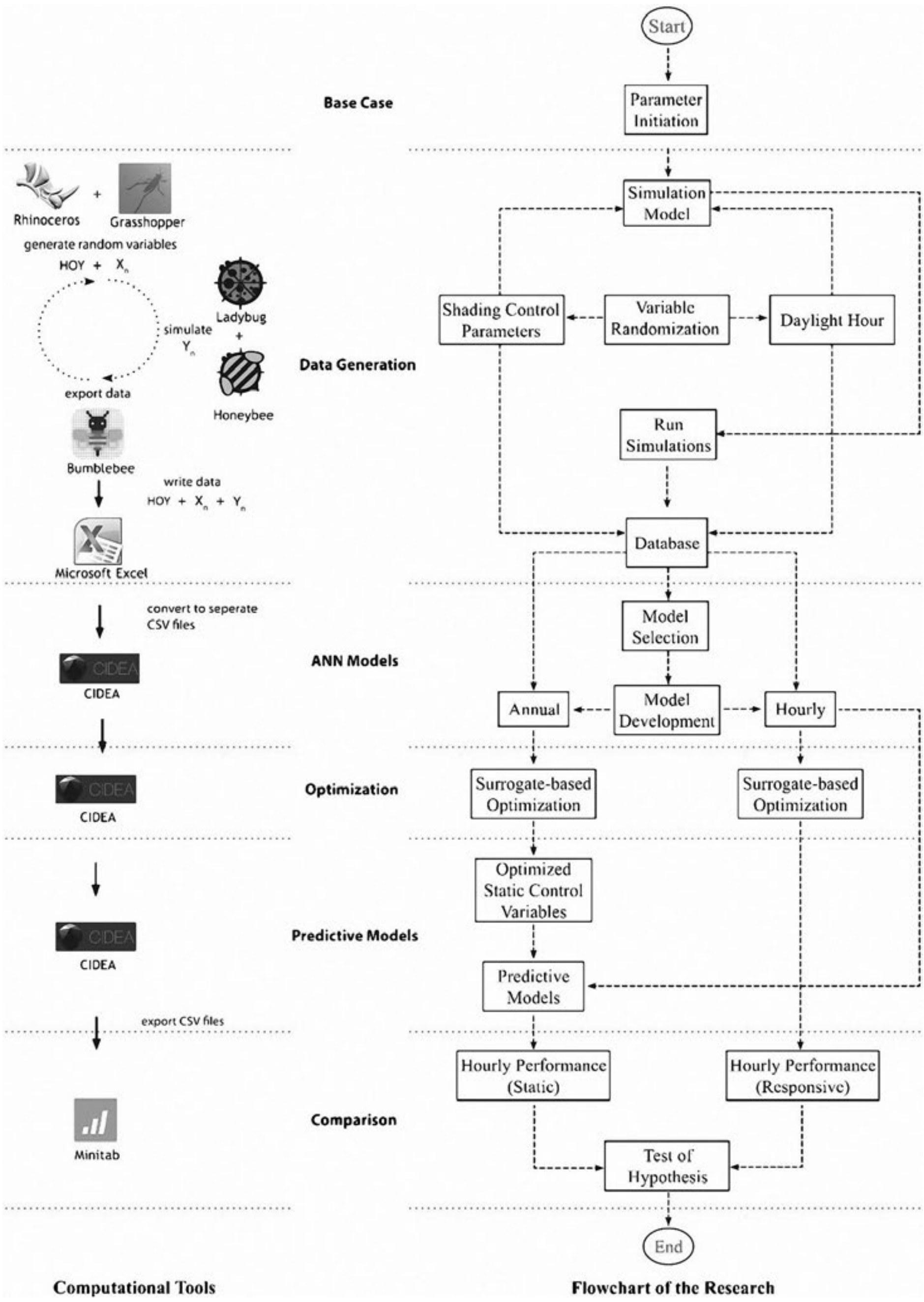


Fig.1.The computational tools used and the flow-chart of the experimental design

performance metric is denoted by $|\Delta lux|$ which is the absolute value of the difference between the average illuminance what was simulated inside the hypothetical box model and 500 lx thresholds. Finally, last performance metric is the average of the *View* percentage from a given point inside to the view frame at the outside

2.1. Box Model Properties

Within the content of experiment design, first, a test box was defined for the study of the exterior shading devices. At each of the shading device scenarios, parameters of this test box were kept constant. The dependent variables of annually-optimized and responsive kinetic shading systems on the base building were examined. The location of the Box-Model was Izmir, Turkey. Crucial to underline, to eliminate the influence of other confounding factors and thus measuring the sole impact of shading device on selected performance metrics; heat transfer was allowed only from the south-facing façade in the current experimental design. Furthermore, it was assumed that there were no internal

Table 1. Parameter Initiation of the Box-Model

Parameters		Values
Location		**Izmir /Turkey**
Dimensions	Width, m	3
	Depth, m	6
	Height, m	3
Reflectance	Floor,%	30
	Ceiling,%	80
	Walls,%	50
	Shading (exterior),%	40
U Values (heat transfer coefficient)	Walls (except South)	Adiabatic
	Roof	Adiabatic
	Floor	Adiabatic
	Window, W/($m^2 \cdot$ K)	2.39
	South Wall, W/($m^2 \cdot$K)	0.49
Internal Loads	Equipment, W/m^2	
	Infiltration Rate, (m^3/s)/m^2	0.003
	Irradiance, W/m^2	0
	People Density, ppl./m^2	0
Window	Orientation	South
	Glazed Area, m^2	7.84
	Window to Wall Ratio	0.87
	Window Construction	Double Pane with Low *E*
Glass Material	Type	Clear glass
	Visible Transmittance	0.79
	Refraction Index	1.52

heat loads. Table 1 demonstrates the initial parameters of the box model.

2.2. Parametrization of Shading Device – Independent (Decision) Variables

Shading device's parameterization was conducted by using Grasshopper an algorithmic modelling platform. The geometry of the shading was generated by subdividing a surface that was 5 cm away from the south façade into six parts. This would allow controlling of the conceptual shading system with zones. Subsequently, each of these parts was subdivided again into 30 parts. These operations generated a data tree with six lists each having 30 items. Each of the surfaces would form horizontal slats of the shading devices with a dimension of 0.03 m ×1.49 m. An axial rotation operation was defined for all the surfaces in six different lists. Shading surfaces in separate lists were controlled by independent rotation parameters (X_1, …, X_6), which could have a value within the range of 0.00 to 180.00 degree. Recall that, the designs of shading devices were identical for both responsive kinetic and static types to facilitate fair comparison.

2.3. Inclusion of Performance Metrics to the Parametric Model

Inclusion of performance metrics to the parametric model was achieved using well-established plug-ins for Grasshopper. Ladybug and Honeybee are open source plug-ins for Grasshopper, developed for aiding the designers to explore and evaluate environmental performance of any design alternative at the conceptual design phases. With help of the programs within Ladybug toolset, it is possible to import EnergyPlus weather data files (EPW) into Grasshopper, make various environmental analyses that rely on previously recorded local time-series data. Honeybee toolset contains programs that connects visual programming environment of Grasshopper with various validated simulation engines such as EnergyPlus, Radiance, Daysim and

OpenStudio [18]. An integrated and flexible design approach can easily be utilized in the design process by means of those plug-ins and the visual scripting environment that Grasshopper platform provides. By generating a definition on Grasshopper various design variables and associative performance data can easily be generated for further research.

2.4. Database Generation

A performance integrated parametric model was generated for exploring the alternatives in the design space and the response variables of the static and responsive kinetic shading devices. The previously established parametric model had six independent variables, and three response variables (objectives) that are referred to as performance metrics. The next step was automating the process of generating and recording random independent variables for the control of shading zones and their computed performance metrics in a database. To achieve this goal 6-steps procedure had to be fulfilled.

- Step 1: Generate 6 random values within the range for shading control parameters (independent variables).
- Step 2: Run daylight, energy and view simulations for each the generated scenarios.
- Step 3: Write shading independent design variables and dependent response variables to spreadsheets.
- Step 4: Iterate the above process for 500 times for each hour.
- Step 5: Change the hours of the year.
- Step 6: Iterate for 50 times.

Nabil and Mardaljevic [19] argued that sub-sampling the meteorological dataset, such as picking only one day from each month, eventually bring biases because different sky and conditions would be excluded. However, in the research presented here, the aim is not making an annual inference, but examining the point in time situation. For this reason, a random sampling of 50 hours was made from total daylight hours of a year, provided that the selected hours were between 9:00 am and 17:00 pm.

Simulations were run on an hourly basis for the randomly sampled times in a year. By assigning random values for the decision variables within the range, 500 simulations were performed for each of the 50 randomly sampled hours. For the static shading, a randomly generated set that contains 500 examples were performed on an annual basis. Therefore, aggregated 25.500 runs were performed in an automated workflow to generate 51 datasets for further development of surrogate models. At each run, the independent variables and their associative variables that contain performance indicator values for each hour and a year were stored in separate spreadsheets. After finishing the database generation procedure, each spreadsheet was converted to comma-separated values (CSV).

2.5. Development of Surrogate Models

In the experimental design of the current study, development of surrogate models played a central role since they served two crucial purposes:

1. First, they were employed as the objective functions for the subsequent optimization process. Since they established the causal relationship among input and output variables, the current work utilized these relationships towards concurrent evaluation of the performance metrics.

2. Second, they functioned as the performance metric predictor of the static shading devices on considered date/hour of the year to facilitate comparative results with the performance results obtained for RKSD.

Feed-forward Artificial Neural Networks (FAAN) was used for development of surrogate models. In feed-forward neural networks, a connection is allowed only from a node in a layer to nodes in the next forward layer. Multi-layer feed-forward networks are very popular and long-established structures of artificial neural networks, which have been used in many applications such as forecasting and function approximation [20]. This class of neural networks is identified by presence of hidden layers between the input and output of the network. Hidden layer contains hidden neurons, which are not directly seen from either input or output [21]. The models that were prepared for the study are in the class of multilayer perceptron (MLP), since they have one hidden layer, other than just having an input and output layer. According to the extensive review conducted by Zhang, Patuwo, and Hu [20] ANN with a single hidden layer are sufficient to approximate any complex non-linear function at any degree of accuracy. Therefore, number of hidden layers was not a parameter to search for in the model selection process that was conducted for finding best performing network models and avoiding over-training of the networks.

Prior to generating MLP, three model selection operations were executed for each performance metrics to determine the network architectures. For network architectures that would be used for RKSD models, a dataset from a random hour was selected for testing network model, other than performing it to all the 50 datasets. The network architecture that outperformed remainders for the selected hour was then used for 49 remainder hours for RKSD. For annually optimized static shading, this was not an issue because the network models used one dataset for annual performance.

For cross validation, Monte Carlo technique was implemented for both model selection and neural network training processes. Using Monte-Carlo, the randomly generated data sample was split into two random sub-samples by a factor of 0.1. That is, 450 random observations (corresponds to 0.9) in the datasets were used for neural network training purposes. To assess predictive ability of trained network on the unseen data, remaining 50 observations, namely test sample was used. This process was then iterated 10 times, generating new training and test partitions at random each time. The performance evaluation criteria for cross-validation is root mean square error (RMSE)[1] which is subject to minimization.

Once the network architectures and number of iterations were determined for the models, the networks were trained using the data that contain simulation-derived observations. MLPs were trained by Resilient Back-Propagation (RProp) algorithm. RProp is a fast learning algorithm for MLPs that performs local adaptation of the weight-updates due to the act of the error function. Detailed information on training algorithm used in the current study can be found elsewhere [22]. Developed by Chatzikonstantinou [23], CIDEA, a Computational Intelligence Decision-Support Environment for Architectural and Building Design was used to conduct the tasks of surrogate model development and multi-objective optimization.

2.6. Multi-Objective Optimization – Objective functions

HypE algorithm was employed for deriving optimal solutions with respect to $|\Delta T|$, $|\Delta lux|$, and

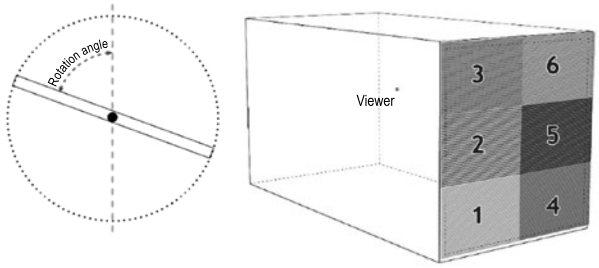


Fig. 2. Exterior shading system with six control zones and the diagram of a single shading control parameter

View. Bader, et. al. [24] proposed *HypE* as an evolutionary multi-objective optimization algorithm that is based on quality measure of hyper-volume indicator. In their study, they compared the algorithm with other evolutionary optimization algorithms such as *NSGA-II, SPEA2* and so on. Their results showed that *HypE* outperformed all the others, in multi-objective optimization problems with a dimension more than two. Therefore, *HypE* algorithm seems adequate for three-dimensional optimization problem that was formulated for the study of exterior shading devices.

According to the problem formulation, while $|\Delta T|$ and $|\Delta lux|$ objectives were minimized, *View* was maximized. This formed an obvious conflicting situation. In the optimization phase, *HypE* algorithm was referenced to the neural networks for each objective function.

The current work used the default settings for optimization to generate 100 generations each having 100 populations, whereas hyper-volume samples and mutation probability was set as 5000, and 0.1, respectively. Surrogate-based optimization method was implemented for both types of conceptual shading devices to reach the best performing design alternatives. For RKSD50 optimization operations were run for each randomly sampled daylight hours. For the static shading, only one optimization operation was performed to find best performing alternatives on an annual basis. At the end of the process, we extracted 100th generation from each of the 51 optimization processes in total, for further operations.

2.7. Test of Hypotheses

The current work hypothesized that responsive-kinetic shading device would outperform optimized-static selected performance criteria. Accordingly, following alternative hypotheses were tested:

---

1 $RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(y_i - \widehat{y}_i\right)^2}$.

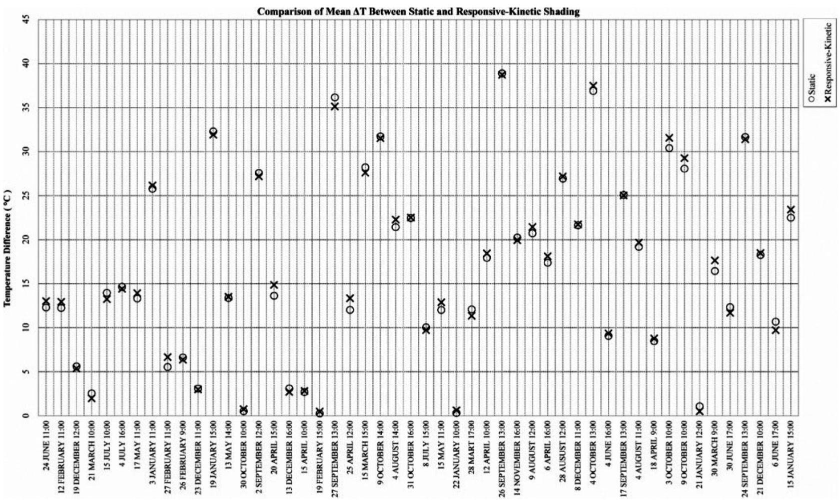


Fig. 3. Comparison of mean $|\Delta T|$ between static and RKSD

- $H_{alt,1} = |\Delta T_{responsive}| - |\Delta T_{static}| \le 0$;
- $H_{alt,2} = |\Delta lux_{responsive}| - |\Delta lux_{static}| \le 0$;
- $H_{alt,3} = View_{responsive} - View_{static} \ge 0$.

The design of experiment dictates to compare the means of one sample having different interventions whereas the data is in continuous domain. The same set of items was measured under two different interventions, namely responsive-kinetic and optimized-static. Therefore, paired-*t* test is the adequate statistics to conduct formal test of hypothesis.

3. RESULTS AND DISCUSSION

Upon successful implementation of the experimental design, exhaustively explained in the previous section, the current work obtained 50 sets of optimized decision variables for 50 randomly selected daylight hours for the responsive shading and one set of optimized decision variables for the static shading. Each of the 51 data sets is consisted of 100 optimized design alternatives.

Prior to implementing surrogate-based optimization, several pilot studies were conducted by using simulation-based optimization method of RKSD on arbitrarily selected daylight hours. The main intent of these studies was to verify the design of experiment as well as to calculate necessary duration of reaching near optimum solutions when using simulation-based technique. In pilot studies, near-optimum solutions for just a single hour in a year emerged only after a process that lasted for more than 60 hours. That is, when an architect chose to implement traditional simulation-based optimization technique towards performance evaluation of RKSD on, say, 50 selected hours of a year, he/she requires approximately 125 days achieving that task. On the other hand, utilizing surrogate models reduced the computational costs significantly. The investigation of the performance for the RKSD, on 50 randomly sampled daylight hours lasted for about 90 hours in total; whereas the computer conducted most of the process in an automated fashion.

Three hypotheses were considered within the content of the current study. In each, it was assumed that the responsive-kinetic shading type would outperform the optimized static one. However, the results of paired-*t* tests significantly demonstrated that, while $H_{alt,2}$ and $H_{alt,3}$ cannot be rejected $H_{alt,1}$ can be rejected. This implies, while responsive kinetic shading outperformed optimized static with respect to daylight intensity and view to outside, there was no significant difference in the comparison of the impacts of the two types of shadings on indoor air temperature.

The first objective function was $|\Delta T|$ minimization. Therefore, we expected lower $|\Delta T|$ values for responsive-kinetic shading type. However, the results suggest there is not enough evidence to conclude that the mean of responsive-kinetic shading is less than static shading at the 0.05 level of significance. We found out that the mean of $|\Delta T_{responsive}|$ is 16.77 °C, while the mean of $|\Delta T_{static}|$ is 16.60 °C.

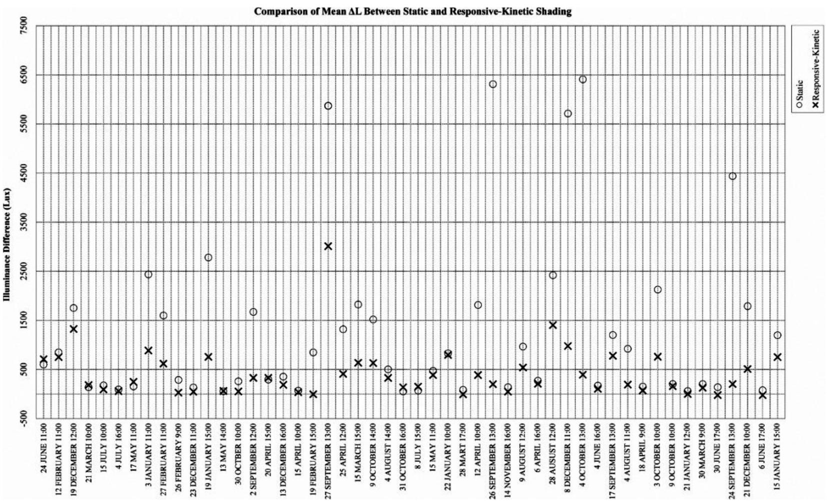


Fig. 4. Comparison of mean $|\Delta lux|$ between static and RKSD

In an indoor space with a solely southern-exposure to the sun in Izmir climate, responsive-shading devices may not contribute to thermal comfort and energy efficiency better than an optimized static shading device. To further underline, the study considered other objective functions in the optimization problem simultaneously. The function of view to outside maximization might have influenced this result, since it is an obviously conflicting objective in most of the weather conditions. Fig. 3 illustrates paired comparison of mean $|\Delta T|$ on randomly selected hours.

The second performance objective function was minimization of $|\Delta lux|$. As in the first objective, the current work aimed at minimizing $|\Delta lux|$ to make the average daylight intensity as close to 500 lx as possible. In the comparison test for $|\Delta lux|$ objective, the findings of the current study suggest that the RKSD performs significantly better than optimized the static shading at the 0.05 level of significance. The results revealed that the mean of $|\Delta lux_{responsive}|$ is 420 lx, while the mean of $|\Delta lux_{static}|$ is 1277 lx. The daylight performance of responsive-kinetic shading is almost three times better than the optimized static shading according to the findings. However, it must be noticed that five of the paired differences were unusual, that is the difference between the pair is much more than the trend, Fig. 4.

This situation contributed to the increase in the total mean difference. Nonetheless, one can be 95 % confident that the true mean difference is less than 507 lx and 90 % percent confident that it is between 507 and 1206 lx.

The final objective function for the performance evaluation was percentage of view to outside (*View*). Maximization was intended for this function, therefore higher values of *View* is desired. The findings suggest that the mean of $View_{responsive}$ and $View_{static}$ is 64.2 and 48.4, respectively. As reported in the results, we can conclude that the mean of responsive-kinetic shading is significantly greater than the mean of optimized static shading at the 0.05 level of significance. We can be 95 % confident that true mean difference is greater than 12.7, and 90 % confident that it is between 12.7 and 18.7. Fig. 5 illustrates paired comparison of *View* objective.

The reason for these results may be related with the formulation of the experiment. The controlled experiment was designed for the investigation of sole impact of sunlight on the interior environment. The solar beams have two diverse but related aspects, namely thermal and daylight. Heat energy cannot reflect but radiate. Both shading devices intercepted the heat energy of solar beams on the outside in a similar manner. However, daylight aspect of solar beams was managed much better by responsive kinetic shading type. Objective performance about window view in the design problem statement, which is not a dynamic measure, conflicts with the other objectives, and might has be contributed to this situation.

CONCLUSION

The current work established a novel framework for adequately exploring design alternatives and optimizing performance of control parameters of responsive-kinetic shading devices with respect to objectives of $|\Delta T|, |\Delta lux|$ *View*. The urge for

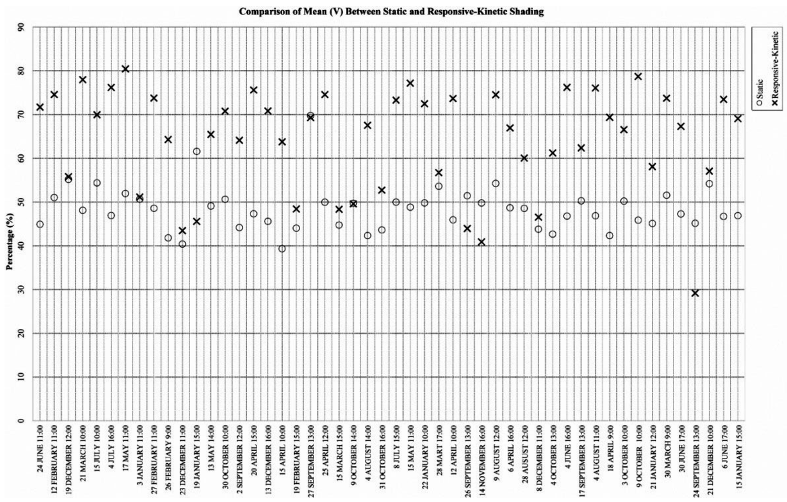


Fig. 5. Comparison of mean *View* between static and RKSD

developing such framework was motivated by the absence of an adequate and efficient method for exploring and evaluating the performance of RKSD. In addition, literature has not addressed the task with consideration of thermal, daylight, and view objectives simultaneously up to now. Findings suggest one can achieve significant reduction in computational time compared to simulation-based methods using proposed framework. A surprising outcome was the optimized static shading slightly outperformed the responsive-kinetic one in the objective $|\Delta T|$. Considering the objectives $|\Delta lux|$ and *View*, however, empirical evidences suggested that RKSD significantly outperformed the optimized-static shading.

In the future works, the relationships between weather conditions, design variables and performance objectives should further be examined. Certain weather parameters, such as global illuminance, global radiation, are required to be extracted from the weather file and match with the design and response parameters to picture the relationships between them.

REFERENCES

1. G. Hausladen, M. de Saldanha, and P. Liedl, *Climate Skin*. Basel: Birkhauser, 2008.

2. H. Fathy, *Natural Energy and Vernacular Architecture*. Chicago and London: The University of Chicago Press, 1986.

3. A. Olgyay and V. Olgyay, *Solar Control and Shading Devices*. New Jersey, 1977.

4. N. Lechner, *Sustainable Design Methods for Architects*. New Jersey: Wiley, 2015.

5. C. Du Montier, A. Potvin, and C.M. Demers, "Energy and daylighting potential for Adaptive Façades: Evaluation of movable insulated panels," Proc. of Int. Conf. on Adaptation and Movement in Architecture ICAMA 2013, Oct. 2013, Toronto, Canada.

6. Y.J. Grobman, I.G. Capeluto, and G. Austern, "External shading in buildings: comparative analysis of daylighting performance in static and kinetic operation scenarios," *Architectural Science Review*, 2016, Vol. **60**, no. **2**, pp. 1–11.

7. K. Kensek and R. Hansanuwat, "Environment Control Systems for Sustainable Design: A Methodology for Testing, Simulating and Comparing Kinetic Facade Systems," *Journal of Creative Sustainable Architecture & Built Environment*, 2011, Vol. 1, no. Nov., pp. 27–46.

8. D. S. Lee, S.H. Koo, Y.B. Seong, and J.H. Jo, "Evaluating thermal and lighting energy performance of shading devices on kinetic façades," *Sustainability (Switzerland)*, 2016, Vol. 8, no. 9, pp. 1–18.

9. M. V. Nielsen, S. Svendsen, and L.B. Jensen, "Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight," *Solar Energy*, 2011, Vol. 85, no. 5, pp. 757–768.

10. M. El Sheikh and D.J. Gerber, "Building Skin Intelligence," *Proceedings of the annual conference of the Association of Computer Aided Design in Architecture ACADIA*, 2011, pp. 170–177.

11. K. Sharaidin, J. Burry, and F. Salim, "Integration of Digital Simulation Tools With Parametric Designs to Evaluate Kinetic Façades for Daylight Performance," *Physical Digitality: Proceedings of the 30th eCAADe Conference,* 2012, Vol. 2, pp. 701–709.

12. T. Wortmann, A. Costa, G. Nannicini, and T. Schroepfer, "Advantages of surrogate models for ar-

chitectural design optimization," *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 2015, Vol. 29, no. 4, pp. 471–481.

13. T. Kazanasmaz, M. Günaydin, and S. Binol, "Artificial neural networks to predict daylight illuminance in office buildings," *Building and Environment*, 2009, Vol. 44, no. 8, pp. 1751–1757.

14. J. Hu and S. Olbina, "Illuminance-based slat angle selection model for automated control of split blinds," *Building and Environment*, 2011, Vol. 46, no. 3, pp. 786–796.

15. M. E. Skavara, "Adaptive cellular automata façade trained by artificial neural network," Barlett School of Graduate Studies, University Collage of London, 2009.

16. E. S. Lee, D.L. DiBartolomeo, and S.E. Selkowitz, "Thermal and daylighting performance of an automated venetian blind and lighting system in a full-scale private office," *Energy and Buildings*, 1998, Vol. 29, no. 1, pp. 47–63.

17. A. Wagdy, F. Fathy, and S. Altomonte, "Evaluating the Daylighting Performance of Dynamic Façades by Using New Annual Climate- Based Metrics Evaluating the Daylighting Performance of Dynamic Façades by Using New Annual Climate – Based Metrics," Proc. of the 32nd Int. Conf. on Passive and Low Energy Architecture, PLEA 2016. 2016, Los Angeles, CA, pp. 941–947.

18. M. Sadeghipour Roudsari and M. Pak, "Ladybug: a Parametric Environmental Plugin for Grasshopper To Help Designers Create an Environmentally-Conscious Design," *13th Conference of International building Performance Simulation Association*, 2013, pp. 3129–3135.

19. A. Nabil and J. Mardaljevic, "Useful daylight illuminance: a new paradigm for assessing daylight in buildings," *Lighting Research and Technology*, 2005, Vol. 37, no. 1, pp. 41–59.

20. G. Zhang, B.E. Patuwo, and M.Y. Hu, "Forecasting with artificial neural networks:: The state of the art," *International journal of forecasting*, 1998, Vol. 14, pp. 35–62.

21. S. Haykin, *Neural Networks and Learning Machines*. 2009.

22. M. Riedmiller and H. Braun, "A direct adaptive method for faster backpropagation learning: The RPROP algorithm," *IEEE International Conference on Neural Networks – Conference Proceedings*, Vol. 1993–Janua, pp. 586–591.

23. I. Chatzikonstantinou, "A Computational Intelligence Decision-Support Environment for Architectural and Building Design: CIDEA," *IEEE Congress on Evolutionary Computation 2016*, pp. 3887–3894.

24. Bader, J., Zitzler, E. HypE: An Algorithm for Fast Hypervolume-Based Many-Objective Optimization // Evolutionary Computation. 2008, Vol. 19, No. 1, pp. 45–76.

Mustafa Teksoy,
partner and main architect in *Tecsoy Yapi Mimarlik Ltd*, Turkey.
He was awarded by Degree of Master of Science in Architecture from Yasar University in 2017. His fields of interests are computational design, architectural robotics, sustainable and energy conscious buildings. Currently, he undertakes responsibility of design and builds of the first nearly zero energy hotel development in Alacati region, Izmir, Turkey

Onur Dursun,
Dr.-Ing. He received his Doctor of Engineering Degree in Construction Economics from University of Stuttgart in 2014. Since then, he has been appointed as an Assistant Professor at Architecture Faculty, Yasar University, Turkey. His current research interests are performance assessment in building design, and construction economics. At present, he is a senior lecture in Department of Built Environment of Liverpool John Moores University

Light & Engineering
Vol. 27, No. 1, pp. 61–70, 2019

LIFE CYCLE COST ANALYSIS ON M1 AND M2 ROAD CLASS LUMINAIRES INSTALLED IN TURKEY

Ramazan Ayaz[1], Asiye Kaymaz Ozcanli[1], Ismail Nakir[1], Pramod Bhusal[2], and Adem Unal[1]

[1] *Department of Electrical Engineering, Yıldız Technical University, Istanbul, Turkey*
[2] *Department of Electrical Engineering and Automation, Lighting Unit, Aalto University, Espoo, Finland*
E-mail: ayaz@yildiz.edu.tr

ABSTRACT

This paper investigates and compares the photometric performance and lifetime cost effectiveness of LED and existing conventional luminaires (high pressure sodium (HPS) and metal halide (MH)). Photometric measurements of the lamps and the luminaires were performed at Yıldız Technical University Lighting Laboratory in Turkey. The performance requirements of the luminaires were analysed according to CIE (International Commission on Illumination) standards. In the simulations, HPS, MH and LED luminaires that provide good lighting criteria for designing M1 and M2 road models were compared in terms of a cost analysis. The life cycle cost analysis (LCCA) method, which comprises installation, energy and maintenance costs, was used in this study. The results of the LCCA showed that LED luminaires have almost the same cost effectiveness as HPS luminaires for the M2 road lighting class, and the total cost of LED luminaires is approximately 11.5 % less than that of HPS luminaires for the M1 lighting class.

Keywords: roadway lighting, LED luminaire, energy efficiency, life cycle cost

1. INTRODUCTION

Worldwide, environmental impacts and energy security issues due to increasing energy consumption have been serious problems since the energy crisis in the 1970s. Globally, lighting consumes approximately 19 % of the total generated electricity [1]. Also, it is estimated that approximately (3–4) % of total generated electricity is used for road lighting around the world [1]. Lighting being a significant consumer of electricity worldwide, energy efficiency improvements in this field can lead to significant reductions in total energy consumption [2].

Significant amount of investments are done in energy efficient lighting to reduce energy costs and CO_2 emissions. Replacing traditional lighting with energy efficient light emitting diode (LED) – based lighting has the potential to reduce green house gas (GHG) emissions by 670 MT annually and decrease energy costs by (50–70)% [3]. Many studies have shown that retrofitted projects in lighting applications could reduce energy costs up to 50 % by employing state-of-the-art lighting technologies [4, 5].

LED light sources are good alternatives for road lighting over traditional sources due to their colour properties, uniform light distribution, improved mesopic vision, controllability, and low environmental impacts [6][7]. Moreover, the illuminance level can be controlled to adapt to variations in the road surface reflectance, traffic density and weather conditions to reduce energy consumption without affecting the lifetime of luminaire [8, 9]. The environmental impact (e.g. acidification, climate change, eutrophication, human toxicity) of LED luminaires per kilometre of lit road is forecasted to be 41 % less than that of HPS luminaires due to reduced energy consumption by 2020 [10].

The life cycle cost analysis method can be used to determine the best choice for an investment decision. This method enables one to determine the profitability of an investment in the road lighting [11, 12]. The LCCA is suitable to determine the lowest cost among alternative installations and to analyse the profitability of a projected investment. Various studies have carried out life cycle cost analysis of conventional luminaires [13, 14]. The lower life cycle cost should be obtained with higher-lifetime products that have low energy consumption (high luminous efficacy) and purchasing price [15]. The LCCA by Tähkämö et al. presents different scenarios based on predicted average electricity price and luminous efficacy of LED luminaire and, so, the payback time of LED luminaires can be reduced in the next years [14]. The results of study, in which LED luminaires were used for M3 road lighting class in Turkey, showed that LED luminaires can provide the lighting quality criteria for M3 road lighting class and can be comparable with conventional luminaires [13]. In addition, some studies include life cycle assessment (LCA) to evaluate environmental impacts of luminaire technologies and road construction [10, 16].

In this study, all sample luminaires are examined for compliance of road lighting requirements. The conventional and LED luminaires are then compared in terms of life cycle costs for M1 and M2 road lighting class. Road lighting classes are defined in terms of speed, traffic volume, weather, traffic composition, intersection density, separation of carriageways, parked vehicles, ambient luminance and visual guidance in the CIE publication [17]. The LCCA method includes installation, maintenance, replacement, energy and salvage costs.

The paper is organized as follows: the methodology and design calculations of road models are presented in Section 2. The description of the life cycle cost analyses is given in Section 3. The results of cost analyses are discussed in Section 4 and conclusions are drawn in Section 5.

2. METHODOLOGY AND DESIGN CALCULATIONS OF ROAD MODELS

This study adopted several methods in three steps to find the most appropriate M1 and M2 class road luminaires to be installed and maintained with the lowest life cycle cost in Turkey. The block diagram of the methodology is given in Fig. 1.

Firstly, HPS, MH and LED road luminaires were procured from six different manufacturers (L1, L2, L3, L4, L5 and L6). There were six conventional luminaires from three different manufacturers and six LED luminaires. The conventional luminaires had HPS (150 W Philips SON-T and 250 W Philips SON-T) and MH (150 W Sylvania CMI and 250 W Philips HPI-T) light sources. The powers of LED luminaires ranged from 80 W to 170 W. The photometric quantities of these twelve luminaires were measured in the Yıldız Technical University Lighting Laboratory in Turkey by using an integrating sphere and goniophotometer. The quantities measured include luminous flux, luminous intensity distribution, maximum light intensity, maximum light angle, luminous efficacy, power, power factor, CIE general colour rendering index (CRI) and correlated colour temperature (CCT).

Secondly, the results of the measurements were saved as EULUMDAT files and transferred to the DIALux lighting design software package. The road models were simulated based on M1 and M2 lighting classes and optimized the most suitable road design. The HPS, MH and LED luminaires that provided minimum road lighting requirements were determined for LCCA.

Finally, according to the results of the design calculations, cost analyses of the HPS and MH luminaires were calculated with the LCCA method. After that, the lowest-life-cycle-cost HPS (150 W L3 for M2 and 250 W L3 for M1) and MH (150 W L3 for M2 and 250 W L1 for M1) luminaires and all LED luminaires were analysed to compare the life cycle costs of the luminaires. Installation, maintenance and energy costs were calculated using recent prices in Turkey. The HPS and MH luminaires completed their lifetime at the end of the project (about 30 years), so salvage costs were not considered in this study. In contrast, salvage costs were considered for the LED luminaires due to the unused period of the luminaire lifetime.

2.1. Measurement Equipment and Photometric Data

The HPS and MH lamps were first measured with an integrating sphere (Everfine Photo-E-Info Co., Ltd.). The lamps were seasoned for 100 operating hours before they were tested [18]. The lamps were measured with ballast and igniter of the luminaire, and the luminous flux, CCT and CRI were obtained. The CCT of HPS and MH lamps ranged from 2039 K to 2083 K and from 4062 K to 4127

Table 1. Photometric Data of Conventional Luminaires

No	Luminaire type	Measured Power, W*	Power factor	Luminous flux, lm	Luminous efficacy, lm/W	Max. radiation angle, grad (C, γ)	Luminous intensity curve type
1	150W HPS L1	166.0	0.939	13,087	78.8	5;24	limited
2	150W HPS L2	174.9	0.951	13,824	79.0	320;18	unlimited
3	150W HPS L3	148.6	0.930	12,579	84.7	145;19	semi-limited
4	150W MH L1	163.5	0.939	9,554	58.4	180;58	limited
5	150W MH L2	169.7	0.942	9,392	55.3	185;67	unlimited
6	150W MH L3	148.8	0.931	9,398	63.1	10;64	semi-limited
7	250W HPS L1	278.6	0.772	26,227	94.1	15;31	limited
8	250W HPS L2	263.7	0.950	23,224	88.1	345;48	limited
9	250W HPS L3	234.5	0.951	21,524	91.8	200;14	semi-limited
10	250W MH L1	296.1	0.641	20,966	70.8	155;25	semi-limited
11	250W MH L2	277.6	0.858	18,132	65.3	355;64	limited
12	250W MH L3	263.2	0.844	17,784	67.6	350;66	unlimited

** It is included ballast losses.*
L1, L2, L3, L4, L5, L6: Names of various road luminaires manufacturers.

K respectively. The CRI of HPS and MH lamps ranged from 28.7 to 29.6 and from 62.3 to 65.1 respectively. The CCT and CRI of LED luminaires ranged from 4000 K to 4500 K and from 70 to 80 respectively. After the lamp luminous flux was measured using the sphere, the luminous intensity distribution of the luminaires, luminaire luminous flux and it's efficacy were determined using goniophotometer (Everfine Photo-E-Info Co., Ltd.) measurements.

The LED light sources were integrated in LED luminaires without a replaceable LED module. Therefore, the LED luminaires were only measured with the goniophotometer. Moreover, the LED luminaires were tested without seasoning. It should be noted, that the light output of some LEDs can increase slightly during the first 1000 h of operation, but many LED sources do not exhibit similar behaviour [19]. The temperature and humidity of the laboratory were maintained at 25±1 °C and 65 % respectively, with the help of an air condition unit. The luminous intensity of these luminaries was measured at 5º intervals in the range of (0–355)º, yielding 72 different C planes, and the γ angle was sampled at 1º intervals in the range of (0–90) º for each C plane. The results of photometric and electrical measurement of the luminaire samples are shown in Tables 1 and 2.

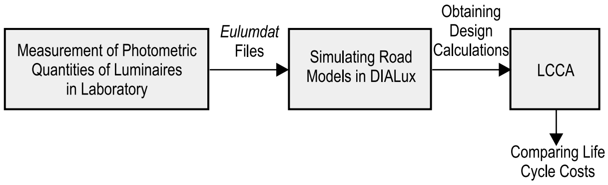


Fig. 1. Block diagram of the methodology

In Table 1, about 67 % of luminaires have power factors greater than 0.90. The luminous efficacy varies between 55.35 and 94.14 lm/W.

As can be observed from Table 2, the measured power is almost the same as the nominal power for different LED luminaires. The power factor of all LED luminaires is better than that of conventional luminaires. The luminous efficacy of LED luminaires varies between 78.77 and 122.34 lm/W.

2.2. Design Calculations Using the DIALux Lighting Design Program

Each sample luminaire has a different luminous intensity distribution; thus, the road lighting design has to take into account different characteristics to satisfy road lighting criteria [20]. When using different luminaires, design calculations such as pole spacing, montage height, tilt angle, and overhang

Table 2. Photometric Data of LED Luminaires

No	Luminaire type	Measured power, W	Power factor	Luminous flux, lm	Luminous efficacy, lm/W	Max. radiation angle, grad (C, γ)	Luminous intensity curve type
1	80W LED L1	79.35	0.984	7,392	93.1	180;63	limited
2	80W LED L4	79.9	0.934	8,654	108.3	45;49	semi-limited
3	105W LED L4	105.3	0.964	11,503	109.2	135;50	semi-limited
4	114W LED L5	112.6	0.980	8,869	78.8	160;60	semi-limited
5	170W LED L3	163.6	0.972	15,331	93.7	15;61	limited
6	153W LED L6	152.5	0.987	18,656	122.3	155;67	unlimited

differ from each other. Road lighting design should be optimized based on the maximum pole spacing.

According to the minimum road lighting quality criteria, the maximum pole spacing (*s*) was calculated using DIALux for the M1 and M2 road lighting classes. Other design parameters, such as the mounting height (*mh*), overhang (*oh*) and luminaire arm angle (θ), were determined according to the performance requirements.

2.2.1. Road Design for the M2 Lighting Class

The road model was simulated to assign lighting quality criteria to the luminaires. In general, 150 W HPS and MH luminaires are used for the M2 and M3 road lighting classes [21]. In this simulation, 150 W HPS and MH luminaires from three different manufacturers (L1, L2 and L3) and LED luminaires (80 W-114 W) from three different manufacturers (L1, L4 and L5) were used for the M2 lighting class. The road geometry and designed road model for the M2 lighting class are shown in Fig. 2a.

The road model consists of a four-lane divided road. The width of each lane is 3.5 m. The road model is illuminated with the luminaires placed opposite one another, i.e., in an opposite arrangement. This lighting situation is evaluated as A1 on a motorway on which the typical speed of a motorized vehicle user is greater than 60 km/h. The road surface used is the R3 pavement class. The luminaire maintenance factor considered is 0.89 [22].

2.2.2. Road Design for the M1 Lighting Class

In the roads with M1 and M2 lighting classes, 250 W HPS and MH luminaires are commonly used. In this simulation, the M1 lighting class is selected and simulated as three lanes on both side. The width of each lane is 3.5 m. The lighting design is defined with the median arrangement in the A1 lighting situation. The road surface pavement type and maintenance factor are R3 and 0.89 respectively. The road geometry and designed road model for M1 lighting class are given in Fig. 2b.

The HPS and MH luminaires (250 W) from three different manufacturers (L1, L2 and L3) and two types of LED luminaires from two different manufacturers (L3 and L6) are simulated for the M1 lighting class.

2.2.3. Results of the Road Design Calculations

The results of the road design calculations for the M1 and M2 lighting classes are in DIALux. As-

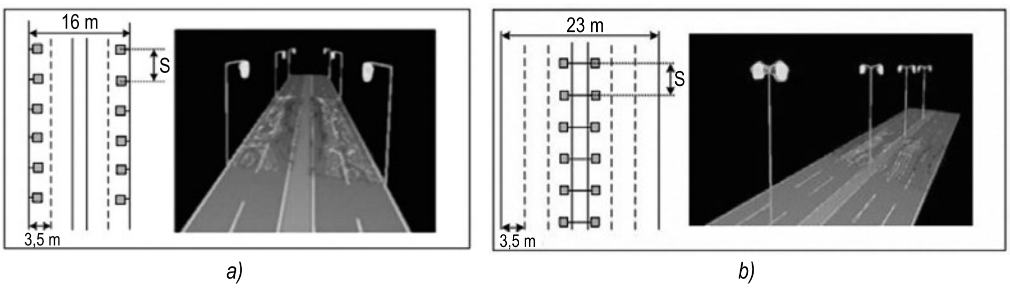


Fig. 2. Road Geometry: a) M2 Lighting Class, b) M1 Lighting Class

Table 3. Properties of Used Luminaires for LCCA in M2 Lighting Class

No	Luminaire type	Number of luminaires (piece/km)	Poles number (piece/km)	Lamp lifetime (h)	Replacement cycles (Year)	Price of luminaire (TL/piece)	Price of lamp (TL/piece)
1	150W HPS L3	58	58	20,000	5	140.00	33.00
2	150W MH L3	72	72	12,000	3	140.00	33.00
3	80W LED L1	74	74	50,000	13	420.00	-
4	80W LED L4	74	74	50,000	13	470.00	-
5	105W LED L4	64	64	50,000	13	530.00	-
6	114W LED L5	64	64	50,000	13	630.00	-

Table 4. Properties of Used Luminaires for LCCA in M1 Lighting Class

No	Luminaire type	Number of luminaires (piece/km)	Poles number (piece/km)	Lamp lifetime (h)	Replacement cycles (Year)	Price of luminaire (TL/piece)	Price of lamp (TL/piece)
1	250W HPS L3	64	32	20,000	5	212.00	45.00
2	250W MH L1	68	34	12,000	3	212.00	45.00
3	170W LED L3	76	38	50,000	13	400.00	-
4	153W LED L6	68	34	50,000	13	550.00	-

sociated with luminaire glare, the threshold increment of 150 W L2 luminaire does not comply with the requirement of ≤10 for the M2 road class.

The L1 HPS luminaire had a maximum pole spacing of 36 m, and the installed power of the L1 luminaire is calculated to be 9,296 W/km. The L3 HPS luminaire consumes 8,619 W/km at a pole spacing of 35 m. In this case, the number of L1 luminaires per km is less than that of L3 luminaires, so the installation and maintenance costs will be less. On the other hand, the energy cost per km of the L3 luminaire is less than that of the L1 luminaire. Therefore, the total cost of the L1 and L3 luminaires (HPS and MH) should be calculated based on LCCA to determine the most cost-effective luminaire.

In terms of energy consumption per km, LED luminaires are the most advantageous. However, installation and maintenance costs should also be examined to compare conventional and LED luminaires. The cost calculations and analysis of the luminaires for the M2 road lighting class are performed in Section 3.

3. LIFE CYCLE COST ANALYSIS (LCCA)

The life cycle cost analysis includes the installation, maintenance, replacement, operation and salvage costs over the project lifetime. The net present value (NPV) is used to determine the present value of an investment, so all costs are converted into their present values in the LCCA method. The equation (1) for the NPV total cost used in this study, considers both inflation and the interest rate.

$$NPV = \sum_{k=1}^{30} A * \frac{(1+e)^k}{(1+i)^k}, \tag{1}$$

where A is the present cost, e is the inflation rate, i is the interest rate, k is the years.

First, the costs of the conventional luminaires were compared between themselves according to the LCCA method. After the cost analyses, the HPS and MH luminaires with the minimum total cost were selected. The 150 W HPS and 250 W HPS luminaires produced by manufacturer L3 have the minimum total cost compared with other HPS lu-

Table 5. Results of NPV Total Costs for M2 Lighting Class

No	Luminaire type	Initial cost, TL/km	Energy cost, TL/km	Maintenance cost, TL/km	Salvage value, TL/km	Total cost, TL/km
1	150W HPS L3	154,976.00	173,473.47	11,379.34	-	339,828.82
2	150W MH L3	168,588.00	215,636.21	22,956.06	-	407,180.28
3	80W LED L1	194,139.00	118,111.23	41,683.97	12,670.98	341,263.22
4	80W LED L4	191,734.00	119,004.88	52,888.19	14,179.43	349,447.64
5	105W LED L4	183,712.00	135,255.69	50,740.32	13,828.82	355,879.19
6	114W LED L5	186,944.00	145,045.62	58,943.61	16,438.03	374,495.21

Table 6. Results of NPV Total Costs for M1 Lighting Class

No	Luminaire type	Initial cost, TL/km	Energy cost, TL/km	Maintenance cost, TL/km	Salvage value, TL/km	Total cost, TL/km
1	250W HPS L3	96,704.00	302,071.04	16,322.06	-	415,097.10
2	250W MH L1	99,297.00	405,259.86	28,077.40	-	532,634.26
3	170W LED L3	116,698.00	250,255.23	47,483.18	12,393.76	402,042.65
4	153W LED L6	115,515.00	208,720.46	55,619.08	15,247.58	364,606.96

minaires. Similarly, 150 W MH L3 and 250 W MH L1 luminaires have lower LCCs than other MH luminaires. However, all LED luminaires are incorporated in the LCCA. As mentioned in Section 2.2, the properties of the analyzed luminaires for the M1 and M2 lighting class are listed in Tables 3 and 4. LCCA considers the costs of lighting installation over its entire project life (generally 30 years in road lighting) [14]. The project life is assumed to be 30 years in this analysis, with a road lighting annual operation time of 3,650 hours. The economic life of conventional luminaires is 30 years, and these luminaires are not replaced with new luminaires during this time. Replacement cycle is lamp replacement year for conventional luminaire and luminaire replacement year for LEDs.

On the other hand, LED systems are considered as a whole (including the module, driver, lens, etc.), so the lifetime of the luminaire is determined based on the components of the LED system. The lifetime of the driver is less than the LED source lifetime [23]. More than 90 % of LED systems fail because of the driver [23]. Currently, there is no standard for the replaceable parts of LED luminaires. Luminaire manufacturers urgently note that the lighting industry should improve standardized drivers for use in LED lighting [23]. When luminaire failure occurs individually in road lighting, the replacement and maintenance are more expensive and hence avoided by cities [24]. To achieve more economical and feasible maintenance, the lamps in street lighting luminaires are replaced via group replacements rather than spot replacement. In this study, the components of the LED luminaire (such as the driver and the LED module/light source) are not replaced during the time period but the replacement scheme of LED luminaires considers the entire LED luminaires to be replaced after their use of expected lifetime.

According to LCCA, subtracting the salvage value (SV) from the sum of the installation cost (IC), energy cost (EC) and maintenance cost (MC) yields the total cost (TC) [11]. Cost calculations are made for a per kilometre road lighting investment, and equations are given below. The salvage value is calculated for the unused period of replacement products during the economic lifetime. In other words, only the final replaced LED luminaires over the project lifetime have salvage value. The environmental waste of luminaires and components are recycled for free of charge by municipality in Turkey, so the disposal costs were not considered in the LCCA in this study.

$$TC = IC + MC + EC - SV, \tag{2}$$

$$IC = N*\left(N_p + N_{mp}\right) + L*\left(L_p + L_{mp}\right) + \\ + P*\left(P_p + P_{mp}\right) + C*\left(C_p + C_{mp}\right) + \\ + YC*\left(YC_p + YC_{mp}\right), \tag{3}$$

$$MC = L*\left(L_p + L_{mp}\right) + \\ + \left(S_n * S_p + F_p\right) * N / \left(S * t_d\right), \tag{4}$$

$$EC = N * P_i * 365 * E_p * 10^{-3} * t_o, \tag{5}$$

where N is the number of luminaire, N_p is the price of a luminaire, N_{mp} is the luminaire mounting price, L is the number of lamp, L_p is the price of a lamp, L_{mp} is the lamp mounting price, P is the number of pole, P_p is the price of a pole, P_{mp} is the pole mounting price, C is the cable length, C_p is the cable price per metre, C_{mp} is the cable mounting price per metre, YC is the underground cable length, YC_p is the underground cable price per metre, YC_{mp} is the underground cable mounting price per meter, S is the number of luminaires maintained in an hour, S_n is the number of maintenance staff, S_p is the daily price of staff, F_p is the fuel price of vehicle per day, t_d is the daily working time, P_i is the power of the luminaire, E_p is the energy unit price per kWh, t_o is the daily operation time of luminaire.

Maintenance, energy and salvage costs are calculated with the NPV method [13]. The maintenance cost is separately calculated for every replacement period and then the total maintenance cost is obtained according to NPV method. The replacement cost of electromagnetic ballast is also added to equation (4) for the conventional luminaires. The present value of the total energy cost in the project lifetime is calculated using the following equation [25, 26]:

$$\text{Total Energy Present Value} = \\ = \text{EC}*\left(1+\text{e}\right)*\frac{1-\left(\frac{1+\text{e}}{1+\text{i}}\right)^{30}}{\text{i}-\text{e}}. \tag{6}$$

In this study, the unit of currency used is the Turkish Lira (TL). In contrast with European countries, high interest and inflation rates are used in Turkey, so these rates should be considered for long-time economic investment analysis. The interest (i) and inflation rates (e) of the Turkish Central Bank are considered in the calculations because the luminaires are utilized for road lighting in Turkey. The average inflation and interest rate are taken to be 8.5 % and 10.5 % respectively [27, 28]. The prices of luminaires are obtained from daily luminaire catalogues of manufacturers. Other labour and mounting costs are defined based on recent prices in Turkey.

Maintenance costs for conventional luminaires comprises re-lamping, replacement ballast and cleaning of luminaires. When the lamp is replaced, cleaning of luminaires is also conducted. The replacement of electromagnetic ballast is done two times in project life. The prices of 150 W and 250 W electromagnetic ballasts are 32.00 and 43.00 TL/piece, respectively. Conventional luminaires are assumed to not be replaced during the 30-year lifetime. On the other hand, LED luminaires are accepted as integrated LED luminaire, so re-lamping is not considered for LED luminaires. The lifetime of LED luminaires average 50,000 hours, and the replacement time is calculated to be 13.7 years. LED luminaires are replaced twice in 30 years. These dates of replacement were approximately assumed as 13 and 27 of years. Moreover, maintenance of LED luminaires is performed once every 5 years. The maintenance cost in (4) also depends on staff costs, fuel costs, operation time and number of lamps. Two laborers re-lamp and maintain ten luminaires in an hour. The daily cost for staff and daily working time are 80.00 TL/day and 8 hours, respectively. The daily fuel cost of a vehicle for transportation is 150.00 TL/day. The daily operation time of luminaires is assumed to be 10 hours, and the total annual operating time is 3,650 hours. The unit electrical energy cost for lighting is 0.257 TL/kWh in Turkey. The calculation of the energy cost is shown in equation (5).

The installation cost in equation (3) consists of the lamp, pole, cable, labour and luminaire costs. The numbers of luminaires and poles per km were calculated using the DIALux lighting design program. The price of a pole with accessories averages 750.00 TL/piece, and the pole mounting price is 10.00 TL/meter (of pole height). The prices of the mounting luminaire and lamp are 75.00 and 5.00 TL/piece respectively. The cable cost is calculated for both overhead and underground cables. The underground cable length is calculated by multiplying of the pole numbers with the pole spacing; overhead cable length is calculated by multiplying the mounting height of a luminaire by the number of poles per km. The underground cable and mounting prices are 7.50 and 35.00 TL/m respectively. The overhead cable and mounting prices are 4.50 and 2.00 TL/m respectively.

The salvage value is calculated for the last replaced LED luminaries. If the economic analysis period (project life) is assumed to be 30 years, a LED luminaire will be used for 13.7 years assuming an annual operation time of 3,650 hours and LED luminaire lifetime of 50,000 hours. LED luminaires should be replaced with new ones at the end of 50,000 hours. The last replacement luminaire is thus used only 2.6 years. In this situation, the salvage value of the unused period of the luminaire lifetime should be calculated. Thus, the salvage value is subtracted from the total cost due to the serviceable time of the LED luminaire. When the second replacement is performed, the calculation of the unused rate of the luminaire is shown in (7) [11].

$$100 \times \left(1 - \frac{30 - (2 \times 13.7)}{13.7}\right) = 81\%. \qquad (7)$$

During the project lifetime, 81 % of the lifetime of the last replaced LED luminaire is not used. If luminaire price is 470.00 TL, the salvage value of the last replaced LED luminaire is calculated to be 470.00 TL*0.81=370.70 TL. This value will depend on the inflation and interest rate in the future, so equation (1) is used to calculate the present value of the salvage value.

4. RESULTS OF COST ANALYSES

The life cost cycle analyses of the luminaires are defined for an operation time of 30 years. The NPV of the total cost includes the installation, energy, and maintenance costs and salvage value. The cost results of luminaires per km for the M2 and M1 road classes are listed in Tables 5 and 6.

According to Table 5, HPS L3 and LED L1 luminaires have almost the same life cycle cost and are more cost effective luminaires for the M2 road class. Whereas the energy cost of the HPS L3 luminaire is approximately 32 % greater than that of the LED L1 luminaire, the initial cost of HPS L3 luminaires is approximately 20 % less than that of the LED L1 luminaire. The maintenance cost includes replacement of the whole luminaire for LEDs, but it includes only lamp replacement for conventional luminaires. Therefore, the maintenance costs of LED luminaires are greater than those of conventional luminaires. The MH luminaire has the greatest total cost due to its low efficacy (lm/W) and short lamp lifetime.

According to the results presented in Table 6, the LED L6 luminaire is the most profitable investment compared with other luminaires for the M1 lighting class. Although the number of LED L6 luminaires per km (68 / km) is greater than that of conventional luminaires (64 / km), the energy cost of LED L6 luminaires is less than that of the others because of the high luminaire efficacy. Additionally, the electromagnetic ballast losses of conventional luminaires cause significant energy consumption. The energy and total costs of MH luminaires are approximately 48.5 % and 31 % respectively and are greater than those of the LED L6 luminaire.

5. CONCLUSIONS

In this study, the photometric values of conventional and LED luminaires that belong to the M1 and M2 road lighting classes were measured in the laboratory. Design calculations were performed using the DIALux software package to optimize the maximum pole spacing while satisfying the minimum road lighting criteria for different road lighting classes. The most cost-effective conventional luminaires were compared with state-of-the-art LED luminaires using the LCCA method, which considers the installation, energy, maintenance costs and salvage value.

The LCCA calculations show that the 80 W LED L3 and 150 W HPS L1 luminaires have almost the same cost effectiveness for a new road lighting application assuming a 30-year operation time and the M2 road lighting class. However, using LED luminaires can be more beneficial considering energy savings, CO_2 emissions due to power plants and lighting quality. MH luminaires have the highest total cost for the M1 and M2 road lighting classes. On the other hand, 153 W LED L6 luminaires have lower total cost than the 250 W HPS and MH luminaires in the M1 road lighting class. In all categories, the installation costs of LED luminaires are greater due to their luminaire price, whereas the energy costs of LED luminaires are less than those of conventional luminaires.

This study also shows the importance of comparisons of different luminaire technologies (HPS, MH, and LED) in terms of energy savings, lighting quality, and cost effectiveness. According to the results, the cost effectiveness of LED systems particularly depends on two key parameters: the price of electricity and the price of the luminaire. In the future, LEDs will be more commonly used as the price of the luminaire keeps decreasing. If the price of electricity increases due to depletion of oil resources, LED luminaires will be more advantageous economically for roadway lighting.

ACKNOWLEDGMENT

The authors would like to thank The Scientific and Technological Research Council of Turkey (TUBITAK) and Scientific Research Project Coordination of Yıldız Technical University (YTU-BAPK-Grand Number: 2015–04–02-KAP01) for the financial support during the duration of this study.

REFERENCES

1. IEA (International Energy Agency), "Light's Labour's Lost: Policies for energy-efficient lighting," Paris, 2006.

2. K. A. Avrenli, R.R. Benekohal, and J. Medina, "LED roadway lighting, Volume 1: Background information," FHWA-ICT-12–012, Illinois, 2012.

3. The Climate Group, "Lighting the Clean Revolution: The rise of LEDs and what it means for cities," London, 2012.

4. Dubois M. C and Blomsterberg A, "Energy saving potential and strategies for electric lighting in future North European, low energy office buildings: A literature review," *Energy Build.*, 2011, Vol. 43, no. 10, pp. 2572–2582.

5. E. Juntunen, E. Tetri, O. Tapaninen, S. Yrjänä, V. Kondratyev, A. Sitomaniemi, H. Siirtola, E. Sarjanoja, J. Aikio, and V. Heikkinen, "A smart LED luminaire for energy savings in pedestrian road lighting," *Light. Res. Technol.*, 2015, Vol. 47, no. 1, pp. 103–115.

6. J. D. Bullough, L.C. Radetsky, U.C. Besenecker, and M.S. Rea, "Influence of spectral power distribution on scene brightness at different light levels," *LEUKOS*, 2014, Vol. 10, no. 1, pp. 3–9.

7. DOE (U.S. Department of Energy), "Solid-state lighting program 'R&D plan," 2016.

8. L. Domenichini, F. La Torre, D. Vangi, A. Virga, and V. Branzi, "Influence of the lighting system on the driver's behavior in road tunnels: A driving simulator study," *J. Transp. Saf. Secur.*, 2017, Vol. 9, no. 2, pp. 216–238.

9. S. Guo, H. Gu, L. Wu, and S. Jiang, "Energy-saving tunnel illumination system based on LED's intelligent control," *J. Phys. Conf. Ser.*,2011, Vol. 276, no. 1, p. 12164.

10. L. Tähkämö and L. Halonen, "Life cycle assessment of road lighting luminaires – Comparison of light-emitting diode and high-pressure sodium technologies," *J. Clean. Prod.*, vol. 93, 2015, no. 1, pp. 234–242.

11. K. A. Avrenli, R.R. Benekohal, and J. Medina, "LED roadway lighting, Volume 2: Field evaluations and software comparisons," FHWA-ICT-12–013, Illinois, 2012.

12. FHWA U.S. Department of Transportation Federal Highway Administration Office of Asset Management, "Life-cycle cost analysis primer," Washington, 2002.

13. S. Onaygil, O. Guler, and E. Erkin, "Cost analyses of LED luminaires in road lighting," *Light Eng.*, 2012, Vol. 20, no. 2, pp. 39–45.

14. L. Tähkämö, A. Ylinen, M. Puolakka, and L. Halonen, "Life cycle cost analysis of three renewed street lighting installations in Finland," *Int. J. Life Cycle Assess.*, 2012, Vol. 17, no. 2, pp. 154–164.

15. Y. Jiang, S. Li, B. Guan, and G. Zhao, "Cost effectiveness of new roadway lighting systems," *J. Traffic Transp. Eng.*, 2015, Vol. 2, no. 3, pp. 158–166.

16. T. Welz, R. Hischier, and L.M. Hilty, "Environmental impacts of lighting technologies – Life cycle assessment and sensitivity analysis," *Environ. Impact Assess. Rev.*, Apr. 2011, Vol. 31, no. 3, pp. 334–343.

17. CIE115:2010, "Recommendations for the lighting of roads for motor and pedestrian traffic," Vienna, Austria, 2010.

18. IES LM-54–99, "Guide to Lamp Seasoning," 1999.

19. IES LM-79–08, "The electrical and photometric measurements of solid-state lighting products," 2008.

20. EN13201–3, "Standard EN13201–3 Road Lighting-Part 3 Calculation of performance," 2013.

21. EN13201–1, "Standard EN13201–1 Road lighting – Part 1: Selection of lighting classes," 2004.

22. CIE180:2007, "Road transport lighting for developing countries," Vienna, Austria, 2007.

23. DOE (U.S. Department of Energy), "LED Luminaire Lifetime: Recommendations for testing and reporting," 2011.

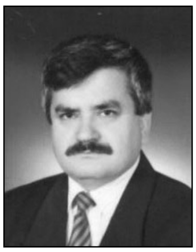
24. L. Tähkämö, R.-S. Räsänen, and L. Halonen, "Life cycle cost comparison of high-pressure sodium and light-emitting diode luminaires in street lighting," *Int. J. Life Cycle Assess*, 2016, Vol. 21, no. 2, pp. 137–145.
25. R. Teodorescu and M. Katsanevakis, "An optimization method for designing large PV plants," *J. Photovoltaics*, 2013, Vol. 3, no. 2, pp. 814–822.
26. State of Illinois Capital Development Board, "Life cycle cost analysis manual," Illinois, 1991.
27. CBRT, "The Central Bank of The Republic of Turkey," 2016. [Online]. Available: http://www.tcmb.gov.tr/wps/wcm/connect/tcmb+en/tcmb+en. [Accessed: 12-Sep-2016].
28. TSI, "Turkish Statistical Institute." [Online]. Available: http://www.turkstat.gov.tr/Start.do. [Accessed: 12-Sep-2016].

Ramazan Ayaz
received the B.Sc, M.Sc. and Ph.D. degrees in the Department of Electrical Engineering from the Yildiz Technical University (YTU) in 2010, 2012 and 2018 respectively. He is working as a Research Assistant at the Department of Electrical Engineering, Yildiz Technical University, Turkey. His research areas are road lighting, lighting measurements, energy efficient and photovoltaic systems

Asiye Kaymaz Ozcanli
received the B.Sc. degree in Electrical Engineering and Mechanical Engineering from Yildiz Technical University in 2014. She received the M.Sc. degree in the Department of Electrical Engineering from Yildiz Technical University in 2016, Turkey. She is currently pursuing doctoral study in Yildiz Technical University, Turkey

Ismail Nakir
received the B.Sc, M.Sc. and Ph.D. degrees in the Department of Electrical Engineering from the Yildiz Technical University (YTU) in 2004, 2007 and 2012 respectively. He is working as an Assistant Professor at the Department of Electrical Engineering, Yildiz Technical University, Turkey. His research areas are lighting technologies and renewable energy resources

Pramod Bhusal
received his Ph.D. in Illumination Engineering in 2009 from Helsinki University of Technology, Espoo, Finland. He is researcher at Lighting Unit, Aalto University, Finland. He has been the key expert in several national and international research, networking and education development projects in the field of lighting. His research interests include energy efficient lighting controls and systems, colorimetry, human centric lighting, and lighting measurements. He has more than 20 scientific publications in the field



Adem Unal
received the B.Sc, M.Sc. and Ph.D. degrees in the Department of Electrical Engineering from the Yildiz Technical University (YTU) in 1978, 1982 and 1995 respectively. He is Assistant Professor at the Electrical Engineering in Yıldız Technical University, Turkey. His research areas are lighting technologies and circuit theory

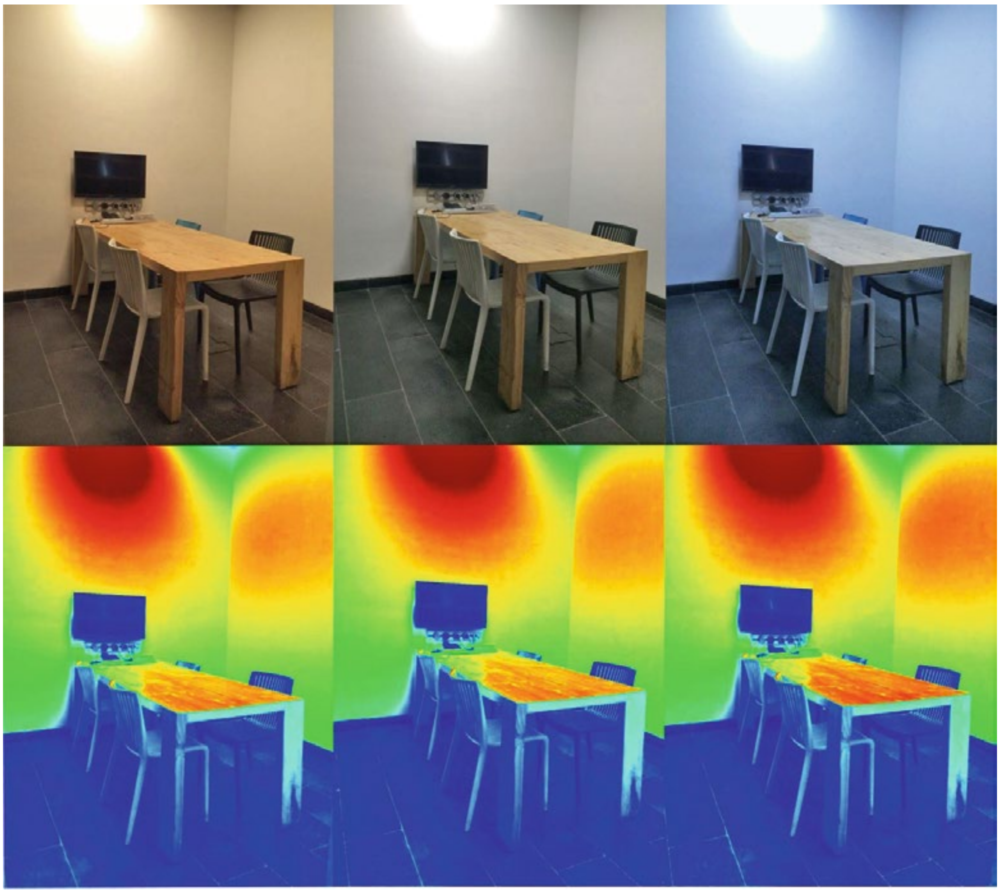


Fig.1. Experimental room with tuneable LED lighting system generating three scenes of CCTs 3000 K, 4000 K and 6500 K respectively at an average constant illuminance of 300 lx at the table-top

Fig.4. Subjects performing the different activities of reading, watching TV, eating and relaxing while being completely immersed in the three different CCT

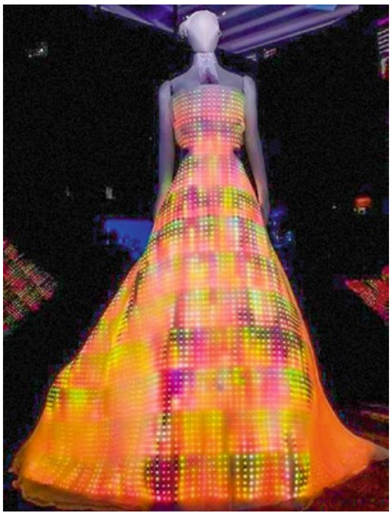


Fig. 1. Galaxy Dress

Fig. 3. A “catching sights” dress

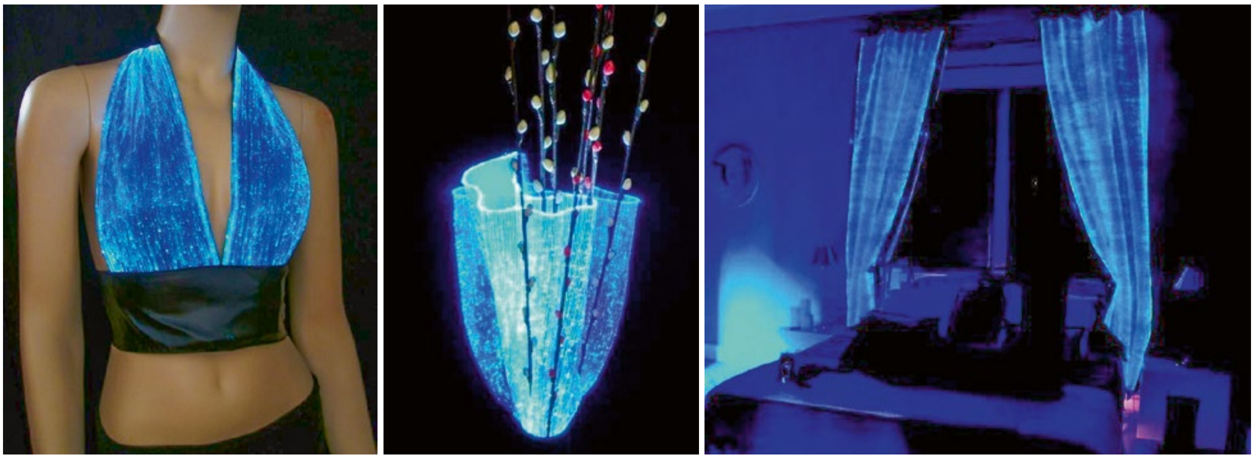


Fig. 2. Textiles of *LumiGram* Company

Fig. 4. The *Bubble* dress

Fig.6. A fragment of the designer *Rami Kadi* collection

Fig. 5.The *Twitter* dress

Fig.7.The fluorescent silk dresses

Fig.8. A fluorescent demi-season jacket

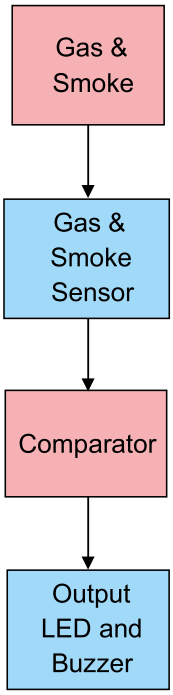


Fig. 1. Block diagram of gas & smoke sensor module

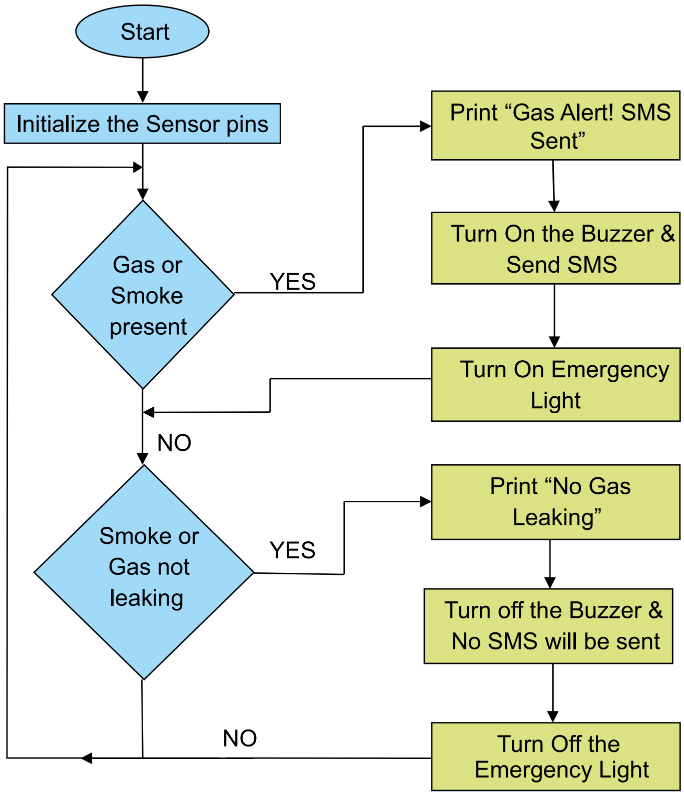


Fig 3. Flow chart to interface gas and smoke sensor with emergency light

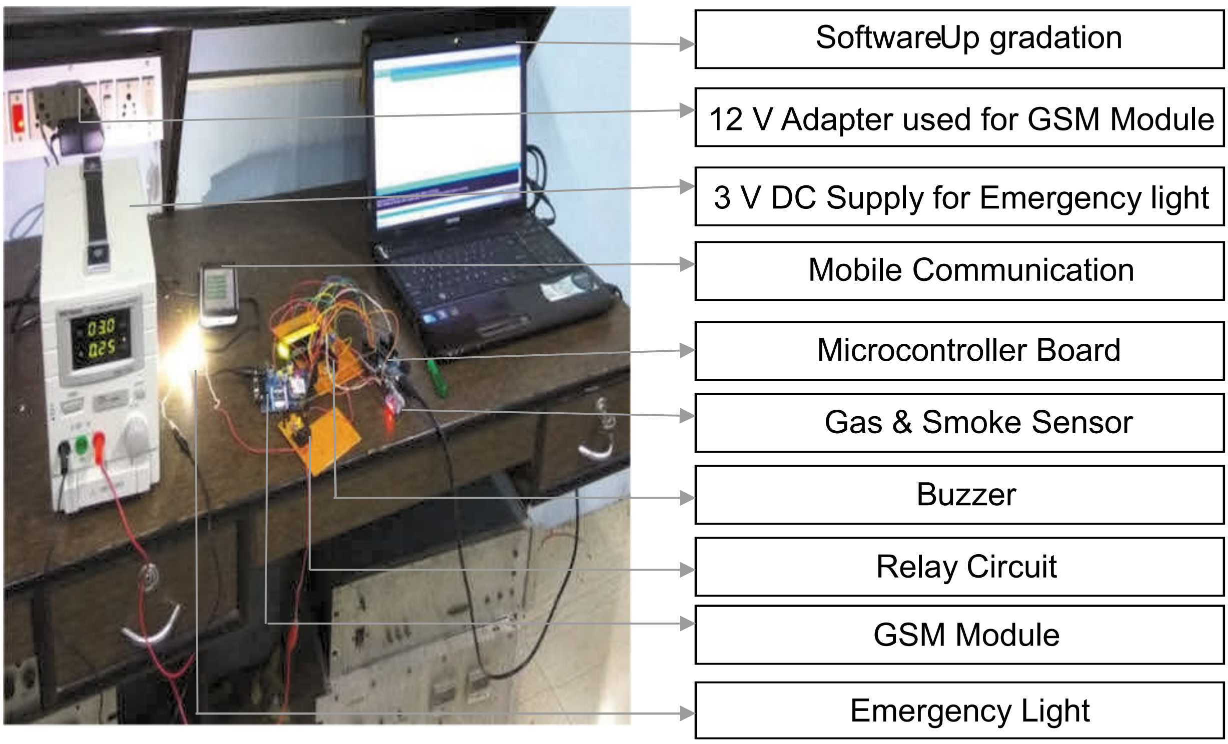


Fig. 4. Experimental setup using microcontroller to interface gas and smoke sensor with emergency light

Light & Engineering
Vol. 27, No. 1, pp. 75–85, 2019

DESIGN OF SOLAR-POWERED LED ROAD LIGHTING SYSTEM

Canan PERDAHCI[1] and Hamdi OZKAN[2]

[1]Department of Electrical Engineering, Faculty of Engineering, University of Kocaeli, Turkey
[2]Litpa Lighting Koza Plaza, ISTANBUL
E-mails: perdahci@kocaeli.edu.tr[1], hamdiozkan@litpa.com[2]

ABSTRACT

Turkey is rich in terms of renewable energy sources and, therefore, is now encouraging the use of sustainable clean lighting systems in road applications. High pressure sodium lamp is the most widely used type in main roads, but other types of lamps such as mercury vapour lamps or metal halide lamps can be utilized for street lighting. Since it enables energy and money saving, LED light technology has replaced high pressure sodium lamps nowadays. Once solar power system (PV) is integrated with LED lamp for street lighting, the amount of saving and local impact might be enriched.

LEDs used as light sources in road lighting luminaires with rising lumen values, decreasing junction temperature, higher colour rendering efficiency, longer lifetime have become more efficient than many light sources with the latest developments. Since the structure of the luminaires in which the LED light sources are used differs from that of the conventional light sources, the optical, thermal and electrical design of the LED luminaires must be considered differently. Thus, this study concentrates upon design considerations and the operating principle of solar-powered LED road lighting luminaire in details. Also, a simple solar panel system was designed and the economical values obtained at the end of 20 years were compared when using the on-grid system and the off-grid system.

Keywords: solar-powered LED luminaire, road lighting, energy saving

1. INTRODUCTION

When evaluated in terms of usage areas of electric energy, it becomes clear that the consumption amount in parks, gardens and road lighting areas is high and it is vital to save on energy in these areas. Providing the same lighting level with less energy consumption without compromising the quality of lighting and using more efficient lighting luminaires as well as obtaining good lighting conditions is energy saving in lighting. The necessity to save energy in lighting caused a great deal of increase in the use of renewable energy. Because the sun is an efficient solution to generate renewable energy since its rays reaches everywhere on earth and free to harness, the renewable energy obtained from the sun has become one of the major energy sources in many applications [1]. Because of being convenient in panel selection depending on the needs, its use in off-grid environments and its integration into existing structures, the use of photovoltaic panels, which is a way of obtaining renewable energy, has become widespread in a short time in lighting systems [2]. Many studies in the field of LED lighting have validated that LED lighting systems are both economically feasible, energy saver as well as preventative of CO_2 emissions [3, 4–9].

Nowadays, thanks to advances in lighting technology, LED lighting systems which are used in many areas offer innovative and timeless solutions in park, garden and road lighting areas. The use of LED luminaires with longer lifetime, higher colour rendering efficiency, easier regulation of luminous flux and lower operating costs than tradi-

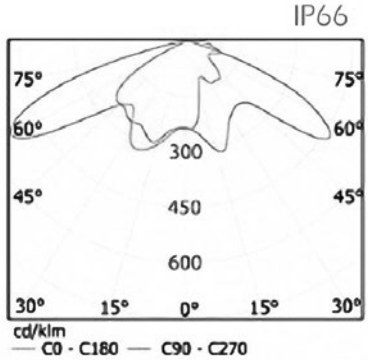


Fig. 1. LITPA LYS20/DC Solar-Powered LED Luminaire

tional luminaires has been an energy-efficient application in recent years. With the ever-evolving technology, the luminous efficiency factor (lm/W) values of the lumen-generated luminous flux per lamp power are increasingly rising and the use of LED light sources in road lighting applications is increasing day by day. [3]

Diodes consisting of semiconductor materials emit light when applied the current and current is obtained when it is exposed to light. When applied the voltage, the LED lamp starts to emit light when its electrons are activated. They are produced in such a way that they can give a wide spectrum of light ranging from infrared to violet [10,11].

Photovoltaic modules are the elements that convert solar energy into electricity. Photons from the sun transfer their energy to the junctions in the cells on a semiconductor module. This transmitted energy triggers the electron movement, which leads to electric current. This electrical current can be used directly as a direct current by connecting a load between the contacts of the cell. [2] The acquired electric current can be used as direct current (DC) or alternatively can be converted to alternating current (AC) or stored for later use [10].

In terms of the amount of solar energy radiation in Istanbul, especially in the winter months, is

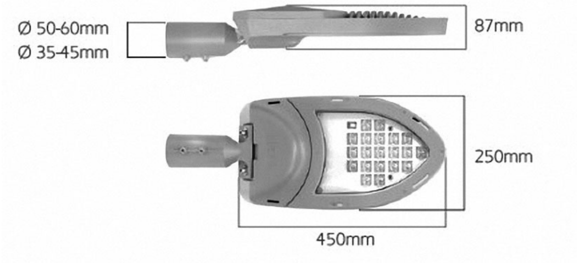


Fig.2. The Dimensions of LITPA LYS20/DC Solar-Powered LED Luminaire

very low levels of lighting energy should be provided at the lowest powers. For this reason, we produced a luminaire with low powers for this system.

2. DESCRIPTION OF SOLAR-POWERED LED ROAD LUMINAIRE DESIGN COMPONENTS

We have designed and produced solar-powered LED lighting luminaires for walking paths, parks and gardens. We can produce our luminaires 33W-45W-67W, and we did not need to produce high-powered luminaires as the system would work with solar energy. The luminaire we have developed is also suitable for use in the road categories M3 and M4. We have also prepared infrastructure for the streets in the M2 road category and we are in the design phase.

Among our targets, we are also planning to develop this type of luminaires for the roads in the M1 category. We plan a solar powered system with sensor and different dim levels that can program itself during the night. That is why our goal is to make sure that the batteries we use have longer lifetimes or are smaller in sizes. In the next stage, we plan to add both the solar and intelligent automation program to the luminaire. Furthermore, the motion sensor will reduce the dim level when not needed.

As the system's nature requires, we did not use the standard drivers sold on the market. In our solar electronic board, Figs. 1,2,3, we used current fixing module, diode, 2 pin terminal, 3 pin terminal, 6 pin connector cable, 6 pin SMD connector, 6 pin horizontal connector.

In order to provide energy efficient solutions for lighting walking roads, parks, gardens and roads, it is necessary to use LED light sources with high luminous efficiency factor values in LED street lu-

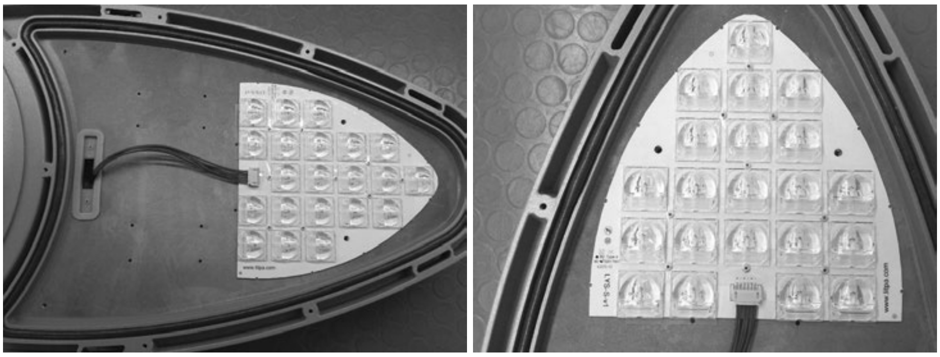


Fig.3. The PCB of LITPA LYS20/DC Solar-Powered LED Luminaire

minaire design. Power LED chips with highly efficient Bin codes in Lumileds, Nichia and Samsung brand 3535 packages are preferred. The luminous efficiency of the luminaire is 130 lm/w and above. Since there is no AC / DC conversion and we have no driver losses, we aim for 160 lm/w. Thanks to the flexibility in the luminaire design, the luminous flux obtained from the luminaire (luminaire size: 450mm×250mm) is obtained as 8.000 lm depending on the requirements of the environment lx level.

It is aimed to provide effective thermal dispersion and cooling by using aluminum PCB in luminaires. The thermal conductivity will be preferred to a minimum of 1.1 W/(m·K). A PCB will have 21 LED chips. Cable connections on PCBs will be via the connectors on them.

We used asymmetric street lighting lenses with minimum shade and minimum glare values to optimally illuminate roads and streets. In fixed angle poles and consoles, the angle of light cannot be regulated. We, however, designed the angle in such a way that it can be regulated form a junction piece on the luminaire.

When selecting the luminaire body, the cooling channels on the body will ensure that the life of the LED chip and its efficiency are at the highest level. The body is manufactured by aluminium injection method and it is resistant to corrosion and rust because it is aluminium. In addition, this aluminium body is painted with polyester, electrostatic powder paint, so, it is very long lasting and rusting free. Moreover, it is not exposed to corrosion in the outside environment. Silicone sealed gasket is used between the back cover and the body. Silicone-based sealing gaskets are used between the windshield and the body. Connection screws are to be stainless steel. Glass will be tempered and roved.

The luminaires are produced with IP66 protection class compatible with outdoor applications.

Instead of the driver in the solar-powered LED lighting luminaire, we designed a special DC / DC card that can work with both 12 V systems and 24V systems.

Chemical materials in the solar-powered LED lighting luminaire, silicon lens structure on the LED, adhesives used to stick the lens and PCB together, thermal band or thermal paste used to provide thermal conduction between PCB and body, body IP materials such as gaskets contain chemical volatile organic compounds (VOCs). In the event of using chemical volatile organic compounds on or near the LED, which are not compatible with it, the lighting system is damaged and the lifetime of the LED used and accordingly the lifetime of the luminaire is reduced.

3. DESIGN OF SOLAR-POWERED LED ROAD LIGHTING LUMINAIRE

In this section, the design of solar-powered LED lighting luminaire system is describing. Luminaire design, prototype production, electronic card design, mechanical design and system performance tests are the steps of the development of solar-powered LED lighting luminaire.

3.1. Luminaire Design

In the project, firstly, research studies were conducted by our engineering and design department about LED lighting technologies and LED products. These studies have been deeply and systematically prepared and database has been created. The luminaire design has been made based on these data. As a result of this study, guidelines about different applications and products in the world and in the literature have been obtained and the general specifications of the luminaires have been determined.

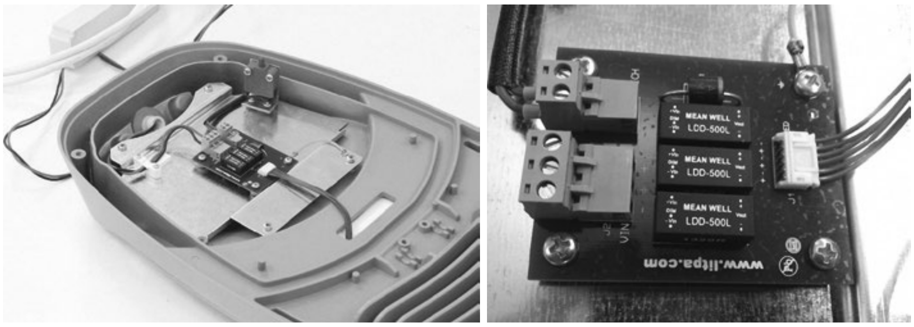


Fig. 4. The Electronic Card of LITPA LYS20/DC Solar-Powered LED Luminaire

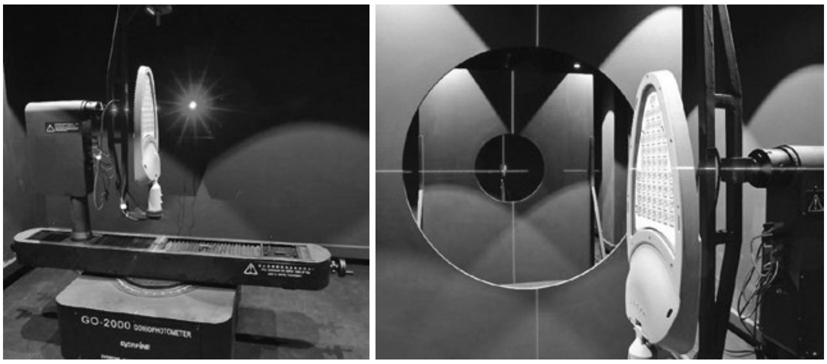


Fig. 5. The Measurement of LITPA LYS20/DC Solar-Powered LED Luminaire

Research and development activities carried out in the luminaire design include the design of a street lighting luminaire consisting of LEDs, the prototype production and the verification of its performance, and the determination of the system's overall energy consumption and lighting performance. The choice of LED, the number and configuration of the LEDs on the luminaires (distance and angles between them) will be determined in line with optical and thermal parameters. The detailed design of the optimum luminaire will be done in computer environment considering the manufacturability, aesthetic, ergonomic and mechanical aspects. Optical and thermal simulations are performed and the design has been verified in the computer environment before the detailed design and technical drawing work have started. This phase has been essential in the production of the optical and thermal design of the product.

3.2. Prototype Production

In this research and development stage, the manufacturing drawings of the components that make up the luminaire will be obtained in the 3D design environment on the computer. In design, a 3D-CAD design package is used and each part and moulds are simulated in computer environment. Luminaires made with detailed designs are transferred to prototype production and after prototype parts have been verified, mould designs have been made for each part individually. It has been carried out within the possibilities of operating moulds or supplier companies.

3.3. Electronic Card Design

The PCB, Fig.4, as the light source of the luminaire consists of 7 series, 3 parallel circuits, and has 21 LEDs. Each parallel circuit is driven by its own current stabilizer. The current-stabilizing module has been selected according to the current we want to drive the LEDs. We selected current stabilizer of 350mA for 22W, 500mA for 33W and 700mA for 48W. We also placed a diode on the circuit that provides reverse polarity protection to prevent the risk of reversing the – and + inputs coming from the battery. Our current-stabilizing modules are to be fed by 24V DC battery voltage so that we can provide energy to 7 series of LEDs via the battery voltage obtained at the output.

The biggest advantage of this electronic card we have developed is that the controller on the system can supply the energy from the battery directly to the lighting luminaire. Thus, the need to use a classic driver in the luminaire is gone. AC / DC

Table1. Calculated Values for Photovoltaic Panel

Month	Energy/Day, kWh/m^2	Coefficient of panel tilt angle	Panel Efficiency,%	Panel Area, m^2	Daily produced amount of energy
1	2	1.15	0.167	1.64	0.629924
2	2.57	1.15	0.167	1.64	0.809452
3	4.2	1.15	0.167	1.64	1.32284
4	5.28	1.15	0.167	1.64	1.662999
5	6.3	1.15	0.167	1.64	1.984261
6	6.79	1.15	0.167	1.64	2.138592
7	6.79	1.15	0.167	1.64	2.138592
8	6.07	1.15	0.167	1.64	1.911819
9	5.09	1.15	0.167	1.64	1.603157
10	3.74	1.15	0.167	1.64	1.177958
11	2.37	1.15	0.167	1.64	0.74646
12	1.8	1.15	0.167	1.64	0.566932

converter is not necessary and the system works much more efficiently from DC to DC.

The electronic board is made of aluminium material with a thickness of 1.6 mm and a heat transfer coefficient of 1.1 W/(m·K). The cable connections were made via the connectors on the PCB. The LEDs and connectors on the card will be automatically sequenced and quality controlled.

3.4. Mechanical Design

The entire luminaire will be designed depending on the optical and thermal priorities. Mounting brackets can be configured so that they can be mounted on both poles and consoles and can be angled up to 15 degrees in 5 degrees increments in + and – directions. The weight optimization was made so as not to affect the thermal performance adversely. It is user-friendly as it is easy to mount and install. Moreover, its ergonomics design makes subsequent service and maintenance activities easy. In this sense, the electrical connections and electronic card maintenance services can be done by opening the back cover without touching the LED part.

3.5. System Performance Tests

Following the prototype production, the product type and performance tests were first made in the goniophotometer system in Litpa Lighting laboratories, Fig. 5, and the second stage tests were carried out in line with the CE marking requirements in the independent testing laboratories. The quality of the product for the industry, such as resistance to environmental conditions and cost of use (energy consumption, ease of maintenance, spare parts, etc.) are extremely important for customer satisfaction and tests under the relevant standards have been thoroughly applied. Energy consumption and lighting performance of the complete system will also be tested and necessary improvements will be made.

4. DESIGN OF SOLAR LED LIGHTING SYSTEM

Traditional grid-powered lighting systems are a lot less complicated than PV lighting systems when their design and installation requirements are considered. PV lighting systems also have higher initial purchase and maintenance cost for many of their components when compared to grid powered traditional lighting systems. Therefore, there is relatively limited usage of lighting applications appropriate for PV lighting systems. Nevertheless, it is possible to develop successful PV lighting applications with the help of comprehensively planned design processes. [12]

The proposed photovoltaic system, which consists of a solar panel, the LED road lighting lu-

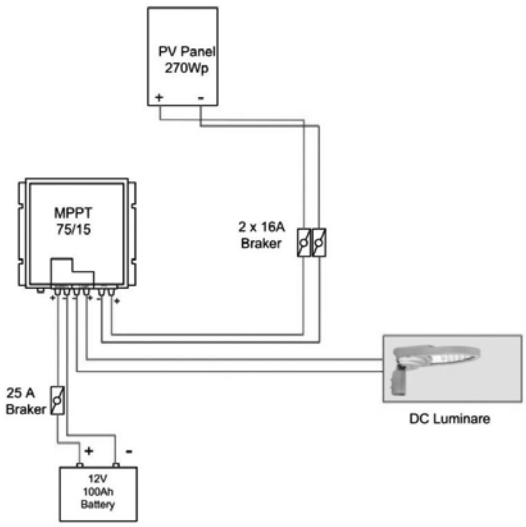


Fig. 6. The Block-Diagram of the Lighting System

minaire, a charge controller/MPPT, an electrical energy storage battery, are illustrated in Fig.6. The working principle of this system (the photovoltaic principle) can be described as the next:

– The solar panels receive solar radiation throughout the day;

– After that, the solar radiation is converted into electrical energy through charge and discharge controller;

– Finally, that electrical energy is stored in the rechargeable battery.

The storage place of the electric power generated by the solar PV panel is the rechargeable battery during the daytime. When the battery is fully charged, the battery charging unit detects this and stops charging and keeps system ready for use. At night, the solar energy stored in the rechargeable battery is released to power the LED lighting system and light the street lamps. The street lights function steadily as the design of the batteries can meet the voltage and current requirements.

5. EXPERIMENTAL RESULTS

Experiment was conducted in Istanbul. There are many parameters that affect the efficient operation of the photovoltaic system. Experiment results are summarized at the Table 1. This table indicates the required parameters' values in order to calculate the amount of energy daily produced.

The determination of the amount of energy to be consumed daily is a crucial part in designing off-grid PV system. We have determined the photovoltaic power according to the daily energy consumption demanded by the user.

Table 2. Solar Cell Parameters (Tommatech), [15]

STK Electrical Parameters	
Nominal Power (Pmax)	TT275–60P
Open Circuit Voltage (V_{OC})	37,30 V
Short Current Voltage (I_{SC})	9,20 A
Nominal Power Voltage (V_{mp})	31,3 V
Nominal Power Current (I_{mp})	8,78 A
Number of Cells	60 (156*156)
Dimension (mm)	1640*990*35
Weight (kg)	19
Max. System Voltage	1000W DC
Max. Series Fuse Rating	15A
Operation Temperature	-40 ^{0}C to +85 ^{0}C

In the first two columns of the Table 1, the daily amount of energy we obtained and the coefficient of panel tilt angle are given. The daily amount of energy values in [kWh/m^2] are based on data from Fig. 7, [13].

The coefficient of tilt angle of the panel for Istanbul is considered as 1,15. The coefficient of panel tilt angle has been calculated in December for the northern latitude of 40 ° 11 ' in which Istanbul is located.

According to panel catalogue information given in Table 2, panel efficiency is calculated by considering the electrical parameters of TT275–60W panel for 1000 W/m^2. When the radiation is 1000 W/m^2 and the rated power is 275 W/m^2, the efficiency of a panel of 1640 mm × 990 mm × 35 mm is acquired as 16 %.

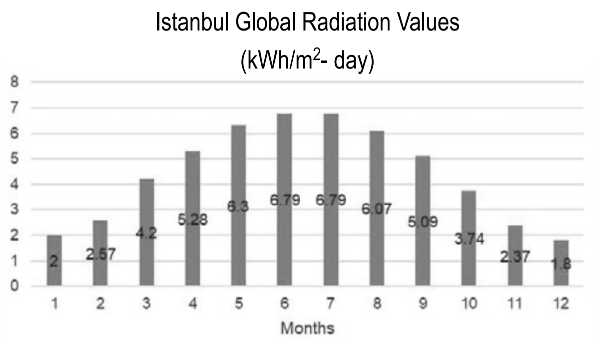


Fig. 7. Istanbul Global Radiation Values (kWh/m^2) per day

The amount of energy daily produced is calculated by multiplying these four parameter values: energy/day in kWh/m^2, coefficient of panel tilt angle, panel efficiency and panel area in m^2.

The panel that produces in December energy per day equal to 0.56 kWh meets the energy we need as 0,42 kWh. Therefore, TT275–60W panel type is suitable for this system.

$$Ppv = \frac{E(L)}{\eta(s).PSH} Sf,$$

$$Ppv = \frac{48W\ x9\ hrs}{0,9\ .2,1\ hrs} x1,2,$$

$$Ppv = 274,28W,$$

were *Sf* is the safety factor, *Ppv* is the panel power, *E(L)* is the daily energy consumption, *η(s)* is the system efficiency, *PSH* is the peak Sun hours

$$Cwh = \frac{E(L)xa(t)}{DODx\eta(c)xVb},$$

$$Cwh = \frac{(48x9)x1}{0,5x0,95x12},$$

$$Cwh = 75.79\ A{\cdot}h,$$

where *a(t)* is the number of autonomous days, *n(c)* is the efficiency of battery, *Vb* is the voltage of battery, *Cwh* is the battery energy storage.

5.1. Charge Controller/ MPPT

$$V(in) = V(oc) \text{ of the PV Panels} = 37,3\ V.$$

$$I(in) = I(sc) \text{ of the PV Panels} = 9,20\ A.$$

$$V(out) =$$
$$= \text{Charge Voltage of the battery group} =$$
$$= 12\ V - 14,4\ V.$$

$$I(out) = \frac{Pp\ x\ \eta(charger)}{\text{Charge Voltage}},$$

$$I(out) = \frac{275 \times 0,95}{14,4\ V},$$

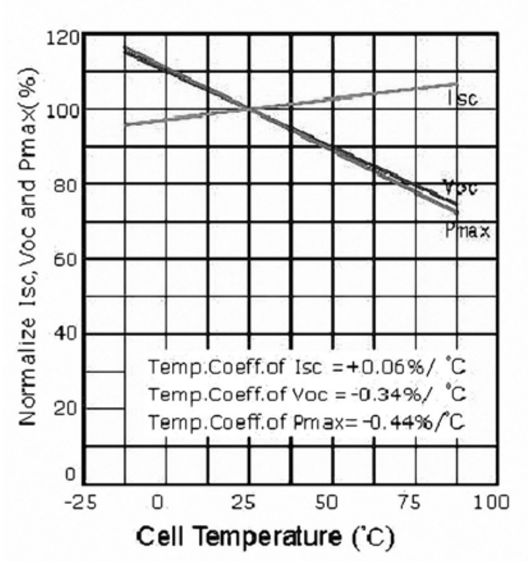


Fig. 8. Temperature dependence of *Isc*, *Voc* and *Pmax*, [15]

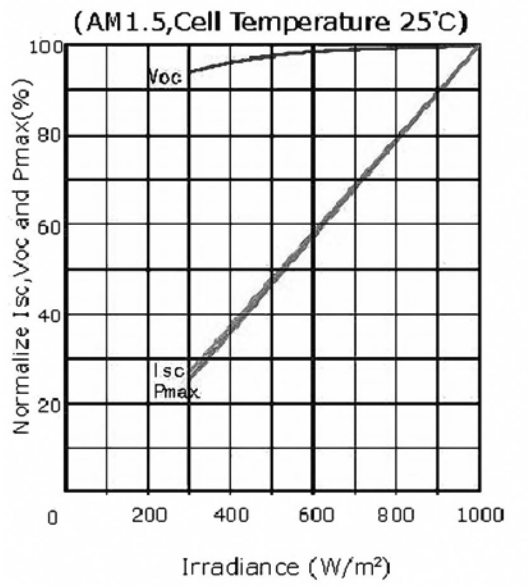


Fig. 9. Irradiance dependence on *Isc*, *Voc* and *Pmax,* [15]

$$I(out) = 18,14\ A, [16].$$

While the solar panel in the blog diagram of the lighting system shown in Fig. 8 is calculated, safety factor 1.2; daily energy consumption 9 hours, lamp power 48 W, system efficiency 0.9 and peak sun hour 2.1 were taken. Accordingly, a panel power of 274.38 W/m^2 was obtained. When calculating the battery capacity, the autonomic duration is 1 day, the battery efficiency is 0.95, the battery voltage is 12V and the DOD (Depth of Discharge) value is 0.5 were taken. Accordingly, the battery capacity is calculated as 75.79 A·h. *Voc* = 37.3 V, *Isc* =

Table 3. Installation Cost of Unit Street Lighting System (Solar-Powered LED)

LYS20-DC ROAD LIGHTING SYSTEM						
No	**Components**	**Model**	**Quantity**	**Unit**	**Price**	**Total Price**
1	Solar Panel	270	1	pcs	$87	$87
2	Road Lighting Luminaire	48W	1	pcs	$113.5	$113.5
3	Battery Gel 12V	100Ah	1	pcs	$140	$140
4	Solar Charger	MPPT 75/15	1	pcs	$90	$90
5	Timer		1	pcs	$30	$30
6	Lighting Pole	4m	1	pcs	$200	$200
8	Cu Cable 4*2.5mm^2		50	meter	$1	$50
9	Montage cost		1		$400	$400
10	Electric Panel		1	pcs	$100	$100
						$1210. 5

Table 4. Installation Cost of Unit Street Lighting System (Grid-power LED)

LYS20-AC ROAD LIGHTING SYSTEM						
No	**Components**	**Model**	**Quantity**	**Unit**	**Price**	**Total Price**
1	Road Lighting Luminaire	52W	1	pcs	$108	$108
2	Lighting Pole	4m	1	pcs	$165	$165
3	Cu Cable 4*6mm^2		50	meter	$1	$50
4	Montage cost		1		$400	$400
5	Electric Panel		1	pcs	$100	$100
						$823

9.2 A, the current was selected as MPPT 75/15 according to 18.14A.

6. LUMINANCE CALCULATION

Because of the fact that visual performance and visual comfort the users of road lighting are affected by road luminance and illumination measurement parameters, road-lighting installation requirements have to be shaped according to these fundamental aspects. [14] Street lighting systems must be designed tailor made for respective roads & streets and should provide adaquate level of illumination and illumination uniformity in relation to international street lighting standards such as EN13201.

The present paper studied quality parameters of the solar-powered roadway lighting using LED luminaires (48 W) for 300 m highway section with 2 lanes. The roadway lighting luminaires are placed on both sides of the road with the pole distance 8 m. In the case study, DIALUX software simulation was used in order to make a comparison between calculated illumination values and the illumination values of standard EN13201.

Figs.10, 11 presents the calculated illuminance and luminance distributions of the road. It should be noted that the all calculated values meet the requirements of EN13201 international standard for a road of ME4a class.

7. ECONOMIC ANALYSIS OF LED AND SOLAR-POWERED LED

The present paper studied the economic feasibility of the solar powered street lighting using LED luminaires (48 W) for 300 m highway with 2 lanes. Economic comparison for two kinds of street lighting design, namely, LED using grid power and so-

Table 5. Installation & Maintenance Costs of Street Lighting System Unit for 20 Years (Solar-Powered LED)

LYS20-DC ROAD LIGHTING SYSTEM FOR 20 YEARS						
No	**Components**	**Model**	**Quantity**	**Unit**	**Price**	**Total Price**
1	Solar Panel	270	1	pcs	$87	$87
2	Road Lighting Luminaire(5 years warranty/50.000 h lifetime)	48W	2	pcs	$113.5	$227
3	Battery Jel 12V	100Ah	2	pcs	$140	$280
4	Solar Charger (5 years warranty)	MPPT 75/15	2	pcs	$90	$180
7	Timer		2	pcs	$20	$40
8	Lighting Pole	4m	1	pcs	$200	$200
10	Cu Cable 4*6mm^2		50	meter	$1	$50
11	Montage cost		1		$400	$400
12	Electric Panel		1	pcs	$100	$100
						$1564

Table 6. Installation & Maintenance Costs of Street Lighting System Unit for 20 years (Grid-Powered LED)

LYS20-AC ROAD LIGHTING SYSTEM FOR 20 YEARS						
No	**Components**	**Model**	**Quantity**	**Unit**	**Price**	**Total Price**
1	Road Lighting Luminaire	52W	2	pcs	$108	$216
2	Lighting Pole	4m	1	pcs	$300	$300
3	Cu Cable 4*6mm^2		50	meter	$3.9	$195
4	Montage cost		1		$400	$400
5	Electric Panel		1	pcs	$100	$100
						$1211

lar power, is carried out. Each unit of solar powered LED street lighting system includes a 270 PV modules, a 100 Ah-12 V batteries, and a 48 W LED lighting luminaire.

Tables 3 & 4 show that the installation costs are 823 USD for LED lighting powered by grid and 1210.50 thousand USD for solar-powered.

Tables 5 & 6 show that the sum of installation, maintenance and operation costs of the system after 20 years for a single luminaire pole. In our project, 38 poles were used with a distance of 8 m on the 300 m ME4a type road. Accordingly, the unit cost of the system used in the system powered by solar energy is 1564 USD, and the cost for 38 poles is 59432 USD. The unit cost of the lighting system supplied by the network is 2558.84 USD, and for the 38 poles it is 97235.92 USD. By spending the same amount of power at the same light level, at the end of 20 years 97235.92 USD –59432USD = 37803.92USD was saved.

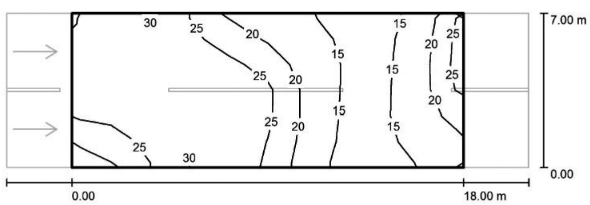
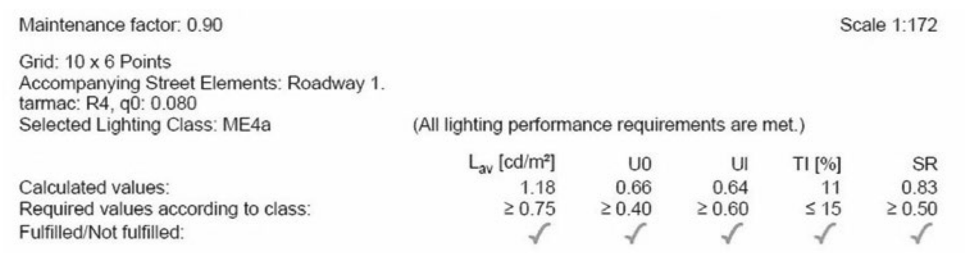


Fig. 10. Illuminance Calculation

Table 7. Cost Analysis of Both AC and DC Road Lighting System 12h /day in 20 years

LYS20-AC ROAD LIGHTING SYSTEM						
System cost ($)	**Total Power Consumption (W)**	**Lighting hours 12hrs×30daysx12months×20y**	**Electricity price ($) 1kWh**	**Total Energy Consumption (kWh)**	**Total Energy Cost ($)**	**Total System Cost for 20 years**
$1.211,00	52	86400	$0.3	4492.8	$1347.84	$2558.84
LYS20-DC ROAD LIGHTING SYSTEM						
System cost ($)	**Total Power Consumption (W)**	**Lighting hours 12h x 30days x 12months x 20y**	**Electricity price ($) 1kWh**	**Total Energy Consumption (Wh)**	**Total Energy Cost ($)**	**Total System Cost for 20 years**
$1.564,00	48	86400	-	4147.2	-	$1564


Maintenance factor: 0.90 Scale 1:172

Grid: 10 x 6 Points
Accompanying Street Elements: Roadway 1.
tarmac: R4, q0: 0.080
Selected Lighting Class: ME4a (All lighting performance requirements are met.)

	L_{av} [cd/m²]	U0	Ul	TI [%]	SR
Calculated values:	1.18	0.66	0.64	11	0.83
Required values according to class:	≥ 0.75	≥ 0.40	≥ 0.60	≤ 15	≥ 0.50
Fulfilled/Not fulfilled:	✓	✓	✓	✓	✓

Fig.11. Calculated Values

7. CONCLUSIONS AND REMARKS

Within the study the operating principles and design considerations for the proposed PV LED road lighting luminaire were described and analyzed in detail. Luminance calculation results of the laboratory prototype were analysed to verify the feasibility of the proposed method

Owing to the fact that they have many advantages over other technologies, solar powered LED street lighting systems have been made available in any many roads and streets. The luminaires used in LED technologies can easily be integrated into photovoltaic illumination systems.

The technology in LEDs has considerably improved in the past couple of years and are good alternatives to the conventional illumination systems. Simple drives, when control and dimming systems are considered, increased lifetime and luminous efficiency are some of the main advantages of using LEDs.

Moreover, luminosity flow can be controlled more effectively via LED luminaries, which allows us to save on an important amount of energy and diminish the public illumination expenditures.

ACKNOWLEDGEMENTS

The authors would like to thank the “The Scientific and Technological Research Council of Turkey (TUBITAK)” for funding the research project with Nr: 7121017 “LED Road Lighting and Automation System Design, Production and Application” which supports this work. The authors would like to also thank University of Kocaeli and LITPA Lighting Co. for their valuable contributions to the present study.

REFERENCES

1. P. Sathya et al., “Design and Implementation of 12V/24V Closed loop Boost Converter for Solar Powered LED Lighting System”, International Journal of Engineering and Technology (IJET), Vol: 5 No: 1 Feb-Mar 2013.

2. I. Çolak, I. Sefa, R. Bayindir, M. Demirtas, “Güneş Enerjisi Kaynaklı LED Armatür Tasarımı”, Journal of Polytechnic, Vol: 10 No: 4 pp.347–352, 2007.

3. M.I. Masoud, “Street Lighting using Solar Powered LED Light Technology: Sultan Qaboos University Case Study”, Proceedings of the 8th IEEE GCC Con-

ference and Exhibition, Muscat, Oman, 1–4 February, 2015.

4. Lina Al-Kurdia, Reem Al-Masria, A. Al-Salaymeh, "Economical Investigation of the Feasibility of Utilizing the PV Solar Lighting for Jordanian Streets," Int. J. of Thermal & Environmental Engineering, 2015, Vol. 10, no. 1, pp. 79–85.

5. Mokhtar Ali, Mohamed Orabi, Emad Abdelkarim, Jaber A. Abu Qahouq, Abdelali El Aroudi, "Design and development of energy-free solar street LED light system," in 2011 IEEE PES Conference on Innovative Smart Grid Technologies – Middle East, Jeddah, pp. 1–7, 2011.

6. M.S. Wu, H.H. Huang, B.J. Huang, C.W. Tang, C.W. Cheng, "Economic feasibility of solar-powered led roadway lighting," Renewable Energy, vol. 34, no. 2009, pp. 1934–1938, 2009.

7. Ika Shinta Mardikaningsih, Wahyudi Sutopo, Muhammad Hisjam, Roni Zakaria, "Techno-economic Feasibility Analysis of a Public Street Light with Solar Cell Power," in Proceedings of the International Multi Conference of Engineers and Computer Scientists 2016, Vol. 2, Hong Kong, pp. 1–5, 2016.

8. Nallapaneni Manoj Kumar, Anup Kumar Singh, K. Vinay Kumar Reddy, "Fossil Fuel to Solar Power: A Sustainable Technical Design for Street Lighting in Fugar City, Nigeria," in 6th International Conferenceon Advances in Computing & Communications, ICACC2016, Cochin, India, pp. 956–966, 2016.

9. Zakariya Rajab, Ashraf Khalil, Moneer Amhamed and Ali Asheibi, "Economic Feasibility Of Solar Powered Street Lighting System In Libya", in the 8th IEEE International Renewable Energy Congress (IREC2017), 2017.

10. D. Tursel Eliiyi, T. Caylan, "Güneş Enerjisi ve LED İle Etkin Enerji Kullanımı: Yol Aydınlatmalarına Yönelik Bir Uygulama", Journal of Industrial Engineering, Vol: 19 No: 2 pp.(2–15), 2008.

11. R. Pode, "Solution to Enhance The Acceptability of Solar-Powered LED Lighting Technology", Renewable and Sustainable Energy Reviews, 14, 1096–1103, 2010.

12. H.A. Mohammed, "Design and Implementation of a Photovoltaic System Used for Street LIGHTS", IEEE2nd International Conference on Control Science and Systems Engineering, pp. 169–175, 2016.

13. http://www.yegm.gov.tr/MyCalculator/pages/34.aspx

14. Wout van Bommel, Road Lighting: Fundamentals, Technology and Application, Springer, 2015.

15. https://www.tommatech.de/

16. Hussein A Kazem, Tamer T.N. Khatib and Kamaruzzaman Bin Sopian, "Sizing of a standalone photovoltaic/battery system at minimum cost for remote housing electrification in Sohar, Oman", Energy and Buildings, 61: 108–115, June 2013.

Light & Engineering
Vol. 27, No. 1, pp. 86–96, 2019

LEDs COLOURS MIXING USING THEIR SPD AND DEVELOPING OF THE MATHEMATICAL MODEL FOR CCT CALCULATION

Canan PERDAHCI[1] and Hamdi ÖZKAN[2]

[1]*Department of Electrical Engineering, Faculty of Engineering, University of Kocaeli, Turkey*
[2]*Litpa Lighting, Koza Plaza, Istanbul, Turkey*

ABSTRACT

Light is a condition that human beings are subjected to in nature. Light is not only a physical parameter but also an important factor, which is affecting the mental and cognitive performance of the person. For this reason, in recent years, many researchers and scientists have been working on and exploring this direction of light. The spectral structure of light in the natural environment shows a continuous change. We can define this natural environment as the spectral transformation of daylight in open air. Thus, people who remain in closed environments during the day are living under unfavourable conditions, such as constant colour temperatures and luminous flux of illumination. The studies aimed at reducing this harmful effect the most. These studies are based on the principle that all intermediate colours are obtained by blending the light in 2 different colours (usually one is very warm white and the other is very cold white) and that the intermediate colours are timed within a certain scenario and illuminated indoors to simulate the outside environment. In this study, the mixture of light sources in different colours was mathematically modelled in computer environment and the CCT in K of the mixture was calculated. It is also optimized to obtain the mixture colour with least mistakes of the mixture functions by comparing with the actual measurement results.

Keywords: light emitting diode (LED), spectral power distribution (SPD), correlated colour temperature (CCT)

1. INTRODUCTION

During the day, the relationship between our biological rhythm and the day's cycle of circulation has led to the emergence of the concept of "Biodynamic Lighting". Biodynamic illumination, which allows people to control the light towards their own desires, can be described as creating a natural lighting environment by following the rhythm of daylight. Thus, the effects of daylight on people are also utilized in working and living spaces. Variable seasons and weather conditions, the day-and-night cycle creates ever-changing light scenarios throughout the day. Therefore, in the biodynamic illumination, the lighting level, colour temperature and light colour vary, not constant. Illumination control systems, such as DALI designed for automation systems or lighting control, and control options provided by these systems can be used to create biodynamic lighting that requires varying levels of illumination or is energy-saving to take advantage of daylight.

Ceiling-recessed LED biodynamic luminaires with dimensions of 600mm×600mm×120mm was designed by LITPA to show the influence of LED biodynamic luminaires with three different lighting scenarios on human performance, Fig.1.

2. SPECTRAL POWER DISTRIBUTION (SPD)

This spectral structure of the light rays determines all the characteristics of the light. This is called spectral power distribution (SPD) and pre-

Table 1. Measuring Data of 2200 K CCT LED & 7000 K CCT LED

2200K LED Measuring Data		
WL(nm)	PL	PE(mW/nm)
360	0,0059	0,2323
361	0,0091	0,3548
362	0,0067	0,2611
363	0,0074	0,2892
364	0,0061	0,2387
365	0,0048	0,188
366	0,0054	0,2124
367	0,0043	0,1667
368	0,0023	0,0915
369	0,003	0,1175
370	0,0044	0,1712
:	:	:
820	0,0121	0,473
821	0,0113	0,4412
822	0,0119	0,4681
823	0,0111	0,4367
824	0,0107	0,4182
825	0,0111	0,4365
826	0,01	0,3916
827	0,0095	0,3706
828	0,0095	0,3732
829	0,0095	0,3731
830	0,0092	0,3624

7000K LED Measuring Data		
WL(nm)	PL	PE(mW/nm)
360	0,0034	0,2717
361	0,0048	0,3859
362	0,001	0,0774
363	0,0041	0,3302
364	0,0059	0,4741
365	0,0025	0,2034
366	0,0047	0,375
367	0,0037	0,2945
368	0,0031	0,2512
369	0,0045	0,3584
370	0,0041	0,3314
:	:	:
820	0,0017	0,136
821	0,0022	0,1753
822	0,0017	0,1338
823	0,0019	0,1505
824	0,002	0,1602
825	0,0013	0,1018
826	0,0018	0,1456
827	0,0015	0,1204
828	0,0015	0,1197
829	0,0015	0,1174
830	0,0016	0,1303

sented in Fig. 2 for worm-white and cold-white LED.

The wavelength that the human eye can perceive is usually given in the range of (380–780) nm. Spectral measuring instruments can perform a wider range of measurements. The Everfine HAAS-1200, we use in this study, can measure from 350 to 1000 nm. However, because of *V(λ)*, we used range (360–830) nm in our measurements and calculations. In the spectral chart, the vertical (y) axis is the spectral flux value at each wavelength of the wavelength range. We measure this value by the spectroradiometric device in [mW / nm].

Fig.1. The biodynamic LED luminaire

3. LABORATORY MEASUREMENTS

Our laboratory measurements consist of two steps. In the first step, we can calculate the spectral power distribution data of the radiation in two different light colours. In the second stage, it was done to find out, which currents of intermediate colours were obtained by driving both colour LEDs at different driving currents and to verify and optimize the calculations according to these measurements.

3.1. Luminaire used in Measurements

The luminaires used in the measurements are Biodynamic and are made with LEDs of both colours at 2200 K and 7000 K CCT values. In addition, the driver output currents can be programmed via the DALI interface by dimming at desired dim levels. There are 90 pieces of 2200 K LEDs and 90 pieces of 7000 K LEDs in the luminaire. LED chips are placed next to each other in order to optimize

Table 2. Meaning of Terms Used in Equation 1

λ	A series from 360 nm to 830 nm (If we take the starting value 0, a series of up to 470)
$W(\lambda)$	(mW/nm) Warm White SPD data
$C(\lambda)$	(mW/nm) Cold White SPD data
$M(\lambda)$	(mW/nm) Mixed SPD data

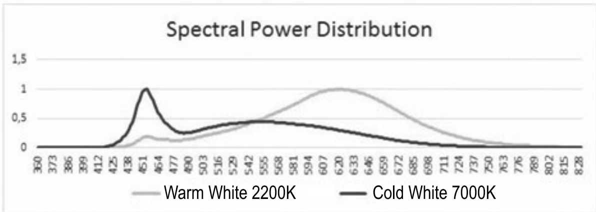


Fig. 2. LEDs Spectral Power Distribution

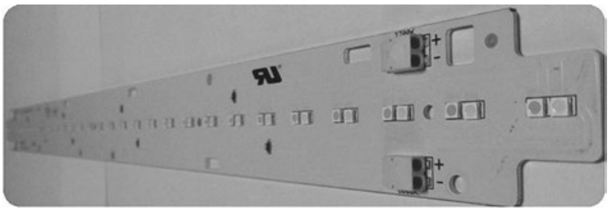


Fig.3. PCB of Biodynamic LED luminaire

the colours (Fig. 3) and a special diffuser (Fig. 4) is used in the luminaire;

90 units of 2200 K LEDs are the 1st group with its own driver. The other 90 LEDs are 7000 K and this 2nd group of LEDs is also driven by a 2nd driver. Both groups have a maximum 500 mA driving current. Output currents in the range of 0 to 500 mA are obtained by dimming via DALI protocol or completely turning OFF the drivers. Linear dimming is used as a method of dimming in operation. When 50 % dimming is done, 250 mA value of max current of 50 % will be taken as output current. Each of the 90 LED circuits in two groups consists of 6 serial 5 parallel circuit connections. Thus, when the driver is supplied with 500 mA, an LED is driven with 100 mA. The dimming ratio from 0 to 100 on the DALI means to drive the LED from 0 to 100 mA current.

3.2 Experimental Study

In two-stage measurements, the dim ratio of 2200 K LEDs in 1 step is set to 100 %, 7000 K LEDs are turned OFF and the spectral data is taken. In the same way, the dimming rate of 7000 K LEDs is adjusted to 100 % and 2200K LEDs are turned on OFF position, and the spectral data of 7000K LEDs are also taken (Table 1).

4. MATHEMATICAL MODEL OF COLOUR MIX

The spectral data are of two types and the first type is the amount of energy flux possessed per wavelength. These sizes constitute the characteristic of the light colour. The second type is the case where the energy value of the wavelength having the maximum value in the collection of these energy values is taken as 1 and the energy values of the other wavelengths are normalized by proportioning accordingly (Figs. 4–5). We can say, the normalization coefficient to the energy value of the maximum value. The normalization coefficient is a special value that is unique to the light source to which it is concerned. Each light source, each different colour and each light form has its own specific normalization coefficient. Therefore, when calculating the mixture colour, we must use the first type data and go through the actual energy values.

To calculate the colour that will result in a colour mixture result, we sum the spectral data of each of the two ranks. In other words, we create the mixture

Fig.4. Special diffuser of Biodynamic LED luminaire

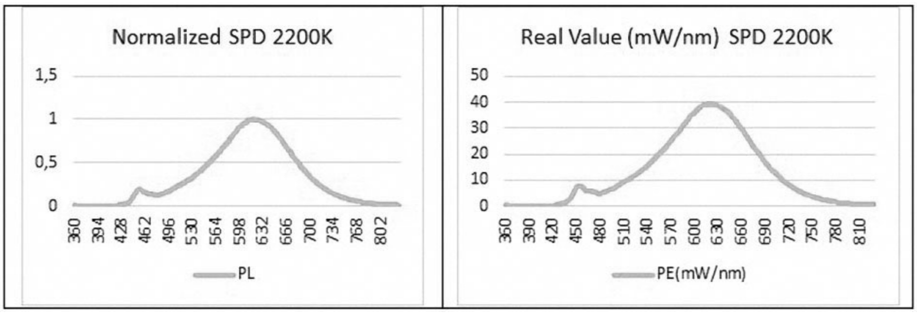


Fig.5. SPD of Light Source at CCT 2200 K

colour by summing the real luminous values of the same wavelengths (Equation 1);

$$M(\lambda)=W(\lambda)+C(\lambda). \quad (1)$$

4.1 Colour Matching Functions

To calculate the CCT values of the colours from the spectral diagram data, we need three main colour spectral value tables. These values are defined in CIE1931 as 2 ° colour equalization functions. (Colour-matching functions for CIE2° Standard Observer (1931)) [1].

Among the colours, red, green, and blue colours are generally regarded as the three main colours of light. The reason for this is that our eyes are sensitive to these three primary colours and the eye contains three types of cones (colour sensors) that are sensitive and allow colour perception. According to the 1931 Standard Observer's definition of CIE [1], Fig. 9 shows spectral sensitivity curves corresponding to the human eye. These are called colour matching functions. It has a high sensitivity in the red, green and blue wavelength regions.

4.2 Calculation of Tristimulus Values

Tristimulus values, which are determined based on colour matching functions and defined by the CIE in 1931, are also referred to as 2 ° *XYZ* tristimulus values. When evaluating the brightness of the colours relative to each other, people see the light in the green parts of the spectrum brighter than the red or blue light of equal power. For this reason, we take the *Y* value representing green light as 100 and form the *K* coefficient and the reduced tristumulus values for *X* and *Z*. [3], see also Table 3.

Calculation of the Tristimulus values using the colour matching functions for CCT 2200 K:

$$X1 = K1 \times \int_{360}^{830} W(\lambda) \times \bar{X}(\lambda) \times R(\lambda) \times d\lambda. \quad (2)$$

$$Y1 = K1 \times \int_{360}^{830} W(\lambda) \times \bar{Y}(\lambda) \times R(\lambda) \times d\lambda. \quad (3)$$

$$Z1 = K1 \times \int_{360}^{830} W(\lambda) \times \bar{Z}(\lambda) \times R(\lambda) \times d\lambda. \quad (4)$$

$$K1 = \frac{100}{\int_{360}^{830} W(\lambda) \times \bar{Y}(\lambda) \times R(\lambda) \times d\lambda}. \quad (5)$$

Calculation of the Tristimulus values using the colour matching functions for 7000 K:

$$X2 = K2 \times \int_{360}^{830} C(\lambda) \times \bar{X}(\lambda) \times R(\lambda) \times d\lambda. \quad (6)$$

$$Y2 = K2 \times \int_{360}^{830} C(\lambda) \times \bar{Y}(\lambda) \times R(\lambda) \times d\lambda. \quad (7)$$

$$Z2 = K2 \times \int_{360}^{830} C(\lambda) \times \bar{Z}(\lambda) \times R(\lambda) \times d\lambda. \quad (8)$$

$$K2 = \frac{100}{\int_{360}^{830} C(\lambda) \times \bar{Y}(\lambda) \times R(\lambda) \times d\lambda}. \quad (9)$$

We calculate the tristimulus values using the matching functions for the mixture colour:

$$X3 = K3 \times \int_{360}^{830} M(\lambda) \times \bar{X}(\lambda) \times R(\lambda) \times d\lambda. \quad (10)$$

$$Y3 = K3 \times \int_{360}^{830} M(\lambda) \times \bar{Y}(\lambda) \times R(\lambda) \times d\lambda. \quad (11)$$

Table 3. Meaning of Terms Used in Formulas

λ	Wavelength (array with increment 1 from 360nm to 830nm)
$W(\lambda)$	SPD for 2200 K
$C(\lambda)$	SPD for 7000 K
$M(\lambda)$	SPD for mixture
$\bar{X}(\lambda)$	CIE1931 standard observer colour equalization function (for Red Main Colour)
$\bar{Y}(\lambda)$	CIE1931 standard observer colour equalization function (for Green Main Colour)
$\bar{Z}(\lambda)$	CIE1931 standard observer colour equalization function (for Blue Main Colour)
$R(\lambda)$	Spectral reflectance ratio (We assume as 1)
K1,K2,K3	Reduction coefficient (Calculated based on Y = 100)
X1,Y1,Z1	Tristimulus values for 2200 K
X2,Y2,Z2	Tristimulus values for 7000 K
X3,Y3,Z3	Tristimulus values for mixture
$X1_T, Y1_T, Z1_T$	Reduced tristimulus values relative to Y1 =100 for 2200K
$X2_T, Y2_T, Z2_T$	Reduced tristimulus values relative to Y2 =100 for 7000K
$X3_T, Y3_T, Z3_T$	Reduced tristimulus values relative to Y3 =100 for Mixture
$X1_x, Y1_y$	Tristimulus values for 2200 K
$X2_x, Y2_y$	Tristimulus values for 7000 K
$X3_x, Y3_y$	Tristimulus values for mixture

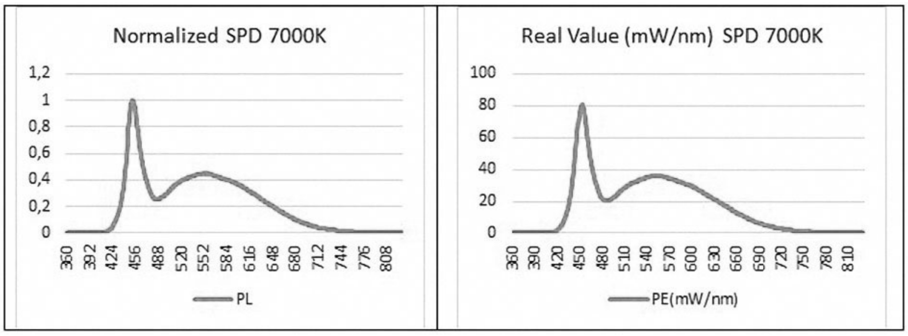


Fig. 6. SPD of Light Source at CCT 7000 K

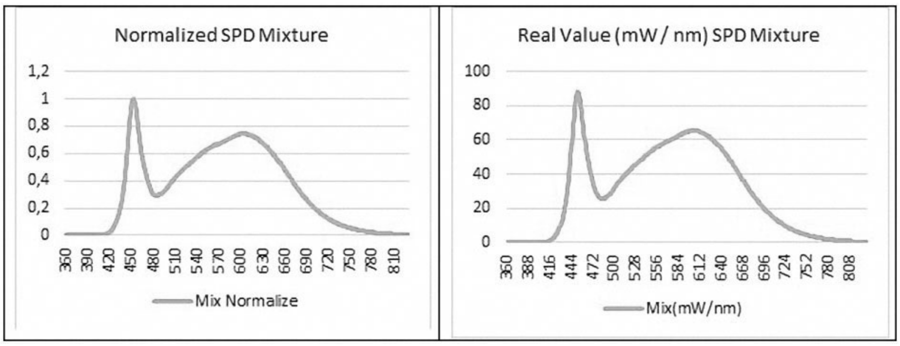


Fig.7. SPD of Mixed Light Source

$$Z3 = K3 \times \int_{360}^{830} M(\lambda) \times \bar{Z}(\lambda) \times R(\lambda) \times d\lambda. \quad (12)$$

$$K3 = \frac{100}{\int_{360}^{830} M(\lambda) \times \bar{Y}(\lambda) \times R(\lambda) \times d\lambda}. \quad (13)$$

4.3. Calculation of Chromaticity Coordinates

The chromaticity coordinates (*x, y*) are based on standard tristimulus (*XYZ*) values. These standards have been established by (CIE) [3]. From the obtained tristimulus values, we calculate the *x* and *y* coordinates of the light colour in CIE1931 colour space with the following formulas;

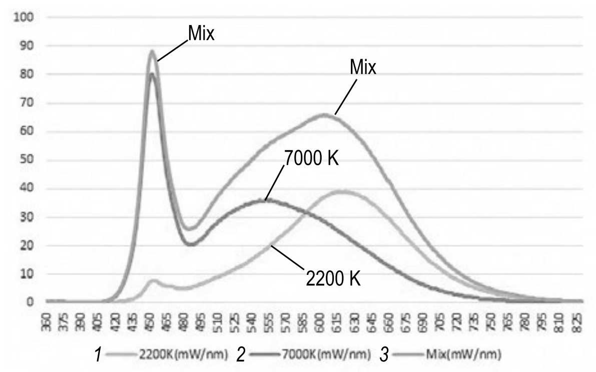


Fig.8. CCT 2200K and CCT 7000K, and their SPD data mixture

$$x = \frac{X}{(X+Y+Z)}. \quad (14)$$

$$y = \frac{Y}{(X+Y+Z)}. \quad (15)$$

4.4. Calculation of CCT

Using the McCamy formula [4], calculate the CCT values in Kelvin using the *x* and *y* coordinates:

$$N = \frac{(x-0.33320)}{(0.1858-y)}. \quad (16)$$

$$CCT = 449\times N^3 + 3525\times N^2 + \\ + 68253.3\times N + 5520.33. \quad (17)$$

5. VERIFICATION OF MEASURED VALUES IN THE EXPERIMENT

First we calculate the tristimulus values using the spectral data, then we calculate the chromaticity coordinates, finally we calculate the CCT (Fig. 10).

We calculate the tristimulus values using the SPD data for the *W (λ)* sequence measured for 2200 K CCT with taking into account Equations 2,3,4,5.

$$X1 = \sum_{\lambda=360}^{830} \bar{X}(\lambda)W(\lambda),\ Y1 = \sum_{\lambda=360}^{830} \bar{Y}(\lambda)W(\lambda),$$

$$Z1 = \sum_{\lambda=360}^{830} \bar{Z}(\lambda)W(\lambda),$$

$$K1 = \frac{100}{Y1},$$

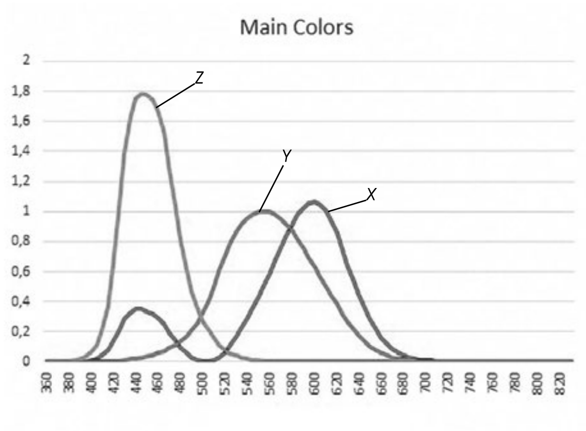


Fig.9. $\bar{X}\bar{Y}\bar{Z}$ colour matching functions

$$X1_T = K1\times X1\ \ Y1_T = K1\times Y1\ \ Z1_T = K1\times Z1.$$

Chromaticity coordinates for 2200 K CCT have been calculated based on Equations 14 & 15;

$$X1_X = \frac{X1_T}{X1_T + Y1_T + Z1_T},$$

$$Y1_Y = \frac{Y1_T}{X1_T + Y1_T + Z1_T}.$$

CCT calculation for 2200 K has been performed based on Equations 16 & 17;

$$N1 = \frac{X1_X - 0.332}{0.1858 - Y1_Y}$$

$$CCT1 = 449\times N1^3 + 3525\times N1^2 + \\ + 6823.3\times N1 + 5520.33.$$

$CCT1 = 2260\,K$ (The measured value by the device is 2277K, difference rate is the 0.7465 %)

We calculate the tristimulus values using the SPD data for the *C (λ)* sequence measured at 7000 K based on Equations 6,7,8,9:

$$X2 = \sum_{\lambda=360}^{830} \bar{X}(\lambda)C(\lambda),\ Y2 = \sum_{\lambda=360}^{830} \bar{Y}(\lambda)C(\lambda),$$

$$Z2 = \sum_{\lambda=360}^{830} \bar{Z}(\lambda)C(\lambda).$$

$$K2 = \frac{100}{Y2},$$

$$X2_T = K2\times X2,\ Y2_T = K2\times Y2,$$

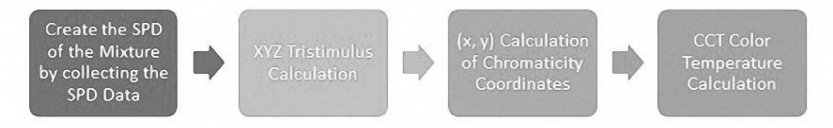


Fig. 10. Flow chart of Verification of Measured Values

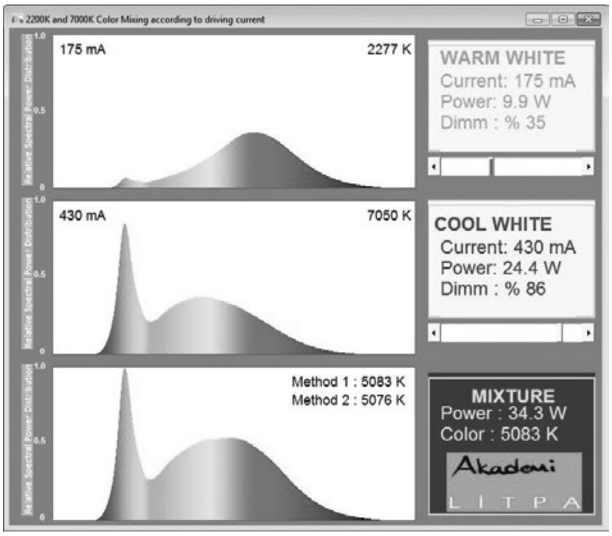


Fig.11. Screenshot of the Software

$$Z2_T = K2 \times Z2$$

Chromaticity coordinates for CCT 7000 K have been calculated based on Equations 14 & 15;

$$X2_X = \frac{X2_T}{X2_T + Y2_T + Z2_T},$$

$$Y2_Y = \frac{Y2_T}{X2_T + Y2_T + Z2_T}.$$

CCT calculation for 7000 K is based on Equations 16 & 17;

$$N2 = \frac{X2_X - 0.332}{0.1858 - Y2_Y}$$

$$CCT2 = 449 \times N2^3 + 3525 \times N2^2 + \\ + 6823.3 \times N2 + 5520.33$$

$CCT2 = 7049\,K$ (The measured value by the device is 7052K, difference rate is the 0.0425 %)

We first calculate the tristimulus values for the mixture colour using the *M (λ)* sequence (SPD Data) calculated by Equation 1 based on Equations 10,11,12,13:

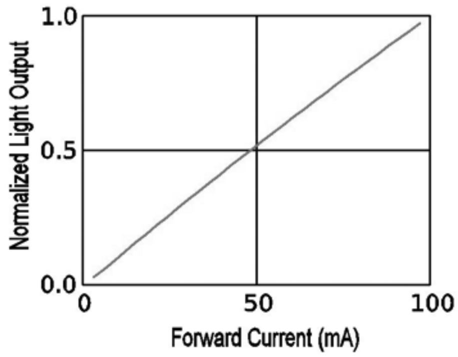


Fig. 12. Current vs. light output diagram

$$X3 = \sum_{\lambda=360}^{830} \bar{X}(\lambda) M(\lambda),\ Y3 = \sum_{\lambda=360}^{830} \bar{Y}(\lambda) M(\lambda),$$

$$Z3 = \sum_{\lambda=360}^{830} \bar{Z}(\lambda) M(\lambda).$$

$$K3 = \frac{100}{Y3}$$

$$X3_T = K3 \times X3,\ Y3_T = K3 \times Y3,$$

$$Z3_T = K3 \times Z3.$$

Chromaticity coordinates of colour mixture were calculated based on Equations 14 & 15:

$$X3_X = \frac{X3_T}{X3_T + Y3_T + Z3_T},$$

$$Y3_Y = \frac{Y3_T}{X3_T + Y3_T + Z3_T}.$$

CCT calculation for Colours Mixture were calculated based on Equations 16 & 17:

$$N3 = \frac{X3_X - 0.332}{0.1858 - Y3_Y}$$

$$CCT_{MIX} = 449 \times N3^3 + 3525 \times N3^2 + \\ + 6823.3 \times N3 + 5520.33.$$

CCT_{MIX} = 4042 *K* (The measured value by the measurement device is the 4033K, difference rate is the 0.0425 %)

Table 4. Comparison of Laboratory Measurement Data with Mathematical Model

Dim ratings,%		Current, mA		Measured CCT, K	Mathematical model, K	Difference rate,%	Optimized mathematical model, K	Difference rate, %
7000 K	2200 K	7000 K	2200 K					
100	0	500	0	7052	7050	-0,028	7071	0,27
100	10	500	50	6378	6356	-0,345	6356	-0,35
100	20	500	101	5839	5898	1,01	5817	-0,38
100	30	500	151	5428	5496	1,25	5411	-0,31
100	40	500	199	5112	5178	1,29	5101	-0,22
100	50	500	247	4860	4911	1,05	4849	-0,226
100	60	500	300	4624	4664	0,87	4623	-0,022
100	70	500	351	4432	4463	0,699	4433	0,023
100	80	500	402	4272	4290	0,42	4274	0,045
100	90	500	449	4149	4152	0,072	4146	-0,072
100	100	500	500	4033	4021	-0,298	4021	-0,297
90	100	448	500	3913	3891	-0,562	3898	-0,38
80	100	401	500	3798	3765	-0,87	3780	-0,47
70	100	350	500	3661	3619	-1,15	3643	-0,49
60	100	297	500	3505	3455	-1,4	3489	-0,456
50	100	252	500	3361	3305	-1,67	3347	-0,417
40	100	198	500	3164	3113	-1,61	3160	-0,126
30	100	150	500	2985	2930	-1,84	2977	-0,268
20	100	100	500	2766	2727	-1,41	2765	-0,036
10	100	52	500	2540	2518	-0,87	2541	0,0394
0	100	0	500	2277	2277	0	2270	-0,307
10	10	52	52	4062	4021	-1,01	4021	-1,01
20	20	101	101	4021	4021	0	4021	0
30	30	151	151	4021	4021	0	4021	0
40	40	199	199	4019	4021	0,0497	4021	0,05
50	50	253	253	4019	4021	0,0497	4021	0,05
60	60	298	298	4021	4021	0	4021	0
70	70	352	351	4026	4024	-0,0497	4024	-0,05
80	80	404	403	4026	4024	-0,0497	4024	-0,05
90	90	452	449	4028	4029	0,025	4013	-0,37
100	100	500	500	4033	4021	-0,297	4021	-0,298
50	100	255	500	3362	3315	-1,398	3357	-0,149
50	90	255	449	3453	3412	-1,187	3452	-0,029
50	80	256	402	3549	3522	-0,761	3557	0,225
50	70	257	351	3678	3666	-0,33	3692	0,38

Dim ratings,%		Current, mA		Measured CCT, K	Mathematical model, K	Difference rate,%	Optimized mathematical model, K	Difference rate, %
7000 K	2200 K	7000 K	2200 K					
50	60	257	298	3846	3847	0,026	3860	0,36
50	50	257	253	4021	4040	0,47	4039	0,448
50	40	257	199	4306	4338	0,74	4317	0,255
50	30	257	151	4644	4691	1,01	4653	0,19
50	20	257	101	5149	5193	0,85	5143	-0,117
50	10	257	53	5850	5880	0,51	5837	-0,22
50	0	257	0	7021	7050	0,41	7090	0,98
0	50	0	254	2274	2277	0,13	2264	-0,44
10	50	53	253	2753	2747	-0,218	2766	0,47
20	50	103	253	3137	3133	-0,127	3164	0,86
30	50	154	254	3482	3474	-0,23	3501	0,55
40	50	203	254	3754	3762	0,21	3777	0,61
50	50	257	253	4021	4040	0,47	4039	0,448
60	50	304	254	4206	4242	0,86	4230	0,57
70	50	359	254	4400	4453	1,20	4419	0,43
80	50	410	254	4561	4623	1,36	4576	0,33
90	50	458	254	4691	4765	1,58	4709	0,38
100	50	500	247	4860	4911	1,049	4849	-0,226

6. SOFTWARE THAT CALCULATES MIXTURE VALUES FOR DIFFERENT DIM RATIOS

By using these two data at hand, we calculated the colour of the mixture when mixing 100 % of both colors, using only the warm white spectral data and the cold white spectral data. So, to calculate what the mixture will be at different mixing ratios, we calculate the mixture after mixing the two SPD values of the two colours with the dim ratio in %.

Our new mixture formula is as follows:

$$M(\lambda) = Dim1 \times W(\lambda) + Dim2 \times C(\lambda). \quad (18)$$

With this software spectral data of CCT 2200 K LED and spectral data of CCT 7000 K LED are visualized, and the mixture colour is calculated by two different methods depending on the desired dim ratio. For the representation of the spectral data, the values are normalized by assuming a maximum value of 1, which is the value of the sequence, and the spectrum chart is formed in this way. The dim ratio determined by the scrolling bars of both colours enlarges the spectral ratio from 0 to 100 as a multiplier of the spectral power values at all wavelengths between 360 nm and 830 nm. This change affects the spectral data sequence with a maximum value of 1 in proportionately. The sum of the two colours is calculated based on the dim ratio and the spectral data of the mixture is displayed simultaneously. Two different calculation methods are used in this software. First method is the McCamy method, which is the calculation method we use in our article. The second method is the CIECAM02 based calculation method. This calculation method will not be examined in this article.

7. LABORATORY MEASUREMENTS AND VERIFICATION

All intermediate values can be calculated with the software. A number of laboratory measurements

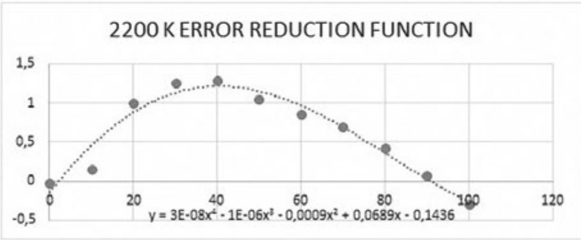


Fig. 13. Difference reduction function diagram for 2200 K CCT

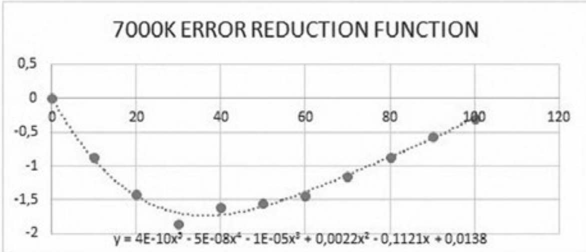


Fig. 14. Difference reduction function diagram for CCT 7000 K

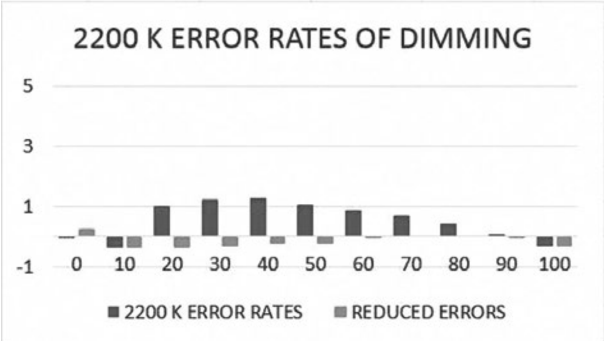


Fig. 15. CCT 2200 K difference rates in dependence of dimming

Fig.16. CCT 7000 K difference rates in dependence of dimming

are needed to verify the mathematical model. For the verification of calculations and software outputs, laboratory measurements were made at the following dim ratios and the deviation ratios were determined by comparing, Table 4.

8. IMPROVING DIFFERENCE REDUCTION FUNCTION AND RE-VERIFYING BY APPLYING TO CALCULATIONS

Calculated values show up to 1.5 % deviations. The regions where these deviations are generated are those where one of the colours is at the maximum level, while the other colour is at 30 %, 40 %, 50 %, 60 % dim levels. This is because the variation of the luminous flux of the LED is not directly proportional to the dim levels. We can see this clearly in the graph of luminous flux change according to the dim levels given in the LED datasheet.

Fig. 13 shows the difference ratios for 2200K LEDs from 0 % to 100 % for each dim level with 10 % increase when the 7000K LED is at 100 % dim. From this graph y = 3E-08x4–1E-06x3–0,0009x2 + 0,0689x – 0,1436 difference reduction function is obtained.

Fig. 14 shows the difference ratios for CCT 7000 K LEDs from 0 % to 100 % for each dim level with 10 % increase when the 2200K LED is at 100 % dim. From this graph y = 4E-10x5–5E-08x4–1E-05x3 + 0.0022x2–0.1121x + 0.0138 difference reduction function is obtained.

When we apply the curved functions of the polynomial structure of the 4th and 5th grades obtained from these graphs to the dim ratio of our mixture formula:

$$Dim1Fix = 3 \cdot 10^{-8} \cdot Dim1^4 - 10^{-6} \cdot Dim1^3 - 0.0009 \cdot Dim1^2 + 0.0689 \cdot Dim1 - 0.1436. \quad (19)$$

$$Dim2Fix = 4 \cdot 10^{-10} \cdot Dim2^5 - 5 \cdot 10^{-8} \times Dim2^4 - 10^{-5} \cdot Dim2^3 + 0.0022 \cdot Dim2^2 - 0.1121 \cdot Dim2 + 0.0138. \quad (20)$$

$$M(\lambda) = Dim1Fix \times W(\lambda) + Dim2Fix \times C(\lambda), \quad (21)$$

we get the final mixture formula.

After applying the difference reduction functions to the main formula, the differences rates have changed by decreasing as seen in the graphs (Figs. 15–16).

9. CONCLUSIONS & DISCUSSION

In order to calculate the mixture colour, it is possible to apply the side sum method of wavelengths we have used here for more than one colour. What we initially need for this is only the spectral data of the primary colours. Using the spectral data of the main colours, we can calculate the CCT of the mixture and the spectral data of the mixture colour by mixing the desired number of different colours mathematically. When we place our mixing ratios as a Dim coefficient before the spectral data of each colour in the total formula:

$$Mix(\lambda) = Dim1 \times Colour1(\lambda) + Dim2 \times \times Colour2(\lambda) + \ldots + DimN \times ColourN(\lambda), \quad (22)$$

and compare the results of the calculations from the software with the measured values again, they are significantly improved and reduced to less than ± 0.5 %, especially at the difference rate of 30 %, 40 %, 50 %, 60 % dim.

ACKNOWLEDGEMENTS

The author would like to thank "The Scientific and Technological Research Council of Turkey (TUBITAK)" for funding the research project with Nr: 3140764 "Biodynamic Lighting Systems Design", which supports this work.

Our unforgettable thanks to the LITPA for funding the research project with Nr: 3140764 "Biodynamic Lighting Systems Design" which supports this work.

The author would like to thank Ms. Deniz Yuce "R&D and Marketing Project Director" of LITPA for their valuable contributions to the present study.

The author would like to also thank University of Kocaeli for their valuable contributions to the present study.

REFERENCES

1. CIE Publication: Color-matching functions for CIE2° Standard Observer (1931).

2. CIE Publication,1932. Commission Internationale de l'Éclairage Proceedings, 1931. Cambridge: Cambridge University Press.

3. CIE15:2004 3rd Edition – CIE Standars on Colorimetry.

4. McCamy, C. S. 1992. Correlated Colour Temperature as an Explicit Function of Chromaticity Coordinates, Colour Research & Application 17:142–14.

Canan Perdahci
received the B.E. and M. Sc. degrees in electrical engineering from the University of Yildiz, Istanbul, Turkey, in 1991 and 1993 respectively and the Ph.D. degree in electrical engineering from the University of Kocaeli, in 1997.

In 1992, she joined the Department of Electrical Engineering as a Lecturer and. in 1998, became an Asisstant Professor. Her current research interests include LED lighting, power quality, tunnel lighting, road lighting

Hamdi Özkan
received the B.D. in machine engineering from the University of Trakya, Edirne, Turkey, in 2003. In 2007, he joined the Production Department of Litpa Lighting as a machine engineer, and in 2003 became a Responsible of Research & Development Department. His current research interests include mechanical and optic design of the luminaires and spectral structure of the light

Light & Engineering
Vol. 27, No. 1, pp. 97–102, 2019

ENERGY SAVING IN THE SPHERE OF STATE PUBLIC INTERESTS

Gulnara F. Ruchkina and Elena Yu. Matveeva

Financial University under the Government of the Russian Federation
E-mail: gruchkina@fa.ru

ABSTRACT

The article considers the categories of energy saving and energy efficiency in the aspect of State public interest. The implementation of energy saving policy is an independent public interest, as it allows solving some global, national tasks systematically. The article investigates the ratio of energy saving to the public interest in reducing the energy intensity of the Russian economy. The authors reveal the relationship between energy saving and public interest in ensuring national energy security of Russia. The authors consider energy saving as a factor contributing to the implementation of the actual public interest in the conservation of exhaustible natural resources reveal the relationship between energy saving and public environmental interest. A part of the article is devoted to the study of energy saving as a direction of state policy, allowing contributing to the preservation of the nation health. Energy saving is also considered in the aspect of public interest to increase the efficiency of budget spending to optimize public spending in the field of municipal authorities (for example, lighting).

The authors correlate all the considered state public interests with the category of "national interest" in the context of the provisions of the national security Strategy of the Russian Federation.

Keywords: energy saving, energy efficiency, state public interests, lighting

1. INTRODUCTION

IEA experts expect that global energy demand will reach 15.3 billion tons of oil equivalent in 2030. Thus, energy consumption will increase by two-thirds compared to the level of the XXI century beginning [1]. The growth of energy consumption will have stable dynamics. Specialists of the Institute of energy research of the Russian Academy of Sciences predict that primary energy consumption in the world in 2010–2040 will increase annually by 1.3 % [2]. The growing demand for energy makes the efficient use of energy resources, energy, and energy carriers a global challenge.

The basic regulatory documents aimed at the implementation of energy saving Russian policies include:

– Federal law No. 261-FZ of 23.11.2009 "On Energy Saving and on Increasing Energy Efficiency and on Amending Certain Legislative Acts of the Russian Federation" (is edited 23.04.2018);

– Energy strategy of Russia for the period till 2030 (approved by order of the Government of the Russian Federation No. 1715-p of 13.11.2009);

– State program of the Russian Federation "Energy Efficiency and Development of Power" (approved by the RF Government resolution No. 321 from 15.04.2014);

– A comprehensive plan of measures to improve the energy efficiency of the economy of the Russian Federation (approved by order of the Government of the Russian Federation No. 703-p of 19.04.2018).

The importance of the problem of energy saving for our country is explained by the fact that the effective use of energy resources greatly contributes to the solution of some pressing social problems and challenges, namely:

– Problems of energy supply and lack of energy capacity and, as a consequence, the problems of energy security of Russia;

– The tasks of reduction of energy intensity of the Russian economy and, as a consequence, assistance to the task of increasing of its competitiveness;

– The tasks of improvement of ecology, reduction of anthropogenic impact on the natural environment;

– The task of preserving natural resources;

– Objectives of the population health protection;

– The problem of reducing budget expenditures.

The research problem of the aspects mentioned above and in General the problem of energy saving are considered and solved in the article through the prism of national public interests.

2. METHODS

General scientific methods of cognition-formal logic, system analysis, generalisation, formal legal and comparative legal methods are used in the article.

Socially significant, nation-wide tasks, the solution of which is important for an unlimited number of persons, are referred to the sphere of public interests. Their correlation with the status of "national interest" in the context of the provisions of the national security Strategy of the Russian Federation [3] is used as an indicator of the relevance and importance of the public interest. We believe that such an approach can be considered justified since this document defines today the officially recognized system of strategic national priorities aimed at ensuring the long-term sustainable development of our state.

3. RESULTS

According to the national security Strategy, national interests are objectively significant needs of the individual, society and the State in ensuring their security and sustainable development.

3.1. Energy Saving and Energy Intensity Reduction of the Russian Economy as a National and State-wide Public Interest

The most critical problem of the Russian economy is the high level of its energy intensity. Energy intensity of the economy is the ratio of consumption of natural fuel resources and gross domestic product of the country.

The energy intensity of the Russian gross domestic product (GDP) is currently 1.5 times higher than the global and American that averaged and twice as high as that of the leading European countries [4]. The high share of energy costs in production costs leads to a decrease in the level of competitiveness of Russian goods, which limits export opportunities in the foreign market and, on the contrary, programs an increase in imports of consumer goods in the domestic market. It disorientates our national economy.

The risks of reducing the competitiveness of the energy-intensive Russian industry and, as a result, the national economy, are unusually high regarding volatility and lower prices for raw materials in the world markets, the development of shale projects, sanctions restrictions.

The national security strategy contains an indication that improving the competitiveness of the national economy is one of the primary national interests of the Russian Federation, and its action is considered in the long term. At the same time, reducing the competitiveness of the national economy is the strategy ranks among the main strategic risks and threats to national security in the economic sphere. Consequently, energy saving is a public interest in the context of reducing energy intensity and increasing the competitiveness of the domestic economy.

3.2. Energy Saving and Public Interest In Ensuring National Energy Security of Russia

The national security Strategy of the Russian Federation contains a direct indication that energy security is one of the main directions of national security of our country in the economic sphere.

The dependence of any society on energy is tremendous, and as a rule, it only increases along with economic development.

When discussing energy security issues, it is usually a question of providing the needs of the economy and society with the energy resources of the required quality and quantity. In the European Union, since the 1990s, energy conservation has traditionally been a factor in improving the energy and environmental security of member States. The preservation of high energy intensity leads to the aggravation of problems related to the energy security of Russia and its regions due to the inability to provide energy capacity needs of the growing economy. The relevance of this problem is confirmed by the fact that at the turn of the century in the country there was no one area (both among Federal districts and economic regions and among regions of the Russian Federation), which would not have problems with the provision of electricity [5].

The concept of "energy security" is also enshrined in the legislation of the Russian Federation, in the Energy strategy of Russia until 2020, which states that energy policy will be used to prevent geopolitical and macroeconomic threats, as well as to preserve Russian independence. It is necessary to increase the power generation at least another 20 thousand MW [5] to cover the growing electricity demand in Russia in the next 2–4 years.

A unit of primary energy obtained by increasing its production on average requires 2–3 times more capital investments than its production by increasing energy efficiency [5]. Thus, it is obvious that in many cases it is cheaper to implement measures to save energy or avoid its use than to increase capacity and energy production.

In conditions of a highly energy-wasteful economy, the power industry will not be able to meet the growing demand for energy. The theme of energy supply becomes so defining that it is impossible not to agree with the famous writer-futurologist Arthur Clark, who predicted that soon the single world currency will be kilowatt-hour [6].

The transition to energy will be the saving way of development, and the formation of an energy-efficient society is a saving way of development of the entire world civilization, as it provides a much cheaper increase in energy production. In the context of the problem of ensuring Russian energy security, there is a close link between the implementation of this strategic national priority and the implementation of energy saving policy, and this proves that energy saving is a public interest in Russia.

3.3. Energy Saving and Conservation of Natural Resources as an Actual Public Interest

Energy saving is inextricably linked with the task of saving fuel and energy resources. The high level of energy intensity of the Russian economy indicates the inefficient and wasteful use of energy resources. Today, fossil fuels (coal, oil, gas), i.e., exhaustible natural resources, the need for which is not adequately replenished over time, account for more than 80 % of the energy resources consumed in the world.

The whole world is interested in the problems of energy saving precisely because the reserves of fuel and energy resources on the planet are not infinite.

The limited reserves of exhaustible fuel and energy resources made us turn to energy saving as to one of the main elements of the modern concept of the world economy. For resource conservation (especially regarding exhaustible minerals), we should recognize the status of public interest also because the resource conservation is the concern of the current society for future generations. The national security Strategy of Russia states that environmental management is one of the strategic national priorities, it is also noted that the depletion of mineral resources because of inefficient and "predatory" nature management and the predominance of the economy of extractive and resource-intensive industries adversely affect the state of environmental safety. Article 9 of the Constitution the Russian Federation defines the status of natural resources as the basis of life and activity of the population [7]. Due to the direct effect of the Constitution, the presence of the constitutional and legal form is the most critical criteria of publicity of the public interest.

Thus, energy saving to achieve the conservation of exhaustible natural resources should be considered as a national public interest.

3.4. Energy Conservation and Public Environmental Interest

The ecology problem is one of the main problems facing humanity today. On the one hand, energy is an essential component of economic prosperity, and on the other hand, its production is a huge component in environmental pollution and environmental degradation.

The problem of energy security and energy saving in recent decades has become closely associated with a whole range of environmental and legal problems. As it is indicated in the UN report on the sustainable development goals in 2017, the task of increasing the share of water, solar and wind energy, i.e., "clean" energy from renewable sources, is facing the entire world community. The fuel and energy complex is one of the main pollutants of the environment. In Russia, most greenhouse gas emissions (about 80 %) are due to the activities of the energy sector [8]. Increasing fuel and energy efficiency is the cheapest way to protect the environment.

The benefits of improving the energy efficiency of the economy for the environment are apparent: the energy that brings the least harm to the environment is the energy that should not be consumed or is not produced. Emissions of pollutants will be automatically reduced in appropriate proportion whenever energy consumption for purposes will be reduced (by improving the insulation of dwellings, the use of more efficient light sources and lighting devices, increasing the efficiency of engines, etc.). The modern world is on the threshold of an environmental disaster, the harbingers of which are: global warming, reduction of the earth's ozone layer, acid rain, reduction of forest area and biological diversity, land degradation, deformation of the social environment, deterioration of public health in ecologically unfavorable regions, and other negative phenomena (deterioration of water quality, migration of harmful substances, desertification).

Article 42 of the Constitution of the Russian Federation proclaims the right of everyone to a favourable environment, and in this norm, the public environmental interest is clothed in the form of subjective law. At the same time, article 58 of the Russian Constitution establishes the duty of everyone to preserve nature and the environment, to take care of natural resources. The fact that two more obligations of citizens are fixed at the constitutional level (to protect the Fatherland and to pay legally established taxes and fees) speaks of the importance of environmental interests, the provision of which directly depends on the state of national security.

The national security strategy of Russia defines the strategic objectives the environmental safety preservation and quality assurance of the environment, as well as the elimination of environmental consequences of economic activity in the context of increasing economic activity and global climate changes. The government of the Russian Federation in its Energy strategy until 2030 sets the task of consistently limiting the load of the fuel and energy complex on the environment and climate, including by reducing energy consumption [9]. Based on the above-stated, it should be concluded that energy saving refers to the public interests as an instrument of conservation and protection of the environment.

3.5. Energy Saving and Preservation of the Nation Health as a National Public Interest

First, human settlements suffer from the irrational use of energy resources, because the total impact of pollutants from the emissions of the fuel and energy complex, industry and transport is accumulated precisely there.

By the conducted studies on the assessment of risks to public health, it was concluded that the costs for the economy from the deterioration of the health of the population due to the negative impact of the fuel and energy complex are $18–35 billion annually.

In "real terms" in addition to a significant increase in the incidence of the population in the country, the damage is at least 6–8 thousand additional deaths per year. Identification of the critical points of energy impact on public health has shown that the most significant contribution to air pollution is made by vehicle exhaust gases, which is the cause of 90 % of health risks in cities [10]. The largest pollutants among stationary sources are power units of thermal power plants, which operate on coal. The health of citizens is the object of constitutional protection that is established by article 7, article 41 of the Constitution of the Russian Federation.

In the comments to the Constitution of the Russian Federation edited by V.D. Zorkin, it is noted: health is one of the highest benefits of a person, without which many other benefits, the opportunity to enjoy other rights can lose their importance [11].

According to the national security strategy of Russia, increasing life expectancy, reducing disability and mortality are strategic goals to ensure national security in the field of health and health care of the nation. In the context of this task, energy saving as a factor that can reduce the negative impact on the health of the population is a national public interest.

3.6. Energy Saving and Public Interest in Improving the Budget Spending Efficiency

Energy conservation also needs to be considered as a task of cost savings in the system of Public Finance.

The national security Strategy of the Russian Federation states that in order to counter the threats to the economic security of the bodies of state power and bodies of local self-government must implement policies to increase the efficiency and quality of state management of the economy, lowering costs and ineffective budget spending. Total spending on electricity in 2016 made 107.315 billion roubles [12]. These are budget expenditures for lighting in the street and road sector, as well as expenditures for the external and internal lighting of organizations of the budget sector. In 2015–2016 the government of Russia implemented a set of regulatory measures aimed at establishing lighting requirements with a focus on the budget sector.

These measures include:

– Approval of energy efficiency requirements for lighting products purchased for state and municipal needs (a prohibition on the purchase of some inefficient lamps and light sources is introduced) [13];

– Dissemination of energy efficiency requirements to purchases of state and municipal unitary enterprises [14];

– Dynamics of the minimum share of LED sources that can be purchased for buildings, highways, main streets of city significance, from 10 % in 2017 to 75 % in 2020 [15];

– The use restriction of inefficient and outdated technologies in the light design of streets and indoor lighting systems [16].

The comprehensive plan of measures to improve the energy efficiency of the economy of the Russian Federation sets targets to reduce the total annual costs of the budget system for electricity regarding to the level of 2016:

– By 2025 to reduce by 7.73 billion roubles;

– By 2030 to reduce by 10.3 billion roubles.

Thus, in the budgetary sphere, the State has vast reserves of management of energy resources effective consumption.

The President's address to the Federal Assembly dated 01.03.2018 states that one of the sources of financing for the development of the country is an increase of the public spending efficiency [17]. Thus, energy saving in the field of lighting is a public interest in the context of saving budgetary resources.

4. CONCLUSION

The Energy Strategy of Russia for the period up to 2030 contains information that the unrealized potential of organizational and technological energy saving is up to 40 % of the total domestic energy consumption. The energy strategy sets the task of reducing of the specific energy intensity by more than two times and the task of reducing of the specific electrical capacity of the gross domestic product by at least 1.6 times by 2030 (compared to the level of 2005) [9].

We assessed the national public interests that depend on the effectiveness of the state policy in the field of energy saving.

As M.M. Karabekov points out, any common goal corresponds to the time interval between its setting and achievement, during which some specific actions are implemented to implement "local" (intermediate) goals, which give the result of achieving a common goal [18]. Thus, to achieve the final goals in practice, it is necessary to implement some other, more local goals (in other words sub-goals).

Continuing this idea, we can say that the energy saving policy on the background of global public interests is a social goal, through the implementation of which common goals are achieved.

We considered the energy saving in the aspect that it contributes to the implementation of some public interests, such as energy security, improving the competitiveness of the domestic economy, the preservation of exhaustible natural resources, environmental safety, public health, optimization of public spending.

Consequently, the implementation of energy saving policy is also an independent significant public interest.

REFERENCES

1. International Energy Agency (IEA) report, "World energy Outlook, 2012," p. 573. URL http://www.worldenergyoutlook.org/publications/weo-2012/#d.en.26099.

2. Forecast of energy development in the World and Russia until 2040. FSBIS "Institute for energy research of the Russian Academy of Sciences," and FSBI "Analytical centre under the Government of the Russian Federation" // https://www.eriras.ru/files/forecast_2040.pdf.

3. The President of the Russian Federation decree No. 683 from 31.12.2015 "On the national security Strategy of the Russian Federation."

4. Makarov A.A, Grigoriev L.M., Mitrova T.A. Development forecast of World and Russia energy// ERI RAS-ATS, 2016, 200 p.

5. Sobolev R.E. Formation of the energy-efficient structure of industrial production as a factor of long-term

growth of the Russian economy. Thesis abstract for the degree of doctor of Economic Sciences, 2011.

6. Leskov. Faraday versus Napoleon // “Izvestia” newspaper, March 2007.

7. Russian Constitution (adopted by popular vote 12.12. 1993, was amended by 30.12. 2008 and 5.02.2014).

8. Government report “On the state and environmental protection in the Russian Federation in 2014.” The Ministry of nature of Russia; Bulletin “Use and protection of natural resources in Russia,” 2015.

9. Energy strategy of Russia for the period till 2030 (approved by the order No. 1715-p of the Government of the Russian Federation on November 13, 2009).

10. Kiryushin P.A. Environmental and economic assessment of energy efficiency in Russia. Thesis abstract for the degree of candidate of Economic Sciences, 2012.

11. Zorkin V.D., Lazarev L.V. A commentary on the Constitution of the Russian Federation (edited by). “EKSMO”- publishing house, 2010, Moscow.

12. The decree of the RF Government from 19.04.2018 No. 703-R “About the approval of the complex plan of actions for an increase of energy efficiency of the economy of the Russian Federation”.

13. Resolution of the Government of the Russian Federation No. 898 from 28.08.2015 “About modification of point 7 of Rules of the establishment of requirements of power efficiency of goods, works, services at the implementation of purchases for ensuring the state and municipal needs”.

14. Federal law No. 321-FZ of 03.07.2016 “About modification of separate legal acts of the Russian Federation concerning purchases of goods, works, services for ensuring the state and municipal needs and needs of separate types of legal entities”.

15. Order of the Ministry of economic development of Russia of 09.06.2016 N362 “About modification of point 6 of requirements of power efficiency of the goods used for creation of elements of designs of buildings, structures, constructions, including engineering systems of resource supply influencing power efficiency of the buildings, structures, constructions, approved by the order No. 229 of the Ministry of economic development of the Russian Federation of June 4, 2010” (Registered on 06.07.2016 under number N42764 in Ministry of justice of Russia).

16. The order No. 777 of the Ministry of construction RF from 07.11.2016 (version: 10.02.2017).

17. “Approval of item SP 52.13330 of “Sanitary Norms and Rules 23–05–95 “Natural and artificial lighting”.

18. The message of the President of the Russian Federation to the Federal Assembly on 01.03.2018

19. Karabekov M.M. Legal acts as means of formation and implementation of legal policy: general-theoretical aspect, the dissertation on competition of a scientific degree of Ph.D. in Low Science, 2010.

Gulnara F. Ruchkina,

Dr. in Low of Science, Professor, an honorary worker of higher professional education of the Russian Federation; member of the Academy of Natural Sciences, Financial University under the Government of the Russian Federation; Head of Department of Legal Regulation of Economic Activity

Elena Yu. Matveeva,

Ph.D. in Low of Science, Financial University under the Government of the Russian Federation, Associate Professor at Department of Legal Regulation of Economic Activity, Financial Director of ILEC “BL GROUP” LLC

Light & Engineering
Vol. 27, No. 1, pp. 103–108, 2019

ALTERNATIVE WAYS OF ATTRACTING INVESTMENTS IN THE ENERGY SAVING TECHNOLOGIES INDUSTRY

Olga N. Anyushenkova, Andrej V. Ryzhik, and Venera K. Shajdullina

Financial University under the Government of the Russian Federation
E-mails: ONAnyushenkova@fa.ru; VKShajdullina@fa.ru

ABSTRACT

The objective of the research is to determine the legal terms of the implementation of alternative ways of attracting investments in the energy saving technology industry. To achieve this goal, the authors examined economic and legal problems of fundraising in the industry of energy-saving technologies and grounded the importance of solving the problems for the lighting equipment industry. The article provides a comparative analysis of the volume of global investments in this area of the economy and identifies a number of problems hampering the access of innovative enterprises to investment for developing energy-saving technologies. The article considers an alternative way of raising funds for innovative start-ups in the field of energy saving, ICOs (ICO stands for Initial Coin Offering). The article, also, analyzes the ICO market with 14 current participants, energy-saving technologies companies. Furthermore, the authors looked at the legislative regulation of this raising capital method in energy saving and energy efficiency in the Russian Federation and abroad in order to identify the best international experience and its implementation in the Russian legal field. As a result of the research, the authors developed practical recommendations for legal support for upcoming ICOs procedures for companies in this industry.

Keywords: investments, energy saving technologies, energy efficiency, legal regulation of energy saving, lighting equipment, energy saving companies and lighting

1. INTRODUCTION

At present, one of the most important directions in the development of lighting technology is the comprehensive solution of energy saving problems with a view to maintaining the ecological integrity of society. Today, the largest lighting organizations produce energy-saving lighting devices, but such companies face a number of economic and legal difficulties associated with attracting investments for innovative projects [1].

In 2017, in accordance with International Energy Agency global investments in the energy-saving technologies industry increased by 9 % to 261 billion dollars (Fig. 1).

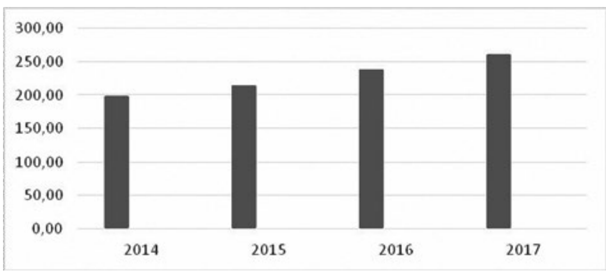


Fig. 1. Global investments in energy-saving technologies from 2015 to 2017, USD billion

The source: compiled by the author according to the International Energy Agency [2].

However, the investment volume in energy saving (despite a small increase) is still far behind the required for the production of renewable energy sources, improvement of lighting equipment, etc. It should be noted, that according to the International Energy Agency (The IEA), global investments in the industry should reach $1 billion per year, which is 4 times more than the volume of investments typical of energy saving [2]. This fact is explained by the analytical centre of the Energy Efficiency Financial Institutions Group (EEFIG) [3]. Having analyzed more than 10 thousand projects in the field of development of energy-saving innovations and improvement of lighting technology, the centre has established the following reasons for the unwillingness of institutional investors financing such projects:

1) The lack of specific tools allowing investors to assess and monitor the investment efficiency in energy saving;

2) Administrative and legal barriers in attracting funds to the industry, consisting of:

– Restriction of foreign investors in equity participation in a company attracting funds;

– The need to coordinate such participation in the state authority;

– The need for state registration of such investments as shares or stakes, etc.

The above is accompanied by the length of the procedures (for example, on average, registration of shares in the United States or Australia takes up to 90 days, taking into account the need to amend the recommendations made by the financial regulator based on the results of the company's bid).

In this regard, there are now alternative ways to raise funds for the implementation of start-up projects in the field of lighting and energy saving – the "Initial coin offering" (ICO) (Table 1).

The source: compiled by the author according to the data of Cryptosale [4].

A distinctive feature of these projects is the release of "crypto-tokens" (digital tokens) within the ICOs – an analogue of digital coins, equated, in these start-ups, either to an energy unit or to a means of payment within the project.

The high popularity of ICOs in the field of energy-saving technologies and lighting equipment is due to the ability to attract investments quickly and in a short time. Since ICOs are marketed on blockchain technology platforms, this allows to purchase tokens online and not to limit the amount of investment. This means that anyone, without significant savings, can invest in a project related to energy-saving technologies and lighting equipment. However, it is worth mentioning that 95 % of all ICO projects are potentially fraudulent [5]. It seems obvious, that the recommendations should take into account both the interests of investors and the interests of projects raising funds. It is also worth indicated that at present there are no researchers devoted to the ICO in the field under consideration. The exception is some works on general issues aimed at solving the problems of implementing ICOs without studying the field features [6–9].

Thus, the purpose of this article is to develop practical recommendations aimed at establishing the regulation of the ICO procedure, as an alternative way of attracting investments to solve problems with investment deficits in the energy saving technologies and lighting equipment industries.

2. THE SOLUTION

For developing practical recommendations for the regulation of start-ups ICO procedures of energy-saving technologies industry, the following stages of the research were conducted:

1) The statistics of the International Energy Agency were analyzed to identify the countries leading in terms of investments in energy-saving and lighting equipment;

2) The sample of countries received and the legislation of these countries regulating the preparation and launching ICOs by the companies of the industry was analyzed.

3. THE RESULT

According to the International Energy Agency, global investments in the energy-saving technology sector in 2017 amounted to 261 billion dollars. At the same time, the European Union, the United States of America, Canada and China remain the undisputed leaders in this matter (Fig. 2).

Therefore, it will be relevant to consider the legislation governing the organization and implement-

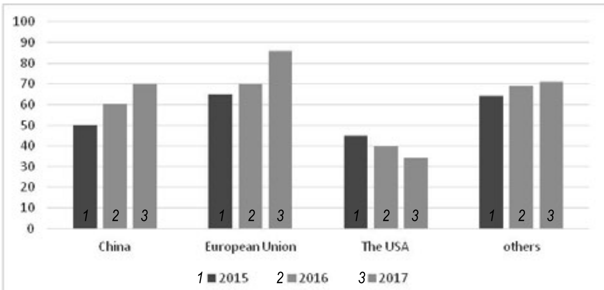


Fig. 2. The volume of investments in the energy saving technologies industry by regions from 2015 to 2017, USD billion [2]

Table 1. ICO Projects Involved in the Development of Lighting and Energy-Saving Technologies

№	Project Title	Implementation Stage	Attracted investments, million USD
1.	Helios Coin (production of alternative energy resources)	ICO launched	0.19
2.	Cryptos lartech (manufacture of solar panels)	ICO launched	83.7
3.	Electrifi.asia (a decentralised energy online marketplace)	ICO launched	0.442
4.	Enegrypremier (an advanced token-based electricity bidding platform)	ICO is being launched	34
5.	Robotina (production of "green" technologies)	ICO launched	28
6.	SiOcoin (production of an innovative installation for the recycling of technological waste)	ICO launched	20
7.	Energymine (a decentralized world platform for energy-saving lighting equipment trading)	ICO launched	15
8.	Farad (ultra-capacitors development and production)	ICO launched	0.824
9.	Carboncoin (carbon recycling for energy saving)	ICO launched	1.2
10.	Hydrominer (equipment production using hydropower energy)	ICO launched	25
11.	Wepower (a blockchain-based green energy trading platform)	ICO launched	0.941
12.	Suncontract (a decentralized solar energy trading platform)	ICO launched	1.7
13.	Solarcoin (production of solar power)	ICO launched	9
14.	Energycoin (production of renewable energy sources)	ICO launched	5

ing of ICOs by companies in the energy saving and lighting industry in these countries. The exception is China, as the People's Bank of China banned implementing ICOs in the territory of the country [10].

3.1. European Union

The EU Directive 2012/27 on energy efficiency is currently in force in the European Union. It establishes a general framework for promoting energy efficiency in the European Union, including measures to stimulate investment in the industry. In this regard, there are no quantitative restrictions in this regional association. However, a company with foreign participation to work in the European Union must meet the certification requirements in order to demonstrate the absence of a threat to the EU's energy security [11].

In the end of 2017, the European Securities Market Authority (ESMA) established supranational requirements for ICOs in the EU. According to the requirements, companies implementing ICOs in EU member countries are required to independently examine the qualifications of the ICOs in order to comply with the legislative requirements of the European Union, as well as the national legislation of the state where the ICOs is implemented. ESMA specifies that in accordance with Directive

2003/71/ EU on Prospectus Directive [12], the project must provide reliable information to potential investors by publishing a prospectus in case of capital raising. If the ICO project contains signs of a public offering of securities, the publication of the prospectus is mandatory. In addition, the competent authority must approve the prospectus. Consequently, the company must be in full compliance with the national requirements of the EU member state where the project is implemented.

3.2. The USA

In the USA, as in some other countries, most of the resources are consumed inefficiently, which entails huge material losses. According to the American Council for Energy Efficient Economy rating, the United States ranks thirteenth in the world in terms of energy consumption [13]. Based on this fact, the US Government currently focuses on attracting investments in the development of innovative energy-saving technologies.

At present, the USA is one of the safest countries for implementing ICOs. Thus, in July 2017, the US Securities and Exchange Commission (SEC) published a report on The DAO, explaining that US securities legislation is applicable to some operations with crypto-currencies, including (1) releasing tokens as a part of IPOs, as well as (2) operations for their exchange transactions [14]. All participants in cryptoeconomy from issuers to stock exchanges, as well as other participants involved in the offering and sale of tokens denoted as securities, will have to comply with US securities laws [15]. Depending on the circumstances, this may mean that tokens must be registered with the SEC or fall under an exemption to registration in the law.

Thus, tokens are securities, if all of the following requirements that make up the Howey Test are met:

1) Capital investments in any form, including cryptocurrencies;

2) Participation of investors in a joint venture, regardless of the fact and place of registration;

3) Realistic expectation of investors to make a profit (the profit can be in the form of dividends, periodic payments or an increase in the value of tokens);

4) Limited participation of investors in the management of the enterprise.

It should be emphasized that in practice, companies often use the exception provided for in "Regulation S" under the US Securities Act. Thus, issuers do not have an obligation to coordinate their actions with the SEC, if their advertising campaigns for the sale of tokens are not aimed at the United States, and selling tokens, companies check that buyers are outside the United States.

At the same time, start-ups of the energy saving industry need to comply with the legislative requirements for such companies. In accordance with the National Energy Law [16], foreign ownership and control over energy facilities are prohibited. Only US citizens have the right to have licenses for the production of power equipment, including energy saving technologies. Restrictions on foreign companies' participation in projects related to the production of power equipment are also established.

3.3. Canada

As mentioned above, in Canada, there is also an acute issue on the development of the energy saving industry including the problems of attracting private capital in the industry. This is because almost all energy saving activities in the provinces of Saskatchewan, Manitoba, Nunavut and New Brunswick are carried out by state-owned companies. That is why to establish private entities in this industry is possible only in Ontario and Alberta. At the same time, in Canada, there are no restrictions similar to the US law. Under the Control of Electricity and Gas Act [17], companies are subject to the same requirements as other organizations.

Currently, Canada has created favourable conditions for implementing ICOs by companies of the energy-saving technologies industry. In August 2017, the Canadian Securities Administrators (CSA) explained their position regarding ICOs in the published statement [18]. The document states that crypto-tokens must be registered in accordance with the securities laws. Requirements to the legal form are established as for other companies issuing shares, without exception. CSA separately drew attention to the fact that marketing moves to denotation tokens as software products do not affect the nature of tokens, because they are essentially investment tools.

3.4. The Russian Federation

The economy of the Russian Federation (further – Russia, The RF) at this stage is characterized by high-energy intensity. The specific energy intensity of Russian GDP is 2.5 times higher than the global average [2]. One of the reasons is the lack of financing for companies involved in the development of energy saving. Currently, many Russian companies in the field of energy saving technologies have started to look for ways to attract foreign capital, including ICOs.

At this stage of crypto economy development of Russia, there is no legal regulation of the organization and implementing ICOs. However, by July 2018, the draft law "On alternative ways of attracting investment (crowd-funding)" [19] will be submitted to the State Duma of the Russian Federation. According to the draft law, tokens are considered digital financial assets. ICOs can be marketed on special investment sites/platforms only by Russian legal entities and individual entrepreneurs.

It is worth saying that a company implementing ICOs must comply with the requirements established in the legislation, which depend on its type of activity. There are no restrictions in case, when a company's activities are limited by conducting research and development work. If a start-up is associated with the construction and operation of energy-saving plants, depending on their capacity, a license may be required [20]. The production of energy-saving equipment (for example, LED lamps) requires mandatory certification.

Summing up, the conducted research allows formulating the following recommendations on the regulation of ICOs in the Russian Federation:

1) It is necessary at the level of Government Resolution of the Russian Federation to develop the procedure of implementing ICOs in the Russian Federation. Namely, it is necessary to determine what legal procedures a company should take implementing each stage of an ICO procedure (development of an offering memorandum, offers to purchase tokens, publication of the company's reports, taxes and fee payment, etc.). In addition, this normative act should establish the legal status of tokens, taking into account the best foreign experience. In case, if tokens have signs of securities, companies applying ICOs will have to register them in the securities register. However, if a token is equated to the price of the goods produced (for example, the unit of energy or the means of payment on the site), registration is not required.

2) Russian regulators need to develop explanatory and advisory documents warning that any ICOs project must comply with all the legislative requirements of the country where it raises funds in the form of ICOs. Such requirements may include restrictions on the legal form of the company, the need to obtain authorization documents, certification of manufactured equipment, etc. Thus, regulators will be able to prevent Russian projects from been prosecuted as a result of ignorance and non-compliance with the legislation of foreign countries.

4. CONCLUSION

Thus, the conducted research shows that at present, launching ICOs, as an alternative way to raise funds, can solve the problem of limited investment in energy saving industry. The leading countries in the industry have already developed loyal legal requirements for companies implementing ICO projects. Obviously, it is necessary to develop a legal and regulatory framework in the Russian Federation to regulate the new economic and legal phenomenon. The recommendations developed by the authors will increase the investment attractiveness of the energy saving industry and help develop ICOs as a promising way of fundraising.

REFERENCES

1. Gvozdev S.V. Upravlenie osveshcheniem dlya povysheniya komfortnosti svetocvetovoj sredy i rabotosposobnosti cheloveka [Lighting control for increasing the comfort of the light-colored environment and human performance]//Zdaniya vysokih tekhnologij, 2018. # 1. p. 18.

2. World Energy Investment 2017. Available at: https://www.iea.org/publications/wei2017/ (accessed: 10.06.2018).

3. Sweetman P. Energy efficiency is a "win-win" for investors. Available at: https://www.greenbiz.com/article/energy-efficiency-win-win-investors (accessed: 10.06.2018).

4. Proekty v sfere ehnergetiki [Energy projects]. Available at: https://cryptoslate.com/category/cryptos/energy/ (accessed: 10.06.2018).

5. Weaver N. Risks of cryptocurrencies // Communications of the ACM, 2018, Vol.61, #6, pp. 20-24.

6. Caldwell T. The miners strike – addressing the crypto-currency threat to enterprise networks // Computer Fraud & Security, 2018, pp. 8–14.

7. Fernández-Caramés T.M., Fraga-Lamas P. A Review on the Use of Blockchain for the Internet of Things // IEEE Access PP, 2018, Vol. X, pp. 1-23.

8. Giudici G., Adhami S., Martinazzi S. Why do businesses go crypto? An empirical analysis of Initial Coin Off erings // Journal of Economics and Business, Forthcoming, 37 p.

9. Guliyeva A., Britchenko I., Rzayeva U. Global security and economic asymmetry: a comparison of developed and developing countries // Journal of Security and Sustainability Issues, 2018, Vol. 7, #4.

10. Uvedomlenie Narodnogo banka Kitaya o zaprete ICO [Notice to the People's Bank of China on the prohibition of ICOs]. Available at: http://www.pbc.gov.cn/goutongjiaoliu/113456/113469/3374222/index.html (accessed: 11.06.2018).

11. Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for internal market in electricity and repealing Directive 2003/54/EC. Available at: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32009L0072 (accessed: 10.06.2018).

12. Directive 2003/71/EC of the European Parliament and of the Council of 4 November 2003 on the prospectus to be published when securities are offered to the public or admitted to trading and amending Directive 2001/34/EC. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32003L0071 (accessed: 10.06.2018).

13. SSHA: kurs na ehnergosberezhenie i ehnergoehffektivnost [US: a course on energy conservation and energy efficiency] Available at: http://www.webeconomy.ru/index.php?page=cat&newsid=2872&type=news (accessed: 10.06.2018).

14. Report of Investigation Pursuant to Section 21(a) of the Securities Exchange Act of 1934: The DAO. Available at: https://www.sec.gov/litigation/investreport/34–81207.pdf (accessed: 10.06.2018).

15. Securities Act of 1933. Available at: https://www.sec.gov/answers/about-lawsshtml.html#secact1933 (accessed: 10.06.2018).

16. National Energy Act. Available at: http://what-when-how.com/energy-engineering/national-energy-act-of-1978/ (accessed: 10.06.2018).

17. Electricity and Gas Inspection Act, R.S.C., 1985, c. E-4.

18. CSA Staff Notice 46–307 Cryptocurrency Offerings. Available at: https://www.securities-administrators.ca/aboutcsa.aspx?id=1606&terms=Staff%20Notice%20 46–307 %20Cryptocurrency%20Offerings (accessed: 10.06.2018).

19. Zakonoproekt "Ob al'ternativnyh sposobah privlecheniya investicij (kraudfandinge) " [The bill "On alternative ways of attracting investment (crowdfundinge)"]. Available at: https://www.eg-online.ru/document/law/365159/ (accessed: 10.06.2018).

20. Federal'nyj zakon "Ob ehnergosberezhenii i o povyshenii ehnergeticheskoj ehffektivnosti i o vnesenii izmenenij v otdel'nye zakonodatel'nye akty Rossijskoj Federacii" [The Federal Law "On Energy Saving and on Improving Energy Efficiency and on Amending Certain Legislative Acts of the Russian Federation] ot 23.11.2009 № 261-FZ // Rossijskaya gazeta, 2009, # 226.

Olga N. Anyushenkova,
Senior Lecturer of Department of Foreign Languages of the Financial University under the Government of the Russian Federation

Andrej V. Ryzhik,
Ph.D. in Law, Associate Professor of Department of General and special legal disciplines of the Belarusian State of the Orders of the October Revolution and the Order of the Labour Red Banner Agricultural Academy, Associate Professor of the Department of legal regulation of economic activity of the Financial University under the Government of the Russian Federation

Venera K. Shajdullina,
Ph.D. in Law, Senior Lecturer of Department of legal regulation of economic activity of the Financial University under the Government of the Russian Federation

Light & Engineering
Vol. 27, No. 1, pp. 109–115, 2019

POWER SUPPLY FOR STATE-OWNED ENTERPRISES

Denis V. Shepelev, Dina V. Shepeleva and Natalia G. Kondrakhina

Financial University under the Government of the Russian Federation
E-mails: denn0508@yandex.ru; DVShepeleva@fa.ru; kondrakhinan@mail.ru

ABSTRACT

This article presents a comprehensive study of energy supply problems for state-owned enterprises. The categories considered (financial activity, legal interests, energy system) allow to reveal the special importance of state enterprises for the state economy. Identification of energy supply problems of state-owned enterprises will allow to assess the optimal power capacities of the public legal sector. The revealed regularities of the energy potential will allow us to assess the risks when planning and predicting energy efficiency. The dynamics of the increase in the consumption of electricity by state enterprises is traced, at the same time as the search for alternative sources of resource support is on. The developed infrastructure of state-owned enterprises implies the search for technologically justified solutions to obtain energy resources in an innovative way. Recommended approach of energy-saving systems usage will allow the enterprise manages to optimize the costs. State enterprise is a unique organizational and legal form with the participation of public and legal entities that allow the state to participate in economic processes in the most optimal, efficient and effective way and realize the most significant state tasks. Such tasks include: implementation of public interests, provision of society with necessary goods and services, implementation of separately subsidized activities, production of military equipment, cartridges, gunpowder, chemical production, disposal of hazardous waste. These tasks emphasize a special priority for the presence of public-legal entities in this sector of the economy. The legal nature of state enterprises allows for the most effective implementation of this activity.

Keywords: energy supply, power supply contract, state enterprise, financing, interests of state enterprises, energy security, electrical system, electrical installations, electric network

1. INTRODUCTION

Modern Russia is rethinking its legal interests in the field of energy supply, as well. One of the main reasons for addressing this issue is the adoption of a number of regulatory legal acts that regulate the energy sector. This process is significantly influenced by such an objective condition as the development of energy systems.

The subject of this study is the legal regulation of state enterprises energy supply, as well as energy saving systems. The following goals were set in the course of this research: identify the features of power supply to public enterprises, consider alternative ways of lighting the premises, analyze innovative methods and devices of lighting sources.

2. METHODS

In the course of this work, a wide range of methods was used, both general scientific and of a particular scientific nature. General scientific methods of cognition (analysis, synthesis, induction, deduction) allowed to analyze the elements of power systems. Particularly scientific methods (cybernetic, statistical) allowed to reveal the specific features of the best lighting equipment.

3. RESULTS

The power supply of state enterprises is carried out while considering the level of technical equipment (devices of electrical installations, electric networks), since defence and security directly depend on power supply along with the realization of national interests accordingly. Implementation of light and shadow, light and local illumination of interiors takes priority when illuminating the premises of public enterprises. Use of various kinds of laser lighting equipment is also under way. Development of innovative methods of optical location made it possible to use devices with fluorescent lamps of various types, which has a beneficial effect on the illumination of premises and on the reduction of expenses for state enterprises. Solid-state lasers and LEDs will save energy.

State-owned enterprises have high significance in the priority areas of the state economy. It is for state-owned enterprises that the state assigns special tasks for the most optimal realization of the state and society needs as a whole, especially in such areas as defence and security, where commercial interest is still present, but is not a priority. State-owned enterprises are full-fledged participants of the energy space. State-owned enterprises are unique organizational and legal formations. Uniqueness can be explained as follows: despite the fact that they are commercial organizations, whose activities are aimed at making profits, these enterprises are established by public legal entities, implementing public and national interests, especially in such areas as defence and security, namely the manufacture, development, production of certain species products (ammunition, military equipment and weapons, explosive and chemically dangerous products), disposal of hazardous chemical waste; – ensuring the state's food security in the loss-making or unprofitable industries, and separately subsidized activities.It is important to note, that other business entities may not always be present in these areas because of the special importance of the defence and security for the state, or from a commercial point of view other organizational legal forms are not interested in operating in unprofitable and marginally profitable industries. A state-owned enterprise organizes its financial and economic activities based on the need to perform certain activities and provide services in accordance with the approved estimates of revenue and expenses and the enterprise operations plan [9, p. 48]. Manufactured goods and earnings resulting from the use of property in the operational management of the enterprise, as well as property acquired by it from the proceeds of its activities, are the property of a public formation, which had established a state enterprise. In their financial activities, state-owned enterprises should be guided by the fact that none of their actions should lead to the creation of conditions under which their functions established by the owner will become difficult or impossible to exercise.

Nowadays, energy supply has become an integral part of life of a modern society, its normal existence. Proper functioning of such vital facilities as medical and educational institutions, housing and utilities facilities, banks, without which functioning of a modern society is inconceivable, depends on a smooth supply of energy. At the same time, there exists uncertainty in many significant aspects of energy supply, and among those there is a special need to highlight the issues of qualification in contractual relations in the electric power industry, and particularly the relationship between the subscriber and the sub-subscriber. Thus, for example, L. Andreeva points out the misregulation of these relationships, noting that in accordance with Article 545 of the Civil Code of the Russian Federation: "A subscriber can transfer energy received from an energy supply organization through an affiliated network to another person (sub-subscriber) only with the consent of the energy supply organization. Thus, in the Civil Code, transfer of energy from the subscriber to the sub-subscriber is formulated as the right, and not the duty, of the subscriber" [2]. This means: "The latter can refuse to transfer energy, and in practice often does so, arguing that this activity is not one of his core activities and is not a public one by character" [2].

When it comes to ensuring security of state-owned enterprises and the state as a whole, first of all, it is necessary to draw attention to the energy supply system. Safety and efficiency of state-owned enterprises functioning depends on the correct use (executed in accordance with specially approved rules) and application of methods and ways of energy supply, considering the level of technological infrastructure. Receivers of electric power of enterprises obtain power from the power supply system, which is an integral part of the energy system. The receiving point of electricity is an electrical installation, which collects electricity for the elec-

Table 1. Four Categories of Luminescent Lamps

Type	Function
T8 with a bulb 26 mm in diameter	A standard lamp used to illuminate most rooms. Power potential of 18 or 36 watts. Sufficiently sensitive to a decrease in air temperature – when the temperature drops below zero, the lamp's trigger mechanism switches off.
T5 with a diameter of 16 mm	Upgraded model, shorter than a standard bulb by 5 centimetres. In the production of T5, a special kind of phosphors, which ensures a more qualitative glow, is used. This lighting device contains a reduced amount of mercury (up to 3–5 g) and is less dangerous for the environment and humans.
T12 with a diameter of 38 mm	Another standard type used in light fixtures where T8 does not fit. Available with different power and colour temperatures.
CFL	Compact lamps, designed to be connected into small light fixtures. They have a traditional E27 (E14 – reduced size) cap or a special design with four pins for connection. Capacity from 18 to 80 W.

tric receivers of enterprises from an external power source. The level of electric receivers power supply uninterruptedness by electric energy at any time is determined by their operation modes. Power load estimation is the first step in the design of any power supply system. Capital investments in the power supply system, operational costs, and the reliability of the electrical equipment depend on the correct assessment of the power loads. Energy issues have been relevant at all times [3]. Electric power in enterprises is considered as one of the components of the production process, along with raw and required materials [4]. When designing a power supply system or analyzing its operating modes, EE consumers are considered as loads. With regard to electricity supply, a unitary enterprise is deemed ineffective, if 50 % or more of the total number of uninterrupted 24-hour power supply violations were liquidated during the year in breach of the requirements established by the current legislation of the Russian Federation. At the same time, a break in the provision of utility services for power supply is not allowed, if it may lead to the disconnection of networks and equipment that is a part of the common property in the apartment building, including pumping equipment, automatic technological protection devices and other equipment that provides trouble-free operation of in-house engineering systems and safe living conditions for citizens. General requirements that must be observed when designing power supply systems and reconstruction of electrical installations are set by the Rules for the installation of electricity generating equipment [4]. These requirements are as follows: perspective of development of power systems and power supply systems, taking into account rational combination of newly constructed electric grids with existing and newly constructed networks of other voltage classes; provision of integrated centralized power supply to all consumers of electrical energy located in the coverage area of electrical networks, regardless of their affiliation; limitation of short-circuit currents to limit levels defined for the future; reduction of losses of electric energy; compliance of decisions with environmental conditions. Simultaneously with such requirements, should be considered external and internal power supply, considering the possibilities and economic feasibility of technological redundancy.

It is also important to notice the requirements regarding the lighting of spaces in the building divided into internal and external. By nature, lighting can be divided into light-and-dark, light-tonal, local and silhouette. Light-and-dark is the kind of lighting when radiation source forms light from the shadow, and diffused light highlights the shadows of the object. Light-tonal is the lighting when scattered light uniformly fills the space and illuminates all points of the object being photographed. Local lighting is the lighting of a limited part of certain space or part of the object being photographed. Silhouette is the lighting, when the objects in the foreground are darkened, and the light falls to the background [5]. The latest advances in lighting technology include

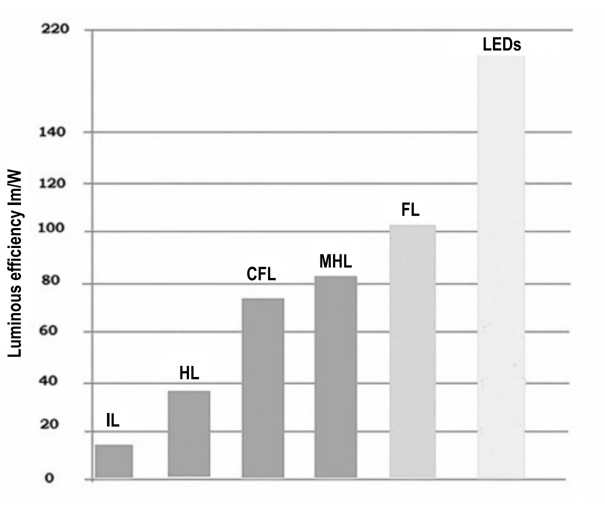


Fig. 1. Luminous efficiency of different types of Lamps

fluorescent lamps, various types of laser illuminators, used both for practical purposes, for example, in measurements of atmospheric pollution, in light reflection, and for decorative illumination of miscellaneous objects [6]. For example, fixtures with fluorescent lamps (these are the ones used in factories) should be used with ballasts that provide a power factor of at least 0.9 with light fixtures for two lamps and more and 0.85 for single-lamp fixtures. Design of the lamp is quite a simple one. Into a hollow flask filled with an inert gas and mercury vapour, electricity is supplied through the electrodes. There appears a discharge that causes ultraviolet radiation and a luminophor glow. This substance is applied by the manufacturers to the inner surface of the tube. It is important to note, that the lamp is safe for the human eye – the glass prevents penetration of ultraviolet radiation beyond the bulb. The exception is the special anti-bacterial lamps, originally designed to combat pathogens and dangerous viruses. The bulb in such light fixtures is made of quartz glass. The main classification of lamps of a luminescent type includes four categories of devices (Table 1).

Such lamps have, of course, both their advantages and disadvantages. The advantages include: possibility of long-term operation; high efficiency (up to 25 %); increased luminous efficiency (compared with an incandescent lamp, an increase of 10 times is observed); possibility to use lighting of different spectrum; low cost of the device. However, certain shortcomings also exist, such as: hazardous effect of the tube contents for the environment; dependence on switching on and off (over time, quality of lighting decreases); dependent on voltage fluctuations; cannot be used without a trigger; dependent on air temperature (less for models with semiconducter ballast). In comparison with incandescent lamps, which, in turn, gradually lose their importance in the use of various organizations, they are actively used by owners of enterprises, organizations, etc. An incandescent lamp (IL) is an electric light source that emits light as a result of the heating of a conductor made of refractory metal (tungsten). Tungsten has the highest melting point among all pure metals (3693 K). The filament is confined in a glass flask filled with an inert gas (argon, krypton, nitrogen). The inert gas protects the filament from oxidation. The glass bulb prevents the negative effect of atmospheric air on the tungsten filament. The advantages of this kind of light fixture include: low cost; instantaneous ignition when switched on; small overall dimensions; wide power range. The disadvantages are: greater luminance (negatively affects the eyesight); short service life – up to 1000 hours; low efficiency (only one tenth of the electric energy consumed by the lamp is converted into a visible light flux, the rest of the energy is converted into thermal energy). Due to their shortcomings, which are significant, such lamps are inferior to luminescent lamps when used in large enterprises. Luminous efficiency of different types of Lamps is presented in Fig. 1

When considering the use of working light, it is recommended to supply it on independent lines from switchgear of substations, boards, cabinets, distribution points, trunk and distribution busbars. In industrial, public and residential buildings, up to 60 incandescent lamps, each with a power of up to 60W, can be connected to single-phase lighting groups of stairways, corridors, halls, technical subfloors and attics. This refers to a grouped network where lines must be protected by fuses or circuit breakers. For outdoor lighting, any light source can be used. The use of discharge lamps is not permitted for the security lighting of the enterprise territories, in cases where the security lighting is not normally turned on and is automatically turned on by the security alarm. It is recommended to make outdoor lighting networks using cable or air using self-supporting insulated wires. In addition, for such illumination the lighting fixtures themselves can be installed on specially designed supports. To ensure the right and proper illumination light guides are needed. Currently, most enterprises use lighting devices with hollow light guides. They are necessary for general uniform internal illumination; illumina-

Table 2. Energy Consumption and Savings

Lighting object location	Basic energy consumption, 10^{15} J / year	Potential of savings, %	Savings (low), 10^{15} J	% of total savings	Savings (high), 10^{15} J	% of total savings
Electric lighting						
In residential apartments	5604	40–60	2242	25	3362	27
In commercial buildings	9551	25–40	2388	27	3821	31
In industry	3272	15–25	491	6	818	7
Street lighting, etc.	1507	25–50	377	4	753	6
Lighting on fuel (kerosene)						
In residential apartments	3603	92–99	3300	38	381	29
Total	**23536**	**37–52**	**8797**	**100**	**12335**	**100**

tion of territories, open spaces and streets; the introduction of buildings and distribution in them both direct sunlight and artificial light. Lighting devices with Hollow Light Guides [7] are hollow cylindrical (or other forms) pipes of a large extent, part of the inner surface (or the entire surface) of which is covered over the entire length by a specularly reflective layer or prismatic film of total internal reflection, while the light flux (of the IC or the group of lamps) is introduced into the ends of the PPS by special optical systems. The Fig. 2 shows the possibilities of saving electricity in lighting installations with fluorescent lamps.

Electrical networks of buildings must be designed to supply the lighting of advertising, shop windows, facades, illuminating, outdoor, fire-fighting devices, dispatching systems, light fire hydrant signs, security sign, bell and other signalling, light barriers, etc. in accordance with the design task. Iluminated surface luminance depends on the intensity of the light source and the nature of the surface itself [8]. It is always less than the luminance of the light source, since a part of the light is absorbed by the illuminated surface, another part is scattered in different directions and only the third part of it is reflected in the direction, from which the surface is viewed. Abroad, studies and experiments were conducted on the influence of lighting on human performance, and also in order to identify possible criteria for the normalization of illumination. "The following indicators were investigated: PT (labour productivity, speed of proof-reading work), visual fatigue (for a relative change in the time of chromatic adisparopy, visibility and luminance of the source at the comfort-discomfort boundary). The following conclusions were drawn from the results of the studies: as a rule, the increase in illumination leads to the growth of PT, but with excessive increase in illumination, fatigue increases" [9]. The Table 2 shows an example of energy savings for different lighting object locations.

Reasoning from the previously said, it can be argued that the energy costs for the production and use of light energy determine to a large extent the lighting level of the industry and the country as a whole. The degree of development of the states can be characterized to the greatest extent not so much by the volumes of steel and pig iron smelting, the extraction of oil or gas, the number of manufactured machines and locomotives, as the "light provision" of this state while minimizing energy consumption.

Security is what is important and what each of us strives to provide. To achieve that, we need to equip ourselves with a certain set of knowledge that will help to prevent emergencies. So, for example, after the disconnection of switches, disconnectors (separators) and load switches with manual control take place, it is necessary to visually verify that they are truly disconnected and there are no bridging

Table 3. Permissible Levels of Magnetic Field

Duration of stay (hour)	Permissible levels of magnetic field H (A / m) / V (µT) when exposed	
	generally	locally
≤ 1	1600/2000	6400/8000
2	800/1000	3200/4000
4	400/500	1600/2000
8	80/100	800/1000

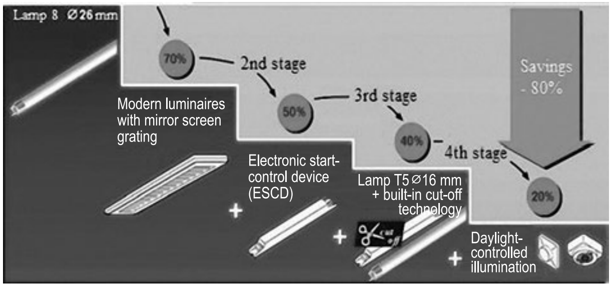


Fig. 2. Stages for energy savings

jumpers [10]. Labour protection is also envisaged for checking the absence of electric voltage. This should be done with the help of special instruments designed for this purpose or by approaching current-carrying parts that are known to be energized. In pre-fabricated switchgear factory-made, the test is performed using built-in stationary voltage indicators. One of the measures may also be the "hanging of prohibitory posters" [11]. For example, on the actuators (handles of drives) of switching devices with manual control, such posters as "Do not switch on! Workers are present!" should be used. Devices that signal the disconnected position of the machinery, blocking devices, and permanently connected voltmeters are only additional means of confirming the absence of voltage, and on the basis of their indications, it can not be concluded that there is no voltage in the electric system. Voltage dips occur in networks when switching power from one source to another without first disconnecting the load [12].

It is important to mention the magnetic field created by the interaction of the conductor with the current. Conductors with electric current act on each other by means of magnetic forces. Moving electric charges (currents) create a magnetic field. In the open switchgear and on the overhead line with a voltage of 330 kV and above, protection of workers from a biologically active electric field, which can have a negative effect on the human body and cause the appearance of electrical discharges when touched to grounded or ground-insulated electrically conductive objects, has to be properly organised. In electrical installations of all voltages, workers must be protected from a magnetic field, which can have a negative effect on the human body. In the Table 3 you can see the permissible levels of the magnetic field.

Also, labour protection is very important when working with portable power tools and lamps, manual electric machines, separation transformers. First of all, all these devices must meet the technical regulations requirements, national standards and technical conditions in terms of electrical safety and be used in compliance work. It is not allowed to use manual electric machines, portable power tools and lamps with associated auxiliary equipment, which have defects and have not passed periodic inspection (tests). Fixtures are intended, as a rule, to illuminate relatively closely located objects or light signals at short distances. Two or more lamps may be installed in light fixtures (in multi-lamp chandeliers, for example, the number of lamps can go as high as to hundreds and even thousands of units). Fixtures for lighting (unlike signal lamps) are, as a rule, abbreviated as luminaires [1]. When using portable luminaires, their wires and cables should, if possible, be suspended. Do not directly touch wires and cables with hot, wet and oily surfaces or objects. Electric cable should be protected from accidental mechanical damage and contact with hot, moist and oily surfaces. If any malfunctions are found, the work must be stopped immediately.

4.CONCLUSION

We can assert with confidence that technical progress does not stand still. Of the major achievements of recent years, creation of a huge variety of solid-state emitters – LEDs and solid-state lasers can be named. In these light sources electric energy directly transforms into optical radiation, which allows to establish contact light displays and panels, widely used in modern devices and computers. In the end, progress in the development of lighting technology is determined by the success in the study of physical processes. The major achievements of STEM disciplines of the past century were made possible by the creation of scientific instruments. As a result of the improvement of technical equipment of enterprises, primarily state-owned, which have great importance for the economy of the state, it is possible to increase the level of power supply efficiency, minimize risks, accidents and emergencies in order to avoid negative consequences for the individual.

REFERENCES

1. Shepeleva D.V. State-owned enterprise as a subject of financial law: Thesis for a PhD in Law. MSLA. Moscow, 2016. 218 p.
2. Andreeva L. Energy - clear legal regulation // the Russian justice, 2001, #8.
3. Ahmad M.W., Mourshed M., Rezgui Ya. Trees vs Neurons: Comparison between random forest and ANN for high-resolution prediction of building energy consumption // Energy and Building, 2017, Vol. 147, pp. 77-89.
4. Rules and regulations of electrical installations arrangement [Text]: All applicable sections of EIC-6 and EIC-7, Novosibirsk: Normateca, 2017, 464 p.
5. Mayorova O.V., Mayorov E.E., Turkbaev B.A. Lighting engineering. SPbGUITMO, 2005. p. 86.
6. Ishunin G.G., Kozlov M.G., Tomskij K.A. The basics of lighting engineering. SPb. // Beresta, 2004, p. 292.
7. Hollow Light Guides Technology and Application. 164-2005 CIE Technical Report. 37 p.
8. Aizenberg Yu.B. The reference book on light engineering 3rd edition // Znak publ., Moscow, 2006, 962 p.
9. H. Claude Weston. The relation between illumination and visual efficiency, the effect of brightness contrast // H.M. Stationery off, London, 1945, 35 p.
10. Sivkov A. A., Gerasimov D. Yu., Saigal A. S. The basics of power supply // Publishing house of Tomsk Polytechnic University, Tomsk, 2012, 180 p.
11. Rules for labor protection and operation of installations // ENAS publ., Moscow, 2017, 190 p.
12. Vafin D.B. Energy supply for enterprises // NHTI (branch) of FSBEI HPE "KNRTU, Nizhnekamsk, 2013, 104 p.

Denis V. Shepelev,
Ph.D. in Law,
Associate Professor of the Department of legal regulation of economic activities, Financial University under the Government of the Russian Federation, Professor of Department of theory of state and law of Kutafin Moscow State Law University (MSAL)

Dina V. Shepeleva,
Ph.D. in Law,
Associate Professor of the Department of legal regulation of economic activities, Financial University under the Government of the Russian Federation

Natalia G. Kondrakhina,
Ph.D. in Philology,
Professor of the Department of language training, Financial University under the Government of the Russian Federation

Light & Engineering
Vol. 27, No. 1, pp. 116–122, 2019

ENERGETIC SECTOR OF ECONOMY: THE RUSSIAN LAW MODEL

Natalya I. Besedkina, Irina I. Romashkova, and Tatyana A. Tantsura

Financial University under the Government of the Russian Federation
E-mails: nbesedkina@fa.ru; iiromashkova@fa.ru; ttancyra@yandex.ru

ABSTRACT

The authors of the article consider the formation of the economy energetic sector with regard to the system of law provisions, governing the state activity in relation to the formation and development of market mechanism in the fuel and energy complex (FEC), and also the activity of business entities in the energy market and its infrastructure. They analyze the set of law provisions, forming the existing energy legislation in Russia, and some practical matters regarding statutory requirements for applying effective and safe lighting equipment. The article draws the conclusion about the necessity of the energy law stabilization and the provision of legal control in the developing sphere of public relations in the area of energy. Authors point out the need of improving legislation in the area of producing energy effective lighting equipment, with the purpose of stimulating the development of scientific research and legal support for manufacturing new goods, which are necessary for customers.

Keywords: energy, energy legislation, lighting, lighting equipment, energy market, energy commodities, stimulation of production, alternative energy sources, energy savings, energy conservation

1. INTRODUCTION

Relations in the area of energy involve the complicated complex of such processes as extraction, refining, downstream and utilization of all kinds of energy resources. Energy stability and independence are the guarantee of successful economy development, that provide the formation and operation of almost all technological processes. Due to these aspects, the essential importance of energy industry for the economy of any state today is not contested. Regardless of the government role in the energy market, the influence of international prices on energy resources will put pressure on the domestic market. It is worth pointing out that the energy market in Russia has been characterized by imbalance of price indicators, since 1990-s. Prices of oil sector products, which are more integrated with the foreign market, were practically free from the direct state impact and were formed on the netback principle. Market pricing also dominates in the coal industry of Russia. However, gas prices are mainly regulated by the government, and the government policy has been changed three times for the last two decades – from rigid price control (to ensure social stability and the competitiveness of industry) to higher-than-market-growth in 2003–2013, and at last, again to blocking of prices resulting from economic slowdown [1].

The variety of objective and subjective factors, characterized with internal and external nature, influence on the economy development. It stands to mention that in spite of immutability of component elements, the influence of some or other factors proportionally changes in course of time. For example, nowadays the role of such factors as environmental safety, political expediency and legislative control is increasing. In considering matters about energy effectiveness, another important aspect is usually ignored – it is the usage of efficient and safe lighting equipment, and in particular, legislative control of this area.

Hence, in this article the attempt to scrutinize the existing energy sector of the Russian Federation economy and its legislative regulation has been made. For this purpose, authors analyze legislative requirements with regard to the introduction of effective lighting equipment, as well as the matters of electric consumers' protection by means of the possibility to search alternative power-generating sources.

2. THE ENERGY MARKET ANALYSIS

Russia has the largest territory (11 %), where up to 15 % of world's developed fuel reserves have been discovered and prepared for use. Russia has the highest capitation supply with relatively cheap energy resources among developed countries. However only 18 % of the country regions are provided with their own energy resources, the rest ones have to import them from other regions, often being hundreds of kilometres away [1]. The Russian fuel and energy complex was created during Soviet times and it was the largest international energy resources manufacturer and the second energy consumption state of that time. After the demise of the Soviet Union, the fuel and energy complex (FEC) together with the whole economy suffered a blow – 40–50 % decline in production of main energy resources.

Partly for these reasons, but mostly because of excessive raw material structure and poor economy management with great technological inferiority, Russia consume 5.5 % of world's energy resources, but the energy intensity of gross domestic product (GDP) (as regard to purchasing power parity of the rouble) is 1.9 times higher than worldwide average one, two times higher than the energy intensity of the USA and three times higher than the energy intensity of leading Europe countries. When combined with the export orientation of the energy sector (up to the half of produced energy resources are exported), the economy burden is 4.5 times higher than worldwide average one: investments to the energy sector reach 6 % of Russia GDP with 1.3 % in the world as a whole.

Some subjective elements putting pressure on energetic development are destabilizing factors, the influence of which should be minimized with the purpose to secure stable and independent energy market. The specific feature of the world's energy market is the impossibility of changing its participants' status. The majority of countries in the world cannot provide themselves with resources to produce energy, as the result of which they have to purchase required volumes from other countries. Exporting countries are also interested in the stability of energy market, because it secures the significant part of national income. According to the data of the national survey "The forecast of world's and Russia energetic development up to 2040" [1], Russia is the fourth largest energy resources producer in the world (after the Organization of Petroleum-Exporting Countries (OPEC), China and the USA) and the sixth largest consumer (after China, the USA, the European Union (EU), OPEC and India), providing 10 % world output and 5 % world consumption of energy resources.

The optimal model of the modern energy market includes not only production but also the rational use of energy gain. This situation is attributable to the factor, that ultimate consumers in any country are interested not only in reliable and stable energy supplies at affordable prices, but for its effective use. Importing countries, having a measure of dependency from exporters, have to seek alternative energy sources and develop energy intensive technology for exported energy storage. In a manner of speaking, energy dependence, or rather attempts to weaken it, in an indirect way helped the growth of technology in the energy sector, aimed at finding solutions for the best use and storage of purchased energy. It stands to mention that increasing the share of alternative energy sources, including renewable ones, is not always economically justified – in most cases for the large scale implementation of such sources government support is used. The state policy of government support enables to draw attention to renewable energy even in those cases, when initial economic indicators (without including support mechanisms, taxation and so on) more than 50 % worse when traditional sources are used. It is paradoxical, but in this case, at the stage of renewable energy sources implementation, high energy prices are psychologically advantageous for importing countries, because they provide an opportunity to justify expenses concerning with the transition to alternative energy sources. According to the data of the Analytical Centre under the Government of the RF, the growth of alternative energy sources will reach 93 % in the year 2040 in relation to forecasted 47 % general increase in energy demand [1].

In addition to that, countries that have been traditionally energy suppliers were less concerned with the problems of diversification of energy and its intensity. Traditional energy sources (such as coal, gas, oil), being the basic ones for the number of countries, were prevalent on the market, and it led to the orientation of exporting countries domestic markets to one type of sources. There was no economic need for diversification, because alternative sources were less effective and more expensive, besides, there was no need in their search. According to the data of the Forecast of world's and Russian energetic development up to 2040, the consumption of primary energy in Russia will increase 0.9 % during 2010–2020, at the same time in the USA the growth will be 0.3 %, and in the European Union countries it will even decline to 0.4 %. The main problem of the Russian energy sector is low efficiency, connected with cold climate, large area, low population density (and its unequal distribution through the territory), and also raw material orientation of the economy and the obsolete technologies for fuel and energy utilization.

3. THE ANALYSIS OF A REGULATORY FRAMEWORK FOR THE ENERGY SECTOR

Securing the legal and regulatory framework of the economy energy sector, the establishment of certain uniform "rules" for the participants of this activity sphere in all its diversity, takes on enormous importance in stabilizing the sector and the formation of its development key directions. The detailed energy laws enable to minimize the influence of external factors and diffuse the impact of negative "non-market" conditions. It should be emphasized that due to the deep penetration of the energetic in all spheres of the economy, legal regulation of this sector is difficult both in theoretical and practical aspects, since developing rules of law it is necessary to take into account possible consequences not only for separate types of energy market, but for the whole economy of the country.

To date the sources of law, governing the relations in the energy sector, include the Constitution of the Russian Federation, federal laws, by-laws, acts of self-regulating organizations, containing rules of law, local normative acts of legal entities, international treaties of the Russian Federation, customs, judicial acts of courts of last resort, doctrine.

National energy legislation cannot develop in a stable way in isolation from the international law that as a result engenders the problem of unification of national and international energy legislation. Hence it may be noted that legislative regulation regards not only to the internal factors of energy sector formation, but it can pretend to be the external factor, which in its turn doesn't always emerge under the influence of objective circumstances. The competition among states in the energy sector poses a number of international problems that is necessary to solve within the established global legal order based on the contemporary international law.

There is a number of international instruments concerning with the energy sphere, in the first place these are the European Energy Charter 1991; the Energy Charter Treaty 1994 and other documents adopted in its development; the Energy Charter Protocol on Energy Efficiency and Related Environmental Aspects 1994; Mining Charter of the Commonwealth of Independent States 1997; the Agreement on Cooperation in the study, exploration and use of raw mineral resources 1997; the Agreement on Cross-border Cooperation in the area of study, development and protection of natural resources 2001; the General Agreement on Tariffs and Trade 1947; the Marrakech Agreement about the establishment of the World Trade Organisation (WTO) 1994; The Barcelona Convention and Statute on Freedom of Transit, the Charter of Organization of Petroleum Exporting Countries (OPEC), agreements of CIS (the Commonwealth of Independent States) countries, and also federal laws of the Russian Federation, reflecting stages of energy politics development.

Rules of law regulating social relations (both public and private law relations), arising in connection with prospecting, extraction of energy resources, production, processing, supply, storage, transportation of various types of energy resources, designing and building energy plants, ensuring energy security, industrial security, counter-terrorist security are constantly being improved.

During the implementation of the Energy Strategy of Russia for the period until 2020, approved by the order of the Government of the Russian Federation of August 28, 2003 No. 1234-p, the adequateness of the majority of its provisions to the real process of the country's energy sector development, even in the conditions of sharp changes of internal and external factors, determining the main parameters of functioning the fuel and energy complex of Russia has been confirmed. Moreover, it was planned to amend this Strategy no less frequently than once every five years.

The adoption of the Order of the Russian Federation Government of 13.11.2009 No. 1715-p "Concerning the Energy Strategy of Russia for the period until 2030" [2] has stipulated the energy law development regulating social relations in the energy sphere and in individual energy industries. The Energy Strategy is the document establishing the goals and objectives of the Russian energy sector long-term growth, priorities and benchmarks, and also the mechanisms of state energy politics at certain stages of its realization in accordance with new objectives and priorities of the country's development. Indeed, the Energy Strategy of Russia for the period until 2030 takes into account new trends of the economy and energy sector development as much as possible, the emergence of new technologies and expanding the time horizon until 2030 in accordance with the necessities of the times.

Since the adoption of the Energy Strategy of Russia for the period until 2030 the considerable amount of laws and regulations have been passed, which ensure the implementation of the strategic objectives. The principle of environmental protection can be distinguished as one of the energy development directions. Ecologically oriented policies are reflected in laws and regulations, devoted to the energy problems. The above-mentioned Energy Strategy of Russia for the period until 2030 defines that the objective of the state energy politics is the most effective use of energy resources and the potential capacity of the energy sector for the steady growth of the economy, the improvement of the country's population quality of life and the assistance in strengthening country's foreign economic positions.

The completeness and sufficiency of the state energy politics regulatory support is manifested in complex framework law in the sphere of energy sector functioning, together with integral systems of relevant by-laws.

At present, the formation of legal regime for energy resources continues, its peculiarities are fixed in the number of legislative acts. For example, the federal law of November 23, 2009 No. 261-FZ "Concerning Energy Saving and Energy Efficiency Improvement and on Amendments to Certain Legislative acts of the Russian Federation" [3] regulates relations regarding energy saving and energy efficiency improvement; establishes the legal, economic and organizational framework for stimulating energy saving and energy efficiency improvement.

The Federal law of 31.03.1999 No. 69-FZ (as amended on 26.07.2017) "Concerning Gas Supply of the Russian Federation" [4] determines legal, economic and organizational framework for relations in the field of gas supply in the Russian Federation and is directed to meet the needs of the state in the strategic kind of energy resources.

The Federal Law of March 26, 2003 No. 35-FZ (as amended on 29.12.2017) "Concerning the Electric Power Industry" [5] establishes legal framework for economic relations in the field of electric power industry, determines the powers of state authorities to regulate these relations, basic rights and obligations of electric power industry entities, when exercising the activity in the field of electric power industry (including production in the mode of combined generation of electricity and heat) and the consumers of the electric power.

The Federal Law of July 27, 2010 No. 190-FZ "Concerning Heat Supply" (as amended and supplemented, and come into force on 10.08.2017) [6] establishes legal framework for economic relations, emerging in connection with production, transmission and consumption of heat energy, heat power, the heat transfer medium with the use of heat supply system, the implementation, functioning and development of such systems, and also determines powers of state authorities, local authorities regarding the regulation and control in the field of heat supply, rights and obligations of heat energy consumers, heating supply companies, heating network organizations.

The development of normative legal base in the field of state regulation energy saving and energy efficiency improvement is exercised including other laws and regulations, and taking into account goals described by the National programme of the Russian Federation "Energy Efficiency and Energy Development" approved by the RF Government Regulation of April 15, 2014 No. 321 (as amended on 30.03.2018) [7], including the development of energy saving and energy efficiency improvement; meeting the demands of the domestic market with reliable, quality and economically justified supply of electric energy and heat; the development of oil-and-gas and coal industries of the fuel and energy complex for the effective supply with hydrocarbon and coal raw materials the demands of the domestic market and the fulfilment of obligations under foreign contracts; promoting innovative development of the fuel and energy complex.

In addition, according to paragraph 60 of the Russian President Decree of 31.12.2015 No. 683 "Russia's National Security Strategy" [8], one of the main directions of national security protection in the economic field for the long term is enhancing energy security, which involves sustainable provision of domestic demand with energy carriers of standard quality, the growth of energy efficiency and energy saving, the competitiveness of national energy companies and manufacturers of energy resources, prevention of the fuel and energy resources deficit, the development of strategic oil reserves, reserve capacity, the production of accessory equipment, constant fuel and energy system performance.

The majority of the mentioned legal acts taking into account their significance and integrated nature are the objects of active work with the purpose of improvement, making necessary amendments and/or the establishment of the system of appropriate by-laws.

It is necessary to note, that at the present time the legislative policy in the sphere of the energy market is changing. In particular, together with requirement strengthening to the energy producers, there is the increase of lawmakers' attention to energy consumers, especially to equipment used by them. The awareness by lawmakers the importance of energy-intensive and energy-saving technologies as regards to the energy security is manifested mainly in adoption of new laws and regulations.

Thus since 1 January 2018 more than 10 provisions of legislative acts come into force, directly affect the interests of Russian producers of light-emitting-diode light engineering. In particular, the RF Government Regulation of April 15, 2017 No. 450 amending the RF Government Regulation of 31.12.2009 No. 1222 [9]; the RF Government Regulation of January 25, 2011 No. 18 "On Approval of Regulations for Restablishing Requirement of Energy Efficiency for Buildings and Structures and Requirements to the Rules of Determining the Class of Energy Efficiency in Blocks of Flats" [10]; The Regulation of November 10, 2017 No. 1356 "On Approval Requirements to Lighting Devices and Electric Bulbs, used for Purposes of Alternating-current and Lighting" [11]. The analysis of the Russian Federation legislation indicates that the Russian light engineering is on the stage of intensive development and improvement.

The energy sector of the economy in any country is the area of state interest, therefore, as a rule, it is under the strict control of the government. The state share at the domestic energy market in different parts can reach 100 %. This situation is primarily connected with the conservatism of the energy business – in order to make some profit it is necessary to receive substantial investment for long terms.

Undoubtedly, the issuers of legislative regulation of renewable or regenerative energy require particular attention. Along with that despite the adoption of a number of statutory acts, designed to put things right in the area of energy supply with the use of renewable sources of power, it would be premature to say that there is the particular systemized base of sources in this sphere. The majority of current legal acts in this sphere are mostly of a declarative nature proclaiming the main aim: "the development of using renewable energy sources", and not proposing the necessary mechanism of its realization, that lead to difficulties in application of these acts. At the present time, the technologies operating on the base of the use of renewable sources of power are not sufficiently developed to be compete in the market, they do not provide for the development of alternative energy suppliers, major suppliers do not seek to diversify deliveries, preferring traditional single sources, that highlights the need for state support of their promotion. In addition, internal and external problems the Russia faces, taking into account economic parameters and the potential capacity of the Russian energy sector, result in the changes in the development model. According to experts' estimates, the rapid increase in the use of renewable sources of power set additional tasks for the whole energy sector, connected with the necessity of reserving power and its accumulation for providing the flexibility of the State energy system activity.

4. CONCLUSION

To conclude, it is necessary to mention, that monopolization of the energy sector by the state at present is disputable in terms of benefits for final consumers. Without contesting the right of state control over production and selling of traditional kinds of energy, it is offered to consumers with the opportunity to seek alternative sources themselves in order to meet their own needs with energy. Besides, legislators should review their position regarding the opportunity for sellers to enter the market of the energy, while the analysis of laws and regulations, governing the energy sector of Russia, shows that at the present time there is no such opportunity for the participants of the market. The peculiarities of the development of the Russian energy sector have resulted to its governmentalisation that at the moment it diverges with the interests of final consumers. To stabilize the relations of alternative sources of energy at the market, it is required to fundamentally review the legislation taking into account the interests of private suppliers. Deciding on the introduction of a new alternative source of energy it is necessary to be sure in its future demand, stability, and legitimacy. It is worth noting that considering the legislative provision of the domestic energy market it is important to deal with the issues of energy efficiency and energy saving. In particular, it is pointed out that lighting equipment allows to reduce energy consumption, and overall energy saving in this case can reach 30 % [12]. The share of lighting in overall energy consumption is high enough, that is why the application of effective sources of light and the development of appropriate technologies is one of the primary ways for solving this problem. For some entities the way out will be not only the diversification of energy supply through the use of renewable energy sources and the emergence of new independent suppliers in the market, but putting into operation safe and effective lighting equipment. It should be noted the increasing role of legislative regulation in this sphere. The introduction of new energy-saving technologies, including the use of legal restrictions and direct instructions, promote the development of a modern energy legislation model, aimed at effective use of produced energy.

As can be seen from the above review of the legislation, the government pays little attention to the potential of alternative energy resources, establishing general rules for all market participants. Moreover, the absence of legislative restrictions with regard to the use of obsolete lighting equipment also leads to the lag of the Russian domestic energy market and contributes to increasing losses of energy for consumers. In keeping with this trend, the most wide use of practice for stimulating energy savings and the development of new technological processes is the policy of rising traditional sources energy prices that is contrary to the interests of final consumers and can increase prices on for a significant number of goods in the domestic market. The introduction of state programs with regards to energy saving and energy efficiency stimulates the application of appropriate technologies and as a consequence conducting scientific research and development in these respects.

REFERENCES

1. The forecast of world's and Russia energetics development up to 2040. FSBUS "The Institute of energetics researches under the Russian Academy of science" and FSBU "The analytic centre under the Government of Russian Federation" // https://www.eriras.ru/files/forecast_2040.pdf access date 14.06.2018.

2. Order of the Russian Federation Government of 13.11.2009 № 1715-p "Concerning the Energy Strategy of Russia for the Period until 2030" // Collected Acts of the Russian Federation, 30.11.2009, No. 48, the article 5836.

3. Federal Law of November 23, 2009 No. 261-FZ (as amended on 23.04.2018) "Concerning Energy Saving and Energy Efficiency Improvement and on Amendments to Certain Legislative Acts of the Russian Federation" // Collected Acts of the Russian Federation, 30.11.2009, No, 48, the article 5711.

4. Federal law of 31.03.1999 No. 69-FZ (as amended on 26.07.2017) "Concerning Gas Supply of the Russian Federation"// Collected Acts of the Russian Federation, 05.04.1999, No. 14, the article 1667.

5. Federal Law of March 26, 2003 No. 35-FZ (as amended on 29.12.2017) "Concerning the Electric Power Industry"// Collected Acts of the Russian Federation, 31.03.2003, No. 13, the article 1177.

6. Federal Law of July 27, 2010 No. 190-FZ "Concerning Heat Supply"// Collected Acts of the Russian Federation, 02.08.2010, No. 31, the article 4159.

7. National programme of the Russian Federation "Energy Efficiency and Energy Development" approved by the RF Government Regulation of April 15, 2014 No. 321 // Collected Acts of the Russian Federation, 05.05,2014, No. 18 (part III), the article 2167.

8. Decree of the President of Russia of 31.12.2015 No. 683 "Russian National Security Strategy" // Collected Acts of the Russian Federation, 04.01.2016, No. 1 (part II), the article 212.

9. RF Government Regulation of April 15, 2017 No. 450 amending the RF Government Regula-

tion of 31.12.2009 No. 1222 // Collected Acts of the Russian Federation, 24.04.2017, No. 17, the article 2572.

10. RF Government Regulation of January 25, 2011 No. 18 "On Approval of Regulations for Establishing Requirement of Energy Efficiency for Buildings and Structures and Requirements to the Rules of Determining the Class of Energy Efficiency in Blocks of Flats" // Collected Acts of the Russian Federation, 31.01.2011, No. 5, the article 742.

11. Regulation of November 10, 2017 No. 1356 "On Approval Requirements to Lighting Devices and Electric Bulbs, Used for Purposes of Alternating-current and Lighting" // Collected Acts of the Russian Federation, 20.11.2017, No.47, the article 6992.

12. Onaygil S., Güler Ö. Determination of the energy saving by daylight responsive lighting control systems with an example from İstanbul// Building and Environment, 2003, Vol. 38, pp. 973–977.

Natalya I. Besedkina,
Ph.D. in Law, senior lecturer of the Department of Legal Regulation of Economic Activities, Financial University under the Government of the Russian Federation, Russia

Irina I. Romashkova,
Ph.D. in Law, senior lecturer of the Department of Legal Regulation of Economic Activities in the Financial University under the Government of the Russian Federation, Russia

Tatyana A. Tantsura,
senior lecturer of the Department of Language Training, Financial University under the Government of the Russian Federation, Russia

Editorial staff of Light & Engineering Journal apologizes for the next missing paragraph in V. 26, #1, p. 16, paper "Technological Lighting for Agro-Industrial Installations in Russia" by Leonid B. Prikupets:

ACKNOWLEDGMENT

Author would like to thank for financial support. This article is written within a project of financial support of applied scientific researches by the Ministry of Education and Science of the Russian Federation. The subject is: ***"Comprehensive studies in the plant photo-culture and creation of high-effective LED phytoirradiators for increase of energy efficiency of industrial greenhouses"***

Agreement on granting subsidy is the #14.576.21.0099 of 9/26/2017. Unique identifier: RFMEFI57617X0099.

Light & Engineering
Vol. 27, No. 1, pp. 123–128, 2019

LEGAL PROVIDING OF APPLICATION OF ENERGY EFFECTIVE LIGHTNING TECHNOLOGY AND INTELLECTUAL NETWORKS IN THE CONDITIONS OF DIGITAL ECONOMY

Maksim V. Demchenko[1], Rostislav O. Ruchkin[2], and Eugenia P. Simaeva[1]

[1] Financial University under the Government of the Russian Federation
[2] Legal Department, Bank of Russia, Moscow, Russia
E-mail: MVDemchenko@fa.ru; Simaeva@fa.ru

ABSTRACT

The article substantiates the expediency of improving the legal support for the introduction and use of energy-efficient lighting equipment, as well as smart networks (Smart Grid), taking into account the ongoing digitalization of the Russian economy and electric power industry. The goal of scientific research is formulated, which is to develop practical recommendations on optimization of the public relations legal regulation in the digital power engineering sector. The research methodology is represented by the interaction of the legal and sociological aspects of the scientific methods system. The current regulatory and legal basis for the transformation of digital electricity relations has been determined. The need to modernize the system of the new technologies introduction legal regulation for generation, storage, transmission of energy, intelligent networks, including a risk-based management model, is established. A set of standard-setting measures was proposed to transform the legal regulation of public relations in the field of energy-efficient lighting equipment with the aim of creating and effectively operating a single digital environment, both at the Federal and regional levels. A priority is set for the development of "smart" power grids and highly efficient power equipment in the constituent entities of the Russian Federation through a set of legal, economic (financial), educational measures.

Keywords: digital economy, energy-efficient lighting equipment, smart networks, intelligent lighting control systems, legal regulation, government programs, digitalization, equipment technical state index

1. INTRODUCTION

In the digital technologies development conditions, the modernization of lighting equipment and electric grids, digital electricity is of particular relevance in the Russian Federation and regions and, consequently, the need for legal support for its development.

In June 2018, the first digital electrical substation "Medvedevskaya" will be put into operation in the Russian Federation, designed to power the Skolkovo Innovation Centre. This fact indicates the development of the digitalization process in the Russian electric power complex.

Digital transformation of the electric power complex is one of the directions for the implementation of the state program "Digital Economy", approved by the Government of the Russian Federation in July 2017. According to the Director of the Department of Operational Control and Management in the Electric Power Industry of the Russian Federation Economy Ministry, today the mechanism of the power system needs significant optimization with the orientation toward the introduction and use of digital technologies, energy efficient lighting equipment, intelligent networks, risk-oriented management model, which in turn requires significant financial costs. However, the results of such a transformation in the electric power industry can exceed all expectations for their energy security, safety and efficiency [1].

In addition, during the St. Petersburg International Economic Forum held in May 2018, an agreement was signed between "GAZPROMNEFT" and "TSIFRA" on the implementation of the "Digital Plant" project, which is necessary to develop a digital platform for managing the oil industry. In the period from 2018 to 2035 the activities of the normative "road map" Energy net of the National Technological Initiative approved by the Government of the Russian Federation will be implemented through the launch of pilot projects, as well as the creation of a legal and economic basis for the wide application of modern solutions in the electric power industry [2].

Development and further improvement of legal support of energy-efficient lighting engineering and intelligent lighting control systems, as components of the Russian Federation power complex is one of the digital economy development priority directions. However, the lack of harmonized Federal and regional regulatory system not only hinders, but prevents further digital development of the Russian power industry.

In this regard, it seems advisable to develop at the federal and regional level a system of legal norms for the integrated economic and legal regulation of relations arising in connection with the development of the digital power industry, as a result of which the regulatory environment in full will provide a favourable legal regime for the emergence and development of modern lighting equipment, intellectual networks, and economic activities related to the use of digital infrastructure tools.

Thus, the goal of the study is to develop practical recommendations for improving the legal support for the use of energy efficient lighting and smart grids in the Russian Federation and the constituent entities of the Russian Federation on the basis of a problematic issues analysis that hinder the effective regulation of the electric power digitalization processes in Russia and the region.

In order to achieve this goal, it is necessary to solve problems:

- To define the operating system of standard and legal regulation of Russian energy efficient lighting engineering and clever networks (Smart Grid) use;
- To estimate positive effects from use of energy efficient lighting engineering and clever networks (Smart Grid) in the conditions of development of digital economy;
- To estimate energy efficient lighting engineering and clever networks (Smart Grid) introduction experience in the Russian Federation.

2. MATERIALS AND METHODS (MODEL)

The problems research methodology of legal support for the use of energy efficient lighting and smart grids in Russia with the aim of further improving the development of digital power engineering is the synthesis of legal science methods based on materialistic dialectics: comparative legal, formal legal, systemic (legal aspect), – with basic sociological research methods: empirical analysis of data, analytical research (sociological aspect).

Formally, a legal (logical) method allows to formulate and analyze the normative legal acts system in the digital power industry field from the point of view of a legal regulation and essential legal gaps and collisions lack sufficiency.

At the moment, the standard and legal regulation system of energy efficient lighting and intelligent lighting control systems is represented by the following normative acts:

- At the federal level: Forecast of the scientific and technological development of the Russian Federation for the period up to 2030; "Russian Energy Strategy for the Period Until 2030"; Federal Law No. 261-FZ of 23 November 2009 (as amended on 23.04.2018) "On Energy Conservation and on Improving Energy Efficiency and on Introducing Amendments to Certain Legislative Acts of the Russian Federation"; Order of the Ministry of Industry and Energy of the Russian Federation of 07.08.2007 No. 311 "On the Approval of the Strategy for the Development of the Electronic Industry of Russia for the Period until 2025"; Order of the Ministry of Construction and Housing and Communal Services of the Russian Federation of 17.11.2017 "On Approval of Energy Efficiency Requirements for Buildings, and Structures" and other by-laws.
- At the regional level (on the example of the Mordovia Republic): Law of the Mordovia Republic of March 26, 2013 No. 18-3 "On the Powers of the Government Bodies of the Mordovia Repub-

Table 1. Effects from Introduction of Smart Grid Technologies [6]

Technological direction	Effect from implementation
Different components of Smart Grid	– Saving 20–45 % of the energy consumed – Reduction of losses from interruptions in the supply of electricity to 15 % – Reducing the capital costs of equipment by (5–10) % – Reduction in the accident rate and the cost of repairs to 10 %
Intelligent instrumentation systems	– Improving the quality and reliability of power grids – Supply and demand balance of electricity – Providing infrastructure for smart cities
The new generation of control and monitoring of distribution networks	– Minimization of expenses at construction of additional (spare) stations
Renewable energy generators with low CO_2 emissions	– Increase in environmental friendliness – Increase in stability of network – Uninterrupted power supply, including, remote regions, of the country.

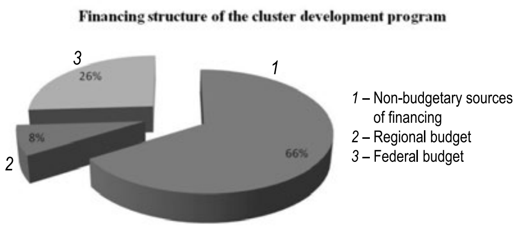


Fig. 1. Total volume of investments in the cluster development program "Energy Efficient Lighting and Intelligent Lighting Control Systems" in 2012–2016 [3]

lic in the Field of Energy Conservation and Energy Efficiency" (Edited 16.04.2015); Decree of the Government of the Mordovia Republic from December 23, 2013 No. 583 "On Approval of the State Program of the Republic of "Mordovia Energy saving and Energy Efficiency in the Republic of Mordovia for 2014–2020".

Besides, in the Republic of Mordovia, the republican program for supporting the development of the innovative territorial cluster "Energy-efficient Lighting Equipment and Intelligent Lighting Control Systems" for 2013–2016 was started, approved by the Resolution of the Government of the Russian Federation of 15.04.2014 No. 316 (an edition of 31.03.2018) "On Approval of the State Program of the Russian Federation "Economic Development and Innovative Economy". Financing of the cluster "Energy-efficient Lighting Technology and Intelligent Lighting Control Systems" is presented in Fig. 1.

At the same time, analyzing the standard regulation system of the public relations in the sphere to power industry, it should be noted lack of coherence of the acts stated above with the "digital economy" program of the Russian Federation. Besides, it is expedient to carry out some systematization of normative legal acts on power industry sphere. In this regard, it is necessary to harmonize the current legislation in the field of digital power industry on the basis of investments attraction continuous monitoring for the energy saving main mechanisms realization and use of "smart" technologies.

Thus, monitoring as purposeful system process of observation at the regional level, helps to provide in due time to public authorities the relevant information on the current investment processes, changes, including, in the digital power industry sphere [4].

3. RESULTS AND DISCUSSION

For the development of smart technologies in the electricity sector, significant funding is needed, mainly budgetary funds. So, since 2007, more than 100 billion roubles have been invested from the federal budget. At the same time, the introduction of intelligent networks in Russian cities will reduce losses in networks by 30 billion kWh per year and save 90 billion roubles. Priority directions in this area are increasing energy efficiency, reducing costs, developing renewable energy sources in the city (sunlight, wind), which is generally accessible and environmentally friendly for the environment [5].

Table 2. Russian Experience of Using Smart Grid. Source: Presentation – Report "Technologies for Smart Cities" [6]

Belgorod and the Belgorod region	The Belgorod region is the only region of the Russian Federation, the networks of which are united by a single centralized control system based on the solutions of the company "IVTBelGU".
Kursk	Implementation of the largest energy service project in Russia with the participation (electronic ballasts) of the electronic ballast "Helios", which allows controlling and dimming the light points.
Sergiev Posad	The automatic metering has reduced the network losses from 26 % in 2005 to 11 % in 2012. Metering shoot multiple parameters, including the voltage level, they can be used to create other services.
Ufa	The project is being implemented by the Bashkir network company in conjunction with Siemens since 2014, the end is planned for 2018. It is expected to significantly reduce losses (from 19 % to 1 %), reduce the time for switching between different segments of the network, to troubleshoot problems up to several minutes.
Kaliningrad region	RES "Mamonovskaya", "Bagrationovskaya". The plans to reduce losses twice, the number of outages per year – four times. More importantly, a decrease in the cost of owning assets, which can be reduced by 25 %.
Lipetsk	Since 2013 (automated control system for outdoor lighting), ASELO "Helios" manages outdoor lighting in the territory of Novolipetsk Metallurgical Combine and uses a modern solution that allows controlling each light with the help of "Helios" semiconducter ballast.
Perm	9736 smart metering devices in multi-apartment and private houses, with legal entities in the territory of Motovilikhinsky district of Perm. All metering devices are integrated into an automated information and measuring system.
Ryazan	In the second half of 2014, the company "IVTBelGU" launched an energy service project: the city's outdoor lighting was completely modernized; LED luminaires and "Helios" automated control systems were installed.
North Caucasus	Optima Engineering has carried out large-scale construction and installation and commissioning works on relay protection and emergency automatics equipment, as well as reconstruction of high-frequency communication channels in more than 60 substations.
Tyumen region, Uspenskoe municipality	A pilot project on adaptation to Russian conditions of Smart Grid technologies was developed based on distribution networks of "TYUMENENERGO".

The main "smart" technologies in the electricity sector, as well as the benefits from their use for the development of the projects "Smart City" and "Smart Region" are presented in Table 1.

The problems of public relations legal provision in the field of energy-efficient lighting and intelligent lighting management systems in the digital economy should be considered primarily through the prism of regulatory and legal normative acts regulating energy conservation and digital electricity.

Due to the high cost of developing energy efficient lighting technology and intelligent lighting control systems, it is advisable to provide for legislative changes in the electric power industry concerning the need to use the form of public-private partnership, especially in the regions of the Russian Federation.

At the moment, the introduction and use of energy-efficient lighting technology and smart technologies in the electric power industry in the Russian regions is presented in Table 2.

The issue of legal support for renewable energy sources remains a topical issue. In the Russian legal system, the subordinate normative acts regulate this sphere: Government Decree No. 449 of May 28, 2013 (as amended on February 28, 2017) "On the Mechanism for Stimulating the Use of Renewable Energy Sources in the Wholesale Electricity and Capacity Market"; Decree of the Government of the Russian Federation No. 426 of 03.06.2008 (as amended on May 23, 2017) "On the Qualification of a Generating Object Operating on the Basis of Using Renewable Energy Sources" and others.

In this regard, it is necessary to envisage fixing at the legislative level a mechanism for the implementation and development of the renewable energy system, taking into account the climatic conditions of individual Russian regions.

4. CONCLUSION

Based on the analysis, we can identify a number of measures to develop legal support for the use of energy-efficient lighting technology and intelligent lighting control systems, both at the federal and regional levels.

First of all, at the federal level, it is necessary to implement the following:

• Optimization of federal legislation in the field of digital power generation, energy saving, giving priority to the development of mechanisms for the use of renewable energy sources in the subjects of the Russian Federation that have specific climatic conditions;

• Creation of legal conditions for the formation of a single digital trust environment that allows participants in the digital power industry to be provided with means of safe, reliable and energy-efficient lighting equipment;

• Creation of a legal field for the necessary tax incentives and a mechanism for protecting the rights and interests of investors in attracting private resources in the form of public-private partnerships with the goal of introducing smart technologies in the regions of Russia;

• Adoption of targeted state programs or other mechanisms of state support at the legislative level to finance the pilot projects "Smart City", "Smart Region".

At the regional level, the improvement of the legal regulation of the digital economy is possible through the implementation of such activities as:

• Development and adoption of a regional normative act – a "roadmap" for the development of digital power generation, taking into account the specifics of the region;

• Development and implementation of the digital project "Smart City" / "Smart Region" within the framework of regional programs for the development of the digital economy in order to improve the quality, safety of people's lives, ensure a high level of urban environment improvement, create opportunities for business development, facilitate interaction between citizens and organizations with state structures;

• Establishment of tax incentives for entities that produce modern, "smart" technologies in the field of digital electricity;

• Provision of consultative and methodological assistance from regional authorities and local governments to business entities on investing in the development of "smart" technologies in electric power engineering;

• Increase of the population literacy on the costs minimization for the use of various kinds of intelligent lighting control systems and energy efficient lighting equipment.

In modern conditions, the introduction of new technologies for generation, storage and transmission of energy should be intensified. In the next six years, it is planned to attract about 1.5 trillion roubles of private investments in the renewal of the Russian electric power industry. Throughout the country, the digital mode of operation must go to the power system [7].

REFERENCES

1. Interview Grabchak E. publication "Regional Energy and Energy Saving" [Interv'yu Grabchaka E. izdaniyu "Regional'naya ehnergetika i ehnergosberezhenie"] – URL: https://minenergo.gov.ru/node/7965 (date of the application 03.06.2018).

2. Digitalization of energy / Official website of the Institute of Energy Higher School of Economics [Cifrovizaciya ehnergetiki/ Oficial'nyj sajt Instituta ehnergetiki Vysshej shkoly ehkonomiki] – URL: https://energy.hse.ru/digitalization (date of the application 03.06.2018).

3. Presentation of the cluster development program "Energy-efficient lighting technology and intelligent lighting control systems" [Prezentaciya programmy razvitiya klastera "Energoeffektivnaya svetotekhnika i intellektual'nye sistemy upravleniya osveshcheniem"] – URL: http://vote.cluster.hse.ru/upload/iblock/3b5/3b5f846ff-2b05cf79a0cd452b5742d3e.pdf (date of the application 03.06.2018).

4. Kvon G.M., Sangadzhiev B.V., Demchenko M.V., Ponomareva M.A., Smirnova E.A. The Implementation Technique Of Investments Monitoring Into The Economy's Real Sector // Espacios. 2018, V. 39. № 1. p. 8.

5. Inyutsyn A. Umnye tekhnologii stanovyatsya dostupnee dlya gorodov. [Smart technologies become more accessible for cities] // Praktika municipal'nogo upravleniya, 2017, #2, pp. 46-55.
6. Prezentaciya "Tekhnologii dlya umnyh gorodov [Presentation "Technologies for smart cities"] URL: http://csrnw.ru/files/publications/doklad_tehnologii_dlya_umnyh_gorodov.pdf (date of the application 01.06.2018).
7. Poslanie Prezidenta RF Federal'nomu Sobraniyu RF ot 01.03.2018 [Message of the President of the Russian Federation to the Federal Assembly of the Russian Federation dated 01.03.2018] // Spravochno-pravovaya sistema Konsul'tant plyus.

Maksim V. Demchenko,
Ph.D. (Science of Law), Associate Professor, Deputy Head of the Department of Legal Regulation of Economic Activity for Scientific Work, Financial University under the Government of the Russian Federation, Moscow, Russia

Rostislav O. Ruchkin,
Ph.D. (Science of Law), Legal Adviser of first category of Banking Supervision Legal Support Department, Legal Department, Bank of Russia, Moscow, Russia

Eugenia P. Simaeva,
Ph.D. (Science of Low), Associate Professor of the Department of Legal Regulation of Economic Activities, Financial University under the Government of the Russian Federation, Moscow, Russia

Light & Engineering
Vol. 27, No. 1, pp. 129–134, 2019

BREACHES OF ENERGY CONSUMPTION LAW

Alexander S. Komarov, Galina V. Kostyleva, and Oksana N. Vasil'eva

Financial University under the Government of the Russian Federation
E-mails: ASKomarov@fa.ru; GVKostyleva@fa.ru; ONVasileva@fa.ru

ABSTRACT

Artificial electric lighting in buildings is an important element of any electrical system. The ample use of artificial electric lighting in modern society is indisputable. Apart from its main purpose, if legally designed and installed, electrical lighting promotes the stable work and development of a country's power engineering. Effective use of energy resources and the capacities of power engineering are keys for the sustainability of economic growth. An increased demand in energy resources has provoked uncontrolled energy consumption and violations in fuel extraction as well as in fuel or electricity use. In the article, the authors try to give an analysis of such violations, which in its turn allows disclosing a few legal loopholes in this economic sector. The owner of energy resources suffers great damages from unauthorized connections to electrical and gas networks. Perpetrators of electrical and thermal energy consumption regulations are subject to civil, criminal, and administrative law. Nevertheless, the authors' analysis of cases in the courts shows that a great number of them are seldom inquired into, and most perpetrators are very rarely held liable. The aim of the article is to analyze the national legislation to withstand the illegitimate energy resources consumption, to bring to light the issues in this economic sector and to suggest some ways of their solution.

Keywords: energy resources, lighting; mineral resources used as sources of power, power infrastructure, electrical equipment, consumers of electricity, generation and use of electrical energy, energy conservation, uncontrolled use of electrical and thermal power, energy consumption supervision, violation of consumption regulations, infringement on energy resources use

1. INTRODUCTION

Effective use of energy resources and the potentialities of the energy sector is the pivot of Russian economic policy. It is aimed to sustain the economic growth in Russia, raise the living standard of the population, and improve external trade status of Russia. A strong focus of its policy is on power engineering security, energy efficiency in economy, effective budgeting, and ecological security of power engineering [1].

The choice of the above-mentioned focus in the Russian energy strategy is determined by a great amount of energy resources, which include electricity as well. This makes it possible to satisfy the country's needs as well as to export them. According to the projections, by 2020 the lighting industry turnover in the world market is expected to catch up with the television industry turnover [2, 3]. The leading economies in today's world strive for an increase of their energy efficiency; one of the means in this great effort is to develop effective lighting technologies. In their simulation of the situation in the world market, the McKinsey analysts show that by 2020 the turnover of lighting industry may reach nearly 110 bn euro with the annual growth by 3 %. The growing population on Earth instigates the growing demand in lighting.

In Russia, owing to energy conservation measures, as well as increase in efficiency of energy projects, there is a possibility to increase current

Table 1. The Increase in Electricity Generation

	2016, bn kWh	2017, bn kWh	%
Electricity Generation, in total	**1071.9**	**1073.7**	**+0.2**
included:			
Thermal electric power stations	628.5	622.4	-1.0
Gas electric power stations	186.7	187.4	+0.4
Nuclear power stations	196.4	202.9	+3.3
Renewable sources of energy	0.61	0.69	+13.1
Electric power stations at industrial works	59.8	60.3	+0.9
Electricity consumption	**1054.6**	**1059.7**	**+0.5**

energy consumption by 30 %. However, Russian power engineering is faced with a number of risks and threats. The complexity of problems places energy security in the foreground of national security. This is predetermined by the depleted available fuel deposits and a continuous increase in electricity or fuel consumption.

This work summarizes the main legislative norms of the national policy in energy consumption. It also investigates the factors, which hinder the further progress in this branch of Russian economy. The article analyzes the main illegal actions by perpetrators, who violate the existing law in energy consumption and highlights the legal regulations, which are designed to eradicate illegal energy consumption.

2. METHODOLOGY

Scientific and technological progress has made contemporary society dependent on the uninterrupted centralised supply of electrical and thermal energies as well as gas and water [4]. Cutting off or limiting their supply not only infringes on customers' civil rights and every day interests, but deprives the customer of their subsistence, which excites very negative reactions on their part. That is why one of the main aims of the Russian national policy is to provide and guarantee energy security measures. This aim is to be achieved by laws and their observance. The methodology is based upon a collection of laws or legal regulations of energy consumption, their analysis, and categorization of unlawful actions in energy use and consumption.

The Strategic Plan of electricity supply network development in the Russian Federation in the period to 2030 is elaborated in accordance with Decree 1567 by President of Russia (22 November, 2012). The document defines the electricity supply network missions, which include electricity transmission, distribution, generation, and selling on the territory of Russia [5].

The power supply system of Russia comprises a federal power supply system and local power supply systems. The expected change in economic development, structural changes of economy, and amount of energy consumption determine domestic demand for energy resources including electricity. According to the information from the Ministry of Energy (Russia), in 2017 the electricity consumption reached 1059.7 bn kWh (1039.9 bn in the federal system), which was higher than in 2016 by 0.5 % (by 1.3 % in the federal system). The highest level of consumption was registered in metallurgy, railway transport, and gas main. The Russian electric power stations together with electric power stations at industrial works generated 1073.7 bn kWh (1053.9 bn kWh in the federal system). The increase in electricity generation was by 0.2 % (Table 1) [6].

In 2017, the electricity consumption in the federal power supply system reached 1 039 879.9 million kWh, which tops the 2016 consumption by 13023.5 million kWh (1.27 %). The growth of the annual consumption of electricity in 2016 (29 February excluded) accounts for 16038.4 million kWh (1.57 %). In comparison to 2015, the growth makes up 31629.1 million kWh (3.14 %).

Non-payment or overdue payment hinders the development of this branch of industry. According to the information presented by *NP Sovetrynok Association,* the arrears amounted to 65.2 bn roubles in the whole-sale market and 243 bn roubles in retail on the end of October 2017. While there are a number of legislative measures, which allow punishing defaulters in the whole-sale market of electricity, the retail market does not have such mechanisms of influence. Supplying the population with electricity as a service of paramount social importance, makes cutting off electricity for defaulters in the retail market impermissible [7].

The Federal Law No. 307-FL of 03.11.2015 issued the amendments aimed at tougher responsibility of energy consumers for non-payment or overdue payment. The Federal Law improved the procedure and established a new system of punishment. The amendments concern the consumers of energy resources or services of electricity transmission and buyers of energy resources or services of water supply and sewage. For example, the Law imposes a fine on debtors and grants financial rights and guarantees to certain categories of electricity consumers. Limitations on electricity consumption are another economic tool for improving the responsibility of the consumers, who neglect their commitments [8]. Moreover, the Federal Law altered the basic rules of consumption limitations. The alterations concerned so-called "not liable to limited consumption" consumers of electricity and initiated partially limited consumption as an obligatory step in the procedure.

Thus, the amendments led to the necessity of reviewing the legal documents regulating the procedure of cutting consumption and to the revision of some procedural steps that stirred up controversy, which resulted in the futility of effective work with debtors. For example, the Russian government enacted Decree No. 624 (24.05.2017) "Amendments in the Acts of the Russian Government on Completely and/or Partially Limited Consumption of Electricity and the Use of Economic Unions' Seals" [9]. In addition, in accordance with the requirements of the Federal Law, the Russian government adopted Decree No. 139 of 04.02.2017 "Amendments in the Decrees of the Russian Government to Ensure the Fulfilment of Obligations to Pay for Energy Resources" [10].

A high degree of generating and networking equipment depreciation is also a deterrent to the development of power engineering. A decreased consumption of electricity was a part of the industrial stagnation in the 1990s. Overdue and insufficient payment for electricity consumption was the reason for the systematic deficit of money allotted to update the capital assets in power industry. It was for a long time that power engineering did not receive a sufficient amount of investment. To date this has resulted in a critical depreciation of the equipment.

According to the overall locating plan of electrical power structures for the period of up to 2035, approximately 46 % of them were put into operation before 1980, i.e. more than 36 years ago. The fleet life of more than 90 GW of steam turbine equipment capacity is finished. Moreover, before 2025 the life of 30 GW of the thermo electric power stations capacity will come to an end [11].

A slow development of power infrastructure and greater demand in all kinds of energy are the reasons for higher unlawful energy consumption [12]. Breaches of energy consumption law is a most widely spread phenomenon of social character. Unauthorised link to electric and other networks causes great damage to the owners of power resources. The amendments introduced into criminal law are aimed to prevent harmful actions and impose amenability on perpetrators. Thus, they are additional legal means of protecting energy resources from theft. However, such harmful actions are still difficult to eradicate because of their latency.

3. RESULTS

Despite many serious challenges, the Russian electric power industry continues growing. The growth of electricity consumption and an increase of the companies' profitability are obvious. Further development and gradual update of the generating companies' power capacities are necessary steps in its growth. The current legislation inflicts administrative, civil, and criminal punishments on consumers, thus enhancing their responsibility for violating the legal rules of electricity, water, gas, and other kinds of energy consumption.

4. ADMINISTRATIVE LAW AND UNLAWFUL ACTIONS IN ENERGY CONSUMPTION

The Administrative Punishment Code of the Russian Federation (APC) specifies cases of unlawful energy use and enforces administrative punishment for illegal energy consumption.

1. Unauthorised connection to and use of electric, thermal, gas, or oil energy (article 7.19 APC)

Unauthorised connection to electric network, gas, or oil pipelines is defined as such in cases, when there is no sanction given by an authorized representative of the national energy inspection. Gas or oil pipelines, and energy networks are technically complex structures, which are built for transportation of gas, oil, oil products, and electric power to their consumers. Consumers are required to forward a written request and ask their energy supplying organization for a sanction to link their dwellings or other buildings with new wiring systems to the electric network. Also, gas use and its supply is not permitted without its calculated amount. The relevant regulations determine in detail the required procedure of its amount registration, control of its characteristics, and general technical conditions for metering units. It should be noted that this unlawful action by the consumer is intentional.

2. Unauthorised commissioning of fuel or energy consuming structures (article 9.9 APC)

This breach of law consists in activities, which violate the established procedure of authorization when commissioning fuel or energy consuming structures. This unlawful action violates the secure work of energy structures, as well as the prescribed regulations in the fuel and energy complex.

The regulations of energy plants' work and maintenance were determined and issued in the following documents: the Federal law "Energy Conservation, Higher Efficiency of Energy Use and Amendments in the Legislative Acts of the Russian Federation" (23.11.2009, No. 261-FL) and the federal law "Communications Network" (07.07.2003, No. 126-FL), and, additionally, in the decrees by President and Government of the Russian Federation, as well as the Ministry of Energy (Russia).

Unauthorized commissioning is an unlawful action intentionally committed by officials, who should observe the established procedure of receiving commissioning authorization. Other perpetrators are entrepreneurs and legal entities that have ignored or neglected the mandatory operating rules for fuel and energy structures.

3. Ignorance or negligence of regulations, which are issued by the Russian government, Ministry of Energy, and other federal governmental agencies and related to fuel or energy use, work, and maintenance of fuel/energy consuming equipment or implements, heating systems, structures for containing, warehousing, selling or transporting machines and appliances, fuel, and its derived products (article 9.11 APC)

The terms of relations between energy or gas suppliers and individuals, who consume their products, are determined in the regulations of electric or thermal energy use, which were approved by the Ministry of Energy. The regulations ban unauthorized use of electric or thermal energy and gas. A consumer is required to forward a written request to the supplier to get a sanction thus linking their dwellings or other buildings with new wiring systems to the electric network.

The regulations of energy or gas use contain conditions for maintenance and installation of electric or gas appliances, energy or gas meters, as well as for energy and gas payments.

This unlawful action is committed intentionally or out of insufficient attention to the regulations by officials, legal entities, or Russian nationals.

4. Unproductive wastage of energy resources (article 9.12 APC)

The Federal Law "Economy of Energy, Higher Efficiency of Energy Use and Amendments in the Legislative Acts of the Russian Federation" (23.11.2009, № 261-FL) defines "unproductive wastage of energy resources" as violation of regulations stipulated by national standards or other legal documents, by technical documentation, passport information, and maintenance schedules for operating equipment. According to the national standards, norms of precise measurements, or other legal and technical documentation, an amount of energy and natural resources (extracted, produced, manufactured, transported, warehoused, or used) are to be mandatorily registered.

This unlawful action infringes on the interaction between the producer and consumer of energy resources as legal entities. The proof of its unlawfulness is based on an analysis of the standards, norms and regulations aimed at energy conservation. For example, the interdepartmental regulations of thermal energy or coolant control, regulations of electricity control, regulations of limited electric or thermal energy consumption, a sanctioning procedure of using electric boilers and other electric appliances, etc.

This unlawful action is committed both intentionally and out of insufficient attention to the regulations by executives at enterprises irrespective of their ownership, legal entities, and employees in charge of energy conservation or its effective use.

5. CONCLUSION

In our opinion, the above-mentioned challenges in administering energy consumption law in courts result from the loopholes in the current legislation of fuel/energy use; secondly, a lack of cooperation between executive bodies and law-enforcement bodies, whose duty is to supervise, make known and counteract unlawful actions of energy consumption, and thirdly, official corruption in this branch of industry.

To sum up, law formulation and creation of legal countermeasures, which secure energy resources protection, are the main tasks in the activities of executive bodies in the Russian Federation. Any breaches of energy consumption law have a negative effect on the development of the energy sector. That is why harmful economic consequences of illegal energy consumption should not be underestimated.

REFERENCES

1. Rasporyazhenie Pravitel'stva RF ot 13.11.2009 g. No. 1715-r "Ob ehnergeticheskoj strategii Rossii na period do 2030 goda" [Regulation by the Government of the Russian Federation of 13.11.2009. No. 1715-r "Energy Strategy of Russia in the Period to 2030" // Sobranie zakonodatel'stva RF, 2009, No. 48, art. 5836 (in Russian).

2. Inyuzin A., Mel'nikov D. O logike tekhnicheskogo regulirovaniya v oblasti osveshheniya [Technical conditions for lighting] // Svetotekhnika, 2018, No. 1, pp. 35–37 (in Russian).

3. Klimenko V.V., Fedotova E.V., Tereshin A.G. Vulnerability of the Russian power industry to the climate change // Energy, 2018, v.142. pp. 1010–1022.

4. Erhan F., Poperscu V., Lupusor I. Study of the influence level current of the short circuit on reliability of the brekers // Problemele energetich regional, 2010, Vol. 12, #1, pp.16–21.

5. Rasporyazhenie Pravitel'stva RF ot 03.04.2013, No. 511-r "Ob utverzhdenii strategii razvitiya ehlektrosetevogo kompleksa Rossiiskoy Federatsii" [Regulation by the Government of the Russian Federation of 03.04.2013, No. 511-r "Development Strategy in the Energy Complex of the Russian Federation" // Sobranie zakonodatel'stva RF, 2013, No. 14, art. 1738 (in Russian).

6. Osnovnye kharakteristiki rossiiskoy ehlektroehnergetiki [Main characteristics of Russian power industry], // Official site of the Ministry of Energy (Russia), URL: https://minenergo.gov.ru/node/532 (Accessed 12.06.2018) (in Russian).

7. Obzor ehlektroehnergeticheskoi otrasli Rossii [Energy industry review], // Official site of EES system operator, URL: http://so-ups.ru/?id=2045 (accessed 12.06.2018) (in Russian).

8. Maggregor J. Determining an optimal strategy for energy investment in Kazakhstan // Energy Policy, 2017, v.107. pp. 210–224.

9. Postanovlenie Pravitel'stva RF ot 24.05.2017 No. 624 "O vnesenii izmeneniy v nekotorye akty Pravitel'stva Rossiyskoy Federatsii po voprosam vvedeniya polnogo i (ili) chastichnogo ogranicheniya rezhima potrebleniya ehlektricheskoy ehnergii, a takzhe primeneniya pechatey hozyaystvennyh obtchestv" [Order by the Government of the Russian Federation of 24.05.2017 No. 624 "Amendments in the Acts of the Russian Government on Completely and/or Partially Limited Consumption of Electricity and the Use of Economic Unions' Seals"] // Sobranie zakonodatel'stva RF, 2017, No. 23, art. 3323 (in Russian).

10. Postanovlenie Pravitel'stva RF ot 04.02.2017 g. No. 139 "O vnesenii izmeneniy v nekotorye akty Pravitel'stva Rossiyskoy Federatsii po voprosam obespecheniya ispolneniya obyazatel'stv po oplate ehnergoresursov" [Order by the Government of the Russian Federation of 04.02.2017 No. 139 "Amendments in the Decrees of the Russian Government to Ensure the Fulfilment of Obligations to Pay for Energy Resources" // Sobranie zakonodatel'stva RF, 2017, No. 8, art. 1230 (in Russian).

11. Rasporyazhenie Pravitel'stva RF ot 09.06.2017, No. 1209-r "O general'noy sheme razmeshheniya ob'ektov ehlektroehnergetiki do 2035 goda" [Regulation by the Government of the Russian Federation of 09.06.2017, No. 1209 "Overall locating plan of electrical power structures for the period of up to 2035" 2017, No. 26 (p. II), art. 3859 (in Russian).

12. Kalubi D. 2017, Struktura ehnergetitcheskoi otrasli v Zambii i Rossii [Structure of power industry in Zambia and Russia], Izvestiya Tomskogo politeknicheskogo universiteta. Inzhiniring georesursov, 2017, v. 328, pp. 25–31 (in Russian).

Alexander S. Komarov,
Associate professor, Ph.D. in Philological Sciences, Financial University under the Government of the Russian Federation; Associate professor, Department of Foreign Languages

Galina V. Kostyleva,
Associate Professor, Ph.D. in Law Science, department of legal regulation of economic activity at the Financial University under the Government of the Russian Federation

Oksana N. Vasil'eva,
Associate Professor, Ph.D. in Low Science, Department of legal regulation of economic activity at the Financial University under the Government of the Russian Federation

Light & Engineering
Vol. 27, No. 1, pp. 135–140, 2019

LEGAL REGULATION OF COMPETITION AT ELECTRICITY RETAIL MARKETS

Alexei V. Barkov, Eugene L. Vengerovskiy, and Natalia V. Zalyubovskaya

Financial University under the Government of the Russian Federation
E-mails: barkov_aleksey@inbox.ru; ELVengerovskij@fa.ru; nvzal2@gmail.com

ABSTRACT

The article considers some features of the competitive relation formation in the electric power industry, a major economy sector. In particular, the paper analyzes the electricity retail market operation and the need for competition promotion, it is associated there with a wide range of consumers, which adds high social significance to the effective operation of relations emerging in this area. The author concludes that the retail electricity market needs to increase private funds and decrease state participation, which will contribute to a wider range of service consumers. The article considers some special aspects on how to ensure the dominant position of power supply companies, as well as defines main barriers for business entities to enter retail electricity markets. It also reviews the best foreign practices that regulate energy retail companies (by the example of the Nordic countries) and offers some options of legal receptions in this area. Moreover, it analyzes the Russian legislation novelties in the field of competition at the electricity markets, in particular, the tariff regulation of electricity distributors by the method of reference costs. Also, the article specifies some proposals on how to improve the legislation that regulates competitive relations at the electric energy market within the National Competition Development Plan.

Keywords: electric energy market, FAS Russia, dominant position, tariff regulation, energy retail companies, electricity distributors, lighting equipment users

1. INTRODUCTION

The study aims to research the competition legal regulation at retail electricity markets in order to draft recommendations on how to improve the legal regulation and identify existing problems. The formation of competitive relations at any product market that operates within the market relation is an important factor for sustainable business development, which directly impacts the state's economy efficiency in general and the quality of services provided. Russian transit to a market economy generated the "entrepreneurial management style" characterized by such an important factor as competition between business entities when producing goods, performing work, or rendering services, in the electric power industry, inter alia [1]. However, some aspects of the electricity retail market have led to global violations of competition principles, which resulted in overstated electricity tariffs. To take steps to solve this issues, the Government of the Russian Federation adopted the Resolution No. 863 "On Amendments to Certain Acts of the Government of the Russian Federation Regarding the Introduction of Guaranteeing Suppliers' Sales Markups Using the Comparative Method and Declaration that Subparagraph 2, Paragraph 11 of the Resolution of the Government of the Russian Federation No. 1178 dated December 29, 2011 is no Longer in Force" on July 21, 2017. The Resolution was the first document in Russian legal space to introduce the concept of the guaranteeing supplier reference costs, which is understood as an economically reasonable specific value of costs associated with performance of regulated activities by the guaranteeing supplier, defined by the comparative method and established for expense items. In other words, this standard served as a measure to deter price competition at the market. The unified costs method is mainly used to encourage electricity retail companies to increase their efficiency.

The research applied general scientific methods, such as analysis, modelling, and comprehensive approach. Moreover, specific scientific methods were used, i.e. legal modelling and legal comparison.

2. MAIN RESULTS

The methodology of the research is based on the application of the dialectical method of cognition, which allows us to study objective economic laws and patterns in their interrelations and interdependencies. Theoretical constructions in the article are considered using general scientific and particular methods of selective research. The factual base is based on the legislative and regulatory legal acts of the Russian Federation, statistical and analytical reports on the research topic. Revenues of electricity retail companies are currently calculated by the method of "costs-plus": the markup is directly proportional to costs, including the purchase price of electricity at the wholesale market. So, it is more profitable for electricity retail companies to pay more for electricity; saving, on the contrary, leads to reduced tariffs and revenues. It is not yet profitable for suppliers to optimize their operating costs (rentals, remuneration, etc.), which also contribute to the tariff amount. The new method proposed by FAS outlines the markup of an electricity retail company to be calculated upon standardized costs of 1 kWh. However, if the company reduces its costs against the standard, it will be able to keep saved funds. The purchase price of electricity at the wholesale market will directly affect the consumer price; in this context, the cheaper the electricity is for the guaranteeing supplier, the more customer-attractive its services will be [2]. According to FAS Russia, when the standard is introduced, the costs of distributor companies will consist of two components: constant component (costs) to be determined by the method of reference costs and an alternating component to be determined based on the company's investment program approved by the regional government. FAS estimated the amount of funds saved by consumers during three years due to the new calculation method at 12.7 billion roubles. Considering the fact that the reference costs for energy companies are set at the nation-wide level, it is also advisable to take into account the electricity market, since regional consumption varies (Table 1). However, according to SO UPS JSC, electricity consumption in Russian Unified Power System amounted to 1039.7 billion kWh in 2017, which is 1.3 % above the consumption volume in 2016. In general, electricity consumption in Russia amounted to 1059.5 billion kWh in 2017, which is 0.5 % higher as compared to 2016. Excluding February 29, 2016, electricity consumption by the national UPS and Russia in general increased by 1.6 % and 0.8 % respectively.

In 2017, electricity generation in Russia amounted to 1 073.6 billion kWh, which is 0.2 % higher than in 2016. Russian UPS power plants produced 1053.7 billion kWh, which is 0.5 % higher than in 2016. Electricity generation by Russian UPS and Russia in general increased by 0.8 % and 0.5 %, respectively, excluding the impact of the leap years extra day.

As far as the electricity market is concerned, it should be noted that this market constitutes a system of relations forming a strategically important economy sector. That is why the state is to create a legal mechanism that will help to protect both market players' interests and public interests. In 2003, there was a reform in the electric power sector motivated by anticipated shortage of generating capacity: consumption boosted impressively; power generating equipment grew out-of-date and was in bad state, while there were no incentives and mechanisms for the construction and equipment update. In 2008, energy generating companies, most of them subsidiaries of RAO UPS of Russia, were acquired by private investors (including foreign ones) during the restructuring of RAO UPS of Russia JSC. Together with generating assets, they also received obligations to implement the investment program (construction and modernization of generating assets) specified in the capacity supply agreements (CSA). Along with the industry's restructuring, there also was a market transition reform, which resulted in a gradual transition from fully regulated pricing to market electricity pricing.

A characteristic feature of electricity retail markets is the presence of guaranteeing suppliers that

Table. 1. Electricity Consumption and Industrial Production Growth According to Russian Statistical Agency

Regions	Industrial production growth in 2015 (operational data), %	Memo: electricity consumption increase in 2015, %	Regions	Electricity consumption growth in 2015, %
Top-5 by fall				
Chukotka Autonomous Okrug	-14.2	n/a	Republic of Mordovia	-9.1
Primorsky Krai	-12.5	1.9	Kurgan Region	-4.6
Republic of North Ossetia-Alania	-10.1	-1.3	Volgograd Region	-4.6
Kaluga Region	-9.1	-0.4	Tomsk Region	-4.2
Amur Region	-9.0	1.1	Nizhny Novgorod Region	-4.0
Top-5 by growth				
Tula Region	+9.4	-0.3	Stavropol Krai	+3.7
Bryansk Region	+13.3	-0.7	Republic of Ingushetia	+4.0
Sakhalin Region	+13.8	n/a	Republic of Dagestan	+5.4
Republic of Altai	+2.6	n/a	Republic of Kalmykia	+6.3
Rostov Region	+54.6	0.7	Republic of Tyva	+6.5

exercise significant influence and act as sellers. However, the natural monopoly segment is operated by distribution companies, which dominant position is presumed by law. Accordingly, the vast majority of violations in the electricity (capacity) retail market is due to the dominant position abused by market participants [3].

According to Federal Law No. 35-FZ dated March 26, 2003 "On Electric Power Industry" [4] (hereinafter, the Law on Electric Power Industry), the retail electricity market actors are as follows:

1. Electric energy consumers;
2. Electric energy suppliers (electric sale companies, guaranteeing suppliers, electric energy producers, who are not eligible to operate at the wholesale market);
3. Regional grid operators rendering electricity transmission services;
4. Operational & dispatching control actors serving the electric power industry and performing the specified management at retail markets.

In addition, the Law on Electric Power Energy specifies that entities engaged in lightning, inter alia, are free to choose their counterparty to the purchase & sale contract or electricity supply contract; a distribution company is not entitled to refuse to enter into an electricity transfer service contract basing on the choice of electricity from a particular supplier made by an electricity consumer. This provision of the Law is the basic principle underlying the competitive relations formation at the electricity retail market.

The Federal Antimonopoly Service (hereinafter, FAS Russia) is the agency authorized by the Government of the Russian Federation to exercise antimonopoly control over electricity markets by:

reviewing monitoring data of electricity (capacity) prices; verification of economic and technological justification of actions taken by an electric power industry actor; conducting scheduled and unscheduled inspections on compliance with the antimonopoly legislation, inter alia, detection of electricity (capacity) prices gouging, consideration of claims against violation of antitrust legislation by electric power industry actors, and other information obtained in accordance with the established procedure; detection of price-gouging at the wholesale and/or retail markets, etc. It should be noted that many countries widely exercise state control, for example Brazil [5]. As a result of its activities, FAS Russia found out that, as for 2017, the electricity (capacity) retail markets in all constituents of the Russian Federation were characterized by high concentration and undeveloped competition. This leads to the fact that entities operating, for example, in the lighting segment, are not able to choose a supplier they need. Consequently, we can speak about the inability to create conditions for a competitive environment and service quality improvement.

The market situation is complicated by the fact that a number of entities with the status of a guarantying supplier (i.e. those who sell electricity and must enter into electric power supply contracts or electric power purchase & sale (supply) contracts with any electricity consumer who contacts it or with any person acting in its own name or on behalf of the specified electricity consumer and wants to purchase electricity) occupy about 75 % at the electricity sale & purchase (supply) market in the relevant constituent entity of the Russian Federation, while in most regions their share is almost 100 %. However, the guaranteeing supplier is the only actor of the electricity wholesale market in a number of regions, and all other sales companies buy electricity from it. Some regions witnessed an increase of the market share of the guaranteeing electricity supplier, inter alia, due to the merging with supply companies.

The share of remaining electricity supply companies does not exceed 35 % at the electricity (capacity) retail markets. It also should be noted that electricity purchase & sale (supply) retail markets are potentially highly competitive markets, provided that electricity is sold by several sales entities located in the area of the guaranteeing supplier's operation and within the electric power system of a respective supplier. This leads to violations of regional antimonopoly laws, which negatively affects the ability of many energy power companies to carry out lighting activities. For example, in January 2018 in the Kostroma Region, a case on the antimonopoly law violation was initiated following the requests from the Local Supply Entity (hereinafter, LSE) and the electricity consumer to completely restrict electricity supply to the transformer substation owned by the LSE. The consumer also claimed in its statement that the non-residential premises owned by the company had been disconnected from the electric power system without notifying the consumer. Based on the results of the case consideration, violations of Part 1, Article 10 of Law "On the Competition Protection" was detected in the actions of KSK PJSC and IDGC of Centre PJSC represented by the Kostroma branch and expressed as follows:

– KSK PJSC abused its dominant position by submitting an unreasonable notice of full restriction of electricity consumption in respect of the properties;

– IDGC of Centre PJSC abused its dominant position by unreasonably and fully restricting electricity consumption at the terminal point, i.e. the transformer substation owned by the LSE. The case materials established an unreasonable restriction of electricity consumption for the LSE, which was unable to conduct its business activities by implementing the technological connection of consumers to its electric power system [6].

As noted by FAS Russia, insufficient competition at electricity retail markets affects the availability of electricity for consumers, leads to overpricing, insufficient reliability of electric supply and a weak payment discipline.

High state intervention in the sector should be recognized as the main problem that hampers the development of competition at electricity retail markets [7]. As for the electric supply industry, the National Competition Development Plan should ensure free consumer choice of an electricity supplier. In this regard, it is interesting to explore the experience of the Nordic states, where the reforms, for example, in Norway, admitted small consumers to the market by introducing reference schedules drafted for them. The purpose of such schedules was to facilitate the electricity consumption accounting and forecast at a two-rate tariff. Moreover, consumers gained an opportunity to change suppliers with no additional costs. In 1995, the Swedish electricity trade regulation and consumer protection rules were amended. From now on, the consumer can choose the electricity supplier on its own, when installing hourly meters [8].

Effective competitive relations in the electricity retail segment is an attribute of the world's leading economies, for example, the UK has the highest level of competitive relations and decreased business capitalization [9]. However, in most countries the largest actors make up the segment of "generating companies", for example, in Hungary and Italy, which ensures the market stability, but leads to overpricing and violates the rights of services consumers [9, 10]. The American States are greatly independent to ensure competition at the electricity retail market, but the country in general is also experiencing the "generating companies" problem [11].

From our point of view, competition at the electricity market will be prompted by the concept, which can provide direct access to retail consumers (including entities that provide lighting services) to wholesale electricity producers and ensure a direct payment for electricity through a system of contracts. Moreover, consumers should be able to change a sales company in a short time, if its quality of service is not satisfactory.

Also, as noted by Valery Seleznyov, Deputy Chairman of the State DUMA Energy Power Industry Committee, lifting the ban on electricity sales to distributors with a limited market share may enhance the development of retail markets and competition [7].

3. CONCLUSION

We believe that the adoption of the Federal Law "On Amendments to the Federal Law "On Electric Power Industry" and Certain Legislative Acts of the Russian Federation Related to the Electricity Sales Licensing" has hampered the development of the electricity retail market. The Law says that electricity sales must be carried out based on a license issued by the federal executive agency authorized by the Government of the Russian Federation. Energy sales entities are required to obtain a license no later than December 29, 2018. After this date, no activities without a license can be carried out. Consequently, these norms have generated new barriers to enter the electricity market. In particular, the Law provides for the following requirement: a license applicant must have no obligations to sell exclusively at the wholesale market all electricity (capacity) produced on the electricity (capacity) production facility (or a part thereof), including power plants, which operates within Russian Unified Power System, the installed generating capacity of which is equal to or greater than 25 MW and which will be or has been used for electricity sales activities. The analysis of the competitive environment of the electricity retail market demonstrated that the competition development is hindered by factors peculiar to all product markets in the Russian Federation. However, it should be taken into account that the competition at the market under consideration directly impacts the life quality of the population and Russian energy security. This is why the country's economy in general will benefit from the implementation of the analyzed measures to support competitive mechanisms.

REFERENCES

1. Korshunov N.M. Business Law: textbook for students of higher educational institutions. // YUNITI-DANA: Law and justice, Moscow, 2012, pp. 250–254.
2. Andrienko A.V. Review of the Electric Power Industry Reform in the Scandinavian Countries // Russian Economy in the 20th century: collection of scientific papers. TPU Ed. Tomsk, 2015, pp. 297–303.
3. Ognevskaya D.V. Features of Establishing a Dominant Position of Economic Actors in the Electricity (Capacity) Retail Market // Laws of Russia: experience, analysis and practice. 2014. No. 2
4. Access mode: http://electricalnet.ru/blog/obzor-izmenenii-rossiiskogo-zakonodatelstva-v-sfere-elektroenergetiki-22012018–28012018 (access date: June 13, 2018).
5. Helder Queiroz P.J. The Electricity Reforms in Brazil: Regulation and Entry of New Players. // Instituto de Economia, Federal University of Rio de Janeiro, January, 2009.
6. Access mode: http://peretok.ru/articles/distribution/15466/ (access date: June 13, 2018).
7. Kamashev A.S. Comparative Analysis of Electricity Industry Operation Models in Russia and the World in the context of the Reform Processes // Rossiyskoye Predprinimatelstvo, 2011, Vol. 12, # 3, pp. 105–111.
8. Access mode:https://www.ruscable.ru/news/2017/03/15/V_Rossii_nedostatok_konkurentsii_na_roznichnom_ryn/ (access date: June 13, 2018).

9. Carriello F. The Italian electricity market // The Regulatory Authority for Electricity and Gas / Market Department, 6 October 2008.

10. Morgan J.P. International Experience of Electric Power Sector Reforming as Applied to Russia. January, 2001.

11. Bruno José Marques Pinto. Regulatory Reforms and Restructuring of the US Electricity Sector: What Happened in California? // Undergraduate School of Economics, EPGE/FGV, June, 2005.

Alexei V. Barkov,
Dr. of Law Science, Professor, Department of Economic activities legal regulation, Financial University under the Government of the Russian Federation

Eugene L. Vengerovskiy,
lecturer, Department of Economic activities legal regulation, Financial University under the Government of the Russian Federation

Natalia V. Zalyubovskaya,
Ph.D., Associate Professor of Department Economic activities legal regulation of the Financial University under the Government of the Russian Federation, member of the Executive Committee of the coordination Council of The International Union of Lawyers, Director of the financial and legal group "Territory of the law"

CONTENTS

VOLUME 27 NUMBER 2 2019

LIGHT & ENGINEERING
(SVETOTEKHNIKA)

PARTNERS OF LIGHT & ENGINEERING JOURNAL

Editorial Board with big gratitude would like to inform international lighting community about the Journal Partners Institute establishment. The list with our partners and their Logo see below. The description of partner's collaboration you can found at journal site *www.sveto-tekhnika.ru*

BL Group
International Lighting Engineering Corporation
BOOS LIGHTING GROUP

ВНИСИ

REFLUX
HID Lighting systems

interlight
MOSCOW
powered by light+building