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SMART ECO-CITY AS AN INNOVATIVE PLATFORM FOR TRANSFORMING ENVIRONMENTAL MANAGEMENT TOOLS: TECHNOLOGICAL FOUNDATION, GOVERNANCE MODEL, AND PROSPECTS FOR UKRAINE

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The article examines the concept of the "Smart Eco-City" as an innovative and integrated platform for the profound transformation of environmental management instruments in the context of the digital era, intensified global urbanization, and growing environmental risks. It is emphasized that modern urban ecosystems are characterized by high polystructural complexity, dynamism, and intricate interactions between social, economic, and natural components, which necessitates a shift from traditional, predominantly reactive approaches toward a proactive, predictive, and scientifically grounded model of environmental governance. The concept of a "Smart Eco-City" is presented as a synthesis of the technological potential of the Smart City – particularly the Internet of Things (IoT), Big Data systems, artificial intelligence, blockchain technologies, and digital monitoring platforms – with the ecological orientation of classical eco-cities aimed at minimizing environmental impact, optimizing resource use, and improving the quality of life for the population. The study substantiates the managerial architecture of the Smart Eco-City, based on the Quadruple Helix (QH) Model, which encompasses the interaction of government, business, science, and civil society and ensures polycentricity, transparency, inclusiveness, and high adaptability of managerial decisions. It is emphasized that the implementation of this model is especially relevant for Ukraine in the context of post-war territorial recovery, infrastructure modernization, the digitalization of governance, and the formation of an effective environmental safety system grounded in sustainable development principles. The research has significant scientific and practical potential, as it offers a methodological framework for implementing the Smart Eco-City as a key element of territorial planning strategies, institutional reforms, optimization of environmental monitoring, and the integration of modern digital technologies into environmental management. *Key words:* Smart City, Smart Eco-City, environmental management, sustainable development.

«SMART ECO-CITY» як інноваційна платформа для трансформації інструментів екологічного менеджменту: технологічний базис, управлінська модель та перспективи для України. Сабєльніков М. П., Сакун А. О.

У статті розглянуто концепцію «Smart Eco-City» як інноваційну та інтегровану платформу для глибокої трансформації інструментів екологічного менеджменту в умовах цифрової епохи, інтенсифікації глобальної урбанізації та зростання екологічних ризиків. Наголошено, що сучасні міські екосистеми характеризуються високою поліструктурністю, динамічністю та складністю взаємодії соціальних, економічних і природних компонентів, що зумовлює потребу у відході від традиційних, переважно реактивних підходів до моделі проактивного, прогнозного та науково обґрунтованого управління. Концепція «розумного еко-міста» подається як синтез технологічного потенціалу Smart City – зокрема, інтернету речей (IoT), систем Big Data, штучного інтелекту, блокчейн-технологій та цифрових платформ моніторингу – з екологічною орієнтацією класичних еко-міст, спрямованих на мінімізацію впливу на довкілля, оптимізацію використання ресурсів та підвищення якості життя населення. У роботі обґрунтовано управлінську архітектоніку Smart Eco-City, що базується на Моделі Квадрупольної Спіралі (QH), яка охоплює взаємодію влади, бізнесу, науки та громадськості й забезпечує поліцентричність, прозорість, інклюзивність та високу адаптивність управлінських рішень. Підкреслено, що впровадження цієї моделі є особливо актуальним для України у контексті післявоєнного відновлення територій, модернізації інфраструктури, цифровізації урядування та формування ефективної системи екологічної безпеки на принципах сталого розвитку. Дослідження має значний науковий і практичний потенціал, оскільки пропонує методологічну основу для реалізації Smart Eco-City як ключового елементу стратегій територіального планування, реформування інституційних механізмів, оптимізації екологічного моніторингу та інтеграції сучасних цифрових технологій у сферу екологічного менеджменту. *Ключові слова:* Smart City, Smart Eco-City, екологічний менеджмент, сталий розвиток.

Problem statement. In the context of global digitalization, the increasing complexity of urban ecosystems, and the need to implement advanced spatial and integrated management methodologies, traditional approaches to environmental management (EM) have become insufficiently effective. The full-scale implementation of such methodologies requires substantial computational capacity and a technological platform capable of collecting, processing, and analyzing large volumes of data. The Smart City concept serves as a key innovative platform that provides the technological foundation for transitioning from reactive to proactive environmental management. This study focuses on analyzing the potential synergy between the technological capabilities of the Smart City and the strategic goals of environmental sustainability

implemented in the format of a "Smart Eco-City." The article explores its technological foundations, conceptual principles, and managerial models, as well as practical pathways for integrating innovative solutions into the environmental management system, taking into account Ukrainian realities and the prospects of post-war recovery.

Relevance of the study is determined by the need to develop an innovative ecosystem that meets the requirements of sustainable development and aligns with the European integration vector. Empirical studies confirm a positive correlation between indicators of digital and sustainable development, proving that the Smart City concept is a scientifically grounded mechanism for implementing sustainability at the territorial level [1]. At the same time, the current military-political situation opens unique strategic opportunities: Shulzhyk and co-authors argue that the war may serve as a powerful catalyst for the accelerated development of "smart cities" in Ukraine, creating a historic chance not only to rebuild destroyed settlements but also to completely rethink their development by integrating advanced technologies and the best global practices [2]. Thus, Smart City in Ukraine serves as an effective foundation for ensuring transparent and accountable governance, as well as for fostering the sustainable development of modern, resilient, and self-sufficient territorial communities.

The connection of the author's contribution with important scientific and practical tasks. The author's contribution provides a theoretical and methodological basis for integrating the technological potential of the Smart City into the system of territorial governance.

The research is closely linked to the scientific task of substantiating that the optimal pathway for urban development is the synthesis of the Smart City and Eco-City concepts into the "smart eco-city" model [9].

In practical terms, the work contributes to solving issues related to the transformation of institutional governance mechanisms. It justifies the need to transition to the Quadruple Helix (QH) Model to ensure synergy between government, industry, academia, and citizens [4], and it also examines the integration of blockchain as a key institutional mechanism for enhancing transparency in territorial governance [5].

Analysis of recent studies and publications. The essence and multidimensional nature of the Smart City concept are widely discussed in the academic community. Kozłowski and Suwar emphasize that the smart city concept has a polystructural nature, which makes its unambiguous definition impossible [6]. Within the scientific discourse, a six-dimensional model has become established, encompassing economy, environment, governance, quality of life, mobility, and human capital [6]. Ben Yahia and co-authors note that smart city governance is formed as a polycentric system [7]. The studies of Bibri and Krogstie specify that the Eco-City model represents a separate vector of urban development focused on environmental sustainability [8]. The synthesis of these concepts into the "Smart Eco-City" format is considered the optimal pathway for urban development [9].

The technological foundation of the Smart City is a necessary condition for the transition to proactive environmental management. Almaliki and co-authors emphasize that the interaction of sensor modules, computer vision systems, and mobile devices enables the creation of an integrated communication space, which forms the technological basis for effective environmental management within the smart city concept [10]. Comber and colleagues specify that the Internet of Things (IoT) represents a global distributed communication infrastructure [11]. The functionality of IoT networks generates large volumes of Big Data, the characteristics of which are structured according to the five-V model [12]. Artificial intelligence (AI) ensures the transition to proactive management of environmental processes. According to Stavska, the implementation of machine learning algorithms and AI-based analytical methods opens opportunities for highly accurate forecasting of changes in natural systems [13]. However, Arshad and co-authors rightly note that the deployment of IoT infrastructure is accompanied by significant environmental challenges, which has intensified scientific research in this field, highlighting the need to develop technologies aimed at reducing carbon emissions and increasing energy efficiency [14].

The transformation of traditional environmental management tools occurs through the evolution of the Smart City into a citizen-driven model [15]. IoT enables the transition from a reactive monitoring model to proactive environmental risk management, which is supported by a positive correlation between digital development indicators and sustainability indicators [1]. Rahman and co-authors argue that the integration of blockchain serves as a key institutional mechanism for enhancing transparency in territorial governance [5]. In the field of waste management, the study by Romano and Masserini confirms the high effectiveness of the Pay-As-You-Throw (PAYTT) system, which is based on IoT technologies [18]. Despite critical challenges related to data quality and verification, international practice (Barcelona and London) demonstrates measurable results, such as a 30 % reduction in CO_2 emissions and a 25 % decrease in energy consumption (Barcelona) [19].

Identification of previously unresolved parts of the overall problem addressed in this article. The overarching problem addressed in this article concerns the need to develop systemic, multi-level mechanisms for implementing the Smart Eco-City model as a new paradigm of sustainable urban development that integrates innovative technologies into environmental management practices. A key challenge lies in finding a balance between universalizing digital solutions and preserving the uniqueness of individual cities, as well as preventing socio-humanitarian risks such as the growing

disconnection of people from nature. At the operational level, critical issues center on ensuring the quality and verification of big data, strengthening the cybersecurity of smart systems, and overcoming financial barriers caused by limited interest in public–private partnerships. Thus, the main purpose of the article is to justify the managerial architecture and technological solutions that minimize these risks and ensure the successful integration of smart approaches into the system of territorial governance.

The novelty of the study lies in the conceptual justification of an integrated "Smart Eco-City" model as a systemic paradigm for proactive environmental management, complemented by the systematization of the qualitative transformation of traditional environmental management tools (particularly through IoT and blockchain) and the substantiation of the transition to the Quadruple Helix Model as a key institutional mechanism.

Methodological or general scientific significance. The study has substantial general scientific significance, as it establishes a systemic approach to assessing efficiency and planning urban development based on the principles of sustainability, integrating technological, institutional, and socio-humanitarian dimensions.

This ensures a transition from descriptive analysis to the creation of a holistic, systemic governance architecture. The methodological significance lies in expanding the polystructural Smart City paradigm (which includes the six-dimensional model of economy, environment, governance, quality of life, mobility, and human capital) by incorporating the Quadruple Helix (QH) Model as a new governance framework.

Thus, the study provides a conceptual model for assessment and planning, where the QH serves as a key institutional and methodological tool that ensures polycentric governance and user-oriented approaches necessary to overcome the identified socio-humanitarian and financial barriers.

Presentation of the main material. The essence and multidimensional nature of the Smart City concept are widely discussed in the scientific community. Kozłowski and Suwar note that the smart city concept has a polystructural nature [6]. Within academic discourse, a six-dimensional model has become established, which includes economy, environment, governance, quality of life, mobility, and human capital. Front and co-authors emphasize that a key feature of urban transformation is its adaptability to the unique characteristics of specific territorial communities [20]. A critical role in the formation of a smart city is played by its managerial architecture, which transforms the "governance" dimension. Ben Yahia and colleagues state that smart city governance is formed as a polycentric system based on the coordinated actions of government institutions, stakeholders, and the public [7]. The studies of Bibri and Krogstie detail that the eco-city model represents a separate vector of urban development focused on environmental sustainability [8]. Since the principles of the eco-city require effective mechanisms for their implementation, Yekhorchenkova and co-authors argue that the optimal pathway of urban development is the synthesis of the smart city and eco-city concepts into the "Smart Eco-City" format [9].

The technological foundation of the Smart City is a necessary condition for transitioning to proactive environmental management. Almaliki and co-authors emphasize that the interaction of sensor modules, computer vision systems, and mobile devices enables the creation of an integrated communication space, which constitutes the technological basis for effective environmental management within the smart city concept [10]. The Internet of Things (IoT) represents a global distributed communication infrastructure. A critically important aspect is the implementation of comprehensive management of the full life cycle of big data, which is a fundamental prerequisite for the successful implementation of the smart city concept [21]. The specificity of big data in the urban context can be structured according to the five-V model: volume, variety, velocity, variability, and value [12]. Artificial intelligence (AI) enables the transition to proactive management of environmental processes. According to Stavska, the implementation of machine learning algorithms and AI-based analytical methods opens up possibilities for highly accurate forecasting of changes in natural systems [13]. However, Arshad and co-authors rightly note that the deployment of IoT infrastructure is accompanied by significant environmental challenges, which has intensified scientific research in this field, highlighting the need to develop technologies aimed at reducing carbon emissions and increasing energy efficiency [14].

The transformation of traditional environmental management (EM) tools is based on the evolutionary development of the Smart City, which culminates in the modern citizen-driven paradigm [15]. Kolupaieva and co-authors identified a positive correlation between indicators of digital development and sustainability [1]. IoT enables the transition from a reactive control model to proactive environmental risk management. Chen and Gan illustrate this in the field of water resource management, where the implementation of wireless sensor networks transforms the approach to managing aquatic environments from reactive to proactive [22]. Rahman and co-authors argue that the integration of blockchain is a key institutional mechanism for enhancing transparency in territorial governance [5]. In the field of waste management, the study by Romano and Masserini confirms the high effectiveness of the Pay-As-You-Throw (PAYTT) system, which is based on IoT technologies [18]. Despite the critical issue of data quality and verification [23], international practice (Barcelona and London) demonstrates measurable results, confirming the effectiveness of the Smart City as a lever for optimizing environmental management [19].

At the current stage, the Triple Helix Model has undergone evolutionary development into the Quadruple Helix (QH) Model [4]. Paskaleva and co-authors emphasize that the QH represents a new model of social dynamics that expands collaboration through the active inclusion of the public (citizens) [4]. Shkurov highlights that the implementation of the Smart City concept faces the challenge of preserving the uniqueness and diversity of cities [24]. Financial mechanisms also require appropriate transformation: Hedegaard and co-authors stress the necessity of engaging public–private partnerships (PPP) to ensure adequate financing of Smart initiatives. Boiko and Vasylenko identify the growing issue of cybersecurity in Smart systems. In the context of recovery and European integration, the Smart City concept can be viewed as a strategic opportunity, as the current military-political situation opens unique prospects for the accelerated development of Smart Cities in Ukraine.

Main conclusions. Effective environmental management within territorial governance requires an integrated approach based on the synthesis of the Smart City and Eco-City concepts, implemented in the form of the Smart Eco-City as a new managerial paradigm. This approach ensures the transition from fragmented environmental responses to a holistic, polystructural governance model, where the technological potential of the Smart City (including sensor networks, analytical platforms, AI algorithms, and blockchain solutions) acts as a driver of transformative change aimed at achieving environmental sustainability goals.

The technological foundation formed by IoT ecosystems, Big Data, and artificial intelligence creates the conditions for a shift toward proactive, predictive, and adaptive management of environmental risks. The evidence base includes a positive correlation between the level of digital transformation of cities and their environmental performance, as confirmed by international practice. The application of digital technologies transforms economic instruments (for example, Pay-As-You-Throw models in the field of waste management) and institutional governance mechanisms (including the use of blockchain to ensure transparency, accountability, and cyber-resilience of environmental data).

However, the implementation of these solutions requires a transition to the Quadruple Helix (QH) Model, which expands the six-dimensional Smart City framework by incorporating the active participation of civil society in decision-making processes, thereby ensuring polycentricity and governance legitimacy. This model is critically important for overcoming institutional barriers, such as low public trust in digital systems, limited business involvement in public-private partnerships, and the fragmentation of governance structures.

Despite significant challenges – such as the need to balance the unification of technologies with the preservation of the uniqueness of local communities, as well as ensuring data quality and verification – the current socio-political situation creates a unique “Window of Opportunity” for Ukraine to accelerate the transition to the Smart Eco-City model.

This positions the Smart City concept not only as a technological foundation, but also as a strategic basis for ensuring sustainable, inclusive, and transparent development of territorial communities in the post-war period.

Prospects for using the research results. The results of the study provide a methodological foundation for further scientific exploration and the practical implementation of the Smart Eco-City model within territorial governance systems. First and foremost, this concerns the use of the model as a strategic basis for the reconstruction of destroyed settlements, which should become the subject of detailed regional studies. A critical area for further research is the development of methodological approaches to address the identified conflict between the unification of digital standards and the preservation of the unique characteristics of cities.

In the institutional dimension, it is necessary to focus on the practical application of the Quadruple Helix (QH) Model mechanisms at the level of territorial communities, as this will ensure polycentric governance and social legitimacy. This should be accompanied by studies of financial barriers, particularly the development of effective mechanisms for stimulating public–private partnerships (PPP), the need for which has been repeatedly emphasized.

The technological direction of further research should focus on issues of cybersecurity in Smart systems and the development of standards for data quality control and verification. The practical application and assessment of the effectiveness of blockchain technology as a tool for increasing system resilience and ensuring the integrity of environmental accounting are among the most urgent priorities. Thus, future research should integrate institutional, financial, and technological aspects to ensure the successful incorporation of the Smart Eco-City model into national sustainable development policy.

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