DOI: 10.31319/2519-8106.1(52)2025.330404
UDC 519.866:620.9:656

Sereda Borys[1], Doctor of Technical Sciences, Professor, Head Department of automobiles and automotive industry
Середа Б.П., доктор технічних наук, професор, завідувач кафедри автомобілів та транспортно-логістичних систем
ORCID: 0000-0002-9518-381X
e-mail: seredabp@ukr.net

Mukovska Daria[2], Postgraduate student of the Department of Transport Systems and Logistics
Муковська Д.Я., здобувач третього (доктора філософії) рівня вищої освіти, кафедра транспортних систем і логістики

Zuyzin Evgeniy[1], postgraduate student, Department of automobiles and transport and logistics systems
Зюзін Є.П., здобувач третього (доктора філософії) рівня вищої освіти, кафедра автомобілів та транспортно-логістичних систем

Orel Vitaliy[1], postgraduate student, Department of automobiles and transport and logistics systems
Орел В.Г., здобувач третього (доктора філософії) рівня вищої освіти, кафедра автомобілів та транспортно-логістичних систем
e-mail: Orel.V@gmail.com

[1]Dniprovsky State Technical University, Kamianske
Дніпровський державний технічний університет, м. Кам’янське
[2]O.M. Beketov National University of Urban Economy in Kharkiv, Kharkiv
Харківський національний університет міського господарства імені О.М. Бекетова, м. Харків

MATHEMATICAL MODELS FOR OPTIMIZATION OF THE USE OF ALTERNATIVE ENERGY SOURCES IN TRANSPORT AND PRODUCTION SYSTEMS

МАТЕМАТИЧНІ МОДЕЛІ ДЛЯ ОПТИМІЗАЦІЇ ВИКОРИСТАННЯ АЛЬТЕРНАТИВНИХ ДЖЕРЕЛ ЕНЕРГІЇ В ТРАНСПОРТНО-ВИРОБНИЧИХ СИСТЕМАХ

The article discusses mathematical models for optimizing the use of alternative energy sources in transport and production systems. Special attention is given to electric vehicles as well as renewable energy sources such as solar, wind, bioenergy, and hydrogen technologies. The study explores the opportunities and challenges associated with the transition to alternative energy sources, including high initial costs, imperfect infrastructure, and the instability of renewable energy supply. Mathematical models for optimizing energy consumption, routing of electric vehicles, and integrating renewable energy sources into logistics processes are highlighted separately. The article also evaluates the prospects for the development of such technologies and provides recommendations for overcoming existing challenges to ensure the sustainable development of transport and production systems.
***Keywords**: alternative energy sources; transport and production systems; electric vehicles; renewable energy sources; solar energy; wind energy; bioenergy; hydrogen technologies; hybrid systems; mathematical models; energy consumption optimization; logistics processes; environmental efficiency.*

У статті здійснюється аналіз застосування математичних моделей для оптимізації використання альтернативних джерел енергії в рамках транспортно-виробничих систем. В умовах сучасних економічних та екологічних викликів, що вимагають скорочення залежності від традиційних викопних енергоносіїв і зменшення викидів парникових газів, перехід на відно-

влювальні джерела енергії набуває стратегічної важливості. Дослідження охоплює основні типи альтернативних джерел енергії, зокрема електричні транспортні засоби, сонячну і вітрову енергію, біоенергетику, а також водневі та гібридні технології.

Особлива увага приділена математичним моделям, що сприяють оптимізації енергоспоживання у процесах транспортування та виробництва. Моделі, що стосуються оптимізації маршрутів електричних транспортних засобів, інтеграції відновлювальних джерел енергії в логістичні процеси, а також багатокритеріальної оптимізації з огляду на економічну та екологічну ефективність, є важливими інструментами для досягнення енергоефективності в цих системах.

Крім того, у статті розглядаються проблеми, що виникають при впровадженні альтернативних джерел енергії, зокрема високі початкові витрати, нестача відповідної інфраструктури та нестабільність в роботі відновлювальних джерел енергії. Одним з важливих аспектів є створення стійких енергетичних та транспортних систем, здатних забезпечити надійне та ефективне постачання енергії.

Перспективи розвитку технологій альтернативних джерел енергії в транспортно-виробничих системах полягають у вдосконаленні технологій зберігання енергії, інтеграції новітніх розробок та покращенні інфраструктури, що дозволить знизити витрати та екологічний вплив, забезпечуючи сталий розвиток галузі в цілому.

У статті також наводяться рекомендації щодо подолання наявних проблем, що сприятимуть більш ефективному переходу до використання альтернативних джерел енергії в транспорті та виробництві.

Ключові слова: *альтернативні джерела енергії; транспортно-виробничі системи; електричні транспортні засоби; відновлювальні джерела енергії; сонячна енергія; вітрова енергія; біоенергетика; водневі технології; гібридні системи; математичні моделі; оптимізація енергоспоживання; логістичні процеси; екологічна ефективність.*

Formulation of the problem

The modern global economy and transportation systems still largely rely on fossil energy sources, such as oil, natural gas, and coal. However, climate change, the finite nature of natural resources, and the economic and political challenges associated with the instability of prices for traditional energy carriers raise doubts about the sustainability of existing energy consumption models. Transport and production systems, which form the foundation of a country's infrastructure and logistics, require modernization to ensure energy security and reduce environmental impact. In this context, the implementation of alternative energy sources, such as electric vehicles, solar and wind energy, bioenergy, and others, becomes particularly relevant.

Analysis of recent research and publications

Traditional energy sources (oil, gas, coal) form the basis of the energy needs of transport and production systems due to their availability and efficiency. However, their use has significant drawbacks. First, fossil fuels cause substantial greenhouse gas emissions, which contribute to global warming. Second, high oil and gas prices, along with dependence on external energy suppliers, make the economy vulnerable to fluctuations in global markets. Moreover, traditional energy sources are non-renewable, which threatens the sustainable development of transport and production systems in the future.

The transition to alternative energy sources is not only an ecological but also an economic necessity. Renewable sources, particularly solar and wind energy, as well as bioenergy and hydrogen technologies, offer significant potential for reducing dependence on traditional sources. However, this process requires substantial investments in new technologies and infrastructure development. Furthermore, the integration of renewable energy sources into transport and production systems is associated with challenges such as the integration of new technologies, ensuring the stability of energy flows, and adapting existing systems to new requirements.

Formulation of research purpose

The aim of this article is to explore the potential of alternative energy sources for optimizing energy consumption in transport and production systems. The article examines mathematical models that enable the effective integration of alternative energy sources into transportation processes, as well as the main challenges and prospects of this transition.

Presenting main material

Electric vehicles, such as electric cars, buses, and trucks, are becoming one of the most promising areas for the development of environmentally friendly technologies in transportation. In particular, electric cars ensure minimal CO_2 emissions, reducing air pollution in cities and lowering the overall environmental impact. To assess the effect of replacing conventional transport with electric vehicles, the following formula can be used:

$$\Delta CO_2 = (E_{TZ} \cdot EF_{DP}) - (E_{ETZ} \cdot EF_{el}), \qquad (1)$$

when ΔCO_2 — CO_2 emissions reduction; E_{TZ} — energy consumption by conventional transport; EF_{DP} — emission factor of diesel fuel; E_{ETZ} — electricity consumption by the electric vehicle; EF_{el} — Emission factor of electricity.

In today's world, there is an increasing number of electric trucks and buses on the market, which helps reduce dependence on traditional fuels and contributes to a decrease in noise pollution. At the same time, for the widespread adoption of electric vehicles, it is necessary to develop the charging station infrastructure and improve battery technologies to ensure longer operation on a single charge.
Solar energy is one of the most promising sources of energy for transportation and production. Installing solar panels on the roofs of warehouses, production buildings, and even vehicles allows for the generation of electricity, the amount of which can be calculated using the following formula:

$$E_{PV} = A \cdot G \cdot y, \qquad (2)$$

when E_{PV} — daily energy generation; A — area of the solar panel; G — average solar insolation; y — efficiency coefficient of the panel.

Wind energy also holds significant potential, especially for regions with high wind resources. Bioenergy includes the use of biomass and biogas, which can serve as fuel for vehicles, particularly in rural areas where there is potential for the development of such technologies.
Hydrogen technologies are one of the most promising directions for replacing fossil fuels. Hydrogen can be used to power vehicles, as well as serve as an energy resource for electricity production. Hydrogen-powered vehicles have low emissions, and their use can help reduce air pollution and mitigate climate change impacts. Hybrid systems that combine traditional engines and electric systems are effective in reducing fuel consumption and energy use, as well as in providing stable energy supply for vehicles. The energy consumption of a vehicle on a route can be modeled as follows:

$$E_{MAR} = \sum_{i=1}^{n} \left(\frac{m \cdot a_i \cdot d_i}{\text{м}_{DV}} + P_{DOP} \cdot t_i \right), \qquad (3)$$

when m — mass of the vehicle; a_i — acceleration; d_i — length of the section; м_{DV} — engine efficiency; P_{DOP} — auxiliary load; t_i — travel time.

The main advantage of alternative energy sources lies in their ability to significantly reduce CO_2 emissions. The use of electric vehicles and renewable energy sources helps decrease the ecological footprint of transportation and production. Furthermore, the implementation of such technologies contributes to increased energy efficiency by reducing reliance on traditional energy carriers and ensuring the stability of energy flows within systems.

Mathematical models for optimizing energy consumption in transport and production systems encompass a variety of approaches for modeling energy flows, managing resources, and determining optimal parameters for integrating alternative energy sources. For example, when planning the placement of charging stations, the following optimization model is used:

$$\min \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} \cdot x_{ij}, \ \text{subject to:} \ \sum_{j=1}^{m} x_{ij} = 1; \qquad x_{ij} \in \{0,1\}, \qquad (4)$$

when c_{ij} — the servicing cost of vehicle i at station j; x_{ij} — binary variable (route selection).

Some of the most relevant models include linear and nonlinear programming, game theory, queuing theory models, as well as statistical methods. These models not only allow for predicting the energy needs of the system but also enable detailed planning of measures aimed at reducing energy costs and CO_2 emissions. An important aspect is the integration of renewable energy sources, such as solar and wind stations, with current energy needs, which significantly reduces dependence on traditional energy sources and enhances the efficiency of production processes.

The optimization of routes for electric vehicles is an important component of strategies aimed at reducing energy consumption and charging costs. Models in this area take into account numerous factors, such as the geographical location of charging stations, charging time, battery types and their capacities, as well as various road conditions. One of the key parameters is the calculation of the maximum driving range of the electric vehicle:

$$D_{max} = \frac{C_{battery} \cdot D_{system}}{E_{consumption}}, \quad (5)$$

when D_{max} — maximum driving range of the electric vehicle; $C_{battery}$ — battery capacity; D_{system} — system efficiency; $E_{consumption}$ — energy consumption.

This allows for an accurate estimation of the distance the vehicle can travel without additional charging. Optimization algorithms aim to identify the most energy-efficient routes, minimizing energy consumption, travel time, and charging costs. Additionally, models consider the impact of weather conditions on battery performance and energy costs depending on the charging location.

The integration of renewable energy sources into logistics processes is a significant step towards sustainable development within transport and production systems and takes into account the instability of energy supply. The energy supply balance in a hybrid system can be described by the following equation:

$$E_{Total} = E_{solar} + E_{wind} + E_{conventional} + \Delta E_{storage}, \quad (6)$$

when E_{Total} — total energy consumption of the system; E_{solar} — energy from solar; E_{wind} — energy from wind sources; $E_{conventional}$ — energy from conventional sources; $\Delta E_{storage}$ — energy taken from or stored in the energy storage system.

Algorithms for integrating such energy sources account for the unpredictability of energy supply from solar and wind installations, as well as the fluctuating energy demand depending on the stages of the production cycle. Models use statistical methods to forecast the available energy from renewable sources and optimization algorithms to determine the most effective energy storage strategies, utilizing batteries and other energy storage systems. Hybrid systems, combining renewable energy sources with traditional energy sources to ensure uninterrupted energy supply, are also considered.

Multicriteria optimization models are applied to solve problems that require simultaneous consideration of various aspects, such as economic feasibility, environmental requirements, and technical capabilities. These models analyze the effectiveness of using alternative energy sources, taking into account integration costs, energy savings, and environmental impacts (reduction of CO_2 emissions). Optimization is carried out using Multicriteria analysis methods, such as Pareto methods, weighted coefficients, or heuristic methods, which help identify the most balanced approaches to technology implementation.

Energy flow management is a crucial step in optimizing energy use within complex transport and production systems. Models for this direction enable effective management of energy flows between various system components, such as vehicles, production capacities, and energy supply networks. These models account for variable energy demand conditions, energy storage capabilities, and backup energy sources. They allow the identification of optimal strategies for the rational use of various energy sources (renewable and traditional) and the provision of uninterrupted energy supply under high demand variability.

The transition to alternative energy sources requires significant initial investments, which may pose a serious obstacle to the widespread adoption of such technologies.
The transition to alternative energy sources can be evaluated using a formula for total capital costs:

$$C = C_1 + C_2 + C_3 + C_4, \quad (7)$$

when C — total capital costs of implementing alternative energy sources; C_1 — initial investments in purchasing equipment (e.g., solar panels, wind turbines, hydrogen systems, etc.); C_2 — costs for developing infrastructure (e.g., creating charging stations, energy supply networks); C_3 — costs for integrating new technologies into existing systems (e.g., adapting vehicles to new energy sources); C_4 — operational and maintenance costs (including costs for equipment upkeep and updates).

The cost of not only purchasing but also installing solar panels, wind turbines, electric vehicles, and infrastructure for charging stations can significantly exceed the initial costs of traditional energy sources. Furthermore, it is essential to consider the expenses for research, development, and adaptation of new technologies. This can become burdensome for businesses with limited access to funding or those facing uncertainty in the alternative energy market. A real challenge is also the need to create effective financing models and government subsidies that can help reduce these costs.

The implementation of alternative energy sources is impossible without appropriate infrastructure. Specifically, for electric vehicles to function effectively, a well-developed network of charging stations is required to provide convenient access to energy. Similarly, for the use of bioenergy, warehouses for storing raw materials are necessary, and for integrating renewable energy sources into production and transport processes, specialized technologies and software solutions for energy consumption monitoring and management are needed. However, the existing infrastructure often does not meet modern requirements, and its modernization requires substantial investments. Moreover, the current infrastructure may not account for the technical requirements for the safe and efficient use of alternative energy sources.

The assessment of infrastructure effectiveness for supporting renewable energy sources may include a formula for the number of required charging stations $N_{station}$ — the total energy demand in the system, kWh.; $D_{station}$ — the average amount of energy that one charging station can supply, kWh.; k — the coefficient that accounts for inefficiency or a reserve to ensure reliability.

The main disadvantages of renewable energy sources, such as solar and wind installations, are their instability and dependence on weather conditions. Increased wind activity or excess sunlight can provide enough energy, while during periods of calm or cloudiness, energy supply may significantly decrease. This irregularity in energy production can lead to interruptions in power supply and difficulties in maintaining a constant electricity supply for transportation and production systems. To address this issue, it is necessary to develop energy storage technologies, such as high-capacity batteries, and improve backup power systems to ensure the stability of energy supply even in the case of unstable sources.

The instability of energy supply from renewable sources can be described by the coefficient of variation CV:

$$CV = \frac{у(E)}{м(E)}, \tag{9}$$

when $у(E)$ — the standard deviation of energy generated over a certain period; $м(E)$ — the mean value of the energy generated over this period.

This coefficient allows for evaluating the risks associated with fluctuations in energy supply and the need for energy storage or the use of backup sources.

Existing transportation and production systems, built on traditional energy sources, require significant adaptation for the effective use of alternative energy resources. This may involve upgrading technical equipment, redesigning infrastructure to integrate new technologies, and training staff to work with new systems. Additionally, adaptation to alternative energy sources may require changes in production processes, which in turn requires careful planning, consideration of economic and technical aspects, as well as testing and optimization. This demands additional time and resource investments and may lead to temporary disruptions in the efficiency of systems during the transitional period.

The adaptation of systems to new requirements can be represented by a formula for the adaptation time T_{adapt}:

$$T_{adapt} = \frac{E_1 + E_2 + E_3}{R_{speed}} \tag{10}$$

when T_{adapt} — the time required for system adaptation, hours; E_1 — costs for equipment modernization; E_2 — costs for infrastructure reorganization; E_3 — costs for staff training; R_{speed} — adaptation speed, determined by the effectiveness of changes and training.

This formula allows for evaluating how much time will be required to adapt existing transportation and production systems to new technologies, taking into account costs and resource base.

The prospects for the development of alternative energy sources in transportation and production systems are directly linked to advances in scientific research and technological innovations. There is a growing interest in improving battery technologies, which allows for enhancing the efficiency of energy storage and usage. One of the key directions is the development of new materials for solar panels that can provide significantly higher efficiency compared to traditional silicon panels. At the same time, progress in hydrogen fuel cell technology, particularly achieving greater stability and operational lifespan, makes these technologies more accessible for transportation. An important component is also the integration of various alternative energy technologies into unified systems to enhance their interaction and provide synergy, which, in turn, can lead to a significant reduction in overall transportation and production costs.

Energy storage systems are one of the key components for ensuring the stability of energy networks, where a major challenge is the uneven production of energy from renewable sources like solar and wind. The search for new solutions in battery technologies, such as lithium-ion batteries with high energy density or emerging technologies like sodium batteries, will contribute to reducing storage costs and improving energy efficiency. Another important technology is hydrogen storage, which can be used not only for transportation but also in other industrial sectors, where it can serve as a backup energy source. The development of more efficient and cost-effective hydrogen storage methods, such as underground storage or new compact storage solutions, will help reduce the costs of energy transport and production.

Integrating alternative energy sources into transportation and production systems will create more resilient and adaptive energy networks. This will not only reduce dependence on traditional fossil energy sources but also significantly decrease the negative environmental impact, particularly CO_2 emissions and other harmful substances. A key aspect is the development of infrastructure for electric vehicle charging, especially the expansion of fast-charging station networks, as well as creating eco-friendly logistics routes for freight transport. Innovative technologies, such as autonomous vehicles powered by renewable energy, will further enhance the efficiency and convenience of these systems. All these factors will contribute to the transition to more efficient and environmentally clean transportation systems, which in the long term will significantly reduce energy supply costs and promote sustainable development.

Conclusions

The transition to alternative energy sources is an important step towards ensuring the sustainable development of transportation and production systems. It will significantly reduce the environmental impact, lower costs for traditional energy carriers, and ensure stable energy independence. At the same time, this process requires a comprehensive approach, including investments in infrastructure, the development of new technologies, and addressing existing challenges related to adapting systems to new requirements.

References

[1] Guo, Z., Afifah, F., Qi, J., & Baghali, S. (2021). A Stochastic Multi-Agent Optimization Framework for Interdependent Transportation and Power System Analyses. arXiv preprint arXiv:2101.00908.

[2] Tran, T. T. D., & Smith, A. D. (2019). Stochastic Optimization for Integration of Renewable Energy Technologies in District Energy Systems for Cost-Effective Use. Energies, 12(3), 533.

[3] Kim, J., Realff, M. J., Lee, J. H., Whittaker, C., & Furtner, L. (2011). Design of biomass processing network for biofuel production using an MILP model. Biomass and Bioenergy, 35(2), 853-871.

[4] Tevjashev, A. D. (2013). Stochastic models and methods of optimization of gas transmission systems. Technology audit and production reserves, (3(1)), 41-45.

[5] Zocca, A., & Zwart, B. (2017). Optimization of stochastic lossy transport networks and applications to power grids. arXiv preprint arXiv:1712.07411.
[6] Li, G., Yang, Z., Sharma, S., Mian, A., Lin, Z., Tsatsaronis, G., & Marechal, F. (2019). Overview of assessment, optimization, and synthesis of energy systems: Methodology and application to thermal power plants. Energies, 12(1), 73. https://doi.org/10.3390/en12010073
[7] Ko, S., Choi, K., Yoo, S., & Lee, J. (2022). Stochastic optimization model for sustainable multimodal transportation for bioenergy production. Sustainability, 14(3), 1889. https://doi.org/10.3390/su14031889.
[8] Hamis, A. K., Abdelaziz, A. Y., Eskaros, M. R., Attia, M. A., & Sameh, M. A. (2023). Optimal electricity flow with stochastic renewable energy using three mixture distribution component functions. Sustainability, 15(1), 334. https://doi.org/10.3390/su15010334
[9] Zhao, Z., Holland, N., & Nelson, J. (2024). Optimization of smart grid performance: A stochastic approach to the integration of renewable energy sources. Sustainable Cities and Society, 111, 105533. https://doi.org/10.1016/j.scs.2024.105533
[10] Gulcan, B. E. (2021). Stochastic optimization for renewable energy system design and operation (PhD dissertation). Clemson University. https://open.clemson.edu/all_dissertations/2864

Список використаної літератури

1. Guo Z., Afifah F., Qi J., Baghali S. A Stochastic Multi-Agent Optimization Framework for Interdependent Transportation and Power System Analyses. arXiv preprint. 2021. arXiv:2101.00908.
2. Tran T.T.D., Smith A.D. Stochastic Optimization for Integration of Renewable Energy Technologies in District Energy Systems for Cost-Effective Use. Energies. 2019. Vol. 12, No. 3. P. 533.
3. Kim J., Realff M.J., Lee J.H., Whittaker C., Furtner L. Design of biomass processing network for biofuel production using an MILP model. Biomass and Bioenergy. 2011. Vol. 35, No. 2. P. 853–871.
4. Tevjashev A.D. Stochastic models and methods of optimization of gas transmission systems. Technology audit and production reserves. 2013. No. 3(1). P. 41–45.
5. Zocca A., Zwart B. Optimization of stochastic lossy transport networks and applications to power grids. arXiv preprint. 2017. arXiv:1712.07411.
6. Li G., Yang Z., Sharma S., Mian A., Lin Z., Tsatsaronis G., Marechal F. Overview of assessment, optimization, and synthesis of energy systems: Methodology and application to thermal power plants. Energies. 2019. Vol. 12, No. 1. P. 73. https://doi.org/10.3390/en12010073.
7. Ko S., Choi K., Yoo S., Lee J. Stochastic optimization model for sustainable multimodal transportation for bioenergy production. Sustainability. 2022. Vol. 14, No. 3. P. 1889. https://doi.org/10.3390/su14031889.
8. Hamis A.K., Abdelaziz A.Y., Eskaros M.R., Attia M.A., Sameh M.A. Optimal electricity flow with stochastic renewable energy using three mixture distribution component functions. Sustainability. 2023. Vol. 15, No. 1. P. 334. https://doi.org/10.3390/su15010334.
9. Zhao Z., Holland N., Nelson J. Optimization of smart grid performance: A stochastic approach to the integration of renewable energy sources. Sustainable Cities and Society. 2024. Vol. 111. Article No. 105533. https://doi.org/10.1016/j.scs.2024.105533.
10. Gulcan B.E. Stochastic optimization for renewable energy system design and operation: PhD dissertation. Clemson University, 2021. https://open.clemson.edu/all_dissertations/2864.

Надійшла до редколегії 21.03.2025