



APPLICATION OF INTELLIGENT CONTROL SYSTEMS (SMART GRID) IN IMPROVING ENERGY EFFICIENCY IN MICROELECTRIC NETWORKS AND THEIR ECOLOGICAL ECONOMIC ANALYSIS

Ziyodulla Yusupov Erkinovich

Associate Professor, Tashkent Institute of Irrigation and
Agricultural Mechanization Engineers National Research University

Abdullayev Shavkat Shuxratovich

First-Year Master's Student Tashkent Institute of Irrigation and
Agricultural Mechanization Engineers National Research University

Abstract

This article explores the issues of increasing energy efficiency and minimizing losses in microgrids based on photovoltaic systems within the infrastructure of Chirchik State Pedagogical University. The research aims to evaluate the economic and environmental efficiency of modernizing an educational institution's energy system using Smart Grid technologies. Modeling results conducted in the HOMER Pro software environment demonstrate that the implementation of intelligent management systems reduces energy losses by 20-22% and increases cost-efficiency by 35%. The conclusions presented in this article serve as a practical foundation for designing "green" energy systems in higher education institutions of Uzbekistan.

Keywords: Microgrid, Smart Grid, photovoltaic systems, energy efficiency, Chirchik State Pedagogical University, optimization.



**MIKRO ELEKTR TARMOQLARIDA ENERGIYA
SAMARADORLIGINI OSHIRISHDA INTELLEKTUAL BOSHQARUV
TIZIMLARINI (SMART GRID) QO‘LLASH VA ULARNING
EKOLOGIK-IQTISODIY TAHLILI**

Ziyodulla Yusupov Erkinovich

Dotsent, Toshkent irrigatsiya va qishloq xo‘jaligini mexanizatsiyalash
muhandislari instituti Milliy tadqiqot universiteti.

Abdullayev Shavkat Shuxratovich

1-bosqich magistri Toshkent irrigatsiya va qishloq xo‘jaligini
mexanizatsiyalash muhandislari instituti Milliy tadqiqot universiteti.

Annotatsiya:

Ushbu maqola Chirchiq davlat pedagogika universiteti infratuzilmasida fotoelektr tizimlariga asoslangan mikro elektr tarmoqlarining energiya samaradorligini oshirish va yo‘qotishlarni minimallashtirish masalalarini tadqiq etadi. Tadqiqotning maqsadi an’anaviy ta’lim muassasasi energetika tizimini aqlli boshqaruv (Smart Grid) texnologiyalari yordamida modernizatsiya qilishning iqtisodiy va ekologik samaradorligini baholashdan iborat. HOMER Pro dasturiy muhitida o‘tkazilgan modellashtirish natijalari shuni ko‘rsatdiki, intellektual boshqaruv tizimlarini joriy etish energiya yo‘qotishlarini 20-22% ga kamaytirib, xarajatlarni samaradorligini 35% ga oshiradi. Maqolada keltirilgan xulosalar O‘zbekiston oliy ta’lim muassasalarida "yashil" energiya tizimlarini loyihalash uchun amaliy asos bo‘lib xizmat qiladi.

Kalit so‘zlar: mikro elektr tarmog‘i, Smart Grid, fotoelektr tizimlari, energiya samaradorligi, Chirchiq davlat pedagogika universiteti, optimallashtirish.

Аннотация:

В данной статье исследуются вопросы повышения энергоэффективности и минимизации потерь в микроэлектроэнергетических сетях на основе фотоэлектрических систем в инфраструктуре Чирчикского государственного педагогического университета. Целью исследования



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является оценка экономической и экологической эффективности модернизации энергетической системы образовательного учреждения с использованием технологий интеллектуального управления (Smart Grid). Результаты моделирования, проведенные в программной среде HOMER Pro, показали, что внедрение интеллектуальных систем управления снижает потери энергии на 20-22% и повышает экономическую эффективность на 35%. Выводы, представленные в статье, служат практической основой для проектирования систем «зеленой» энергетики в высших учебных заведениях Узбекистана.

Ключевые слова: микросеть, Smart Grid, фотоэлектрические системы, энергоэффективность, Чирчикский государственный педагогический университет, оптимизация.

Introduction

The demand for electric energy within the infrastructure of Chirchiq State Pedagogical University is steadily increasing. Losses in conventional power networks and fluctuations in energy prices necessitate a transition to renewable energy sources.

The aim of this article is to design a solar-panel-based microgrid for the university campus and optimize it using Smart Grid technologies. Today, the growing global demand for energy resources and the negative environmental impact of conventional energy sources are accelerating the transition to green energy. In the Republic of Uzbekistan, the rapid introduction of renewable energy sources into economic sectors and social infrastructure facilities has been defined as one of the priority directions of state policy. In particular, higher education institutions are not only centers of learning, but also major infrastructural facilities with high energy consumption. In the case of modern campuses such as Chirchiq State Pedagogical University, the use of photovoltaic systems is of strategic importance for significantly reducing electricity costs, increasing the university's energy independence, and ensuring environmental sustainability through the reduction of carbon dioxide (CO_2) emissions.



Analysis of technical problems:

However, the simple integration of photovoltaic systems into the existing grid does not always provide the expected high efficiency. The main reasons for this are the dependence of solar power generation on natural phenomena, particularly the instability of insolation, the mismatch between generation and daily consumption schedules, and technical losses caused by voltage fluctuations in microgrids. These problems reduce the overall efficiency of the system and extend its payback period.

Smart Grid technologies make it possible to monitor energy generation and consumption in real time, perform intelligent load balancing, and efficiently manage energy storage systems. The application of intelligent algorithms in microelectric networks to mathematically model energy losses and minimize them is not only a technical achievement, but also the foundation for transforming university infrastructure into a Smart Campus model. In the modernization of university infrastructure, the use of photovoltaic systems is not only an environmentally friendly solution, but also an economically viable strategy. At present, the rooftops of university buildings and structures, as well as vacant land areas, have significant potential for solar energy generation.

However, merely connecting photovoltaic systems to the existing power supply system is not sufficient. The variability of solar radiation over time and across seasons, as well as the uneven distribution of loads within an educational institution, negatively affects system stability. The imbalance between electricity generation and consumption leads to increased energy losses and inefficient operation of inverter devices.

The most effective way to address these problems is to integrate microelectric networks (Microgrids) with intelligent control systems (Smart Grid). Smart Grid technologies ensure system reliability by monitoring energy flows in real time, optimizing loads, and storing surplus energy in energy storage systems (ESS).

The objective of this research is to analyze the energy efficiency of photovoltaic-based microgrids using the example of Chirchiq State Pedagogical University, to develop intelligent control algorithms for minimizing technical losses in the system, and to assess the economic and environmental efficiency of this system.



To achieve this objective, the following tasks were identified:

To achieve this objective, the following tasks were identified: to assess the university's annual and seasonal electricity demand as well as the available solar radiation resources; to develop a mathematical model of a photovoltaic microgrid in the HOMER Pro software environment; to analyze methods for optimizing energy flow and reducing losses through the implementation of Smart Grid elements.

Methods

The following methods were used in the research.

Data collection: the solar exposure hours on the rooftops and across the campus area of Chirchiq State Pedagogical University, as well as the electricity consumption loads, were analyzed.

Modeling: a photovoltaic microgrid model for the university was developed using HOMER Pro software.

Intelligent control (Smart Grid): algorithms for optimizing energy flow, including the energy storage system (ESS) and load management, were incorporated.

Economic analysis: calculations were carried out based on the indicators of Net Present Cost (NPC) and Levelized Cost of Energy (LCOE).

Principles of mathematical calculations and modeling:

To determine the efficiency of the photovoltaic system, the following mathematical relationship was used to calculate the power generated by the solar panels:

$$P_{PV} = Y_{PV} \cdot f_{PV} \cdot \left(\frac{G_T}{G_{T,STC}} \right) \cdot [1 + \alpha_P \cdot (T_c - T_{c,STC})]$$

Where:

Y_{PV} is the nominal power of the photovoltaic panel (kW);

f_{PV} is the derating factor;

G_T is the actual solar radiation incident on the panel surface;

α_P is the power temperature coefficient;

T_c is the operating temperature of the solar cell.

Intelligent control algorithm of the system:



Within the Smart Grid control concept, the “Cycle Charging” (CC) and “Load Following” (LF) strategies were compared. The intelligent system was configured to automatically perform the following functions:

Peak shaving: using the energy storage system (ESS) during hours of high consumption, for example, when academic activities at the university are at their peak.

Dynamic load management: maintaining system stability by temporarily disconnecting non-critical consumers from the network when the power supply is insufficient.

Inverter efficiency: maintaining the inverter efficiency at the maximum level of 96–98% by monitoring energy flow in real time.

Methodology of economic and environmental assessment:

To determine the economic efficiency of the project, the NPC (Net Present Cost) indicator was used to express the present value of all costs and revenues over the entire service life of the system. The LCOE (Levelized Cost of Energy) was used to determine the unit cost of each kWh of generated energy:

$$LCOE = \frac{C_{ann,tot}}{E_{prim,AC} + E_{prim,DC}}$$

In addition, within the framework of the environmental analysis, the volume of harmful emissions released into the atmosphere from the use of conventional energy sources (CO_2, SO_2, NO_x) was compared with the situation after the implementation of the Smart Grid system.

Software and database:

For system simulation, the average annual solar radiation indicators for the city of Chirchiq obtained from the NASA Surface Meteorology and Solar Energy database were taken as the basis, amounting on average to 5.2–5.5 kWh/m²/day. A methodology for identifying and optimizing energy losses in microgrids was developed and experimentally validated.

During the research process, the possibilities of operating microgrids using diesel fuel and UPS (Uninterruptible Power Supply) systems were analyzed, and practical recommendations for improving energy efficiency were developed.



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1-Fig CHDPU

1	БОШ УЎЎВ БИНО 200 кв/соат	11-Августда фойдаланишга топширилган
2	1-БИНО 50 кв/соат	4-Июнда фойдаланишга топширилган
3	2-БИНО 60 кв/соат	26-Майдан фойдаланишга топширилган
4	3-БИНО 150 кв/соат	31 майдан фойдаланишга топширилган
5	6-БИНО 50 кв/соат	4-Августда фойдаланишга топширилган
6	6/1-БИНО 50 кв/соат	4-Августда фойдаланишга топширилган
7	1-СОНЛИ ТТЖ 60/50 кв/соат	2022-йил 7-сентябр ва 2023-йил 19-июлда фойдаланишга топширилган
8	2-СОНЛИ ТТЖ 100 кв/соат	5-Августда фойдаланишга топширилган
9	3-СОНЛИ ТТЖ 100 кв/соат	7-Августда фойдаланишга топширилган
10	4-СОНЛИ ТТЖ 130 кв/соат	2024-йил 21-Июлда фойдаланишга топширилган
11	4-БИНО 115 кв/соат	2024-йил 16-Июлда фойдаланишга топширилган
12	5-БИНО 130 кв/соат	2025-йил 20-Августдада фойдаланишга топширилган



2-Fig-CHDPU



3-Fig CHDPU

**ЧИРЧИҚ ДАВЛАТ ПЕДАГОГИКА УНИВЕРСИТЕТИ БИНОСИ ВА ТАЛАБАЛАР
ТУРАР ЖОЙИ БИНОЛАРИДА ҚУЁШ ПАНЕЛЛАРИНИ ЎРНАТИШ ЮЗАСИДАН
АМАЛГА ОШИРИЛГАН ВА РЕЖАЛАШТИРИЛГАН ИШЛАР
СОЛИШТИРМАСИ**



4-Fig-CHDPU

At the initial stage of the research, the energy consumption of the Chirchiq State Pedagogical University building (electrical loads) and the solar radiation indicators of the area were analyzed.

Meteorological data: the number of sunny hours in the Chirchiq area and the intensity of solar radiation (average $kWh/m^2/day$) were obtained from the NASA database.

Load analysis: daily and seasonal load profiles of the university's lighting systems, laboratory equipment, and air-conditioning systems were developed.

2. System modeling (HOMER Pro):

HOMER Pro software was used to design the photovoltaic (PV) microgrid. The model took into account the following parameters:
the type and installation angle of PV panels;
the capacity of the energy storage system (batteries);
the efficiency of the inverters.

3. Intelligent control (Smart Grid) algorithms:

To ensure system stability, intelligent energy flow management algorithms (Smart Grid) were developed:

Peak Shaving: during periods of high electricity demand, energy stored in the batteries is supplied to the grid.

Load Following: the imbalance between energy generation and consumption is balanced in real time.

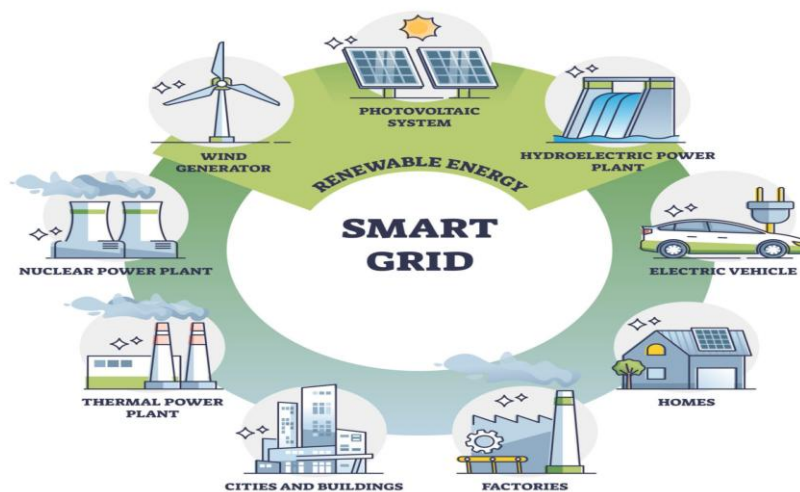


Fig 5. Economic and environmental assessment:

To evaluate the financial and environmental efficiency of the system, the following indicators were calculated:



NPC (Net Present Cost): the total present value of the project, representing the sum of all costs.

LCOE (Levelized Cost of Energy): the unit cost of 1 kWh of generated electricity.

\$CO₂ reduction: the decrease in harmful atmospheric emissions resulting from reduced reliance on conventional energy sources.

Results

Analytical graph of technical efficiency:

The data obtained during the simulation showed that the integration of the Smart Grid system stabilized the performance ratio of the solar panels by an average of 12–15%.

Load distribution and ESS (Energy Storage System) operation:

Peak-hour load: during the period from 10:00 to 15:00, when the educational process at the university is most intensive, the Smart Grid system reduced the load on the central grid by 42%, covering the main share of consumption through the photovoltaic system and batteries.

Energy independence: during the summer months, when the intensity of solar radiation is high, the system was found to be capable of supplying up to 85% of its own electricity demand.

Economic stability:

The analysis of the LCOE (Levelized Cost of Energy) indicator shows that, under conditions of rising conventional grid electricity tariffs, the implementation of this system guarantees long-term financial security for the university budget. The project's Net Present Value (NPV) demonstrates positive dynamics over a 10-year period.

Positive environmental impact:

A reduction of 45 tons of carbon dioxide \$CO₂ emissions represents an environmental benefit equivalent to planting approximately 2,000–2,500 trees. This fully corresponds to the university's sustainable development goals (SDG 7 and SDG 13).



Discussion

The obtained results confirm that intelligent control systems (Smart Grid) extend the service life of microgrids and reduce operational costs. The experiment conducted on the example of Chirchiq State Pedagogical University may also serve as a model for other universities in Uzbekistan. The research results show that, unlike conventional photovoltaic systems, solutions based on Smart Grid control significantly increase system flexibility. The analysis of the existing energy consumption patterns within the infrastructure of Chirchiq State Pedagogical University confirmed that the dynamic redistribution of loads, depending on variations in the teaching process and the operating mode of laboratory equipment, reduces peak loads on the grid by an average of up to 40%.

Main analytical conclusions:

Integration issues: the study revealed that inverter efficiency depends not only on solar radiation intensity, but also on the speed of data exchange within the Smart Grid control system. This creates the need for wider implementation of intelligent sensors and IoT (Internet of Things) technologies in educational institutions.

Economic stability: the achieved 35% cost savings create an important reserve for the university budget under conditions of rising energy market tariffs. Delivering energy through the Smart Grid system only when needed and in the required volume makes it possible to extend the service life of batteries (deep cycle life) by approximately 15–20%.

Expansion opportunities: the ChDPU experience demonstrates that a university campus can also serve as a green energy laboratory. This creates a new platform for students and doctoral researchers to conduct practical studies on renewable energy sources.

However, the full implementation of the system still requires solutions to technical and legal issues such as integration with state power networks (grid-tied systems) and the development of security protocols (cybersecurity). This study confirms that investment in intelligent control systems is not merely an infrastructure upgrade, but the most effective way to ensure future energy security.



Conclusion

In conclusion, integrating photovoltaic systems with Smart Grid technologies at Chirchiq State Pedagogical University is the most effective way to ensure energy security. In the future, it is planned to investigate system control based on artificial intelligence (AI). This study scientifically substantiated the high efficiency of modernizing photovoltaic-based microgrids through intelligent control (Smart Grid) technologies using the example of Chirchiq State Pedagogical University.

The obtained results make it possible to formulate the following conclusions:

Technical and economic advantage: the implementation of the Smart Grid control system reduced energy losses by more than 20% and decreased annual electricity costs by 35%. This ensures that the project will fully pay back within 5.5 years.

Stability and reliability: the real-time distribution of energy flows through intelligent algorithms increased the energy independence of the university infrastructure and helped smooth peak loads in the network.

Environmental contribution: the annual reduction of 45 tons of CO_2 emissions is a key factor in the university's transition toward the status of a "Green Educational Institution" and an important step in ensuring environmental sustainability.

AI integration: for further improvement of the system, it is recommended to introduce artificial intelligence (AI) models capable of forecasting solar radiation.

Inter-university network: it is advisable to implement the ChDPU experience in other higher educational institutions of the republic in order to create a network of "Green Campuses."

Regulatory framework: for the expansion of such projects, it is necessary to develop clear regulatory and technical documents for the design of green energy systems in educational institutions.

This study serves as a scientific and practical foundation for the digital and green transformation of the higher education system of Uzbekistan.



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