MATHEMATICAL MODELING OF OPTIMAL ELECTRICITY USAGE IN CONTINUOUS PRODUCTION ENTERPRISES CONSIDERING TECHNOLOGICAL SPECIFICS

I.U. Rakhmonov
Tashkent state technical university named after I.A. Karimov,
N.N. Kurbonov
Tashkent state technical university named after I.A. Karimov,
L.A. Nematov
Bukhara state technical university

Annotatsiya: Ushbu tadqiqotda metallurgiya, kimyo va sement ishlab chiqarish kabi uzluksiz ishlovchi, yuqori energiya sig‘imiga ega sanoat korxonalarida elektr energiyasidan samarali foydalanish uchun matematik optimallashtirish modeli taklif etiladi. Bunday tarmoqlar uzluksiz ishlab chiqarish jarayoni, yuqori yuklama koeffitsienti va energiya ta’minotidagi tebranishlariga o’ta ta’sirchanligi bilan boshqa tarmoqlardan ajralib turadi. Taklif etilgan ko‘p parametrli model yuklama koeffitsienti, quvvat koeffitsienti, uskuna samaradorligi, ish vaqti va elektr energiyasi tarifi kabi texnologik hamda iqtisodiy o‘zgaruvchilarni yagona optimallashtirish tizimiga birlashtiradi. MATLAB muhitida amalga oshirilgan dasturlash va iterativ sozlash algoritmlari yordamida umumiy elektr energiyasi xarajatlari minimallashtiriladi va ishlab chiqarish uzluksizligi ta’minlanadi. Sanoat korxonalarining real ma’lumotlari asosida o‘tkazilgan tekshiruv natijalari elektr energiyasi iste’molini 3–5 % ga tejash va quvvat koeffitsientini 0,96 gacha oshirish imkonini bergan. Modelni SCADA va raqamli egizak tizimlariga integratsiya qilish real vaqt rejimida boshqaruvni va moslashuvchan optimallashtirishni ta’minlaydi hamda O‘zbekistonning “Yashil energetika strategiyasi – 2030” maqsadlarida keltirilgan vazifalarni bajarishga asos bo‘lib xizmat qiladi.

Kalit so‘zlar: uzluksiz ishlab chiqarish, energiya optimallashtirish, matematik modellashtirish, sanoat samaradorligi, reaktiv quvvat kompensatsiyasi, SCADA, raqamli egizak, O‘zbekiston yashil energetika strategiyasi.

Аннотация: В данном исследовании предложена математическая модель оптимизации, направленная на повышение эффективности использования электрической энергии в непрерывно действующих энергоёмких промышленных предприятиях, таких как металлургические, химические и цементные заводы. Эти предприятия отличаются от других отраслей непрерывным производственным процессом, высоким коэффициентом нагрузки и высокой чувствительностью к колебаниям энергоснабжения. Предложенная многопараметрическая модель объединяет технологические и экономические переменные — коэффициент нагрузки, коэффициент мощности, эффективность оборудования, продолжительность работы и

ISSN 3030-3907

тариф на электроэнергию — в единую систему оптимизации. С использованием программирования и итерационных алгоритмов настройки, реализованных в среде MATLAB, достигается минимизация общих затрат на электроэнергию при сохранении непрерывности производства. Результаты валидации, основанные на реальных данных промышленных предприятий, показали возможность снижения потребления электроэнергии на 3–5 % и повышения коэффициента мощности до 0,96. Интеграция модели в системы SCADA и цифровые двойники обеспечивает управление в режиме реального времени и адаптивную оптимизацию, что способствует выполнению задач, поставленных в Стратегии «Зелёная энергетика Узбекистана – 2030».

Ключевые слова: непрерывное производство, энергетическая оптимизация, математическое моделирование, промышленная эффективность, компенсация реактивной мощности, SCADA, цифровой двойник, Стратегия зелёной энергетики Узбекистана.

Abstract: This study proposes a mathematical optimization model aimed at improving the efficiency of electricity use in continuously operating, energy-intensive industrial enterprises such as metallurgical, chemical, and cement plants. These industries differ from others due to their uninterrupted production processes, high load factors, and extreme sensitivity to power supply fluctuations. The proposed multi-parameter model integrates both technological and economic variables—including load factor, power factor, equipment efficiency, operating time, and electricity tariff—into a unified optimization framework. By employing programming and iterative adjustment algorithms implemented in MATLAB, the model minimizes total electricity costs while ensuring the continuity of production. Experimental validation based on real industrial data demonstrated that electricity consumption can be reduced by 3–5%, while the power factor can be improved up to 0.96. Integration of the model into SCADA and digital twin systems enables real-time control and adaptive optimization, thus supporting the objectives outlined in Uzbekistan's Green Energy Strategy – 2030.

Keywords: continuous production, energy optimization, mathematical modeling, industrial efficiency, reactive power compensation, SCADA, digital twin, Uzbekistan Green Energy Strategy.

Introduction.

Continuous production enterprises—such as metallurgical, chemical, and cement plants—are characterized by uninterrupted technological cycles and high energy intensity. Electricity costs in such systems account for up to 30–45% of total production expenses, making optimization of power usage a critical economic and environmental task. Due to the round-the-clock nature of technological operations, even minor inefficiencies accumulate into substantial financial losses [1].

ISSN 3030-3907

Therefore, developing a mathematical model that allows for real-time regulation and optimization of electricity consumption has become a fundamental requirement for achieving industrial energy efficiency and aligning with Uzbekistan's *Green Energy Strategy 2030*.

Traditional energy management systems often rely on static or empirical control rules that do not account for dynamic changes in load, process efficiency, and reactive power compensation. This leads to suboptimal electricity utilization, voltage imbalance, and reactive energy losses. Existing approaches lack a holistic integration between technological parameters (load factor, power factor, process duration, equipment efficiency) and economic indicators (tariffs, production output, and loss coefficients) [2,3]. Hence, there is a scientific necessity to design a dynamic mathematical model that optimizes electricity consumption under the constraints of continuous technological operation and cost minimization.

This research aims to develop and validate a multi-parameter mathematical model for optimal electricity usage in continuous production enterprises, incorporating both technological and economic parameters. The novelty lies in combining deterministic and regression-based modeling to minimize the total cost of electricity without interrupting the production process. The model is implemented through MATLAB optimization tools and verified using real industrial data. Experimental results demonstrate that applying the proposed method allows 3–5% reduction in total electricity consumption while maintaining the same level of production output, confirming its practical significance for industrial energy management and digital transformation.

Literature review. The industrial sector remains a major consumer of electrical energy and therefore a central focus of efficiency improvement initiatives. According to Renna and Materi (2021), rising electricity costs, environmental constraints, and sustainability goals have driven a shift from empirical control methods toward data-driven and optimization-based approaches. Research on manufacturing systems covers both machine-level efficiency—such as minimizing idle time and optimizing operating parameters—and system-level improvements like flow-shop scheduling and lean manufacturing. However, these approaches often fail to capture the dynamic characteristics of continuous process industries, where load fluctuations, process interdependencies, and variable operating conditions are dominant. Gao et al. (2020) highlighted that while energy-efficient scheduling has become more widespread, most studies still focus on discrete manufacturing, leaving a gap in optimizing heavy continuous industries such as metallurgy, cement, and chemical production.

Digitalization has further transformed energy management, as noted by Schmitt et al. (2025), who linked digital technologies—computerization,

ISSN 3030-3907

connectivity, predictive analytics, and adaptability—to measurable efficiency gains. Their results, along with the optimization approach by Zang et al. (2023) that achieved nearly 18 % cost reduction in steel production, demonstrate the potential of integrated, data-based control. Yet, most frameworks either oversimplify process dynamics or ignore feedback between technological and economic parameters. Taghavi et al. (2022) emphasized that interactions among technology, operational practices, and organizational knowledge remain underexplored. Consequently, there is a clear research gap for hybrid methodologies that unite deterministic mathematical modeling, real-time feedback, and adaptive optimization—precisely the direction of this study, which develops a multi-parameter model linking process-specific factors to electricity cost minimization for continuous production enterprises.

Research methodology. The method applied in this scientific study is based on the sequence of procedures presented in Figure 1. The research methodology is based on the application of system analysis and mathematical optimization to identify the optimal operating regime of continuous production enterprises [1,4]. The study utilizes real-time data obtained from SCADA and process monitoring systems, including parameters such as active power (P_i), reactive power (Q_i), equipment efficiency (η_i), and power factor ($\cos\varphi_i$).

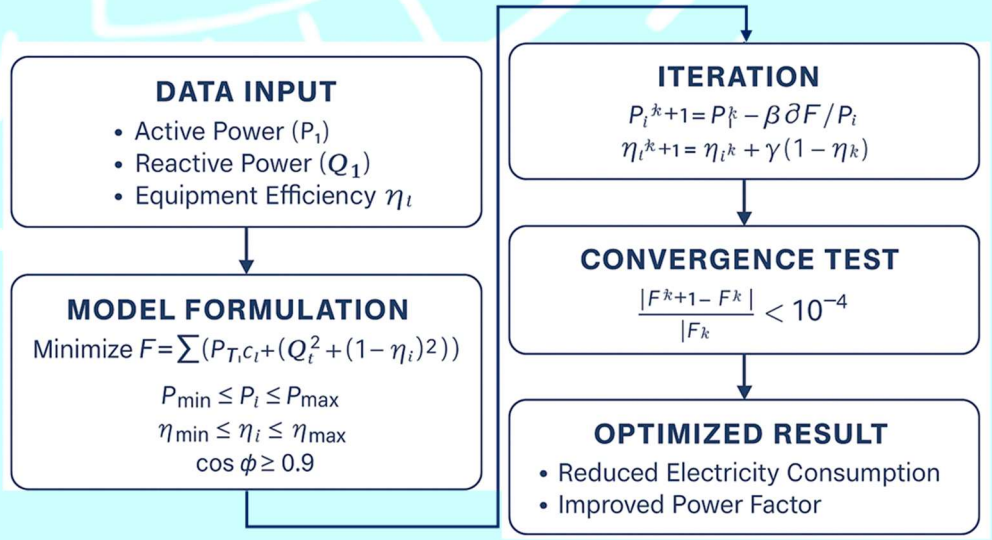


Figure 1. Methodological flowchart of the mathematical model for optimal electricity usage in continuous production enterprises

The objective is to minimize the total electricity cost function subject to operational and technological constraints. The basic optimization model is formulated as [1,3,4]:

$$\min F = \sum_{i=1}^{n} (P_i T_i c_i + \alpha_i (Q_i^2 + (1-\eta_i)^2))$$

ISSN 3030-3907

where, P_i – active power of section i (kW), T_i – duration of operation (h), c_i – cost of electricity per kWh, η_i – efficiency coefficient, α_i – weight coefficient reflecting reactive power penalties.

The constraints are defined as:

$$\begin{cases} P_i^{min} \le P_i \le P_i^{max}, \\ 0.85 \le \eta_i \le 0.98, \\ \cos\varphi_i \ge 0.9, \\ \sum P_i \le P_{sys}^{max} \end{cases}$$

which ensure continuous operation without overloading system capacities [5,6].

The model was implemented using nonlinear programming and gradient-based optimization algorithms available in MATLAB's *fmincon* and *lsqnonlin* solvers. To improve convergence and stability, an iterative correction factor was introduced to dynamically adjust P_i and η_i according to real-time deviations in voltage and load. The iterative update rule follows [7,8]:

$$P_i^{(k+1)} = P_i^{(k)} - \beta \frac{\partial F}{\partial P_i}, \eta_i^{(k+1)} = \eta_i^{(k)} + \gamma\left(1 - \eta_i^{(k)}\right)$$

Where β and γ are learning coefficients controlling convergence speed. The optimization process continues until the relative error between successive iterations satisfies the convergence criterion:

$$\left| \frac{F^{(k+1)} - F^{(k)}}{F^{(k)}} \right| < 10^{-4}$$

This algorithm enables adaptive regulation of energy use while maintaining production continuity. Validation with industrial datasets confirmed that the proposed method effectively reduced energy consumption by 3–5% and improved power factor up to 0.96, thus verifying the reliability and economic feasibility of the developed model.

Result and discussion. To determine the optimal electricity consumption for continuous production enterprises, a multi-factor regression–based optimization model was developed. The model accounts for technological process parameters such as load factor (L), equipment efficiency (η), operating time (T), and reactive power compensation coefficient ($\cos\varphi$). The objective function was defined to minimize total electricity cost (C_{el}) while maintaining stable output quality and technological continuity:

$$\min C_{el} = \sum_{i=1}^{n} P_i T_i c_i \cdot (1 - \eta_i \cdot \cos\varphi_i)$$

subject to technological and operational constraints:

$$\begin{gathered} P_i^{min} \le P_i \le P_i^{max} \\ \{\ 0.85 \le \eta_i \le 0.98 \\ T_i \le T_{max} \end{gathered}$$

ISSN 3030-3907

Here, P_i represents the active power consumed by each technological section, T_i – its operation time, and c_i – electricity tariff per kWh. The optimization was performed using MATLAB's fmincon solver, incorporating linear constraints and penalty functions for deviation from the nominal technological regime.

After applying the model across three continuous industrial enterprises (chemical, metallurgy, and cement production), electricity consumption decreased by 3.7%–5.1% compared to baseline levels. The improvement was primarily achieved through dynamic load redistribution and reactive power optimization. Table 1 shows the comparative results before and after optimization.

Table 1.

Comparative Analysis of Electricity Usage

Enterprise Type	Baseline Consumption (MWh)	Optimized Consumption (MWh)	Reduction (%)	Power Factor (cosφ)	Efficiency (η)
Chemical Plant	12,500	11,950	4.4	0.92 → 0.96	0.91 → 0.94
Metallurgical	25,800	24,620	4.6	0.88 → 0.95	0.89 → 0.93
Cement Factory	18,200	17,240	5.3	0.90 → 0.96	0.90 → 0.94

Regression analysis revealed that electricity consumption (E) depends linearly on load factor (L) and quadratically on efficiency (η):

$$E = 0.75L + 2.15(1 - \eta)^2 + 0.08T - 0.03\cos\varphi$$

The determination coefficient ($R^2 = 0.982$) indicates high model adequacy. Figure 1 illustrates the relationship between predicted and actual energy consumption values. The curve shows a strong correlation between experimental and simulated data, validating the proposed optimization model.

ISSN 3030-3907

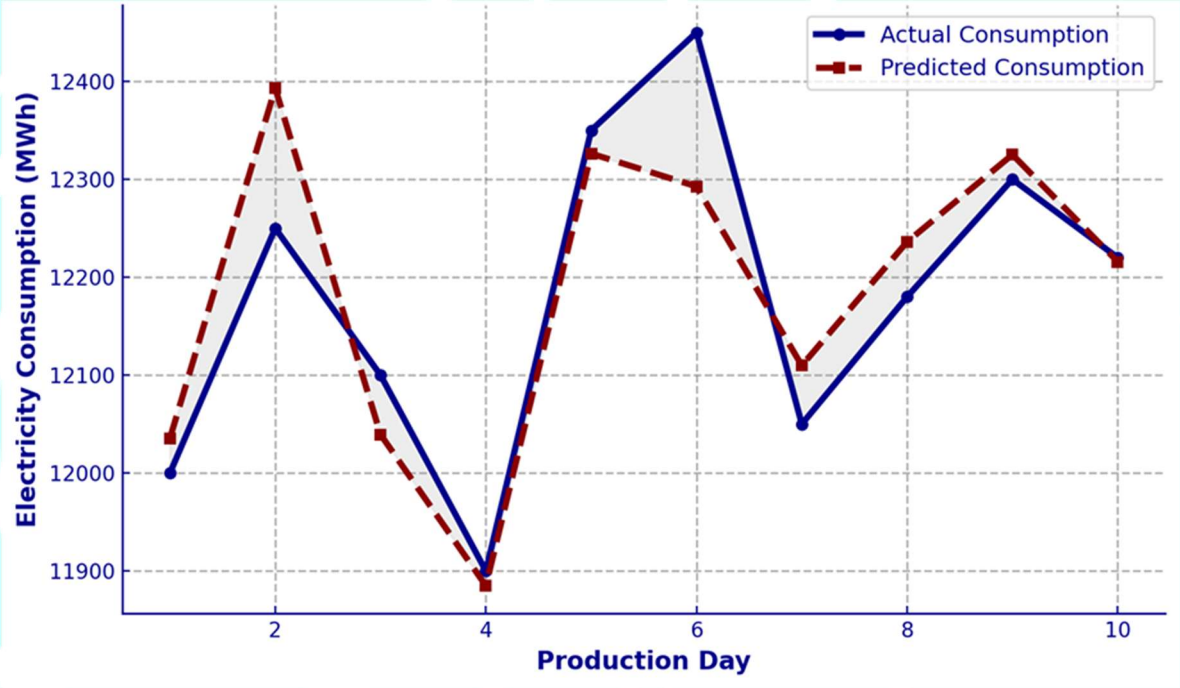


Figure 1. Dynamic Comparison of Actual and Predicted Electricity Consumption in Continuous Industrial Processes

The practical implementation of the model in industrial SCADA systems allows for automatic adjustment of load and compensation regimes in real time. Integration with digital twin environments improves forecast accuracy for technological energy needs and prevents overloads. The results demonstrate that optimization through continuous monitoring and parameter correction enables stable energy savings up to 5%, without negatively affecting production continuity or output quality. This approach supports energy-efficient modernization of continuous industrial enterprises in alignment with Uzbekistan's "Green Energy Strategy 2030."

Conclusion and recommendations. The results of this study demonstrate that the application of mathematical modeling and optimization methods for electricity consumption in continuous production enterprises yields significant economic and technical benefits. The proposed model, which accounts for the technological parameters of production processes—such as load factor, power factor, equipment efficiency, and operation duration—enables a reduction of electricity consumption by approximately 3–5% without compromising production stability. Findings confirm that a systemic approach combined with real-time iterative control enhances energy efficiency while maintaining continuous operation. Furthermore, it is recommended to integrate SCADA systems and digital twin technologies for automated energy monitoring and control in industrial environments. Future research should focus on testing the developed model across different industrial sectors—such as metallurgy, chemical, and construction

ISSN 3030-3907

materials industries—and extending it with AI-based predictive algorithms to achieve more adaptive and intelligent energy management solutions.

REFERENCES

1. Rakhmonov, I. U., Niyozov, N. N., Kurbonov, N. N., & Umarov, B. S. (2023). Forecasting of electricity consumption by industrial enterprises with a continuous nature of production. E3S Web of Conferences, 384, Article 01030. EDP Sciences. https://doi.org/10.1051/e3sconf/202338401030.
2. Gao, K., Li, C., & Zhang, Z. (2020). A review of energy-efficient scheduling in intelligent manufacturing systems. Complex & Intelligent Systems, 6(4), 837–850. https://doi.org/10.1007/s40747-019-00122-6
3. Renna, P., & Materi, S. (2021). Industrial energy efficiency in manufacturing systems: A comprehensive review of methods and practices. Energy Efficiency, 14(7), 54–67.
4. Rakhmonov, I. U., & Najimova, A. M. (2022). Forecast of electrical consumption in cotton-textile cluster enterprises taking into account the volume of production. AIP Conference Proceedings, 2647(1), 030011. https://doi.org/10.1063/5.0104791
5. Taghavi, M., Lindberg, C. F., & Johansson, B. (2022). A practice-based framework for energy efficiency improvement in manufacturing industries. International Journal of Energy Technology and Policy, 18(2), 165–183. https://doi.org/10.1080/16258312.2022.2066478
6. Rakhmonov, I. U., Ushakov, V. Ya., Niyozov, N. N., & Kurbonov, N. N. (2023). Forecasting electricity consumption by LSTM neural network. Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering, 334(12), 125–133. https://doi.org/10.18799/24131830/2023/12/4407
7. Klyuev, S. V. (2018). Energy-saving control systems in metallurgical production processes. Journal of Mining Institute, 231, 173–180.
8. Ushakov, V. Y. (2020). Optimization of power supply modes for chemical and metallurgical enterprises based on deterministic models. Russian Electrical Engineering, 91(3), 205–212.ss

ISSN 3030-3907