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Outdoor lighting system upgrading based on Smart Grid concept

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Abstract

The article studies the matters of Smart Grid concept implementation within outdoor lighting systems. Present work examines technical and economic mechanism of evolutionary modernization of external lighting systems in one of the largest Russian universities on the basis of implementation of intelligent systems of control over LED-illuminants. The goal of the upgrade project, which involves Smart Grid technologies, is stepping up efficiency and operation reliability. This paper evaluates the payback period of the modernization project – the outdoor lighting system of a university campus – based on light emitting diode lamps, which feature enhanced operational reliability. The payback period of initial investment taking into account the repayment target financing is 4 years and 10 months.

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Keywords: Smart Grid; energy saving; energy efficiency; lighting system; repayment target financing

1. Introduction

The priority area of the state policy for the development of energy infrastructure of the Russian Federation is the performance of activities relating to energy saving in all spheres of the national economy. The electricity consumption for lighting represents 19% of the world's total electricity consumption [1]. Lighting of street and buildings accounts for up to 75% in electricity demand of lighting [2]. Therefore, the issue of energy saving in street lighting systems is a very important. The main trend of lighting products development is to increase the requirements for energy efficiency and environmental performance of products and improve the performance of the produced products [3-5]. Streetlights are equipped with modern electronic control gear for monitoring and control [3, 6-8]. One of the central focus areas of increasing efficiency of complex street lighting systems is the implementation of automated control

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systems. Modern automated outdoor lighting systems allow operative from a central console to manage the completely lighting system and each luminaire separately [9-12].

The analysis of various literature sources shows that the main task of the developers of advanced systems of automated street lighting control is to increase reliability and durability of control networks, as well as to increase the level of safety of people and traffic safety [13-15], to increase the quality and efficiency of street lighting and court area lighting, to reduce operational costs relating with maintenance of street lighting control networks, to reduce financial costs of payment for electricity consumed in order to ensure outdoor lighting.

2. Implementation of the Smart Grid concept within outdoor lighting systems

Currently experts in the Russian Federation are working on the development and implementation of the new generation of Smart Grids within the energy sector. Implementation of the Smart Grid concept within outdoor lighting systems stipulates for availability of the possibility of customized control and diagnostics of each lamp, which enables to increase energy efficiency and operational reliability of outdoor lighting networks [16, 17]. The energy saving effect can be achieved largely owing to dimming of lighting fixtures (flexible adjustment of brightness of lamps) during the day depending on conditions of natural lighting and special requirements to natural brightness and to the intensity of illumination depending on the time of day. Dimming of lighting fixtures can be technologically achieved by applying special electronic devices, which are built inside lighting fixtures. At the same time, the modern approach to creating a system of street lighting control with the dimming function provides for the implementation of a function of targeted dispatch of control commands from automated power sources to lighting fixtures. This enables to perform customized or group-level adaptable control of operation of lighting fixtures by introducing differentiated modes of reduced (dimmed) brightness of lamps and accounting for the requirements to the quality of outdoor lighting of certain segments of roads.

The result of implementation of this function is the achievement of the maximum possible savings of electric energy while ensuring the required level of brightness. Customized dimming provides additional opportunities for energy savings.

Control of operating modes and technological parameters of lighting fixtures in real time mode enables to improve the quality of operation of lighting networks as it enables to quickly obtain information about the status of a particular lamp and identify possible faults in lighting networks.

In outdoor lighting systems, there are various types of lamps used. For example, LED lamps (light emitting diode lamps), high-pressure sodium arc lamps (HPS), plasma lamps, light emitting diode lamps, etc. Despite the high-energy efficiency of LED sources of light, their utilization in street lighting systems is constrained by their high cost. In the forecasted period, the trend for replacement of mercury arc lamps with energy efficient light sources and lighting fixtures based on this technology will continue; also outdoor lighting fixtures will be equipped with advanced ECG systems (electronic control gear) in order to control and manage operation of lighting fixtures.

This is why the hybrid system of street lighting is the optimum one, as it enables to control operability and ensures real time flexible control of various types of lighting fixtures.

Advanced hybrid systems of automated street lighting control are based on a three-tier architecture, which includes:

- Local control block of a lamp or a group of lamps inside a street lighting fixture
- Zonal control level cabinet (street or quarter)
- Area's central server

The new methods of street lighting control based on network technologies enable to configure street lighting in real time mode and in a scientifically justifiable and dynamic manner. This solution is able to not only save a great amount of electricity but also reduce environmental pollution relating with the generation of electric energy.

The three-tier system of automated street lighting control is shown in Fig. 1.

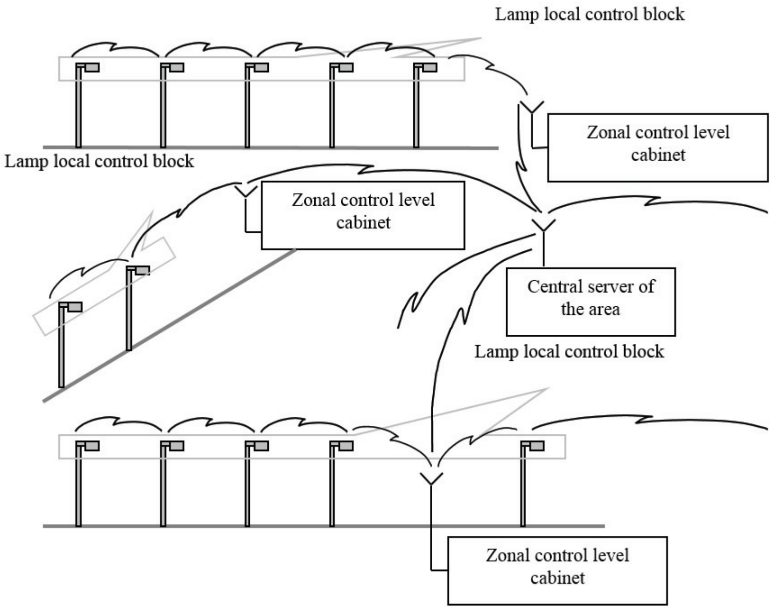

Fig. 1. The three-tier system of automated street lighting control

Urban outdoor lighting is rated and regulated depending on the category of road (highways, district roads, etc.) and the amount (intensity) of traffic per unit of time (per hour). Normally in the course of designing street lighting systems, they provide for a certain technological reserve depending on wattage of lamps - 10% - 15%. These factors in reality often result in excessive level of illumination of streets and roads, which leads to direct losses of electric energy. This is especially the case for nighttime lighting as traffic intensity is significantly lower. Therefore the Russian Federation adopted its SNiP (Construction Norms and Regulations) No. 23-05-95* "Natural and artificial lighting." These regulations allow for reduction of the level of brightness during nighttime hours by up to 50% (energy saving mode). However, the duration of an energy saving lighting mode is adjusted depending on traffic intensity.

Technologically the control of the level of illumination is performed by way of dimming of lighting fixtures (adjustment of a lamp's brightness level) using electronic devices, which are built inside lamps of various types (for instance, HPS, electrodeless lamps, LED lamps, and plasma lamps).

The approach to devising an outdoor lighting control system with the dimming function provides for the implementation of a communication system for targeted dispatch of control commands from automated power sources to lighting fixtures. This enables to perform customized or group-level adjustment of the brightness level of lamps by introducing energy saving modes of dimmed brightness. The main criterion for switching the lighting modes is the schedule, which is programmed for each day of a calendar year (Fig. 2). Brightness sensors can also be used for the adjustment of switch on/off time.

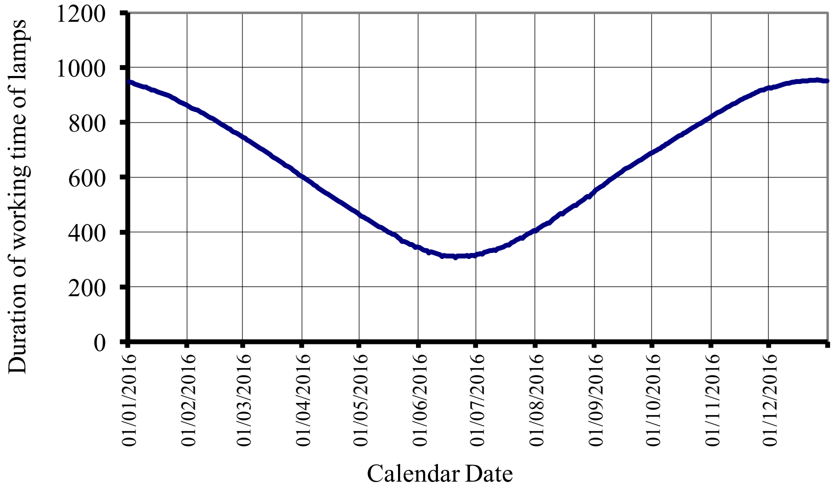

Fig. 2. Schedule for switching the lighting modes

In order to increase the comfort level within the energy saving mode additional brightness gradations can be introduced. The switching between the said gradations of brightness is programmable. The interval of time of switching is preliminarily calculated based on the analysis of traffic intensity level.

Due to the current economic conditions, the amount of initial sources of financing of the works is limited; therefore, it is expedient to enhance financing based on the existing potential for energy saving based on technical and economic mechanism of repayment target financing. The scheme of repayment target financing (funding) stipulates for allocation of initial budget funding for the partial performance of energy efficient works. It is proposed to allocate the funds from savings to the repayment target fund. Further funding of the works will be performed using the savings – assets of the repayment target fund [18].

3. Technical and economic approach of the repayment target financing

The goal of implementation of the automated control system possessing flexible iterative structure and being able to adjust brightness of the street lighting smoothly is to improve energy efficiency, reliability and quality of the street lighting, due to the centralized automated and real-time dispatcher control for the operating mode of the light emitting diode lamps designed for lighting of streets, facilities, cities and towns being in moderately cold climates.

To analyze and justify the study, it's necessary to estimate the economic efficiency of the street lighting system modernization including implementation of the automated dispatcher control system and replacement of the current lamps by more efficient light emitting diode ones.

The economic efficiency of implementation and operation of the automated dispatcher control system results from the following main factors:

- Switching on/off the lights based on the actual level of daylight, daylight hours and weather factors (operation mode adjustment "dull day" or "sunny day");
- Efficient operating mode lying in partial lighting during night hours based on the individual phase control for power supply (cut-off of the first phase during night hours) or smooth reduction the light emitting diode lamps capacity;
- Savings due to increased useful life of lamps resulting from the reduced time the lamps being switched on;
- Payment based on the metering stations measurements and actual consumption, not on the set capacity;
- Ability to control illegal hooking up based on the readings of the electric meters, enabling the user to monitor changes in the actual power consumption, currents, and phase wise voltage ;

- Savings due to the accident-preventative measures: emergency prevention, maintenance savings, transport costs, increased operating time of the devices (lamps, cables) etc.

The estimate cost requires month-wise operating parameters of the street lighting system unequipped with the automated dispatch control system (ADCS) and equipped with the automated control system operating in the mode of partial lighting during night hours based on the standards.

The estimate cost is based on the assumption that due to the potential reliability improvement of the implemented light emitting diode lamps and reduced time of the lamps being switched on in the automated dispatcher control system their operating life increases from 10 up to 12 years.

Besides, the process of the gradual implementation of the energy efficient street lighting systems suggests initial budgetary financing partially covering implementation of the energy efficient systems. The obtained saving is practicable to keep in the repayment target fund. Further financing of the system implementation is performed by means of the savings from the payment target fund.

At this stage, it is necessary to estimate the initial volume of financing required for gradual implementation of the street lighting systems.

Based on the volume of financing, the number of lamps, which will be replaced by the adjustable light emitting diode lamps during gradual implementation of the automated dispatcher control system, is estimated.

We hereby calculate the payback period of replacement of a HPS lamp with a LED lamp, taking into account both the fixed rate and increased electricity rate.

The cost of replacement C_{repl} of the existing lighting fixture with MSI circuit with ADCS (including installation):

$$C_{repl} = C_{LED} + C_{lamp.repl} + C_{ADCS}, \tag{1}$$

Where C_{LED} – cost of a LED lamp, RUB; $C_{lamp.repl}$ – cost of replacement of a lamp, RUB; C_{ADCS} – specific cost of ADCS (software and hardware and communications) calculated as per 1 lamp, RUB/lamp.

Specific cost of ADCS (software and hardware and communications) calculated as per 1 lamp:

$$C_{ADCS} = \left(C_{impl} + C_{grid}\right) \cdot \frac{1}{N} \tag{2}$$

where C_{impl} – cost of implementation of ADCS, RUB; C_{grid} – cost of connection to the grid, RUB; N – number of replaced LED lamps controlled by the dispatch control system (ADCS).

Consumption of electric energy by a LED lamp per year:

$$G_{LED} = \sum_{i=1}^{365} P_{LED} \cdot t_{hi} \tag{3}$$

where G_{LED} – electricity consumption, kWh; P_{LED} – LED wattage, W; t_{hi} – working hours of lighting system per day. The number of working hours in the month we obtain from the Fig. 2.

Consumption of electric energy by the existing HPS lamps per year:

$$G_{HPS} = \sum_{i=1}^{365} P_{HPS} \cdot t_{hi} \tag{4}$$

where G_{HPS} – consumption of HPS electric energy, kWh; P_{HPS} – wattage of HPS, W.

Electric energy savings due to replacement of one HPS lamp with a LED lamp we calculate using the following formula:

$$S_{LED} = (G_{HPS} - G_{LED}) \cdot C_c \quad (5)$$

where S_{LED} – savings of electric energy due to using LED, RUB; C_c – cost of kWh - common rate, RUB/kWh.

Amount of cash funds saved due to replacement of HPS lighting fixture with an adjustable LED lamp we calculate using the following formula:

$$S_{ADCS} = C_C \cdot G_{LED} \cdot S \cdot \frac{1}{100} \quad (6)$$

where S_{ADCS} – additional savings from using ADCS, RUB; C_C – cost of kWh – common rate, RUB/kWh; G_{LED} – consumption of LED electric energy, kWh; S – Savings of electric energy due to the implementation of ADCS, %.

Savings from maintenance of a LED lamp as compared with a HPS lamp we calculate as following:

$$S_{m.LED} = C_{m.HPS} - C_{m.LED} \quad (7)$$

where $S_{m.LED}$ – Savings from maintenance of LED, RUB; $C_{m.HPS}$ – HPS maintenance costs, RUB; $C_{m.LED}$ – LED with ADCS maintenance costs, RUB.

Accumulated savings from replacement of a lighting fixture with a HPS lamp with a LED lamp we calculate using the formula:

$$AS_{LED} = S_{LED} + S_{ADCS} + S_{m.LED} \quad (7)$$

where AS_{LED} – accumulated LED savings, RUB per month.

Further expenses from the fund are equal to the savings obtained during the previous period.

4. Software for Designing the Process of Evolutionary Energy Efficient Street Lighting Systems

Street lighting system development planning requires the use of up-to-date techniques and tools reducing span time. Simulation modeling is the effective way adequate to the tasks being solved. It is based on a scenario approach. Simulation models allow running different options of enterprise development and external economic environment condition. They allow checking various ideas, hypotheses and assumptions regarding business development, analyzing the impact of their implementation [16-18].

One of the options for creating software for designing the process of evolutionary implementation of energy efficient street lighting systems based on innovative technical and economic mechanism of repayment and purpose-oriented leveraging of budget financing is the use of Microsoft Excel spreadsheets with pre-programmed operational sequences (programs) written in Visual Basic for Applications (VBA) programming language. This option is universal because today Microsoft office program suite is the most common in the Ural region and in Russia as a whole.

The program contains items with data entry, calculation of economic parameters and output of calculation results as graphs and spreadsheets to the user's monitor and to the printer is developed.

Basic input data for the calculation includes lamp specifications such as installed capacity and the number of working lamps in the lighting system.

In addition, tariff details for the current calculation period with the forecast are input data for the calculation.

Figure 3 shows the basic parameters of financing in case of budget deficit, i.e. the options of partial initial financing for lighting system modernization project.

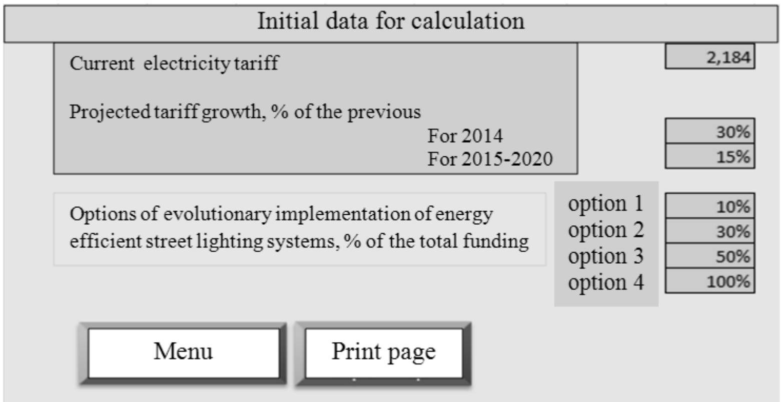

Fig. 3. The basic parameters of amount of financing in case of budget deficit

This software provides 4 options of evolutionary implementation of energy efficient street lighting systems based on innovative technical and economic mechanism of repayment and purpose-oriented leveraging of budget financing.

When entering basic data on operation of street lamps with breakdown by month, a calculation is carried out of reducing operation (lighting) time of lamps in street lighting system in case of implementation of automated dispatch control system with smooth luminance control. The case of 30% decrease in lamp brightness is considered in the calculations.

Figure 4 shows an option of funds saving calculation in case of evolutionary implementation of energy efficient street lighting systems depending on the year of modernization program execution at partial initial funding of the program for 10%.

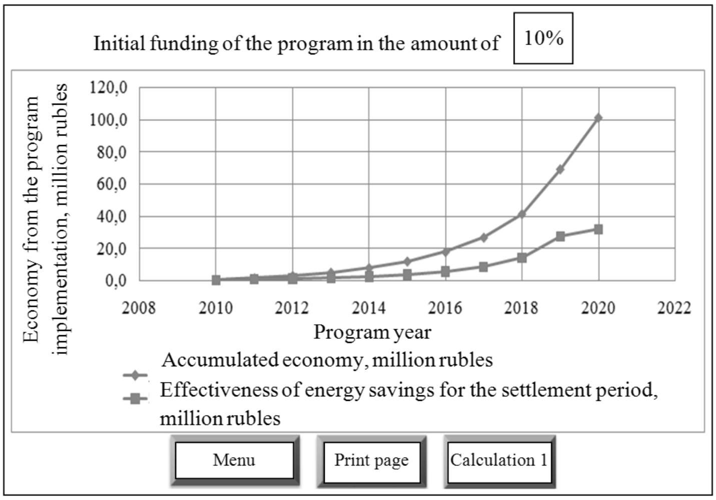

Fig. 4. Option of funds saving calculation in case of evolutionary implementation of energy efficient street lighting systems

Comparison of four options of lighting system modernization calculation is possible. You can view execution efficiency charts for lighting system modernization program.

5. The estimated payback of the street lighting system modernization in the campus of South Ural State University (National Research University)

The study provides the estimated cost of the street lighting system modernization based on the implementation of the automated dispatcher control system and light emitting diode lamps possessing high operational reliability. As a result of implementation of the automated dispatcher control system and optimization of the light emitting diode lamps to achieve their maximum functional efficiency based on the their weight and dimensions, the operating life of the light emitting diode lamps increases from 10 up to 12 years, and, consequently the functional efficiency of the light emitting diode lamps improves.

The estimated payback of the street lighting system in the campus of South Ural State University (National Research University) is based on the following values:

- The number of the lamps in the lighting system subjected to replacement with the light emitting diode lamps - 101 pc.,
- the lamp type – high-pressure sodium arc lamp (HPS), 250 W,
- the capacity of the light emitting diode lamps that will be installed constitutes 110 W,
- the number of hours the lighting street system operates for Chelyabinsk per year – 3,866 hours,
- the estimated cost of the dispatcher center for South Ural State University (National Research University) – 510 kRUB,
- the estimated cost of the control center of South Ural State University (National Research University) – 140 kRUB,
- the estimated cost of the automated dispatcher control system implementation - 650 kRUB,
- the estimated saving of the electricity due to the automated system and reduced time of operation during night hours constitutes 39 per cent.

Figure 5 shows the graphs of the saved funds in relation to the year when the modernization program of the street lighting system is fulfilled. Figure 5 illustrates the initial investment, savings from the introduction of outdoor lighting control system and the savings from the introduction of outdoor lighting management system considering the initial investment for the purchase of LED lights. Modernization of the street lighting system together with implementation of the automated dispatcher control system and installation of the 101 light emitting diodes lamps across the campus of South Ural State University (National Research University) gives the payback period equal to 6.6 years.

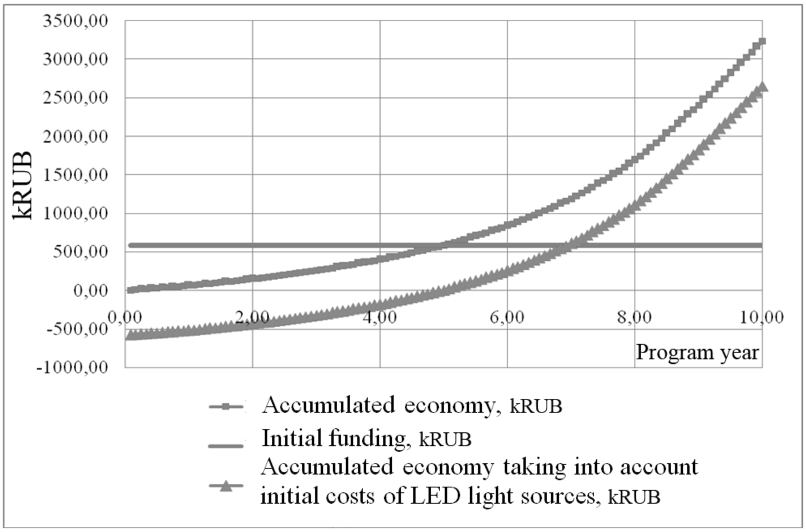

Fig. 5. Cash funds saved in relation to the year when the modernization program of the street lighting system

Table 1 shows the comparison of payback period of the outdoor lighting system modernization project in case of replacement of lamps with LED lamps and the implementation of the Automated Dispatch Control System (ADCS).

Table 1. The comparison of payback period of the outdoor lighting system modernization project.

№	Modernization option	Savings of electric energy per estimated useful lifetime, kRUB/lamp	Savings in maintenance, kRUB/lamp	Payback period, years
1	Implementation of ADCS and replacement of all lamps with LED lamps	20.8	9.9	6.6
2	Implementation of ADCS and replacement of all lamps with LED lamps and increasing electricity rate by 10% per annum	37.0	9.9	5.6

Due to the long payback periods of the projects aimed for modernization of the street lighting system together with implementation of the automated dispatcher control system and installation of the light emitting diodes lamps, as well as limited budget financing, the repayment target financing projects should be considered.

The initial investment for RUB 575,000 together with the repayment target financing under the period considered enables modernization of the entire street lighting system in the campus of the National Research South Ural State University.

The payback period of the initial investment together with repayment target financing constitutes 4 years and 10 months. The payback period is lower than shown in Table 1. This is related to the fact that the repayment target financing assumes reduction of the initial investment. Thus, obtained savings are used for the further modernization of the lighting system.

We evaluated the payback period and cost savings of electricity for outdoor lighting system modernization of South Ural State University including branches in Chelyabinsk region. Table 2 shows specific (per 1 lamp) indicators of efficiency of the implementation of a smart hybrid ADCS for outdoor lighting depending on the rates for electricity consumed with the following options:

- Option A: The current electricity rate in Chelyabinsk Region for municipal enterprises. The rate is RUB 1.457 per 1 kWhe;
- Option B: The rate is RUB 1.457 per 1 kWhe accounting for the electricity rate increase by 10% per annum.

Table 2. Comparison table of specific indicators of efficiency of various uses of lamps.

№	Parameter	Option	Replacement of lamps with LED lamps (without ADCS), estimated useful lifetime is 10 years	Implementation of ADCS, replacement of lamps with LED lamps, estimated useful lifetime is 12 years
1	Operational expenses by the line items purchases and replacement during estimated useful lifetime, kRUB/lamp	10 years	15.5	–
		12 years	–	19.5
2	Electric energy savings during estimated useful lifetime, kRUB/lamp	Current rate	10.7	15.9
		Accounting for electricity rate increase by 10% per annum	17.0	28.3
3	Payback period, months (years)	Current rate	81 (6.75)	89 (7.42)
		Accounting for electricity rate increase by 10% per annum	71 (5.92)	75 (6.25)
4		Current rate	6.8	10.3

Total accumulated savings during estimated useful lifetime, kRUB/lamp	Accounting for electricity rate increase by 10% per annum	13.1	22.8

Testing of a new system has shown its undeniable predominance in comparison with outdated standard technologies. Main competitive advantages of innovative technologies are following: monitoring; remote control and measuring; overall improvement of the quality of electric power; lower operational expenditures; reduction of expenses for visual examinations of the system; calculation of time and working parameters of specific equipment in automatic mode, aimed at performing timely preventive maintenance; fast and easy access in the database of the system; reduction of electric energy losses; reduction of the rate of light and noise contamination; improvement of security and reliability; flexibility of the system in case of alteration of external conditions; and improvement of environmental conditions.

6. Conclusion

Promotion of the Smart Grid concept in the Russian Federation is in its early stages. At the same time, the advantages of smart power grids over conventional grids are obvious: Increased operational reliability, energy efficiency, environmental preservation, and their economic efficiency. However, the implementation of a holistic concept of a smart power grid entails a number of difficulties including technological, regulatory and legal, financial ones, etc. This is precisely why the Smart Grid system has not been fully implemented in Russia.

Thus, the following must be performed in order to achieve energy savings effect in outdoor lighting systems:

- Application of advanced lighting equipment in energy saving projects. Such equipment and systems employ controllable light sources which yield the maximum energy saving effect. The energy saving effect can be achieved for the most part thanks to adjustable control of lighting fixtures during the day depending on conditions of natural lighting and special requirements to light brightness depending on the time of day;
- While designing outdoor lighting systems one should provide for the possibility to transfer data which enable to control operating modes and technological parameters of lighting fixtures in real time mode which enables to improve the quality of operation of lighting networks as it enables to quickly obtain information about the status of a particular lamp and to identify possible faults in lighting networks and, as a consequence, to improve the quality of operation of lighting networks;
- Enhancement of funding of outdoor lighting system modernization taking into account the current budget deficit and based on the existing potential for energy savings and the technical and economic mechanism of repayment target financing.

This paper evaluates the payback period of the modernization project – the outdoor lighting system of a university campus – based on light emitting diode lamps, which feature enhanced operational reliability.

The payback period of initial investment taking into account the repayment target financing is 4 years and 10 months.

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