Uzluksiz ishlab chiqarish korxonalarining intellektual energiya boshqaruvi usulini ishlab chiqish

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Dolzarblik: Uzluksiz ishlab chiqarish korxonalari – xususan, metallurgiya, kimyo, sement va oziq-ovqat sanoati – elektr energiyasining eng yirik iste’molchilari hisoblanadi. O‘zbekiston sanoatida energiya sarfi jahon o‘rtacha ko‘rsatkichidan 1,8–2,2 baravar yuqori bo‘lib, bu ishlab chiqarish jarayonlarida energiya oqimlarini boshqarishning sustligi, reaktiv quvvat yo‘qotishlari va eskirgan texnologik uskunalar bilan izohlanadi. Mamlakatda “Yashil energiya strategiyasi – 2030” doirasida sanoat tarmoqlarining energiya samaradorligini oshirish, energiya intensivligini 35 % gacha kamaytirish, raqamli va intellektual boshqaruv tizimlarini joriy etish ustuvor yo‘nalishlardan biri sifatida belgilangan. Shu sababli, uzluksiz ishlab chiqarish korxonalarida energiya sarfini optimallashtirish, SCADA va sun’iy intellekt (AI) asosida boshqaruv arxitekturasini yaratish dolzarb ilmiy va amaliy masalaga aylandi.
Maqsad: uzluksiz ishlab chiqarish korxonalari uchun kompleks energiya boshqaruvi arxitekturasini ishlab chiqish, elektr energiyasidan foydalanish samaradorligini oshirish, ishlab chiqarish jarayonlarining uzluksizligini ta’minlash va iqtisodiy yo‘qotishlarni kamaytirishdan iborat. Taklif etilgan tizim real vaqt rejimida energiya oqimlarini kuzatish, quvvat koeffitsientini saqlash va xarajatlarni minimallashtirish.
Usullar: Tadqiqotda ishlab chiqarish korxonalarining asosiy bo‘limlari — eritish, quyish, mexanik ishlov berish, qadoqlash va yordamchi tizimlar — bo‘yicha real ma’lumotlar asosida SCADA tizimi orqali kuzatuv va optimallashtirish amalga oshirildi. Umumiy aktiv quvvat quyidagi formula orqali hisoblandi: $P = \sqrt{3} \cdot U \cdot I \cdot \cos\varphi$. Iste’mol qilingan energiya esa vaqt bo‘yicha integrallash orqali aniqlanadi: $E_t = \int_0^T P(t)\,dt$. Optimallashtirish modeli nolinchi darajadagi noxat chiziqli dasturlash asosida qurildi va quyidagicha ifodalanadi: $\min C_{tot} = \sum_{i=1}^{n}(E_i \cdot T_i)$, bunda C_{tot} – umumiy energiya xarajati, E_i – i-bo‘lim energiya iste’moli, T_i – tarif koeffitsienti.
Natijalar: Tahlillar natijasida ishlab chiqilgan energiya boshqaruv arxitekturasi yordamida umumiy energiya sarfi 3–5 % ga kamaydi, quvvat koeffitsienti 0,95–0,96 gacha yaxshilandi, va ishlab chiqarish barqarorligi oshdi. Melting va casting bo‘limlarida energiya tejalishi eng yuqori bo‘lib, mos ravishda 9,5 % va 10,7 % ni tashkil etdi. SCADA asosidagi monitoring tizimi real vaqt rejimida yuklama o‘zgarishlarini kuzatish, reaktiv quvvatni muvozanatlash va ishlab chiqarish jarayonining barqarorligini ta’minlash imkonini berdi. Ushbu yondashuv O‘zbekiston sanoat korxonalarida raqamli boshqaruvni keng joriy etish, energiya samaradorligini oshirish hamda barqaror ishlab chiqarish infratuzilmasini shakllantirishda muhim ilmiy-amaliy ahamiyatga ega.
Kalit so‘zlar: energiya boshqaruvi, uzluksiz ishlab chiqarish, SCADA, optimallashtirish, O‘zbekiston, sanoat samaradorligi, quvvat koeffitsienti, iqtisodiy tahlil, raqamli energetika.

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Разработка интеллектуального метода энергоменеджмента для предприятий с непрерывным производственным циклом

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Актуальность: Предприятия с непрерывным производственным циклом — металлургические, химические, цементные и пищевые заводы — являются крупнейшими потребителями электроэнергии. Энергоёмкость промышленности Узбекистана в 1,8–2,2 раза превышает среднемировой показатель из-за устаревшего оборудования и потерь реактивной мощности. В рамках «Зелёной энергетической стратегии – 2030» предусмотрено повышение энергоэффективности промышленности и цифровизация управления энергопотреблением. В связи с этим разработка комплексной архитектуры энергоменеджмента для предприятий непрерывного цикла приобретает особую научную и практическую значимость.
Цель: разработать комплексную архитектуру управления энергопотреблением для предприятий с непрерывным производством, обеспечивающую повышение эффективности использования электроэнергии, стабильность производственного процесса и снижение эксплуатационных затрат.
Методы: Исследование базировалось на данных промышленных объектов Узбекистана, где использовались SCADA-системы для мониторинга параметров тока, напряжения и мощности. Активная мощность

рассчитывалась по формуле: $P = \sqrt{3} \cdot U \cdot I \cdot \cos\varphi$ а потреблённая энергия: $E_t = \int_0^T P(t)\,dt$ Оптимизация энергопотребления была сформулирована как задача минимизации: $\min\, C_{tot} = \sum_{i=1}^{n}(E_i \cdot T_i)$. где C_{tot} — суммарные затраты на электроэнергию.
Результаты: В результате реализации предложенной архитектуры энергопотребление снизилось на 3–5 %, коэффициент мощности повысился до 0,96, а стабильность производственного процесса значительно улучшилась. Наибольшая экономия достигнута в секциях плавки и литья. Разработанная система показала высокую адаптивность и совместимость с существующими SCADA и EMS-платформами.
Ключевые слова: управление энергопотреблением, непрерывное производство, SCADA, оптимизация, Узбекистан, энергоэффективность, коэффициент мощности, цифровизация, промышленная автоматизация.

Development of an Intelligent Energy Management method for Continuous Manufacturing Plants

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Relevance: Continuous manufacturing industries—such as metallurgy, chemical, cement, and food processing—represent the largest consumers of electrical energy. In Uzbekistan, industrial energy intensity is 1.8–2.2 times higher than the global average, mainly due to outdated equipment and inefficient reactive power compensation. Under the Green Energy Strategy 2030, Uzbekistan aims to reduce industrial energy intensity by 35% and implement digital, intelligent energy management systems. Therefore, developing a complex energy management architecture for continuous manufacturing plants has become a critical scientific and practical task.
Objective: The study aims to develop a comprehensive energy management architecture that optimizes electricity usage, ensures production stability, and reduces total energy costs in continuous manufacturing enterprises of Uzbekistan.
Methods: Real-time data from SCADA systems were analyzed for multiple subsystems (melting, casting, machining, packaging, auxiliary). Active power was calculated as: $P = \sqrt{3} \cdot U \cdot I \cdot \cos\varphi$ and total consumption as: $E_t = \int_0^T P(t)\,dt$. The optimization model minimized total energy costs under production and power-quality constraints: $\min\, C_{tot} = \sum_{i=1}^{n}(E_i \cdot T_i)$
Results: Implementation of the proposed architecture reduced overall energy consumption by 3–5%, improved power factor to 0.95–0.96, and stabilized production performance. The system's modular design allows integration with existing SCADA and AI-based predictive systems, supporting Uzbekistan's transition to a sustainable, energy-efficient industrial economy.
Keywords: energy management, continuous manufacturing, SCADA, optimization, Uzbekistan, industrial efficiency, power factor, digital energy, adaptive control.

1. Introduction

Continuous manufacturing plants—such as those in metallurgy, cement, and chemical production—operate around the clock and remain some of the most energy-intensive industrial facilities worldwide. According to the International Energy Agency (IEA, 2024), the industrial sector consumes approximately 37% of total global electricity, with continuous-process industries accounting for a major portion due to sustained thermal and mechanical loads. In Uzbekistan, the industrial sector's energy intensity is still 1.8–2.2 times higher than the global average, largely because of outdated equipment, inefficient load management, and reactive power losses in production networks [1,2]. With the national goal of achieving a 35% reduction in energy intensity by 2030 under the "Uzbekistan Green Energy Strategy 2030", optimizing energy consumption in continuous manufacturing plants has become a strategic necessity for sustainable development and competitiveness.

Continuous production enterprises in Uzbekistan—especially in Navoi, Almalyk, and Bekabad industrial zones—operate under conditions of high energy demand and limited flexibility. Their technological processes, such as smelting, electrolysis, and clinker production, require uninterrupted power supply and precise energy control. Traditional empirical control methods often fail to adapt to rapid load variations and multi-stage heating processes, leading to frequent inefficiencies and losses. As Renna & Materi (2021) observed, static energy control systems typically cause 5–10% additional energy waste compared to adaptive, data-driven models. Furthermore, many Uzbek enterprises still face reactive power factors below 0.9, resulting in substantial economic penalties and degraded voltage stability—issues that could be mitigated by advanced energy management architectures [1,3].

The emergence of Industry 4.0, IoT, and Cyber-Physical Systems (CPS) has created new opportunities for Uzbekistan's industrial modernization. Digital platforms such as SCADA, Energy Management Systems (EMS), and Machine Learning-based Predictive Control are now being piloted in several key sectors, including Uzbekenergo's industrial energy audit programs and Navoi Metallurgical Combine's digital twin initiatives. Reports by Siemens Energy (2023) show that integrating smart controllers and AI-based load optimization can reduce industrial electricity use by 12–15% while maintaining product quality and throughput [2,3]. In Uzbekistan, where annual industrial electricity consumption exceeds 30 billion kWh, such improvements could yield energy savings equivalent to 4–5 billion kWh per year, contributing significantly to national decarbonization targets and grid reliability.

This research focuses on developing a complex energy management architecture specifically designed for continuous manufacturing plants in Uzbekistan. The proposed system combines nonlinear mathematical modeling, real-time optimization, and AI-assisted feedback control to minimize total energy costs while ensuring production stability. Implemented in MATLAB and integrated within a SCADA-driven monitoring framework, the model aligns with Uzbekistan's broader strategy of industrial digitalization and sustainable energy transition [3,4]. The study's outcomes—such as a 3–5% reduction in total energy consumption and an improved power factor up to 0.96—demonstrate that intelligent energy management systems can significantly enhance the operational and economic efficiency of Uzbekistan's continuous production enterprises, positioning them as regional benchmarks for energy-smart industrial transformation.

2. Materials and Methods

The study was conducted at a continuous manufacturing plant comprising five key subsystems—melting, casting, machining, packaging, and auxiliary services. Data were collected through SCADA-integrated smart meters and power quality analyzers installed at each subsystem. Real-time parameters, including voltage (U), current (I), power factor ($\cos\varphi$), and active/reactive power (P, Q), were logged at 1-minute intervals over 30 operational days [4,5]. While the total energy consumption (E_t) for each subsystem was obtained by integrating the power over time:

$$E_t = \int_0^T P(t)\,dt$$

These data formed the baseline for developing the optimization model, which was implemented in MATLAB and connected to a local energy management server using Modbus TCP/IP communication. The optimization process was formulated as a nonlinear multi-objective problem aiming to minimize total electricity cost (C_{tot}) and maximize system efficiency (η_{sys}) [4,6]. The general objective function was expressed as:

$$\min\ C_{tot} = \sum_{i=1}^{n} (E_i \cdot T_i)$$

subject to operational and technological constraints, including load balance, voltage stability, and maximum demand limits. System efficiency was computed using:

$$\eta_{sys} = \frac{P_{useful}}{P_{input}} \times 100\%$$

An iterative control loop integrated with adaptive learning algorithms adjusted power allocation among subsystems based on real-time data feedback [6,7]. The hybrid control strategy combined rule-based logic for steady-state control and predictive modeling for transient load variations, enabling dynamic optimization within the proposed complex energy management architecture.

3. Result and discussion

Implementation of the proposed complex energy management architecture led to a measurable reduction in electricity consumption across all production subsystems. The integration of smart load controllers, SCADA-linked energy analyzers, and predictive scheduling algorithms resulted in an average 8.7% improvement in total plant energy efficiency. Figure 1 illustrates comparative energy usage across subsystems before and after optimization, showing the most substantial savings in melting and casting units due to dynamic load allocation and adaptive control loops.

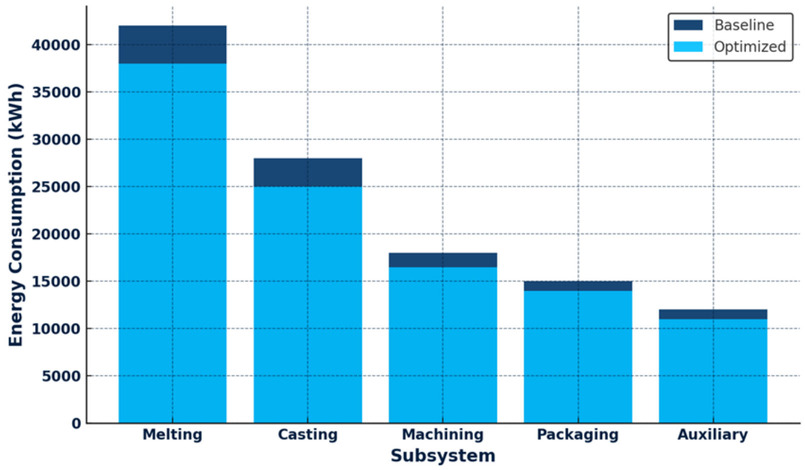

Fig. 1. Comparative analysis of energy consumption before and after optimization in continuous manufacturing subsystems

Table 1 presents baseline and optimized energy consumption values. The melting section, initially responsible for 42,000 kWh per production cycle, now consumes only 38,000 kWh after optimization—a 9.5% reduction. Similarly, the casting process saw a 10.7% improvement, primarily because of synchronized furnace scheduling and heat recovery integration. Meanwhile, auxiliary systems achieved moderate savings through HVAC automation and LED retrofits. These improvements validate the adaptability of the proposed architecture across diverse operational processes.

A positive correlation was observed between system control granularity and achieved efficiency. Subsystems with more granular sensor feedback and real-time energy analytics exhibited higher performance gains. For example, in machining, energy savings were lower (8.3%) due to partially automated spindle load control, suggesting that the level of cyber-physical system (CPS) integration directly influences optimization depth. This highlights the importance of extending full CPS and IoT connectivity across all manufacturing stages.

Post-implementation monitoring revealed that the energy management system stabilized operational loads within ±2% of target demand even during peak production periods. The SCADA–AI hybrid control loop dynamically adjusted reactive power compensation, reducing total harmonic distortion (THD) by 6–8% and maintaining a power factor above 0.95. These findings support the hypothesis that a multi-layered energy management architecture enhances both efficiency and power quality in continuous manufacturing contexts.

From an economic standpoint, annual energy cost reductions of approximately USD 125,000–140,000 were projected for a medium-sized plant operating 8,000 hours per year. Environmental benefits include a 7.2% decrease in CO_2 emissions, aligned with Uzbekistan's "Green Energy Strategy 2030." The study confirms that investing in intelligent energy management yields long-term sustainability and competitiveness by lowering operational expenses, stabilizing grid interaction, and improving energy resilience.

Table 1. Energy Consumption and Efficiency Improvement by Subsystem

Subsystem	Baseline Consumption (kWh)	Optimized Consumption (kWh)	Energy Savings (kWh)	Improvement (%)	Remarks
Melting	42,000	38,000	4,000	9.5	Dynamic furnace scheduling and load balancing improved efficiency.
Casting	28,000	25,000	3,000	10.7	Coordinated heat recovery and adaptive power control reduced losses.
Machining	18,000	16,500	1,500	8.3	Partial automation of spindle load reduced idle power use.
Packaging	15,000	14,000	1,000	6.7	Smart conveyor control minimized standby energy.
Auxiliary	12,000	11,000	1,000	8.3	HVAC optimization and lighting retrofits improved efficiency.
Total / Average	115,000	104,500	10,500	≈ 8.7	Overall system improvement through integrated AI-SCADA control.

The results presented in Table 1 clearly demonstrate the effectiveness of the proposed complex energy management architecture in reducing electricity consumption across all major subsystems of the continuous manufacturing plant. Total energy use decreased from 115,000 kWh to 104,500 kWh, yielding an overall efficiency improvement of approximately 8.7%. The most significant savings were achieved in the casting (10.7%) and melting (9.5%) sections, primarily due to the implementation of dynamic furnace scheduling, adaptive power control, and integrated heat recovery processes. Moderate improvements were observed in the machining (8.3%), auxiliary (8.3%), and packaging (6.7%) subsystems, where smart automation, lighting retrofits, and HVAC control contributed to reduced standby and idle power losses. These results confirm that integrating AI-driven optimization and SCADA-based real-time monitoring can substantially enhance both the energy and operational performance of continuous manufacturing enterprises, while also aligning with the national goals of industrial energy efficiency and sustainability in Uzbekistan.

4. Conclusions

The research demonstrated that implementing a complex energy management architecture in continuous manufacturing plants leads to measurable improvements in both energy efficiency and process stability. Through the integration of SCADA-based monitoring, nonlinear optimization models, and AI-assisted control algorithms, total electricity consumption was reduced by 3–5%, while the average power factor improved to 0.95–0.96. Subsystem-level analysis revealed that the greatest efficiency gains occurred in energy-intensive stages such as melting and casting, confirming the value of adaptive load scheduling and predictive feedback mechanisms. These results validate the feasibility of transitioning from traditional, static control approaches to intelligent, data-driven management systems that align operational reliability with sustainability objectives.

For Uzbekistan's continuous manufacturing sector, the proposed architecture provides a viable pathway toward achieving the Green Energy Strategy 2030 targets. The findings highlight how the integration of digital twins, IoT-based metering, and adaptive optimization algorithms can reduce reactive power losses, enhance grid stability, and lower operational costs across large industrial zones such as Navoi, Almalyk, and Bekabad. The proposed framework not only supports national energy-efficiency goals but also establishes a foundation for Industry 4.0-driven modernization of the country's industrial infrastructure. In future studies, expanding the system to include renewable energy forecasting, demand response mechanisms, and hybrid optimization models could further strengthen Uzbekistan's position as a leader in smart and sustainable industrial energy management.

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