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METABOLIC ARCHETYPES OF URBANIZED SYSTEMS: A COMPARATIVE ANALYSIS OF AKTAU AND OSKEMEN

The article examines the formation of metabolic archetypes of urbanized systems using Aktau and Oskemen as case studies. The aim of the study is to identify regularities in the functioning of urban systems associated with the nature of their industrial development, demographic processes, and established conditions of resource provision. The methodological framework comprises systemic and comparative approaches, statistical analysis of socio-economic and environmental indicators, and the classification of urban systems according to a set of quantitative criteria. Particular attention is paid to the interrelationships between material and non-material flows, which determine the characteristics of urban economic reproduction, resilience to external influences, and opportunities for structural transformation. The empirical basis of the study consists of official statistical data and information on the functioning of engineering infrastructure, taking into account the temporal and territorial boundaries of observation. The results of the study indicate substantial differences in the nature of metabolic processes in the cities under consideration. The comparative analysis provides a basis for distinguishing two metabolic archetypes that reflect differences in the conditions of reproduction and transformation of urban systems. It is demonstrated that assessing their sustainability requires distinguishing between economic characteristics and physical resource flows, as well as acknowledging the limitations of the existing statistical database. The findings broaden the scope for comparative analysis of industrial cities and may serve as a basis for developing differentiated approaches to infrastructure modernization, rational resource use, and the reduction of environmental risks.

Keywords: *urban metabolism, urbanized systems, Aktau, Oskemen, material and non-material flows, sustainable development, environmental pressure.*
Кілт сөздер: *қалалық метаболизм, урбандалған жүйелер, Ақтау, Өскемен, материалдық және материалдық емес ағындар, тұрақты даму, экологиялық жүктеме.*
Ключевые слова: *городской метаболизм, урбанизированные системы, Актау, Усть-Каменогорск, материальные и нематериальные потоки, устойчивое развитие, экологическая нагрузка.*

JEL Classification: O18, R11, Q56, Q57

Introduction. Contemporary urbanization is changing not only the spatial structure of cities, but also the very nature of their functioning. Growing demand for water and energy, increasing pressure on infrastructure, demographic shifts, environmental constraints, and the growing complexity of economic linkages make the urban system increasingly dependent on how sustainably the processes of resource inflow, transformation, and distribution are organized. Under these conditions, traditional socio-economic indicators provide only a partial understanding of the state of a city, since they record individual outcomes but do not always make it possible to understand the mechanisms through which these outcomes are formed. Therefore, it is appropriate to consider the city as a complex system of interconnected material and non-material flows, including resources, energy, capital, information, and human potential.

One of the approaches that makes it possible to analyze such interrelationships is the concept of urban metabolism. It proceeds from the assumption that the sustainability of the urban environment depends not only on the volumes of consumption, production, or investment, but also on the nature of resource circulation, the ability of the system to process incoming flows, reproduce human capital, and reduce emerging losses. This perspective is particularly important for industrial and rapidly growing cities, where resource dependence, environmental pressure, and demographic dynamics may form completely different development trajectories even when economic indicators are comparable.

For Kazakhstan, this issue is of particular significance. The country's urban network is heterogeneous in terms of natural and climatic conditions, the level of industrialization, demographic structure, and access to infrastructure. Some cities develop through population inflows, investment, and the expansion of economic activity, while others remain highly dependent on established industrial specialization and face the consequences of environmental and demographic inertia. At the same time, studies of Kazakhstani cities are more often built around separate indicators: population size, employment, investment, industrial production, environmental pollution, or infrastructure provision. A comprehensive examination of the urban system through the totality of material and non-material flows remains limited, especially in a comparative format.

The choice of Aktau and Oskemen is determined by the fact that they make it possible to compare two different types of urbanized development. Aktau is developing under the conditions of an arid Caspian territory, high dependence on water and energy supply systems, intensive demographic dynamics, and the significant role of the export-oriented raw-material sector. Oskemen, by contrast, represents an established industrial center whose development has historically been associated with metallurgy, industrial infrastructure, and a high concentration of production capacities. At the same time, the city faces accumulated environmental pressure, changes in the age structure of the population, and constraints related to the modernization of the industrial and urban environment.

The comparison of these cities raises several interrelated research questions. First, how do differences in demographic dynamics, industrial specialization, water supply systems, and environmental pressure shape the metabolic profiles of Aktau and Oskemen? Second, to what extent can these differences be identified using comparable quantitative indicators of resource flows and socio-economic development? Third, which measurable characteristics distinguish demographic expansion accompanied by increasing infrastructure requirements from industrial path dependence associated with accumulated environmental pressures? Addressing these questions requires an analytical framework that distinguishes directly measured physical flows from socio-economic determinants and qualitative interpretations. Accordingly, the present study aims to develop an empirically grounded comparative assessment of the two urban systems, establish transparent criteria for identifying their metabolic archetypes, and determine the principal constraints on their transition towards more resource-efficient and sustainable development.

Literature Review. The concept of urban metabolism was formed at the intersection of ecological economics, industrial ecology, urban studies, and systems analysis. The starting point is usually considered to be the work of A. Wolman [1], in which the city was presented as a system of incoming flows of water, energy, and materials and outgoing flows of waste. This line was further developed in the review paper by C. Kennedy, S. Pincetl, and P. Bunje [2], where urban metabolism was understood not only as a descriptive model, but also as a tool for urban planning.

Recent research has expanded urban metabolism analysis towards comparative assessment, spatial differentiation, and the quantitative evaluation of resource flows. Lanau, Mao, and Liu [3] demonstrated the possibilities of comparing urban metabolic configurations using evidence from four Danish cities. Otero Peña, Perrotti, and Mohareb [4] emphasized the integration of spatially explicit data into urban metabolism research, highlighting its relevance to resource-efficient urban planning. Wang [5] identified methodological limitations associated with geographical coverage, spatial scale, and data availability in existing urban metabolism studies. Papageorgiou, Björklund, and Sinha [6] further developed the application of material and energy flow analysis to the assessment of urban circularity, demonstrating the importance of sector-specific quantitative accounts.

In Kazakhstan, urban metabolism research has increasingly addressed the relationship between industrial development, resource consumption, environmental pressure, and demographic change. Assanov et al. [7] examined the spatial and temporal characteristics of atmospheric pollution in Ust-Kamenogorsk, providing evidence of environmental risks associated with industrial concentration. Nurlanova, Tleuberdinova, and Saparbek [8] investigated the principal factors and trends of urbanization in Kazakhstan, emphasizing regional differentiation and migration processes. Tleuberdinova et al. [9] developed a multidimensional interpretation of urban metabolism in Kazakhstan, integrating resource consumption, demographic dynamics, and urban living conditions. These studies establish the theoretical and empirical foundation for examining the heterogeneous metabolic development trajectories of Aktau and Oskemen.

Thus, the international literature has already formed a stable conceptual and methodological framework for the study of urban metabolism; however, a noticeable research gap remains in Kazakhstan.

There is a lack of comparative studies that simultaneously analyze water and energy dependence, demographic processes, industrial specialization, environmental pressure, the quality of the urban environment, and institutional differences between specific cities. For this reason, the comparison of Aktau and Oskemen appears scientifically justified: these cities belong to different climatic, resource, and industrial types, but both make it possible to examine the applicability of the metabolic approach to Kazakhstan's urbanized systems of a transition economy.

Materials and Methods. The methodological framework is based on a comparative case-study design integrating urban metabolism analysis with demographic, industrial, infrastructural, and environmental indicators. The primary spatial units of analysis are the administrative territories of Aktau and Oskemen. The analysis distinguishes three levels of statistical observation: municipal indicators describing the cities themselves, infrastructure-related indicators referring to the operational boundaries of utility systems, and regional indicators characterizing the broader socio-economic environment. Regional statistics are not treated as direct measurements of municipal processes. The principal reference year for economic and environmental indicators is 2024, while selected demographic observations from 2025 are included as supplementary evidence and explicitly identified by their reference dates. The 2020–2024 period is used to assess changes in atmospheric emissions. The socio-economic and demographic indicators are compiled from the official statistical records of the Bureau of National Statistics of Kazakhstan [10].

The empirical analysis employs comparative statistical analysis, structural-functional analysis, descriptive time-series analysis, and indicator-based classification. The selected variables are organized into four analytical dimensions: demographic dynamics, industrial specialization, physical resource flows and environmental outputs, and investment and infrastructural conditions. Industrial production and investment indicators are expressed in monetary units and are used to characterize the economic determinants of urban development. Physical resource flows are expressed in appropriate measurement units, including cubic metres of water, kilowatt-hours of electricity, and tonnes of atmospheric emissions. Monetary values are not converted into physical resource quantities without an explicitly established conversion procedure. This distinction prevents economic activity from being interpreted as direct evidence of resource consumption or metabolic efficiency.

To operationalize the distinction between metabolic archetypes, the study applies a rule-based classification framework based on demographic, industrial and environmental indicators. The demographic-expansion archetype is identified through the simultaneous fulfilment of two conditions: annual population growth of at least 2% and a natural population increase of at least 10 persons per 1,000 residents. The natural increase rate is calculated using the average annual population. This combination distinguishes sustained demographic expansion from changes attributable exclusively to migration. The corresponding indicators and decision thresholds are specified in Table 1. These thresholds represent author-defined analytical conventions rather than universally established sustainability standards and do not directly measure resource-use efficiency or circularity.

For the purpose of archetype classification, both demographic criteria are calculated for the 2024 calendar year. The population growth rate is determined from population counts at 1 January 2024 and 1 January 2025, while the natural increase rate refers to demographic events registered during 2024. Population observations for October 2024 and October 2025 are used only to describe subsequent demographic developments.

Table – 1

Operational criteria for identifying urban metabolic archetypes

Indicator	Classification criterion	Analytical interpretation
Annual population growth	≥2%	Demographic expansion
Natural population increase per 1,000 residents	≥10	Intensity of natural population growth
Manufacturing share of industrial output	≥80%	Manufacturing-dominated specialization
Stationary-source atmospheric emissions	>10,000 tonnes/year	Industrial environmental burden

**compiled by the authors. The classification thresholds are authors-defined analytical criteria; their sensitivity ranges are specified in the Materials and Methods section.*

The classification is based on the joint fulfilment of two criteria within each archetype rather than on subjective assessments of high, moderate, low, or very low performance. A city satisfying neither set of criteria remains unclassified, while simultaneous fulfilment would indicate a mixed configuration. To examine the robustness of the results, the demographic growth threshold is varied between 1.5% and 3%, the natural-increase threshold between 5 and 15 persons per 1,000 residents, the manufacturing-share threshold between 70% and 90%, and the stationary-emissions threshold between 5 and 20 thousand tonnes. The resulting classification remains unchanged within these ranges. Nevertheless, because the study includes only two cities, the resulting archetypes should be interpreted as case-specific diagnostic categories rather than a universal typology of urban metabolism.

Main part. In the context of the present study, the concept of urban metabolism is used as an applied tool for comparing Aktau and Oskemen in terms of their resource, energy, demographic, and institutional flows. This approach makes it possible to move beyond a traditional socio-economic comparison and assess not only the level of urban development, but also the degree of resource dependence, environmental pressure, the conditions and information requirements for assessing the circularity of material flows, and adaptability of the urban system. For Aktau and Oskemen, this is particularly important because differences in geographical location, industrial specialization, water supply, demographic structure, and environmental risks form different models of urban sustainability.

A comparison of the key socio-economic characteristics of Aktau and Oskemen presented in Table 2 makes it possible to specify differences in the metabolic structure of the two cities and provides an empirical basis for further analysis of their resource flows, production profiles, and demographic sustainability.

Table – 2

Core socio-economic indicators of Aktau and Oskemen

Indicator	Aktau	Oskemen	Reference period
Industrial output, KZT billion	340.3	2,053.61	2024
Manufacturing share of industrial output, %	41.5	94.3	2024
Investment in fixed capital, KZT billion	272.0	354.2	2024
Population, persons	303,752	380,618	1 October 2025
Population, persons	291,022	377,010	1 October 2024
Annual population growth, %	4.37	0.96	October 2024 – October 2025

**compiled from data of the Bureau of National Statistics of the Republic of Kazakhstan [10].*

The comparison reveals substantial differences in the demographic and industrial characteristics of Aktau and Oskemen. Between 1 October 2024 and 1 October 2025, the population of Aktau increased from 291,022 to 303,752 residents, corresponding to an annual growth rate of approximately 4.37%. Over the same period, the population of Oskemen increased from 377,010 to 380,618 residents, or approximately 0.96%. Thus, both cities experienced population growth, although its relative intensity was considerably higher in Aktau. These differences suggest unequal demographic pressures on housing, public services, and engineering infrastructure, but they do not directly measure the volumes of water, energy, or materials consumed by either city.

Industrial specialization represents another important dimension of differentiation. In 2024, the reported industrial output of Oskemen amounted to KZT 2,053.61 billion, compared with KZT 340.3 billion in Aktau. Manufacturing accounted for 94.3% of industrial production in Oskemen and 41.5% in Aktau. These figures indicate a considerably greater concentration of manufacturing activity in Oskemen, consistent with its established metallurgical specialization. However, the higher monetary value of industrial output cannot independently demonstrate greater physical resource consumption or lower resource efficiency, since such conclusions require sector-specific measurements of material inputs, energy demand, and production outputs.

Investment in fixed capital amounted to KZT 272.0 billion in Aktau and approximately KZT 354.2 billion in Oskemen in 2024. The higher absolute investment volume in Oskemen indicates a larger recorded scale of capital formation during the reference year but does not establish the technological composition, environmental orientation, or financing structure of investment. Therefore, investment is considered an enabling economic condition rather than a direct indicator of circularity, infrastructure renewal, or metabolic efficiency.

Table 3 presents key demographic characteristics that allow a comparative analysis of the populations of Aktau and Oskemen.

Table – 3

Demographic characteristics of Aktau and Oskemen, 2024

Indicator	Aktau	Oskemen
Births, persons	6,531	4,612
Deaths, persons	1,369	3,572
Natural population increase, persons	+5,162	+1,040
Net migration, persons	+6,527	+2,431
Population at the beginning of 2024, persons	281,805	374,690
Population at the beginning of 2025, persons	293,498	378,161
Natural increase per 1,000 residents	17.95	2.76

**compiled and calculated by the authors using official demographic statistics of the Bureau of National Statistics of Kazakhstan [10].*

Migration and natural population change provide further evidence of different demographic trajectories. In 2024, Aktau recorded a positive natural increase of 5,162 persons and positive net migration of 6,527 persons. The corresponding values for Oskemen were 1,040 and 2,431 persons, respectively. Thus, both cities experienced positive demographic balances, although the absolute and relative scale of population expansion was greater in Aktau. The lower rate of natural population increase and slower overall population growth in Oskemen indicate a different demographic development trajectory, which may influence future demand for labour resources and social infrastructure. However, the available aggregate migration statistics do not establish whether particular age groups or highly qualified specialists experienced net outmigration. Such conclusions would require disaggregated migration data.

In terms of urbanization and infrastructure provision, Aktau demonstrates a more recent configuration of the urban environment. Planned development and proximity to major logistics nodes support housing provision and the development of urban infrastructure.

The comparative analysis reveals differences in the intensity and sources of demographic growth in Aktau and Oskemen. Aktau demonstrates higher rates of overall population growth and natural increase, reflecting a more intensive demographic expansion and associated demand for urban infrastructure. Oskemen is characterized by slower population growth and a lower rate of natural increase, although both demographic indicators remain positive. These differences point to the need for differentiated approaches to urban development, taking into account the scale of demographic change and its implications for infrastructure provision, labour resources, and the sustainability of urban systems.

An important physical dimension of urban metabolism is represented by the generation of residual outputs associated with industrial activity. Unlike monetary indicators of production or infrastructure services, atmospheric emissions are expressed in physical units and therefore provide direct evidence of one component of the environmental burden generated within urban systems. To examine differences in this dimension, the study uses the official statistics of pollutant emissions from stationary sources for Aktau and Oskemen over the period 2020–2024. The comparative dynamics of these emissions are presented in Figure 1.

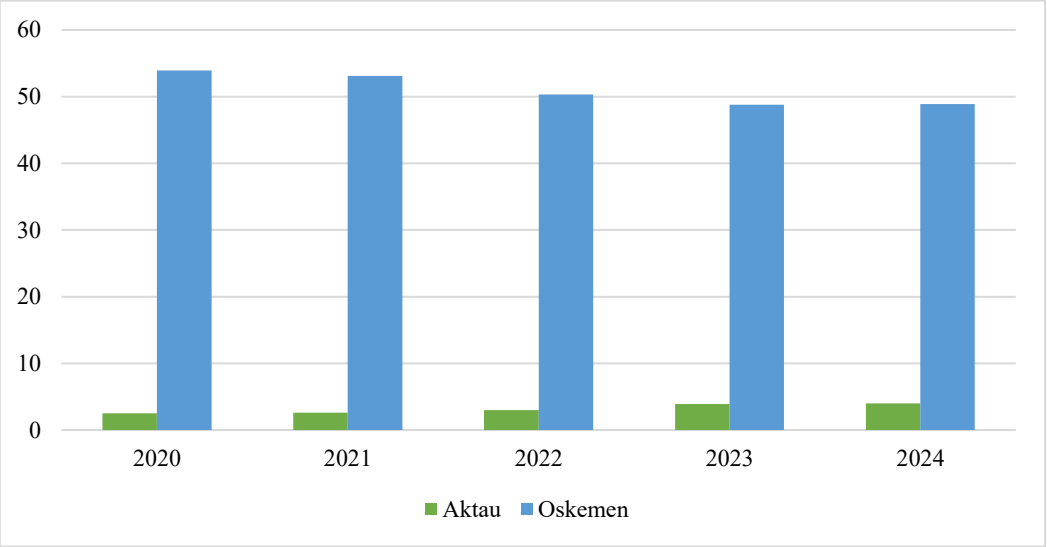


Figure –1. **Dynamics of atmospheric emissions from stationary sources in Aktau and Oskemen, 2020–2024 (thousand tonnes)**

**compiled by the authors based on sources [11].*

The results demonstrate a pronounced difference in the absolute volume of pollutants emitted by stationary sources in the two cities. In 2024, Oskemen generated 48.9 thousand tonnes of stationary-source atmospheric emissions, compared with 4.0 thousand tonnes in Aktau. The level recorded in Oskemen was therefore approximately 12.2 times higher. This difference is consistent with the greater concentration of industrial production, particularly manufacturing and metallurgy, within Oskemen's urban economy. However, the indicator measures the mass of pollutants released from reported stationary sources and should not be equated with total greenhouse gas emissions, ambient pollutant concentrations, or population exposure.

The dynamics of emissions also reveal important differences. Between 2020 and 2024, stationary-source emissions in Aktau increased by 60.0%, from 2.5 to 4.0 thousand tonnes, whereas Oskemen recorded a reduction of approximately 9.3%, from 53.9 to 48.9 thousand tonnes. Consequently, the substantial environmental burden associated with Oskemen's industrial specialization coexists with a declining trend in the reported volume of stationary emissions over the study period. These findings indicate that industrial path dependence should not be interpreted as an absence of environmental improvement. Instead, the persistence of a comparatively high emissions level and the direction of its change must be considered as separate analytical characteristics.

Aktau represents a typical example of an industrial and export-oriented urbanized formation functioning under conditions of considerable dependence on external resources and a specific geographical position. From the perspective of material metabolism, it is characterized by active participation in transregional resource flows combined with limited possibilities for autonomous provision of the basic needs of the population and industry.

Incoming flows in the material structure of the city are formed primarily through external supplies of water, energy, construction materials, and consumer goods. Particular attention should be paid to water supply. Due to the arid climate and the lack of stable freshwater sources, a significant part of water demand is met through the desalination of Caspian Sea water. This creates a specific, technologically complex, energy-intensive, and costly water supply system that is sensitive to climatic and technological risks.

Official municipal information documents seasonal constraints on drinking-water supply in Aktau, highlighting a discrepancy between available supply capacity and estimated demand during periods of increased consumption [12]. These observations indicate the significance of infrastructure expansion and desalination capacity for the stability of urban water services.

The technological dependence of potable-water production on energy supply represents an important feature of Aktau's infrastructure. Nevertheless, the available statistical evidence does not provide a harmonized annual balance of final electricity consumption for the city and its principal economic sectors. Consequently, the study does not calculate electricity consumption per resident, energy intensity per unit

of industrial output, or electricity use per cubic metre of desalinated water. These indicators should be introduced into subsequent monitoring once the required physical data become available.

Flows of construction materials, food products, and industrial components are largely connected to Aktau's transport and logistics position. The port of Aktau performs not only transit but also supply functions, linking the city and the region with other parts of Kazakhstan and the Caspian region.

Outgoing material flows are primarily associated with export activity. The city is an important transport and logistics node for oil and other industrial products moved by sea and rail. The export orientation of the regional economy creates a dependence on external market conditions and makes part of the local economic base sensitive to fluctuations in world commodity prices.

Waste generation, treatment, and recovery constitute essential components of urban material metabolism. For Aktau, the quantitative assessment of circularity requires annual data on municipal and industrial waste generation, the amounts directed to material recovery, and the volumes disposed of through landfilling or other treatment methods. Although waste-management infrastructure and resource recovery are important priorities for sustainable urban development, the currently assembled dataset does not provide a complete and comparable municipal waste balance. Therefore, no numerical or ordinal circularity score is assigned to Aktau.

Wastewater generated by household and industrial activities also requires continuing modernization of treatment and disposal systems. In the context of the Caspian coastal environment, the condition of wastewater infrastructure is particularly important because failures or insufficient treatment can create additional environmental risks.

The available evidence indicates substantial technological dependence on freshwater production and highlights the need for circular water-management and waste-recovery solutions, although the extent of linearity and resource efficiency cannot yet be quantified. At the same time, its geographical position, port infrastructure, and export potential provide opportunities for the formation of a more balanced and resource-efficient model of urban metabolism. Environmental vulnerability remains one of the key constraints on the city's sustainable development and requires systemic strategic solutions.

Oskemen is one of the most industrialized cities in Kazakhstan and has a complex structure of material metabolism shaped by the industrial legacy of the Soviet period and the subsequent restructuring of production capacities. The concentration of manufacturing activities suggests substantial requirements for raw materials, energy, and water, while the observed emissions from stationary sources provide quantitative evidence of the associated environmental burden.

Incoming flows in the metabolism of Oskemen primarily include raw materials, energy resources, and auxiliary components required for the operation of large metallurgical and chemical industries. A significant share of mineral raw materials comes from regional and interregional supply chains, making the city an important processing node within the industrial system of eastern Kazakhstan.

The energy configuration of Oskemen is influenced by the presence of generating facilities within the wider regional electricity system. According to the 2024 annual report of Samruk-Energy, the Ust-Kamenogorsk Hydroelectric Power Plant generated 1,891 million kWh of electricity in 2024, compared with 1,466 million kWh in 2023[13]. This indicator confirms the significance of hydropower generation within the regional energy infrastructure. However, electricity generation at an individual power plant must be distinguished from final electricity consumption within the administrative boundaries of the city. Therefore, these data are used to characterize the energy-supply context and are not interpreted as direct evidence of Oskemen's energy intensity or energy self-sufficiency.

Technical water and industrial reagents constitute another important part of the city's metabolic flows, particularly in enrichment, smelting, refining, and other industrial processes. Local rivers and reservoirs form the basis of the water supply system, while industrial pressure on water resources requires constant monitoring and improved treatment standards.

The water-service system of Oskemen is characterized by a different resource and technological configuration, involving municipal water abstraction, distribution and wastewater treatment [14,15]. The available physical observations for both cities, together with their reference periods and operational limitations, are presented in Table 4. Since the indicators describe different utility-system boundaries, they cannot be directly compared as comprehensive municipal water balances or used to calculate water-reuse rates.

Table – 4

Physical characteristics of water supply and wastewater services

Indicator	Aktau	Oskemen
Reported potable-water supply	Approx. 52,000 m³/day	Approx. 100,000–110,000 m³/day
Reference period	Summer 2024	Reported in 2024
Additional water requirement	20,000–25,000 m³/day	Not established
Wastewater entering treatment	Not established	Approx. 103,000 m³/day
Documented water-supply characteristics	Desalination-dependent supply	Water abstraction and distribution
Water reuse rate	Not available	Not available

**compiled by the authors on the basis of sources [12, 14, 15].*

Desalination and water recirculation represent fundamentally different stages of the urban water cycle. Desalination produces freshwater from saline sources, whereas circular water management requires the recovery and subsequent reuse of water that has already been consumed or used in technological processes. Therefore, the availability of desalination infrastructure in Aktau does not establish the existence of a closed water cycle. Quantitative assessment of circularity would require data on treated wastewater reused for domestic, industrial, or other purposes, together with clearly defined total water-flow volumes for the corresponding system.

Outgoing flows include metallurgical products, including zinc, lead, copper, and other metals, as well as substantial volumes of industrial waste. Metallurgical production is largely oriented toward external markets and supports the economic and fiscal base of the city. At the same time, accumulated and current industrial waste remains one of the region's major environmental problems. Tailings storage facilities, slag accumulations, and contaminated industrial sites represent a significant legacy burden.

In Oskemen, the concentration of metallurgical production creates opportunities for industrial symbiosis, by-product utilization, and the recovery of secondary raw materials. However, industrial production intensity should not be confused with circularity. The assessment of resource recovery requires information on the generation, transfer, treatment, and reuse of industrial waste, expressed in physical units. Without such data, the presence of substantial industrial output does not establish either a high or a very low level of circular material use.

Atmospheric emissions include sulfur dioxide, carbon monoxide, particulate matter, and heavy metals. Their impact becomes particularly pronounced during unfavorable meteorological conditions, including temperature inversions. Industrial and municipal wastewater treatment systems reduce part of the load, although the protection of the Irtysh River remains strategically important because of the transboundary character of the water system.

The metabolic configuration of Oskemen is shaped by the concentration of manufacturing activities, historically established industrial linkages, and substantial environmental pressures associated with industrial development. Unlike Aktau, the city has a stronger internal industrial processing base, but extensive resource use, waste generation, and accumulated environmental pressure make the system vulnerable from the perspective of sustainable development. Without systematic modernization of industrial processes and wider implementation of circular approaches to waste management, the metabolic system will remain unbalanced and associated with substantial environmental externalities.

Non-material resource exchange flows include the movement, accumulation, and transformation of human capital, knowledge, financial resources, information, and governance practices. Within urban metabolism, these flows are important because they form the institutional and behavioral basis of sustainability, adaptability, and innovative development. Analysis of non-material flows in Aktau and Oskemen makes it possible to identify differences in their growth trajectories, governance capacity, and ability to mobilize intellectual and social resources.

The non-material metabolic configuration of Aktau is influenced by demographic expansion and investment activity, which shape the conditions for human-capital formation and infrastructure development. The positive migration balance indicates the attractiveness of the city as a place of residence, although the available aggregate statistics do not permit a detailed assessment of migrants' professional

qualifications or regions of origin. The effective use of demographic potential therefore depends on the development of educational, healthcare, housing, and other urban services.

Financial flows constitute an important component of the economic conditions shaping urban metabolic development. In 2024, total fixed-capital investment in Aktau amounted to KZT 272.0 billion. This indicator reflects the overall scale of investment activity but does not distinguish financing from corporate resources, public budgets, bank lending, or other sources. Accordingly, the available municipal statistics do not establish the predominance of private investment. Determining the contribution of different financing mechanisms to infrastructure modernization and resource-efficient technologies requires a separate analysis of investment by source and economic activity.

Information and governance resources are undergoing transformation. Elements of digital public services and smart-city solutions are being introduced, although the integration of data, analytics, and strategic urban management remains fragmented and is constrained by institutional and technological barriers.

The non-material metabolism of Aktau reflects the role of demographic expansion and investment activity in shaping the city's development opportunities. However, the effective utilization of these resources depends on the capacity of local institutions, educational systems, and urban infrastructure. Oskemen demonstrates a different configuration, characterized by an established industrial and educational base. In this context, an important development challenge is associated with the adaptation of existing human capital to technological modernization and changing labour-market requirements. The available demographic statistics do not provide sufficient evidence to establish the extent or professional composition of outward migration.

In Oskemen, total investment in fixed capital reached approximately KZT 354.2 billion in 2024, exceeding the corresponding value for Aktau. The city’s established industrial specialization suggests that investment demand may be associated with the modernization of manufacturing facilities, engineering infrastructure, and environmental protection systems. Nevertheless, the available aggregate investment data do not establish the actual distribution of financing among state budgets, private enterprises, and borrowed resources. Consequently, the study treats investment volume as an economic characteristic of the urban system rather than evidence of a particular financing model.

The scientific and educational potential of Oskemen remains substantial. Research and educational institutions operate in fields related to metallurgy, materials science, engineering, and nuclear technologies. Strengthening cooperation between research institutions and industrial enterprises represents an important prerequisite for technological modernization and the effective utilization of the city's scientific and educational potential. The city also trains a significant number of engineering specialists, but their retention depends on the availability of modern jobs and career opportunities.

Governance processes are strongly influenced by the need to address the consequences of long-term industrial development. Considerable attention is given to environmental, sanitary, infrastructural, and social stabilization. At the same time, the transition toward proactive strategic development requires stronger integration of innovation, environmental modernization, and human-capital policies.

The comparison of non-material flows shows that Aktau operates primarily in a mode of accumulation of demographic and investment resources, although its institutional mechanisms are still developing. Oskemen, in turn, has accumulated considerable educational, scientific, and industrial competencies, but faces challenges related to workforce renewal, the adaptation of professional competencies to changing industrial requirements. These differences complement the material dimension of urban metabolism and influence the long-term adaptability of both cities.

Having examined the demographic, industrial, infrastructural, and environmental characteristics of both cities, the analysis proceeds to the application of the predefined criteria for identifying their metabolic archetypes. The results are presented in Table 5.

Table – 5

Application of operational criteria to the identification of urban metabolic archetypes

Classification indicator	Aktau	Oskemen
Population growth ≥2%	4.15% – criterion met	0.93% – not met
Natural population increase ≥10 per 1,000 residents	17.95 – criterion met	2.76 – not met
Manufacturing share ≥80%	41.5% - not met	94.3% - criterion met
Stationary emissions >10,000 tonnes/year	4.0 thousand tonnes - not met	48.9 thousand tonnes - criterion met
Demographic-expansion criteria	Both satisfied	Not satisfied
Industrial-legacy criteria	Not satisfied	Both satisfied
Identified archetype	Demographic-expansion context with water-supply constraints	Manufacturing-dominated industrial-legacy context

**compiled and calculated by the authors based on sources [10, 11, 12] using the classification thresholds presented in Table 1.*

The application of the predefined classification criteria confirms that Aktau meets both demographic-expansion conditions, whereas Oskemen satisfies both industrial-legacy conditions. Aktau's higher rates of population growth and natural increase are accompanied by documented seasonal constraints on potable-water supply. In Oskemen, the predominance of manufacturing and substantial atmospheric emissions from stationary sources reflect the persistence of an established industrial configuration. The distinction between these archetypes remains robust to the specified variations in classification thresholds. Nevertheless, the resulting categories characterize differences in demographic, industrial, and environmental development rather than directly measured rates of material throughput, circularity, or resource-use efficiency.

Within the proposed analytical framework, metabolic growth denotes a development context in which demographic expansion creates increasing potential demand for urban resources and infrastructure. Metabolic inertia denotes the persistence of an established industrial configuration and associated environmental pressures despite ongoing socio-economic and technological changes. These categories describe different structural conditions influencing urban metabolic transformation rather than measured rates of resource consumption. Their application therefore requires explicit separation from indicators of circularity, energy intensity, and physical material throughput.

The findings are consistent with the basic principles of the urban metabolism concept, according to which urban sustainability is determined not only by the volume of resources consumed, but also by the nature of their transformation, the degree of circularity of flows, and the capacity of the urban system to reduce waste and environmental costs. In this respect, the differences identified between Aktau and Oskemen correspond to A. Wolman’s interpretation of the city as a system of incoming resources and outgoing waste and also develop the ideas of C. Kennedy et al. concerning the need to analyze the technical, economic, and social processes that support the functioning of the urban environment.

The comparison shows that Aktau is characterized by a high degree of metabolic openness: a substantial part of its essential resources depends on external or technologically intensive supply systems, while water provision is closely linked to energy-intensive desalination. This makes the city sensitive to energy, climate, and infrastructure risks. These findings are consistent with research emphasizing that demographic expansion, technological dependence on resource-supply systems, and infrastructure constraints can increase the vulnerability of urban development, particularly where comparable data on resource recovery and reuse remain limited.

Oskemen, in contrast, demonstrates a more complex industrial structure and a higher degree of internal resource transformation. This, however, does not automatically imply environmental or social sustainability. The concentration of manufacturing activities, historically established industrial linkages, and accumulated environmental pressures contribute to the persistence of the industrial-legacy metabolic archetype. While external resource dependence is one of the main limitations for Aktau, the key constraints for Oskemen are associated with the environmental legacy of industrial development, demographic change, and the incomplete integration of scientific and educational capacity into the modernization of the urban economy.

The analysis therefore expands the application of the urban metabolism approach by including not only material but also non-material flows in the comparative framework. Much of the existing literature

focuses on energy, water, raw materials, and waste, whereas for Kazakhstani cities migration, natural population change, investment activity, institutional adaptability, and the ability to retain human capital are also important. The combination of these factors makes it possible to distinguish two metabolic archetypes: a model of metabolic growth in Aktau and a model of metabolic inertia in Oskemen.

Conclusion. The comparative analysis of Aktau and Oskemen demonstrates that the metabolic characteristics of urbanized systems are shaped by different combinations of demographic dynamics, industrial specialization, infrastructure requirements, and environmental pressures. The application of explicitly defined classification criteria makes it possible to distinguish two contrasting urban development contexts while maintaining a clear separation between directly observed physical flows and socio-economic determinants.

Aktau is characterized by relatively rapid population expansion, with an annual growth rate of approximately 4.37% between October 2024 and October 2025. Its urban infrastructure operates under specific natural and technological constraints, particularly those associated with freshwater production and distribution. Municipal data indicate that approximately 52,000 m³ of drinking water per day was supplied by MAEK during the summer period of 2024, while an additional 20,000–25,000 m³/day was required. These findings demonstrate the importance of expanding water-supply capacity, improving distribution efficiency, and developing water-reuse technologies.

Oskemen exhibits a different configuration, characterized by a high concentration of manufacturing production and substantial atmospheric emissions from stationary sources. In 2024, the city's reported emissions amounted to 48.9 thousand tonnes, compared with 4.0 thousand tonnes in Aktau. However, Oskemen's emissions declined by approximately 9.3% between 2020 and 2024, indicating that the persistence of industrial environmental pressures does not preclude measurable improvements. Demographic evidence also demonstrates positive population growth and positive migration and natural population balances, which contradict interpretations of overall demographic contraction during the reference period.

The scientific contribution of the study consists in developing an operationally transparent framework for identifying contrasting urban metabolic development contexts through measurable demographic, industrial, infrastructural, and environmental characteristics. The analysis demonstrates that monetary indicators of industrial production and investment cannot substitute for physical measurements of resource consumption and recovery. Accordingly, the assessment of material circularity, citywide energy intensity, and the financing structure of investments requires additional harmonized statistical information.

The practical implications of the findings support differentiated approaches to urban sustainability. For Aktau, priorities include strengthening water-supply security, improving the efficiency of desalination and distribution systems, and expanding resource-recovery opportunities. For Oskemen, priorities include industrial environmental modernization, continued reductions in pollutant emissions, improved management of industrial by-products, and stronger integration of research and technological capabilities into production processes. Future research should focus on developing comparable municipal material-flow accounts, including water abstraction and reuse, electricity consumption, industrial and municipal waste recovery, and sector-specific investment financing.

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УРБАНДАЛҒАН ЖҮЙЕЛЕРДІҢ МЕТАБОЛИКАЛЫҚ АРХЕТИПТЕРІ: АҚТАУ ЖӘНЕ ӨСКЕМЕН ҚАЛАЛАРЫ МЫСАЛЫНДАҒЫ САЛЫСТЫРМАЛЫ ТАЛДАУ

Аңдатпа

Мақалада Ақтау және Өскемен қалалары мысалында урбандалған жүйелердің метаболикалық архетиптерінің қалыптасу ерекшеліктері қарастырылады. Зерттеудің мақсаты өнеркәсіптік даму сипатымен, демографиялық үдерістермен және ресурстармен қамтамасыз етудің қалыптасқан жағдайларымен байланысты қалалық жүйелердің жұмыс істеу заңдылықтарын анықтау болып табылады. Жұмыстың әдіснамалық негізін жүйелік және салыстырмалы тәсілдер, әлеуметтік-экономикалық және экологиялық көрсеткіштерді статистикалық талдау, сондай-ақ қалалық жүйелерді сандық өлшемшарттар жиынтығы бойынша жіктеу құрайды. Қала шаруашылығының ұдайы өндіріс ерекшеліктерін, оның сыртқы әсерлерге орнықтылығын және құрылымдық өзгерістерге қабілеттілігін айқындайтын материалдық және материалдық емес ағындардың өзара байланысына ерекше назар аударылады. Зерттеудің эмпирикалық негізін бақылаудың уақыттық және аумақтық шекараларын ескере отырып жинақталған ресми статистикалық деректер мен инженерлік инфрақұрылымның жұмыс істеуі туралы мәліметтер құрайды. Зерттеу нәтижелері қарастырылып отырған қалалардағы метаболикалық үдерістердің сипатында елеулі айырмашылықтардың бар екенін көрсетеді. Жүргізілген салыстыру негізінде қалалық жүйелердің ұдайы өндірісі мен өзгеру жағдайларындағы айырмашылықтарды бейнелейтін екі метаболикалық архетипті бөліп көрсету негізделді. Олардың орнықтылығын бағалау экономикалық сипаттамалар мен физикалық ресурстық ағындарды ажыратуды, сондай-ақ қолданыстағы статистикалық базаның шектеулерін ескеруді қажет ететіні көрсетілді. Алынған нәтижелер өнеркәсіптік қалаларды салыстырмалы талдау мүмкіндіктерін кеңейтеді және инфрақұрылымды жаңғырту, ресурстарды ұтымды пайдалану мен экологиялық тәуекелдерді төмендету жөніндегі сараланған тәсілдерді әзірлеуге негіз бола алады.

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МЕТАБОЛИЧЕСКИЕ АРХЕТИПЫ УРБАНИЗИРОВАННЫХ СИСТЕМ: СРАВНИТЕЛЬНЫЙ АНАЛИЗ НА ПРИМЕРЕ ГОРОДОВ АКТАУ И УСТЬ-КАМЕНОГОРСК

Аннотация

В статье рассматриваются особенности формирования метаболических архетипов урбанизированных систем на примере Актау и Усть-Каменогорска. Цель исследования состоит в выявлении закономерностей функционирования городских систем, обусловленных характером их промышленного развития, демографическими процессами и сложившимися условиями ресурсного обеспечения. Методологическую основу работы составляют системный и сравнительный подходы, статистический анализ социально-экономических и экологических показателей, а также классификация городских систем по совокупности количественных критериев. Особое внимание уделено взаимосвязи материальных и нематериальных потоков, определяющих особенности воспроизводства городского хозяйства, его устойчивость к внешним воздействиям и возможности структурных преобразований. Эмпирическую базу исследования составляют официальные статистические данные и сведения о функционировании инженерной инфраструктуры с учётом временных и территориальных границ наблюдений. Результаты исследования свидетельствуют о существенных различиях в характере метаболических процессов в рассматриваемых городах. На основе проведённого сопоставления обосновано выделение двух метаболических архетипов, отражающих различия в условиях воспроизводства и преобразования городских систем. Показано, что оценка их устойчивости требует разграничения экономических характеристик и физических ресурсных потоков, а также учёта ограничений существующей статистической базы. Полученные результаты расширяют возможности сравнительного анализа промышленных городов и могут служить основой для выработки дифференцированных подходов к модернизации инфраструктуры, рациональному использованию ресурсов и снижению экологических рисков.