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*Ijtimoiy, iqtisodiy, texnologik, ilmiy, ommabop jurnal*

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08.00.01 Iqtisodiyot nazariyasi
08.00.02 Makroiqtisodiyot
08.00.03 Sanoat iqtisodiyoti
08.00.04 Qishloq xo‘jaligi iqtisodiyoti
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08.00.16 Raqamli iqtisodiyot va xalqaro raqamli integratsiya
08.00.17 Turizm va mehmonxona faoliyati

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# MUNDARIJA

MUNDARIJA СОДЕРЖАНИЕ CONTENTS

# DIGITAL TRANSFORMATION OF DECISION-MAKING IN THE NATIONAL ELECTRICITY GRID OF UZBEKISTAN

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Abstract. This study focuses on the computer simulation modeling of the national electricity grid of Uzbekistan. The operation of the electricity grid was simulated using a hybrid simulation model, in which each region was considered as an individual agent integrated into a stochastic model, while the energy supply to the agents was designed using a system dynamics approach. Input data modeling revealed that electricity supply and consumption patterns across regions and different months are characterized by various probability distribution types depending on the nature of the observed data.

The developed hybrid simulation model made it possible to analyze potential developments of Uzbekistan's national electricity supply system by considering several strategic energy projects, including the introduction of additional hydroelectric power generation, photovoltaic power stations, and nuclear power plants, as well as increases in industrial electricity demand, electric vehicle consumption, and population growth. The findings demonstrate that the integration of green energy (GE) reduces $CO_2$ emissions from conventional power plants (PPs), particularly when energy losses within the electricity grid are reduced simultaneously.

Key words: electricity grid, digital modeling, hybrid simulation model, green energy, $CO_2$ emissions, prescriptive analytics.

Annotatsiya. Mazkur tadqiqot O'zbekiston milliy elektr tarmog'ini kompyuter simulyatsiyasi asosida modellashtirishga bag'ishlangan. Elektr tarmog'ining faoliyati gibrid simulyatsiya modeli asosida modellashtirildi, bunda har bir mintaqa alohida agent sifatida ko'rib chiqilib, ular stoxastik model doirasida birlashtirildi, agentlarga energiya ta'minoti esa tizim dinamikasi modeli asosida ishlab chiqildi. Kirish ma'lumotlarini modellashtirish natijalari shuni ko'rsatdiki, har bir mintaqaning elektr energiyasi ta'minoti va iste'mol ko'rsatkichlari hamda turli oylar bo'yicha kuzatilgan ma'lumotlar o'z xususiyatiga ko'ra turli ehtimollik taqsimotlari bilan ifodalanadi.

Ishlab chiqilgan gibrid simulyatsiya modeli qo'shimcha gidroelektr stansiyalar, fotoelektr stansiyalar va atom elektr stansiyalarini joriy etish, shuningdek, sanoat elektr iste'moli, elektromobillar soni va aholi o'sishini hisobga olgan holda milliy elektr ta'minoti tizimining istiqboldagi rivojlanish variantlarini tahlil qilish imkonini berdi. Tadqiqot natijalari shuni ko'rsatdiki, yashil energiya (GE) ulushining oshirilishi an'anaviy elektr stansiyalaridan (PP) chiqariladigan $CO_2$ emissiyalarini kamaytiradi, ayniqsa elektr tarmog'idagi energiya yo'qotishlari bir vaqtning o'zida qisqartirilgan taqdirda.

Kalit so'zlar: elektr tarmog'i, raqamli modellashtirish, gibrid simulyatsiya modeli, yashil energiya, $CO_2$ emissiyasi, preskriptiv analitika.

Аннотация. Данное исследование посвящено компьютерному моделированию национальной электросети Узбекистана. Работа электросети моделировалась на основе гибридной имитационной модели, в которой каждый регион рассматривался как отдельный агент, интегрированный в стохастическую модель, а энергоснабжение агентов было разработано с использованием модели системной динамики. Моделирование входных данных показало, что модели электроснабжения и потребления электроэнергии по регионам и различным месяцам характеризуются различными типами вероятностных распределений в зависимости от особенностей наблюдаемых данных.

Разработанная гибридная имитационная модель позволила проанализировать возможные направления развития национальной электроэнергетической системы с учетом реализации ряда стратегических энергетических проектов, включая внедрение дополнительных гидроэлектростанций, фотоэлектрических станций и атомных электростанций, а также рост промышленного потребления электроэнергии, увеличение количества электромобилей и рост населения. Результаты исследования показали, что увеличение доли зеленой энергии (GE) способствует снижению выбросов $CO_2$ от традиционных электростанций (PP), особенно при одновременном сокращении потерь энергии в электрической сети.

Ключевые слова: электросеть, цифровое моделирование, гибридная имитационная модель, зеленая энергия, выбросы $CO_2$, прескриптивная аналитика.

## INTRODUCTION

The importance of Green Energy (GE) has become one of the central topics in global economic and environmental policy discussions. Countries around the world are actively pursuing the transition toward carbon-neutral and sustainable economic systems, and Uzbekistan is also following this global trend. In this context, green energy serves as one of the key pillars of national and international strategies aimed at achieving carbon neutrality and ensuring long-term environmental sustainability.

Significant investments are currently being directed toward the development and implementation of renewable energy projects. However, the return on investment of certain renewable energy sources, measured in terms of megawatt-hours (MWh) generated per unit of investment, is often lower compared to traditional forms of power generation such as thermal and nuclear power plants. This is primarily because the efficiency and utilization rates of renewable energy facilities, particularly solar and wind power stations, largely depend on weather and climate conditions.

From an economic perspective, some researchers argue that allocating a greater share of investments toward conventional power plants could provide more stable and affordable electricity generation, thereby improving the quality of everyday life and supporting industrial development. Nevertheless, despite these challenges, the transition toward green energy remains strategically important due to its long-term environmental, economic, and social benefits, including the reduction of greenhouse gas emissions, improvement of energy security, and support for sustainable economic growth.

## LITERATURE REVIEW

Heath et al. (2011) discuss several major simulation approaches, including event- and process-oriented discrete-event simulation (DES), system dynamics (SD), and agent-based simulation (ABS), as well as hybrid models created through the integration of these methodologies. Their research highlights the practical applications and advantages of combining different simulation techniques for analyzing complex systems.

Bazan and German (2012) combined agent-based modeling and system dynamics to simulate renewable energy generation and storage grids at the micro level. Their simulation model incorporated electricity generation and consumption components at the household level and dynamically connected these elements to the electricity grid. Their work provided important conceptual guidance for the present study by demonstrating the potential of hybrid simulation approaches and encouraging the extension of such models from the micro level to the macro level, specifically at the national scale. In particular, the interaction between two distinct simulation models became a key methodological foundation for the development of this research model.

Pruckner and German (2013) developed “a hybrid simulation model for large-scale electricity generation systems” by integrating System Dynamics (SD) and Discrete-Event Simulation (DES). In their study, system dynamics was used to represent continuous energy flows, while discrete-event simulation was applied to model operational and managerial decision variables. Their simulation examined future annual electricity balances, $CO_2$ emission balances, electricity imports and exports, and wholesale electricity prices. The researchers concluded that Bavaria, Germany, could potentially face shortages in electricity generation capacity if excessive emphasis were placed solely on renewable energy sources without sufficient support from conventional generation systems. They emphasized the importance of constructing additional gas power plants to compensate for future increases in electricity demand, although they also acknowledged that such measures could lead to higher $CO_2$ emissions. Their analysis and conclusions significantly influenced the present study and inspired the application of a similar experimental framework to the case of Uzbekistan.

Jarrah (2016) developed a simulation model for renewable energy sources within Smart Grid systems using Discrete-Event Specification (DEVS). The research primarily focused on determining the required capacity of electricity generation systems at the micro level. Jarrah's formulation of an adaptive electricity generation framework based on dynamic demand indicators provided valuable methodological insights for the development of the stochastic energy model applied in this study.

## RESEARCH METHODOLOGY

This research applied prescriptive analytics tools, including data modeling and dynamic simulation modeling techniques based on agent-based modeling (ABM) and system dynamics (SD). The simulation model was developed to analyze the operational behavior and future development scenarios of Uzbekistan's national electricity grid system.

The data used for simulation modeling were obtained from the electronic transaction processing systems and the Project Office of the Ministry of Energy of the Republic of Uzbekistan. In addition, weather-related data were collected from the Committee for Metrology, while economic and demographic indicators were obtained from official publications of the Statistics Committee of the Republic of Uzbekistan.

Appropriate data modeling procedures were conducted for each input parameter. Statistical characteristics of all datasets were analyzed, and goodness-of-fit tests were performed to identify the most suitable probability distribution for each dataset. Datasets with positive goodness-of-fit test results were represented using appropriate random probability distributions, while datasets that did not satisfy the required statistical conditions were modeled using empirical data distributions.

The simulation model was implemented for the period 2021–2027 using initial input data from 2020–2021. To improve the reliability and stability of the simulation outcomes, the model was executed with 100 replications based on different initial random seeds.

The output parameters of the digital hybrid simulation model were verified and validated through comparison with actual operational outcomes of the real electricity system. The research findings and simulation results were also presented to experts from the National Research Institute of Renewable Energy Sources under the Ministry of Energy of Uzbekistan for professional evaluation and expert review.

## ANALYSIS AND RESULTS

Data related to electricity supply and demand in Uzbekistan were obtained from the Ministry of Energy (MoE) and the Energy Coordination and Dispatch Center (CDC). Weather-related factors were not directly incorporated into the simulation model; instead, the simulation was conducted using a set of standardized assumptions applied uniformly across all regions.

The collected data were calculated and preprocessed using Microsoft Excel and its analytical add-in tools, including @RISK. The hybrid simulation model was then developed and executed using AnyLogic Professional 8.7.8.

The developed model consists of two main components:

a) stochastic agent populations;

b) system dynamics modeling.

The simulation framework includes seven principal input parameters across these two interconnected models:

1. Agent population in each region;
2. Stochastic electricity consumption by each agent measured in megawatt-hours (MWh);
3. Electricity supply generated from power plants (PPs);
4. Total electricity consumption by agent populations;
5. Energy losses occurring during electricity transmission from power plants to consumers;
6. Geographic Information System (GIS)-based location of agent populations;
7. Hourly updated electricity production and consumption measured in MWh (Figure 1).

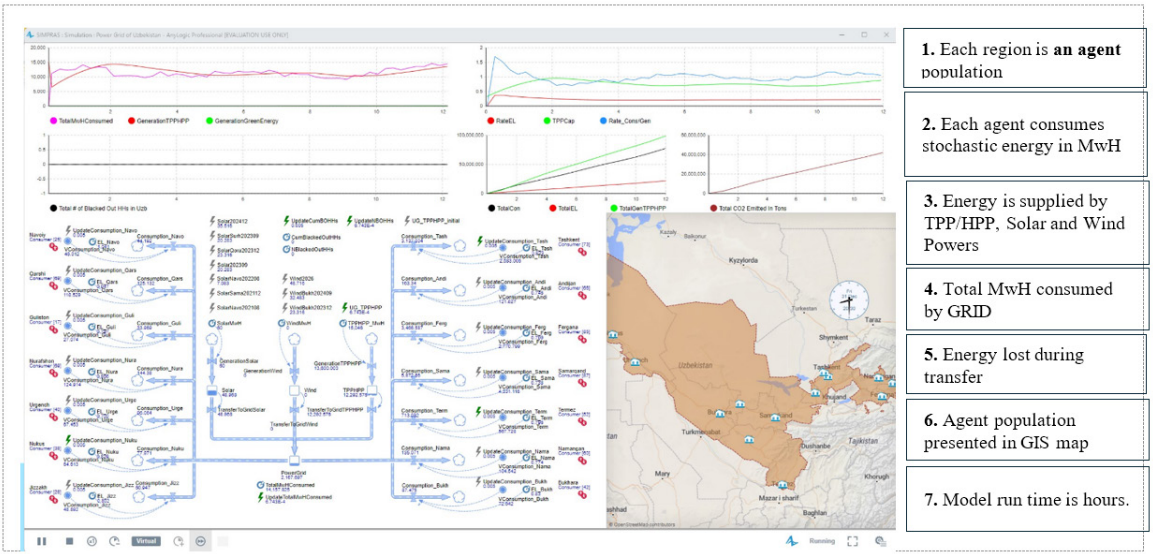


Figure 1. National Energy Grid simulation model and its main input parameters (created by authors using AnyLogic software application)[1]

Each agent within the agent population follows a set of predefined states and stochastic transitions that determine its level of electricity consumption relative to the base megawatt-hour (MWh) consumption rate specific to each region and month (Figure 2). The model incorporates four main operational states:

1. Passive state – in this state, the agent consumes approximately 70% of the regional base electricity consumption rate, simulating off-peak periods such as nighttime hours;
2. Active state – in this state, the agent consumes approximately 110% of the base consumption rate, representing peak demand periods, particularly daytime activity;
3. Extreme weather state – in this condition, the agent consumes approximately 138% of the base consumption rate, simulating periods of extremely hot or cold weather when electricity demand significantly increases due to heating or cooling requirements;
4. Blackout state – in this state, the agent consumes 0% of the base consumption rate, representing situations in which the electricity grid is unable to supply sufficient energy to consumers due to shortages or system failures.

All state transitions are stochastic in nature, enabling the simulation to capture variations in the behavior of individual agents under different operational and environmental conditions. As a result, the total electricity consumption (measured in MWh) for each regional population is calculated as a weighted average based on the number of agents in each state multiplied by the corresponding regional base consumption rate (Figure 2).

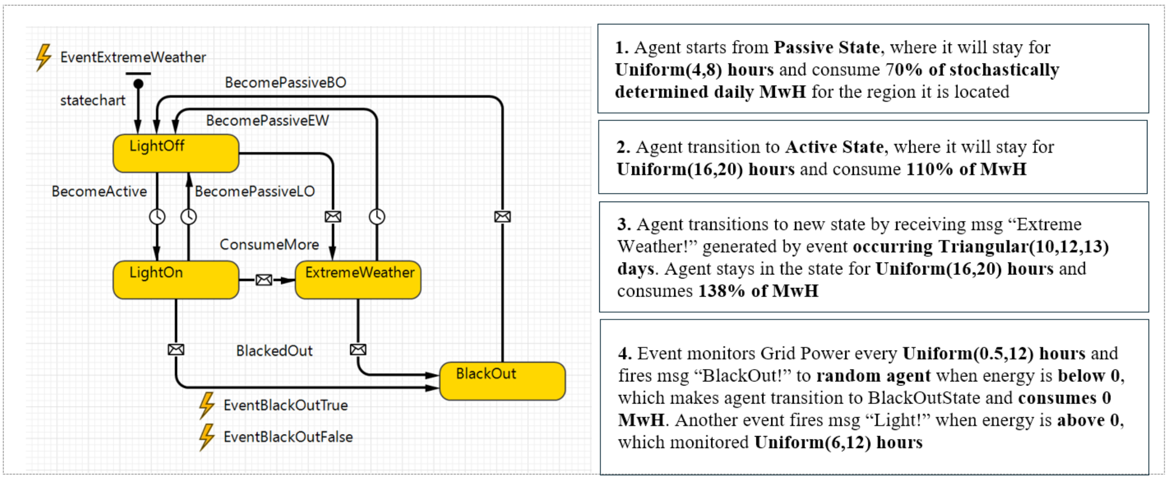


Figure 2. Agent state and transitions (developed by authors using AnyLogic software)[2]

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The model also tracks several aggregate national key performance indicators (KPIs), including:

1. Weekly levels of electricity consumption and generation measured in megawatt-hours (MWh);
2. Hourly numbers of agents operating in the blackout state;
3. Weekly energy loss rates, represented by the proportion between generated and consumed electricity, as well as the thermal power plant (TPP) utilization rate, defined as the proportion of electricity generated by TPPs relative to their total production capacity;
4. Monthly cumulative indicators of electricity generation, consumption, and energy losses;
5. Total $CO_2$ emissions generated by power plants throughout the simulation period.

The hybrid simulation model was developed based on six major categories of assumptions:

1. Annual percentage growth in population size, electricity consumption base rate, and energy loss rate;
2. Electricity generated by green energy (GE) sources being maintained at a constant daily average generation level;
3. Thermal power plant (TPP) capacity, frequency of utilization updates, and corresponding $CO_2$ emission rates;
4. Regional agent population size;
5. Base electricity consumption rates;
6. Total electricity consumption across the national grid.

Two main types of experiments were conducted within the simulation framework:

1. An experiment designed to evaluate the model's performance against actual electricity consumption data for 2021;
2. An experiment aimed at assessing projected $CO_2$ emission levels and blackout frequency in the year 2027.

In the first experiment, the simulation was executed 100 times as a stochastic simulation using different random seeds. The average total monthly electricity consumption measured in megawatt-hours (MWh) was then compared with actual historical consumption data in order to validate the accuracy and reliability of the developed model (Figure 3).

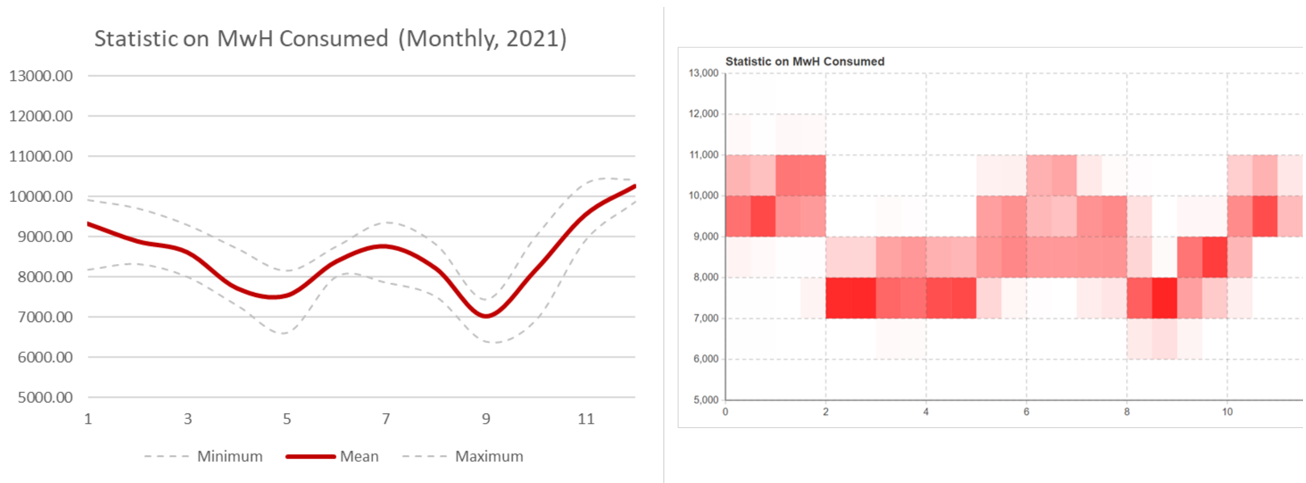


Figure 3. Model validation: actual vs simulated data comparison[3]

In the chart on the right, each gradient within the bins on the x-axis (months) represents the probability distribution of the corresponding electricity consumption value in megawatt-hours (MWh) obtained from 100 stochastic simulation runs. The chart on the left illustrates the monthly minimum, mean, and maximum values derived from the actual observed data. As shown in the charts, the simulated results demonstrate a high level of consistency with the real-world data, confirming the reliability and accuracy of the developed hybrid simulation model.

Following the successful validation of the model, a second experiment was conducted to address the primary research problem formulated in this study.

The second experiment compared the results for:

1. Total $CO_2$ emissions;
2. Total number of consumers affected by blackouts in 2027;

under four different simulation scenarios:

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Scenario A: All green energy (GE) power plant projects are implemented, and energy loss within the electricity grid is not considered.

Scenario B: None of the green energy (GE) power plant projects are implemented, and energy loss within the electricity grid is not considered.

Scenario C: All green energy (GE) power plant projects are implemented, and energy loss within the electricity grid is incorporated into the simulation.

Scenario D: None of the green energy (GE) power plant projects are implemented, and energy loss within the electricity grid is incorporated into the simulation.

Each scenario was simulated 100 times using stochastic Monte Carlo simulation with different random seeds. The average values of total $CO_2$ emissions and the total number of blackout-affected consumers were then calculated based on the outcomes of these simulation runs.

The year 2027 was selected as the target simulation year because it represents the projected completion period for the majority of currently planned green energy projects in Uzbekistan. Therefore, this year is expected to demonstrate the most significant observable impact of green energy integration on the national electricity grid system.

Table 1 summarizes the results of the second experiment. The presented values represent the average outcomes obtained from 100 Monte Carlo simulation runs. These findings provide the basis for addressing the research problem and formulating practical policy recommendations regarding the future digital transformation and sustainable development of Uzbekistan's national electricity grid system (Table 1).

Table 1. Simulation outcome: $CO_2$ emission in 2027 (based on 100 replications)[4]

| CO2 Emission in 2027 | ALL of GE PPs are implemented | NONE of GE PPs are implemented | A/B & CD (%) |
|---|---|---|---|
| Energy Loss is NOT applied | A 32,800,000 tons | B 39,960,000 tons | 82.1% |
| Energy Loss is applied | B 55,070,000 tons | D 55,230,000 tons | 99.7% |
| A/C & B/D (%) | 59.6% | 72.4% | |

Simulation results for the year 2027 demonstrate that when energy losses within the electricity grid are present, the impact of green energy (GE) on reducing $CO_2$ emissions remains relatively limited, with an average reduction of only 0.3%. This outcome indicates that the additional electricity generated from renewable energy sources is insufficient to fully compensate for the growing electricity demand and the increasing level of energy losses within the grid over time.

However, when the same simulation model is executed under the assumption that there are no energy losses within the electricity transmission system, the effect of green energy becomes substantially more significant. Under these conditions, $CO_2$ emissions decrease by an average of 17.9%, demonstrating the considerable environmental benefits of renewable energy integration when supported by an efficient electricity transmission infrastructure.

The greatest reduction in $CO_2$ emissions was observed under the scenario combining both full implementation of green energy projects and the elimination of energy losses within the grid. In this case, average $CO_2$ emissions decreased by approximately 40.4%.

The simulation findings clearly indicate that reducing energy losses within the national electricity grid has a greater impact on lowering $CO_2$ emissions than the implementation of green energy projects alone. Specifically, the effect of eliminating energy losses contributes, on average, 22.5% more $CO_2$ reduction compared to the impact achieved solely through green energy implementation (Table 2).

Table 2. Simulation outcome: Number of of blackouts in 2027 (based on 100 replications)[5]

| No of Black-Outs in 2027 | ALL of GE PPs are implemented | NONE of GE PPs are implemented | A/B & CD (%) |
|---|---|---|---|
| Energy Loss is NOT applied | A 0.2 times per consumer | B 0.1 times per consumer | 230.1% |
| Energy Loss is applied | B 118.3 times per consumer | D 149.2 times per consumer | 79.4% |
| A/C & B/D (%) | 0.2% | 0.1% | |

The simulation results reveal an even more significant impact in terms of the projected number of blackouts in 2027. When energy losses within the electricity grid are excluded from the model, the existing generation

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capacity of traditional power plants (PPs), together with the additional capacity provided by green energy (GE) projects, appears sufficient to satisfy the growing electricity demand. Under this scenario, consumers experience almost no blackouts throughout the year.

However, when energy losses are incorporated into the simulation model, the situation changes substantially. Regardless of whether green energy projects are implemented, the results indicate that each citizen of Uzbekistan could experience, on average, more than 100 blackout events per year. Although the introduction of green energy reduces the number of blackouts by approximately 20.6%, this reduction is still insufficient to fully compensate for the rapidly increasing electricity demand and the negative impact of energy losses within the grid system.

## CONCLUSION AND RECOMMENDATIONS

The findings of this study demonstrate that the introduction of green energy (GE) contributes to reducing $CO_2$ emissions from traditional power plants (PPs) only when energy losses within the electricity grid are simultaneously minimized. The simulation results indicate that the effectiveness of renewable energy integration depends not only on the expansion of generation capacity, but also on the operational efficiency and technical condition of the national electricity transmission infrastructure.

According to the simulation forecasts for 2027, if energy losses within the grid are not adequately addressed, the environmental impact of existing green energy projects will remain highly limited. The results suggest that the anticipated growth in electricity demand, combined with ongoing degradation and inefficiencies within the electricity grid, may offset most of the positive effects achieved through the introduction of renewable energy sources. In such conditions, the additional capacity generated by green energy projects alone would not be sufficient to substantially reduce $CO_2$ emissions or ensure long-term energy reliability.

Therefore, this research recommends that investments in green energy projects should be implemented in parallel with comprehensive modernization and renovation of the national electricity grid infrastructure. Particular attention should be given to policies and technological solutions aimed at reducing technical and operational energy losses, including the gradual introduction and wider dissemination of smart grid technologies, digital monitoring systems, and advanced electricity distribution management solutions.

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