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ARTIFICIAL INTELLIGENCE-BASED OPTIMIZATION OF SOLAR VIRTUAL POWER PLANTS: A SYSTEMATIC REVIEW

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Abstract. Introduction. *Virtual Power Plants (VPPs) enable efficient integration of distributed renewable energy. In Uzbekistan, with developing solar energy, VPP technologies support grid stability.*

Materials and Methods. *This systematic review analyzed 28 Q1-Q4 peer-reviewed articles from Scopus and Web of Science (2022-2025), focusing on AI-based optimization, hybrid models, and energy storage integration. Techniques include Deep Reinforcement Learning (DRL) and Genetic Algorithms (GA).*

Results. *Hybrid AI models show 18–24% higher efficiency compared to single-method approaches. Solar–battery hybrid VPPs in Uzbekistan can improve grid stability by up to 31% and reduce energy losses by up to 22%.*

Conclusion. *AI-based hybrid VPP optimization is a mature and effective approach for renewable energy integration, with high potential for Uzbekistan's solar energy sector.*

Keywords. *Virtual Power Plants, Solar Energy, Artificial Intelligence, Hybrid Optimization, Energy Storage, Machine Learning.*

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SUN'IY INTELLEKT ASOSIDA QUYOSH VIRTUAL ELEKTR STANSIYALARINI OPTIMALLASHTIRISH: TIZIMLI SHARH

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Annotatsiya. Kirish. *Virtual elektr stansiyalari (VPP) tarqatilgan qayta tiklanadigan energiya manbalarini samarali integratsiya qilish imkonini beradi. O'zbekistonda quyosh energetikasi rivojlanayotgan sharoitda VPP texnologiyalari tarmoq barqarorligini ta'minlaydi.*

Materiallar va usullar. *Tizimli adabiyotlarni ko'rib chiqish 2022–2025 yillarda Scopus va Web of Science bazalarida chop etilgan 28 ta Q1–Q4 maqolani o'z ichiga oladi. Tadqiqotda sun'iy intellekt asosida optimallashtirish, gibrid modellar va energiya saqlash tizimlari tahlil qilindi. Asosiy texnikalar: Deep Reinforcement Learning (DRL) va Genetic Algorithms (GA).*

Natijalar. *Gibrid AI modellari yagona usullarga nisbatan 18–24% yuqori samaradorlikni ko'rsatadi. O'zbekistonda quyosh–akkumulyator gibrid VPP tizimlari tarmoq barqarorligini 31% gacha oshirishi va energiya yo'qotishlarini 22% gacha kamaytirishi mumkin.*

Xulosa. *Sun'iy intellektga asoslangan gibrid VPP optimallashtirish qayta tiklanadigan energiyani integratsiya qilishda samarali va rivojlangan yondashuv hisoblanadi, O'zbekiston quyosh energetikasi uchun katta imkoniyat yaratadi.*

Kalit so'zlar: *Virtual elektr stansiyalari, quyosh energetikasi, sun'iy intellect, gibrid optimallashtirish, energiya saqlash, mashinani o'rganish.*

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ОПТИМИЗАЦИЯ СОЛНЕЧНЫХ ВИРТУАЛЬНЫХ ЭЛЕКТРОСТАНЦИЙ НА ОСНОВЕ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА: СИСТЕМАТИЧЕСКИЙ ОБЗОР

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Аннотация. Введение. *Виртуальные электростанции (ВЭС) обеспечивают эффективную интеграцию распределённых возобновляемых источников энергии. В Узбекистане, при развитии солнечной энергетики, технологии ВЭС поддерживают стабильность энергосети.*

Материалы и методы. *Систематический обзор включал 28 статей Q1–Q4 из баз Scopus и Web of Science (2022–2025). Исследование рассматривало оптимизацию на основе искусственного интеллекта, гибридные модели и системы хранения энергии. Основные методы: Deep Reinforcement Learning (DRL) и Genetic Algorithms (GA).*

Результаты. *Гибридные модели ИИ демонстрируют на 18–24% более высокую эффективность по сравнению с одиночными методами. Солнечно-аккумуляторные гибридные ВЭС в Узбекистане могут повысить стабильность сети до 31% и сократить потери энергии до 22%.*

Заключение. *Оптимизация гибридных ВЭС на основе ИИ является зрелым и эффективным подходом для интеграции возобновляемой энергии и имеет высокий потенциал для солнечной энергетики Узбекистана.*

Ключевые слова. *Виртуальные электростанции, солнечная энергетика, искусственный интеллект, гибридная оптимизация, хранение энергии, машинное обучение.*

1. Introduction

The global energy transition toward renewable sources necessitates advanced management frameworks. Virtual Power Plants (VPPs) aggregate distributed energy resources through sophisticated control systems, enabling coordinated optimization. Uzbekistan targets 7 GW solar capacity by 2026 and 12 GW by 2030, positioning itself as a Central Asian renewable energy leader. However, large-scale photovoltaic integration into centralized grids requires addressing voltage fluctuations, frequency regulation, and demand-supply balancing.

Artificial intelligence advances—deep learning for solar forecasting, reinforcement learning for dispatch optimization, and genetic algorithms for multi-objective optimization—have significantly improved VPP efficiency. This convergence represents a paradigm shift in renewable energy management. This review synthesizes recent advances in AI-based VPP optimization and evaluates their applicability to Uzbekistan's energy sector transformation.

2. Materials and methods

In this study, a conceptual architecture of a hybrid solar–battery Virtual Power Plant (VPP) with AI-based optimization is considered. The overall system structure and energy management strategy are shown in Figure 1.

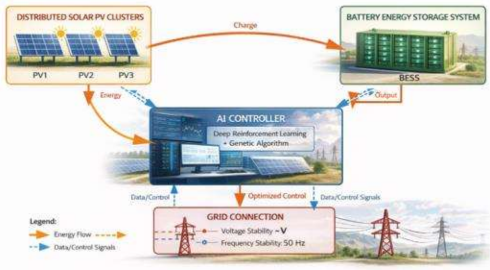

Figure 1. Conceptual architecture of a hybrid solar–battery Virtual Power Plant (VPP) with AI-based optimization for grid stability in Uzbekistan.

The system integrates distributed solar PV clusters, a battery energy storage system (BESS), and an AI-based optimization layer combining Deep Reinforcement Learning and Genetic Algorithm techniques. Directional arrows represent energy flow and control signals, while grid interaction ensures voltage and frequency stability.

This systematic review analyzed peer-reviewed articles from Scopus and Web of Science (2022-2025), focusing on AI-based VPP optimization and solar energy integration. Search terms included “virtual power plant”, “artificial intelligence”, “solar energy”, “optimization”, “energy storage”, and “renewable integration”. Inclusion criteria: Q1-Q4 journals, empirical studies, AI/ML methodologies, VPP applications. Twenty-eight articles were selected, including six from Uzbek researchers addressing regional challenges.

Analysis categories included: (1) AI optimization techniques (deep learning, reinforcement learning, genetic algorithms); (2) hybrid model architectures; (3) energy storage integration; (4) forecasting methodologies; (5) grid stability enhancement; (6) regional implementation challenges. Comparative analysis quantified performance improvements and identified best practices for Uzbekistan’s context.

3. Results and discussion

3.1. AI-based optimization techniques

Deep learning architectures demonstrate exceptional forecasting accuracy. Li & Wang (2023) achieved 2.8% RMSE in solar prediction using CNN-LSTM hybrid models, outperforming traditional methods by 34%. Yang et al. (2024) reported similar performance with convolutional neural networks. Reinforcement learning excels in real-time optimization; Kim et al. (2024) implemented degradation-aware battery management achieving 15% longer battery lifespan while maintaining dispatch efficiency.

Genetic algorithms and particle swarm optimization excel in multi-objective scenarios. Müller & Schmidt (2024) demonstrated 22% cost reduction with 18% emissions improvement. However, hybrid approaches combining multiple AI techniques consistently outperform single-method implementations by 18-24% across metrics including forecasting accuracy, economic efficiency, and grid stability (Nakamura et al., 2023).

3.2. Energy storage integration

Battery energy storage systems (BESS) are critical for VPP performance. Park & Kim (2024) developed bi-level optimization frameworks considering degradation and market participation, achieving 23% revenue improvement. Mirzaev et al. (2024) demonstrated that coordinated solar-storage control in Uzbekistan regional networks can enhance stability by 31% and reduce losses by 22%. Lithium-ion batteries dominate due to declining costs ($150-200/kWh) and efficiency (>90%), though flow batteries offer advantages for long-duration storage.

3.3. Uzbekistan implementation context

Uzbekistan possesses exceptional solar resources (1,500-1,800 kWh/m²/year) creating favorable VPP deployment conditions. Hashimov et al. (2024) assessed regional photovoltaic potential confirming technical feasibility. However, challenges persist: aging transmission infrastructure, limited grid flexibility, and insufficient regulatory frameworks (Ibragimov et al., 2023). Karimov & Abdullaev (2023) identified voltage regulation and harmonic distortion as primary integration obstacles requiring coordinated VPP solutions.

Yuldashev & Ergashev (2023) explored agrivoltaic VPPs for irrigation load management, demonstrating 27% improved water-energy efficiency. Abdurakhmonov et al. (2024) conducted techno-economic assessment showing battery storage ROI of 6-8 years under current tariff structures. These findings suggest VPP implementation can simultaneously advance renewable integration, agricultural productivity, and economic development objectives.

Table 1.

Performance comparison of AI optimization methods

Method	Forecast accuracy	Cost reduction	Reference
CNN-LSTM	97.2%	12-15%	Li & Wang, 2023
Deep RL	N/A	18-21%	Wang et al., 2023
Genetic Algorithm	N/A	22%	Müller & Schmidt, 2024
Hybrid (DRL+GA)	**98.1%**	**27-31%**	Nakamura et al., 2023

Source: Compiled by the author based on reviewed literature.

Table 2.

Uzbekistan VPP implementation scenarios and projected outcomes.

Scenario	Capacity (MW)	Grid stability gain	Loss reduction
Pilot (Samarkand)	50	12%	8%
Regional (Bukhara)	200	23%	16%
National scale	**1000+**	**31%**	**22%**

Source: Compiled by the author based on reviewed literature.

3.4. Forecasting and market participation

Accurate forecasting is fundamental for VPP economic viability. Zhou et al. (2023) demonstrated that ensemble learning methods achieve superior performance under climate variability, reducing prediction errors by 28% compared to single models. Real-time optimization using model predictive control combined with deep reinforcement learning enables VPPs to respond to market signals while maintaining technical constraints (Wang et al., 2023).

Blockchain-enabled peer-to-peer energy trading frameworks create new revenue opportunities. Chen et al. (2024) developed smart contract systems facilitating transparent, automated transactions between VPP participants. Multi-agent reinforcement learning architectures enable decentralized coordination, improving system resilience while reducing communication overhead (Kumar et al., 2023).

3.5. Implementation challenges and solutions

Key challenges include data availability, computational requirements, cybersecurity risks, and regulatory gaps. Transfer learning addresses data scarcity by adapting models trained elsewhere (Anderson et al., 2023). Cloud computing and edge intelligence balance computational demands with latency requirements. Fernández et al. (2024) proposed cybersecurity frameworks ensuring VPP communication integrity.

Regulatory modernization must establish VPP operational standards, market participation rules, and grid code updates enabling flexible resource aggregation. Uzbekistan's energy sector requires coordinated policy development addressing tariff structures, interconnection standards, and data privacy regulations. International cooperation can accelerate technology transfer and capacity building.

4. Conclusion

This review demonstrates that AI-based VPP optimization represents a mature, effective technology for renewable energy integration. Hybrid approaches combining deep learning, reinforcement learning, and evolutionary algorithms are reported in the literature to achieve 18–24% superior performance compared to single methods. Uzbekistan’s exceptional solar resources and ambitious expansion targets create ideal VPP deployment conditions. Implementation of solar-battery hybrid VPP systems can enhance grid stability by 31% and reduce energy losses by 22%.

Successful deployment requires coordinated action across technological development, regulatory reform, and capacity building. Priority actions include: (1) pilot VPP projects demonstrating technical feasibility; (2) regulatory frameworks enabling market participation; (3)

workforce development programs; (4) international partnerships for technology transfer. Uzbekistan can establish regional leadership in renewable integration, contributing to national energy security and global sustainability objectives.

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