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IMPROVING THE "SMART CAMPUS" MODEL IN HIGHER EDUCATION INSTITUTIONS BASED ON THE INTEGRATION OF DIGITAL TECHNOLOGIES AND ALTERNATIVE ENERGY

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Abstract. The integration of digital technologies and alternative energy solutions into the activities of higher education institutions is investigated, and the organizational and technological mechanism of the "Smart Campus Uzbekistan" model, adapted to the conditions of Uzbekistan, is improved. The integration of artificial intelligence, the Internet of Things (IoT), Big Data, Digital Twin, Building Energy Management System (BEMS), energy storage systems, and renewable energy sources is analyzed in terms of energy consumption monitoring, demand forecasting, predictive assessment of equipment conditions, and optimization of the campus energy balance. The study employs systematic, comparative, and statistical analysis, technological benchmarking, and phased modeling methods. The results demonstrate the feasibility of implementing the Smart Campus system in five stages: establishing the core digital infrastructure, deploying alternative energy sources, integrating artificial intelligence, enabling P2P energy exchange, and achieving full platform integration. The proposed model is aimed at improving energy efficiency in higher education institutions, reducing energy costs and CO_2 emissions, and integrating real-world energy data into educational processes and scientific research.

Keywords: digital economy, alternative energy, Smart Campus, artificial intelligence, IoT, Big Data, Digital Twin, BEMS, energy efficiency, higher education.

Annotatsiya. Raqamli texnologiyalar va muqobil energetikaning oliy ta'lim muassasalari faoliyatiga integratsiyalashuvi tadqiq etilib, O'zbekiston sharoitiga mos "Smart Campus Uzbekistan" modelining tashkiliy-texnologik mexanizmi takomillashtirilgan. Sun'iy intellekt, Internet of Things (IoT), Big Data, Digital Twin, Building Energy Management System (BEMS), energiya saqlash tizimlari va qayta tiklanuvchi energiya manbalarining o'zaro integratsiyasi energiya iste'molini monitoring qilish, talabni prognozlash, uskunalarning texnik holatini oldindan baholash hamda kampusning energiya balansini optimallashtirish nuqtayi nazaridan tahlil qilingan. Tadqiqotda tizimli, qiyosiy va statistik tahlil, texnologik benchmarking hamda bosqichli modellashtirish usullaridan foydalanilgan. Olingan natijalar Smart Campus tizimini besh bosqichda — asosiy raqamli infratuzilmani shakllantirish, muqobil energiya manbalarini joriy etish, sun'iy intellektni integratsiyalash, P2P energiya almashinuvini yo'lga qo'yish va to'liq platformaviy integratsiyani ta'minlash orqali amalga oshirish maqsadga muvofiqligini ko'rsatadi. Taklif etilgan model oliy ta'lim muassasalarida energiya samaradorligini oshirish, energiya xarajatlarini kamaytirish, CO_2 emissiyasini qisqartirish hamda real energetik ma'lumotlarni ta'lim va ilmiy tadqiqot jarayonlariga integratsiya qilishga yo'naltirilgan.

Kalit so'zlar: raqamli iqtisodiyot, muqobil energetika, Smart Campus, sun'iy intellekt, IoT, Big Data, Digital Twin, BEMS, energiya samaradorligi, oliy ta'lim.

Аннотация. Исследована интеграция цифровых технологий и альтернативной энергетики в деятельность высших образовательных учреждений, а также усовершенствован организационно-технологический механизм модели «Smart Campus Uzbekistan», адаптированной к условиям Узбекистана. Проанализирована интеграция искусственного интеллекта, Internet of Things (IoT), Big Data, Digital Twin, Building Energy Management System (BEMS), систем хранения энергии и возобновляемых источников энергии с точки зрения мониторинга энергопотребления, прогнозирования спроса, предварительной оценки технического состояния оборудования и оптимизации энергетического баланса кампуса. В исследовании применены методы системного, сравнительного и статистического анализа, технологического бенчмаркинга и поэтапного моделирования. Полученные результаты свидетельствуют о целесообразности внедрения системы Smart Campus в пять этапов: формирование базовой цифровой инфраструктуры, внедрение альтернативных источников энергии, интеграция искусственного интеллекта, организация P2P-обмена энергией и обеспечение полной платформенной интеграции. Предложенная модель направлена на повышение энергоэффективности высших образовательных учреждений, снижение затрат на энергоресурсы и выбросов CO_2, а также интеграцию реальных энергетических данных в образовательный процесс и научные исследования.

Ключевые слова: цифровая экономика, альтернативная энергетика, Smart Campus, искусственный интеллект, IoT, Big Data, Digital Twin, BEMS, энергоэффективность, высшее образование.

INTRODUCTION

In the modern economy, digital transformation and the energy transition are becoming complementary strategic directions. While artificial intelligence, the Internet of Things (IoT), Big Data, and cloud technologies are expanding opportunities for managing energy production, distribution, and consumption in real time, renewable energy sources contribute to reducing the environmental and economic constraints associated with conventional energy systems.

Higher education institutions represent a distinct area of this transformation. Since university campuses consist of multifunctional buildings, laboratories, dormitories, and service infrastructure, they provide a suitable environment for the practical implementation and testing of digital energy management solutions. At the same time, Smart Campus infrastructure can serve as a practical laboratory for students and researchers, enabling them to work with real-world data.

The purpose of this study is to systematize the economic and technological effects of integrating digital technologies and alternative energy solutions into higher education and to improve a phased Smart Campus model for higher education institutions in Uzbekistan.

LITERATURE REVIEW

The concept of digital energy, or "Energy 4.0," integrates physical energy infrastructure with digital monitoring, data analysis, and automated management tools. The reviewed materials indicate that digital technologies have the potential to improve energy efficiency, reduce maintenance costs, and minimize energy losses.

The Smart Campus concept is generally interpreted as the integration of physical, digital, and service layers. The physical layer encompasses buildings, energy facilities, and networks; the digital layer includes sensors, databases, and cloud computing; and the service layer comprises AI-based management, forecasting, and user interfaces.

The experience of international universities demonstrates the potential of digital energy solutions to promote energy savings and reduce emissions. Given that the indicators reported by different universities vary in terms of infrastructure, climatic conditions, and calculation methodologies, their application as a basis for technological benchmarking provides a methodologically appropriate approach to comparative assessment.

RESEARCH METHODOLOGY

The information base of the study consisted of materials on digital energy, artificial intelligence, IoT, Smart Campus, Digital Twin, the experience of international universities, and indicators related to the proposed phased implementation model for Uzbekistan. The study employed systematic analysis, comparative analysis, technological benchmarking, grouping, and phased modeling methods.

The effects of AI technologies were systematized across the areas of energy production management, demand forecasting, smart lighting, predictive maintenance, battery management, and grid balancing. For intermediate indicators, the mean values of the specified ranges were used solely for visualization and diagrammatic comparison purposes.

The Smart Campus model for Uzbekistan was divided into five stages in accordance with the principle of technological maturity. For each stage, the implementation period, key activities, technologies, and expected outcomes were assessed in an interconnected manner.

ANALYSIS AND RESULTS

The results of the analysis indicate that the economic efficiency of a Smart Campus is determined not by a single technology but by the integration of multiple digital and energy components. AI facilitates energy production and demand forecasting, IoT enables real-time monitoring, BEMS provides automated management of building energy loads, while Digital Twin technology enables the preliminary assessment of modernization decisions in a virtual environment.

Table 1

Areas of Application of AI Technologies in Alternative Energy and Their Expected Effects[1]

Area of Application	Technology	Efficiency Result	Cost/Disruption Reduction
Solar panel management	Deep Learning (CNN)	+15–20%	−12%

1 Author's elaboration

Energy demand forecasting	LSTM	Accuracy: 94%	−18%
Smart lighting	Reinforcement Learning	+30%	−35%
Predictive maintenance	Random Forest	Disruptions: −60%	Costs: −28%
Battery management	Model Predictive Control	+22%	−15%
Grid balancing	Multi-Agent System	+18%	−20%

The data presented in Table 1 demonstrate that AI technologies perform various functions within energy systems. The highest relative effect is observed in smart lighting systems, where energy efficiency can increase by up to 30%, while costs can decrease by up to 35%. In predictive maintenance, the principal effect is reflected in a reduction in disruptions of up to 60%. These findings demonstrate that, within a Smart Campus, AI serves not only as a tool for energy conservation but also as a means of improving equipment reliability and management quality.

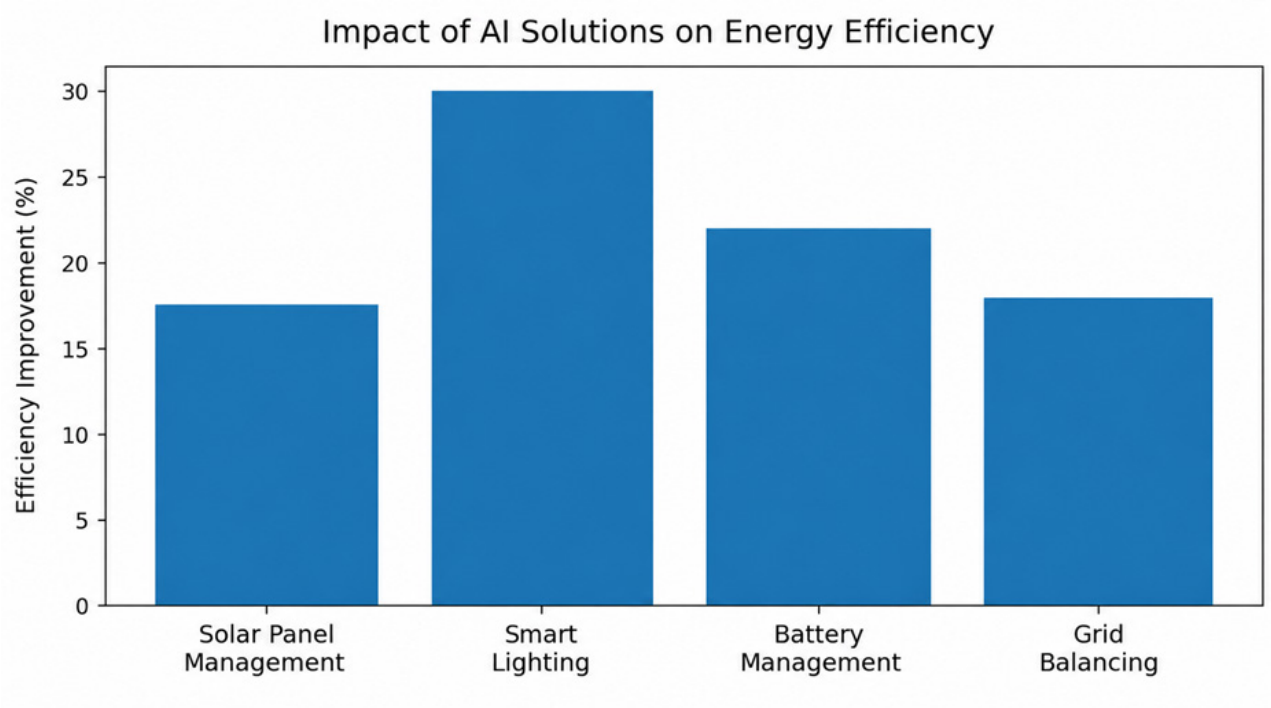

Figure 1. Impact of AI Solutions on Energy Efficiency. Note: For indicators presented as ranges, the mean value of each range was used for graphical representation. Source: Author's elaboration based on the research materials[2]

According to Figure 1, among AI-based management solutions, smart lighting and battery management demonstrate relatively high potential for improving energy efficiency. Since these indicators reflect different technological conditions, they are appropriately interpreted as comparative indicators representing the potential impact range of Smart Campus technologies rather than as a strict ranking.

Table 2
Mechanism for the Phased Implementation of the Smart Campus Model in Higher Education Institutions of Uzbekistan[3]

Stage	Period	Key Activities	Technologies	Expected Effect
1. Digital infrastructure	2025–2026	IoT sensors, smart meters, network modernization	IoT, Smart Meter	Energy metering accuracy: +40%
2. Alternative energy	2026–2027	Solar panels and energy storage systems	PV, BESS	Energy tariff costs: −30%

2 Author's elaboration
3 Author's elaboration

3. AI integration	2027–2028	BEMS, AI forecasting modules, Digital Twin	AI, ML, Cloud	Energy efficiency: +25%
4. P2P energy exchange	2028–2029	Digital trading platform and grid integration	Blockchain	Additional revenue: +15–20%
5. Full integration	2029–2030	Unified campus platform and dashboards	Full-stack IoT	CO_2 emissions: −50%

Table 2 proposes the sequential implementation of the Smart Campus model in accordance with the level of technological complexity and investment requirements. The first stage focuses on establishing a high-quality data collection infrastructure, thereby creating the necessary foundation for the effective operation of subsequent AI and Digital Twin modules. Therefore, IoT and smart meters are regarded as the fundamental technological layer. At the subsequent stages, renewable energy, AI-based management, and platform integration are introduced, contributing to lower energy costs and enhanced environmental sustainability of the campus.

Table 3
Comparative Indicators of Smart Campus Elements at Leading Universities[4]

University	Country	Solar Capacity (kW)	Digital Management	Energy Performance
Arizona State University	USA	18,000	IBM Watson IoT	Savings: −35%
Tsinghua University	China	200,000	Baidu AI Platform	Savings: −40%
NUS (SDE4)	Singapore	1,225	NUS Smart Campus	Net positive: +22% energy generation
Delft University of Technology	Netherlands	5,200	Digital Twin	Savings: −18%
IIT Bombay	India	8,000	Indigenous AI	Savings: −28%
NUUz	Uzbekistan	150	Initial stage	Savings: −8%

Table 3 demonstrates the diversity in the scale of Smart Campus solutions implemented in international practice. At large campuses such as Tsinghua University and Arizona State University, high-capacity solar energy systems are integrated with AI platforms, while NUS SDE4 is presented as a building model capable of generating more energy than it consumes. In higher education institutions in Uzbekistan, the process is at an initial stage, providing opportunities for the gradual adaptation of international experience in accordance with local climatic conditions, campus size, and investment capacity.

The results also demonstrate that the Smart Campus model can generate distinct economic value for education and scientific research. Real-time data collected through IoT sensors and BEMS can serve as a practical database for students in the fields of energy, economics, information technology, and environmental studies.

From a financing perspective, combining university budget resources with additional financing mechanisms can enhance the feasibility of implementing the model. Accordingly, the combination of the ESCO mechanism, green financing, public-private partnerships, and resources from international financial institutions provides opportunities to distribute the investment burden. In this context, the economic efficiency of each technological stage should be assessed separately.

CONCLUSION AND SUGGESTIONS

The study demonstrates that the integration of digital technologies and alternative energy contributes to the formation of a new energy management model in higher education institutions. When AI, IoT, BEMS, Digital Twin, and renewable energy systems are applied in an interconnected manner, opportunities for monitoring, forecasting, maintenance, and consumption optimization are significantly expanded.

Under the conditions of Uzbekistan, it is proposed that the Smart Campus model be implemented through a five-stage transformation mechanism. Initially, digital metering and monitoring infrastructure should be established, followed by the implementation of alternative energy, AI-based management, digital energy exchange, and a unified platform.

The proposed approach provides opportunities not only to reduce energy costs and improve environmental

4 Author's elaboration

efficiency but also to transform the university campus into an educational and scientific laboratory. Future research should focus on econometric assessments of investment costs, NPV, IRR, discounted payback periods, and energy-saving indicators based on real monitoring data from individual higher education institutions.

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