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Role of engineering solutions and environmental impact analysis: Kazakhstani and Ukrainian sustainable urban infrastructure development

Yurii Pivnenko [1*], Yevhenii Reutskyi [2], Sergey Kutyenko [3], Vitaliy Omelyanenko [4], Valeriia Pererva [5]

[1] Department of Heat and Gas Supply and Ventilation, School of Civil and Environmental Engineering, O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, UKRAINE
[2] Joint Stock Company “Kyivgas”, Kyiv, UKRAINE
[3] Abylkas Saginov Karaganda Technical University, Karaganda, KAZAKHSTAN
[4] Institute of Industrial Economics of National Academy of Sciences of Kyiv, Kyiv, UKRAINE
[5] Department of Thermal Engineering and Energy Technology, Faculty of Electrical Engineering, Dnipro University of Technology, Dnipro, UKRAINE
***Corresponding Author:** pivnenko.yura@gmail.com

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ABSTRACT

This article examines the role of engineering in promoting sustainable urban-infrastructure development, focusing on sustainable development goal 11. It analyzes technical solutions and environmental impacts on Ukraine and Kazakhstan. The study emphasizes engineering solutions such as energy-efficient systems, waste management, and transportation infrastructure, along with environmental impacts involving carbon footprints, greenhouse gas emissions, and resource consumption like water and energy. It uses a comparative approach between the Ukrainian cities of Kyiv and Lviv, and Astana and Almaty in Kazakhstan. The study utilized both multiple linear regression and correlation matrix analyses, and findings show that energy-efficient systems, resource consumption, and waste management practices have a significant correlation with carbon footprint output for both countries. Furthermore, Ukraine’s engineering solutions highlight resilient post-conflict recovery efforts to promote sustainable urban infrastructure, while Kazakhstan’s focus is on innovation, driven by urbanization needs stemming from regional imbalances, uneven population distribution, and migration.

Keywords: sustainable development goals, Ukraine, Kazakhstan, environmental impact, urbanization

INTRODUCTION

Since over 50% of the global population lives in urban areas, and the number of urban dwellers increases by approximately 73 million annually, it is projected that 70% of the world’s gross domestic product (GDP) will be generated in cities. Cities are under increasing strain on economic, social, environmental, and governmental elements as a result of the enormous growth in global urbanization, which is predicted to reach around 70% by 2050 (Delanka-Pedige et al., 2021; Heinrichs et al., 2023). Nearly 3 billion people are living in inadequate housing conditions as a result of urban expansion and population growth, and by 2030, they will require quality and affordable housing, according to the recent United Nations (UN) report (Fei et al., 2021).

Countries must create and carry out national urban plans to solve the issue of the sluggish rate of new affordable home construction relative to the world’s population increase. Urbanization should be a key focus of the 2030 sustainable development agenda. Many of the sustainable development goals (SDGs), particularly SDG 11 (“sustainable cities and communities”), are seen to be considerably aided by the revitalization of urban slums in developing nations. The creation of equitable, secure, versatile, and environmentally viable towns and residential areas is the goal of SDG 11. It provides a unique opportunity to accomplish inclusive, group advancement and global sustainable development (Teferi & Newman, 2018). The transition to a society with low emissions depends on infrastructure that is sustainable, effective, and climate change-adaptable. Maintaining resilient and sustainable infrastructure systems able to endure floods is crucial to ensuring essential services like energy and water delivery. This includes maintaining transportation routes and guaranteeing the dependability of building constructions (Fei et al., 2021). One possible blueprint for urban expansion is the economic, social, and ecological foundations that constitute sustainability (UN, 2019).

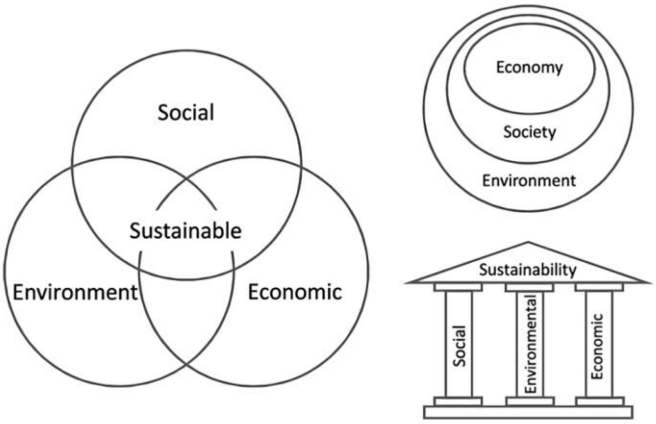

Figure 1. Three pillars and principles of sustainability (Hariram et al., 2023)

The implementation of sustainable infrastructure is a requirement for planned urbanization to guarantee the social and economic well-being of the residents without endangering the environment (Adshead et al., 2019).

Social, fiscal, cultural, and environmental factors all play a part in sustainable urban growth, as shown in **Figure 1**. The challenge of sustainable urban development includes the issues faced within cities, the problems caused or created by cities, and potential solutions that cities can identify and implement. The increase in population in cities relates to their appeal, as large settlements serve as centers of employment. Multi-functional cities offer diverse livelihood opportunities and job options, along with a broad range of cultural and social activities and services.

According to the UN (2019), most modern cities have negative issues, the main ones of which are intensive pollution of the environment by products of economic activity concentrated in one place (Semenyuk et al., 2023).

Based on the UN report (UN-Habitat, 2009), a sustainable city design ought to guarantee the creation of green spaces that can easily be accessed, the construction of eco-friendly transportation, affordable accommodations, and improvements in the towns' ecological effectiveness, including the growth of the utilization of clean energy sources, and the avoidance of water contamination.

The purpose of this paper is to evaluate how engineering contributes to the sustainable growth of urban infrastructure facilities in Ukraine and Kazakhstan using an analysis of technical solutions and environmental impact. The choice of Ukraine and Kazakhstan, for this comparative study, is compelling as both countries shared a post-Soviet legacy, differing economic trajectories, and unique urban development challenges, such as Ukraine's post-conflict reconstruction needs and Kazakhstan's rapid urbanization driven by resource wealth. This study's focus is on engineering solutions such as energy-efficient systems, waste management, transportation infrastructure, and environmental impacts, including carbon footprint and greenhouse gas (GHG) emissions, resource consumption related to water and energy. A comprehensive evaluation and in-depth review of the aforementioned areas of focus is, however, constrained by the availability of data or regional policy differences.

Although there are studies on viable urban development in Kazakhstan and Ukraine, respectively, Lytvyn et al. (2023) researched Ukraine's economic obstacles to the SDGs. According to their assessment, the financial challenges following the conflict and the COVID-19 epidemic encompass ethical, social, financial, and legal elements that satisfy the standards of sustainable development. In their work on the green concepts for sustainable development of the transportation and road networks of Ukrainian cities, Vnukova et al. (2020) suggested a standard for assessing the environmental effectiveness of the development of the local bicycle transport network. This criterion is based on the substitution of bicycle transport for motor transport and the consequent decrease in fuel usage, pollutants released, and noise load.

Semenyuk et al. (2023) studied the urban design and ecosystem of Kazakhstani towns in the 21st century. They concluded that two of the main obstacles to sustainable urban growth are the long-term strategy of economic and industrial activities and the requirement to integrate resource-saving, inexpensive, and zero-waste technology into all production processes. Turdanova and Muzdybayeva (2024) evaluated the sustainability of the urban system planning in Shu City, Kazakhstan, based on the opinions of the locals. According to their analysis, Shu City's urban system planning has a poor degree of sustainability across all six assessed parameters. The indicator analysis indicates that the resolution of several fiscal, social, and ecological problems in Shu City was largely unsatisfactory to the local population. The authors suggested that to address this issue, the officials in charge of urban systems design should work with all relevant stakeholders to create a program framework for sustainable growth. The reality, however, reveals that there are very limited comparative studies on Ukraine and Kazakhstan, if any, or insufficient focus on engineering's environmental impact in these countries. Hence, this study's goal is to undertake the evaluation and comparison of the contribution of technical solutions to the construction of sustainable urban infrastructure development in Ukraine and Kazakhstan, with a focus on technical innovations and their environmental impacts.

The following research questions will guide this study: What engineering solutions are currently implemented in Ukraine and Kazakhstan to ensure sustainable urban infrastructure development? How do these solutions differ in terms of design, implementation, and effectiveness between the two countries? What are the environmental impacts (e.g., carbon emissions, resource use) of these engineering solutions in each country? How do national policies and economic conditions in Ukraine and Kazakhstan influence the adoption of sustainable engineering practices?

THEORETICAL FRAMEWORK

Key Concepts

The World Commission on Environment and Development defines sustainable development as expansion or advancement that satisfies existing demands while not endangering the capacity of future generations to accomplish

Figure 2. The SDGs' interconnectedness (Fei et al., 2021)

their own. Despite covering only about 5% of the global land area, large cities with dense populations account for approximately 70% of energy consumption, 70% of carbon footprints, and other forms of environmental degradation. The UN unanimously adopted the 2030 agenda for sustainable development to address the anticipated adverse effects of urbanization for the benefit of the global community and all people (UN, 2018). The 17 interconnected SDGs (**Figure 2**) that make up this agenda include 169 goals that must be accomplished by 2030. The growth of cities has a direct influence on the 17 SDGs, particularly SDG 11 (sustainable cities and communities) and urban infrastructure (such as buildings, transportation, and utilities), which aims to make towns and residential neighborhoods open to everyone, safe, and sustainable (UN, 2020).

Engineering in Sustainability

The broad idea of sustainability is propelling innovation and change at every societal level. It encompasses a wide variety of issues, including waste disposal, technological infrastructure, expansion of cities, conservation of energy, and the security and health of the public. In modern cities, sustainability has emerged as a key concern (Khan et al., 2020).

This paper examines sustainable urban transitions through the multi-level perspective framework, focusing on green buildings (GBs), life-cycle assessment (LCA) tools, and smart technologies.

Green design

One of the ways that sustainable growth is being implemented is through GBs, which are a set of development objectives and approaches that include the comprehensive management of building construction and the use of environmentally conscious and resource-efficient technologies throughout the lifespan of a structure, encompassing site selection, planning, construction, repairs, renovation, and dismantling (Bungau et al., 2022). The serious consequences of global warming and growing concern about climate change serve as the context for this article, which addresses the reduction of CO_2 and other GHG emissions, emphasizing sustainable design as a key approach to promoting long-term environmental progress. The implementation of Green principles and features in building construction and renovation is dictated by the concepts established in GB practices. **Figure 3** shows the main GB principles schematically.

Life-cycle assessment

The ecological dimension of sustainability includes emissions to land, waterways, and the atmosphere, including resource utilization, and the assessment of their environmental impact. The ecological dimension of sustainability includes resource use, emissions to the atmosphere, waterways, and land, and the evaluation of their effects on the environment.

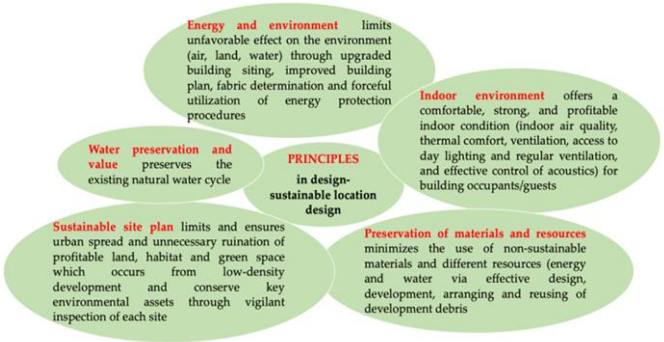

Figure 3. The rules that regulate the use of "green" features in building construction (Bungau et al., 2022)

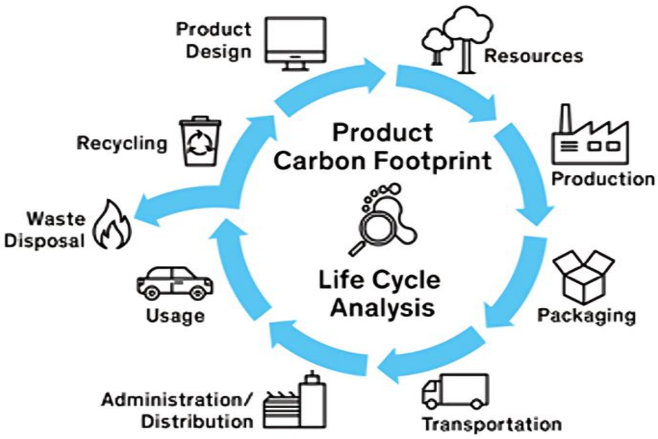

Figure 4. LSA chart (https://www.myclimate.org)

LCA, a systematic technique for measuring the carbon footprint of goods and services throughout their full life cycle from cradle to grave or cradle to cradle, is the main component of the ecological aspect (**Figure 4**). The LCA technique, often known as a cradle-to-grave evaluation, has been in use since the early 1970s. Several accreditation processes for structures and elements, such as LEED and BREEAM, also employ this method to evaluate products and solutions related to green community and city growth. The approach makes a distinction between two evaluation frameworks. The final point method is damage-oriented and concentrates on the ultimate effects on specified protection classifications, such as the health of people, whereas the midway technique is primarily problem-centered and evaluates the ecological implications at the middle stage of the impact chain, such as climate change (Becker et al., 2022).

Smart technologies

The balance between ecosystem restoration and economically viable growth is known as sustainable development. It is the prospect of achieving future urban objectives without sacrificing our natural surroundings, the standard of living, or the general welfare of society. Therefore, to accomplish smart and SDG, several communities worldwide have adopted incorporating state-of-the-art technology into urban planning, centered on a technological route toward the philosophy of the smart city (see **Figure 5**).

Figure 6 displays these objectives. Rapid advancements in data collection have made it easier and more effective to meet

Figure 5. Smart infrastructure programs using emerging technologies (Zechman et al., 2020)

SDGs, especially those that are directly related to urban situations, such as SDG 11 (Heinrichs et al., 2023).

The use of both new and established technologies (Adzor et al., 2023; Afabor & Ikikru, 2022) has surged recently due to the deployment of devices that collect huge amounts of data and monitor variations in energy consumption, property investments, commuter habits, and land use. Artificial intelligence (AI), the Internet of things (IoT), machine learning, deep learning, artificial neural networks, 5G/6G, and big data are some of the latest technologies that are being deployed to develop, scale, and track the success of smart and sustainable development worldwide. In light of this, AI has emerged as an up-and-coming technology for intelligent and sustainable urban planning. As diverse as the management of land, regulations and approval, ecological design, and mode of transport, the potential uses of AI in sustainable development and city design are numerous (Sanchez et al., 2022). Similarly, among other factors, urban planning systems have used "AI in smart energy management, airworthiness tracking, crime surveillance, transportation control, and monitoring for water leaks" (Sanchez et al., 2022).

Urban ghettos, vehicle congestion, and demographic modeling–including buildings, land use, and the environment–are just a few of the worldwide urban issues that machine learning and computer vision can identify (Heinrichs et al., 2023). According to some academics, IT and telecommunications are tools that assists cities in accomplishing their developmental goals in addition to offering strategies to encourage urban growth (Khan et al., 2020).

Ukraine and Kazakhstan: A Comparative Context

Ukraine and Kazakhstan shared historical ties with the former Soviet Union; however, both countries declared independence in 1991 after the collapse of the Soviet Union.

Figure 6. The 17 SDGs (www.un.org/sustainabledevelopment)

Since gaining independence, both countries have continually strived to improve their economies and infrastructure, albeit with differing success. Rapid urbanization and its attendant challenges have been thrust upon both countries alike. The need to attain sustainable urban infrastructure development targets based on SDG 11 has become imperative. The ability of a metropolitan area or urban center to foresee, prepare for, react to, rebound from, and cope with a variety of difficulties, adverse events, and pressures that it may encounter is known as urban resilience.

This section, therefore, focuses on the general comparative analysis of sustainable urban infrastructure development currently implemented in Ukraine and Kazakhstan, employing the triple bottom line (economic, social, and environmental sustainability) framework. The idea of sustainable development is based on the triple bottom line hypothesis, which aims to bring into equilibrium the ecological, social, and economic aspects of sustainability. The goal of environmental sustainability is to safeguard the environment's well-being. Preserving natural and human capital to raise living standards is the main goal of economic sustainability. Additionally, social sustainability aims to emphasize the significance of human rights and equality (Klarin et al., 2018).

Ukraine

Primarily, works amongst others devoted to the study of urban infrastructure development in Ukraine were consulted, including those by Vnukova et al. (2020), Kryshtal et al. (2024), Masyk et al. (2023), Viktor et al. (2021), and Kuryltsiv et al. (2018). Ukraine's focus on a resilient infrastructure post-conflict explores the crucial impact that engineering practices play in fortifying the resilience of urban environments, focusing on the dynamic cities of Kyiv and Lviv.

Cities now play an important role in how well a country is doing and are evolving into more autonomous players in the global economy. The capital, which serves as a hub for business and finance, holds a unique place in the national economy. For instance, Kyiv, the capital of Ukraine, has remarkable economic prospects. The fact that 6% of the nation's population lives in Kyiv has a significant effect upon the country's economy. The city is the hub of retail commerce (18%), produces around 19% of the GDP, and completes 23% of all building projects. With almost 60% of the nation's economic wealth domiciled in Kyiv, the city plays an integral part in maintaining the fiscal health of the nation.

According to Ukraine's voluntary national review (2015-2019) on the SDGs, under the heading "sustainable development of cities and communities," SDG 11 addresses several sector-specific goals (habitat, safety, ecology, etc.) that are intended to be implemented locally with the sole purpose of ensuring the growth of regions and territories through coordinated strategy and collaborative management. According to data from the Ministry for Development of Communities and Territories of Ukraine (2020) as obtained from Ukraine's Voluntary National Review (2015-2019) on the SDGs, the percentage of areas that have approved and implemented regional development strategies and initiatives, which were developed with public participation, shows that each of the 25 regions of Ukraine has 100% coverage of programs for providing affordable housing to different segments of the population.

Furthermore, Blinova and Rodyk (2024) noted that feedback is getting better and that interactions between all parties involved across the "government–local administration –inhabitants–skilled groups" spectrum are steadily growing as part of Ukraine's execution of its sustainable urban development goal.

One consequence of the implementation of an innovative air conditioning evaluation system and fundamental components of air quality control in accordance with the establishment of an integrated authorization was that the amount of atmospheric emissions contaminants from fixed sources in Ukraine dropped in 2019 to 86.1% of the 2015 level.

Kazakhstan

The 2024 UN annual report for Kazakhstan states that the country's GDP grew by 4.8%. Between 2023 and 2024, inflation has steadily declined from 9.8% to 8.6%. By international standards, the public debt is still manageable at 23.5% of GDP. With 42% of objectives on track or advancing, compared to 16% overall, Kazakhstan is surpassing the global average in achieving the SDGs.

Kazakhstan started several national infrastructure projects in 2015 in response to the slowdown in economic growth. The Kazakh government developed an economic stimulus package that included these efforts as its key components to boost domestic economic activity possibilities and develop the nation's transportation and urban infrastructure. The Nurly Zhol state infrastructure initiative was specifically created to solve the country's extremely unequal regional development, as the majority of the population lived in the south, and there was a labor shortage in the north. Additionally, the oil-producing western areas, the cities of Astana (formerly Nur-Sultan between March 2019 to September 2022) in the heart of the nation, and Almaty in the south were the centers of economic activity.

Low levels of green space, unequal access to essential urban services (heating, sanitation, and drinking water), air pollution, and inadequate network infrastructures (public transportation and the internet) are some of the comparable urgent issues facing urban living (Khamit et al., 2024). Therefore, in order to improve sustainability, adaptability, and lessen the effects of severe weather conditions like floods (Zhartybayeva et al., 2022), droughts, and spikes in temperature, Kazakhstan continues to concentrate on urbanization and the creation of smart cities by combining green and blue infrastructure. For example, Kazakhstan's capital city, Astana, occupies 800 km^2 of land, and it is estimated that by 2030, Kazakhstan's population will have grown to 24 million, with Astana accounting for a large portion of that increase. As a result, the "smart Astana" initiative is underway. The six main components of a smart city–economy, administration, living, movements, human beings, and environment–form the foundation of the Astana smart city program. Four smart pilot schemes make up the program: smart schools, smart streetlights, smart payments, and smart health clinics, i.e., multidisciplinary clinics (Atakhanova & Baigaliyeva, 2025).

Policy drivers

Ukraine's urban development sustainability is driven by a reactive and fragmented approach, as evidenced by its post-2014 conflict recovery that prioritizes Kyiv and Lviv's resilience via the development of the SDG 2020 regional plans, but with war disruptions and corruption posing a *hindrance* to progress. On the other hand, Kazakhstan has adopted a proactive, top-down approach that aims to reduce regional inequality, modernize infrastructure, and promote smart cities, e.g., Astana's AI-driven pilot projects.

Implementation challenges

Ukraine's ongoing conflict with Russia drains its resources and promotes corruption that stifles transparency, thereby relying on aid from international bodies such as the UN development program, the European Union (EU), etc. Moreover, internally displaced people have unequal access to services. Also, the Soviet-era infrastructure inherited by Ukraine slows down digital adoption. In contrast, the volatility in oil prices is a risk to Kazakhstan's financial stability. Likewise, the authoritarian nature of the Kazakhstan government hinders civic participation. Rural-urban migrations strain cities, resulting in urban congestion, e.g., Almaty, as well as water scarcity in arid regions, which are other challenges to the implementation of sustainable urban development in Kazakhstan.

Socio-technical transitions

Ukraine has implemented several pilot schemes, such as pilot energy projects in Kyiv, while Kazakhstan has adopted AI and IoT in healthcare and in transportation. However, underfunded research and development is a barrier to Ukraine's efforts, while the risk of exclusion of marginalized groups exists in Kazakhstan's efforts

Role of international actors

The UN/World Bank provides SDG-aligned funding, technical support, and post-war humanitarian aid to Ukraine. The EU also grants energy efficiency funds, promotes green infrastructure, and conditions aid on anti-corruption reforms. Conversely, the UN/World Bank offers Kazakhstan SDG grants and loans for the Nurly Zhol infrastructure program, financed by the ADB. The EU engages in trade via the Eurasian Economic Union, with limited environmental conditions. China funds transport infrastructure through the belt and road initiative.

METHODOLOGY

Research Design

The methodical investigation methods covered in this article include quantitative and qualitative comparisons and analyses. The study adopted a multiple linear regression (Aigerim et al., 2023) and correlation matrix analyses of energy efficiency (kWh/m^2), resource consumption (kg/capita/year), waste management (%), and their environmental impacts, carbon footprints ($kgCO_2e$). These variables were selected as they constitute major contributors to global warming and climate change. A comparative case study approach has been utilized in this article, focusing on urban infrastructure projects in Ukrainian cities such as Kyiv and Lviv and Kazakhstani cities, e.g., Astana and Almaty.

Data Collection

Acquisition of primary data for this study was obtained via conducting interviews with urban planners, engineers, and policymakers in Ukraine and Kazakhstan to understand project implementation and challenges. Additional data were also collected from government reports, academic studies, and international organizations (e.g., UN and World Bank) on infrastructure projects, technical specifications, and environmental impact assessments (see **Appendix A**). 12 interviews are enough for a qualitative study, according to Fei et al. (2021), as more than this reaches a saturation limit. Eleven senior academicians with knowledge of the SDGs and the building sector drawn from various tertiary institutions of both countries, as well as nine professionals from the industry, participated in the interviews. Twenty of the approximately 35 experts who were approached to take part in this stage of the study ultimately consented.

Case Studies

This study examined urban infrastructure development on a country-by-country basis, with each item considered individually.

Public transport systems

Ukraine towards carbon neutrality (UCAN), funded by the EU, has initiated the construction of an underground parking lot in the central part of Lviv. It is a project that provides for the construction of a parking lot on one underground level, with a capacity of 100 parking spaces, of which up to 20 parking spaces will be equipped with charging stations for electric vehicles. The lot will function as an underground shelter (bomb shelter). The estimated cost of the project is €4.6 million and is a public-private partnership initiative. The goal is to significantly reduce vehicle emissions into the atmosphere by reorganizing Kyiv's transportation network through the use of a system of automobile tunnels. This approach will significantly reduce exhaust gas emissions (by 20-30%) into the atmosphere, improve the environmental condition of large cities, enhance residents' health, and mitigate the greenhouse effect.

Also initiated is the construction of a tram track, lanes for public transport and emergency services, and bicycle infrastructure. The project, estimated to cost €64.1 million, involves improving transport accessibility to the Unbroken National Rehabilitation Center through the reconstruction of Mykolaychuk Street. Public pressure compelled Ukrainian officials to build an array of bike lanes in key cities like Kyiv and Lviv. The same is true for the restoration of parks and embankments when the local administration supported efforts initiated by citizen initiative organizations (Blinova & Rodyk, 2024). Yet another project initiated by UCAN in the central part of the city of Lviv, estimated at €2 million, envisages the unification of three separate city trolleybus lines (on Universytetska St., Svoboda Ave., and Ye Petrushevich Square) through the construction of a trolleybus network. The project is expected to improve the efficiency of trolleybus transport and reduce the number of buses passing through the city center, which in turn will improve air quality, as electric transport will replace diesel buses. Anticipated savings on public transport alone are estimated at 2 million euros per year.

With the ONAY! Card, Almaty, unveiled a new e-commerce and billing system for public transportation in 2015. With 158 routes and 2,449 public vehicles (buses and trolleybuses) outfitted with debit card terminals, mobile cash terminals, controller mobile terminals, and driver-assistance on-board computers, the entire network serves the city's public transportation system.

The transport holding of Almaty, with its emphasis on smart data integration and data collection systems, has introduced geo-information data and automated dispatcher control systems for urban passenger transport. This system facilitates the monitoring of passenger movement, the distribution of passenger traffic, and traffic speed at different times of the day. It focuses on enhancing public transit connectivity and mobility by monitoring passenger flow in real time and implementing unified video monitoring.

The complicated venture of the Almaty transport system reform consists of

(a) renewing the number of buses (up to 80%),

(b) building many vehicles and a factory that will manufacture third-generation electric buses,

(c) establishing the nation's first bus rapid transit line,

(d) adding 110 km of roads for public transportation and a one-way traffic system,

(e) creating a bicycle route,

(f) building two subway stations that link the city center with the suburban areas,

(g) changing public transportation transactions to digital payments (more than 97%),

(h) introducing a computerized system of operations control with GPS and CCTV cameras on buses, along with a system of penalties for passenger grievances within subsidized carriers,

(i) there is an arrangement in place to capture traffic infractions on camera and in photos; 709 lanes are under supervision, and

(j) the city has restored all of its subterranean pathways (Turgel et al., 2019).

To organize and decrease congestion, hence lowering GHG emissions, a system known as Sergek was implemented in Astana to track the movement of automobiles along the transportation arteries.

Waste management facilities

Sewage treatment facilities of Lviv receive 350,000 cubic meters of sewage per day. In human equivalent, pollution is 2 million and consumes about 80 MWh of electricity per day. To mitigate these challenges, a project was initiated by UCAN, which envisages the modernization of sewage treatment facilities by installing new sandblasters, replacing blowers, and repairing the outdated equipment and structures. This initiative is expected to urgently reduce the amount of nutrients in the discharge by 50% and reduce electricity consumption by 30%.

In Astana, one storage pond and eighteen wastewater treatment facilities make up the stormwater drainage system, which includes the entire length of the stormwater drainage and ditch sewerage network's primary collectors. In 2022, the built wastewater treatment facilities were commissioned, while in 2023, the landscape enhancements were completed. They will replace the direct flow of water into the Esil River with treating water from rain and snowfall. The surrounding area has been developed, and a green space was built atop the subterranean construction (Bekenova et al., 2024).

Green buildings

In the city of Lviv, positive energy district (PED) technologies, through the integration of energy-efficient solutions, renewable energy sources (RES), and smart energy management in a pilot neighborhood, are being developed. Measures and initiatives included:

- Development of a project for the modernization of heat networks and heat exchange stations at the building and neighborhood levels.
- Development of the project for integrating heat pumps in the neighborhood.
- Development of the project for PV installations in the neighborhood based on solar energy potential.

In addition to achieving carbon neutrality, PEDs are energy-efficient and energy-flexible metropolitan regions or clusters of interconnected buildings that actively manage an annual local or regional excess supply of clean energy. In order to sustain the supply of energy and a good living for everyone in accordance with social, economic, and environmental sustainability, they necessitate the integration of various systems and infrastructures, as well as interaction between structures, consumers, and regional energy, mobility, and ICT systems. In a metropolis, PEDs are not the only energy islands.

Also initiated is the construction of 20 MW of solar generation, at an estimated cost of €10 million, within the Lviv energy hub. The project envisages the creation of a sustainable power and heat generation center to provide critical infrastructure for the use of RES. The construction of a 20 MW gas-piston cogeneration plant for the production of electricity and heat, based on four Norwegian cogeneration plants, is in progress. This technology provides for the possibility of combining cogeneration plants with solar, wind, and hydropower plants.

The installation of a heat pump with a capacity of 15 MW of heat at the discharge of sewage treatment facilities in the city of Lviv is a project that is currently underway in Ukraine and is envisaged to integrate the recovered heat in the centralized heating system. It is one of the most relevant areas of development of heat generation in the context of decarbonization, electrification, and the development of RES. The heat pump at the sewage treatment facilities of Lviv will allow the generation of heat energy from the sewage to heat the homes of more than 50,000 residents of the northern part of the city.

One of the main goals of the municipal government is to make Astana smarter and more sustainable. The six main components of a smart city–"economy, administration, living, mobility, human beings, and environment"–form the foundation of the Astana smart city roadmap, which commenced in 2013. A city-owned business, Astana innovations JSC, is in charge of organizing it. The program comprises four smart pilot projects: smart schools, smart payments, smart street lighting, and smart health clinics (polyclinics), along with several related activities. These projects and activities revolve around technology. As a whole, Kazakhstan and Astana have set high standards for intelligent and sustainable urban development. This resulted in the creation of new organizations as well as progressive laws and policies, such as the Astana smart city initiative and the Kazakhstan 2050 strategy for development. Among these efforts are smart street lighting projects that promote conservation of energy and ecological sustainability, along with smart health clinics, which have improved the quality of healthcare provisions, involving diagnosis and treatment. Additionally, the creation of the smart Astana mobile app and, more broadly, the conversion of governmental services into a digital format have improved accessibility.

Furthermore, Astana unveiled a smart street lighting system that uses LED lights, which are 35-40% more energy-efficient than conventional ones. The city has also taken actions to enhance trash management, such as monitoring city landfills, removing waste, and educating citizens about recycling and waste separation. As a result, Astana Innovations will keep supporting its efforts to revise strategy documents on solid waste management, particularly those pertaining to the production of electricity from solid waste.

Astana has made progress in creating and deploying cutting-edge technologies that optimize water use, lower GHG emissions, lower the cost of waste processing, and lower energy consumption costs via the use of RES. Through the Smart Neighborhood project, the technologies will be evaluated in more than 100 city neighborhoods. Based on the test findings and the needs for the city to use them later, a methodology will be established (United Nations Economic Commission for Europe [UNECE], 2020).

The smart Almaty strategy emphasizes the enhancement of ecological management through the tracking of the condition of the atmosphere and water, particularly in places with high pollution levels. Expanding the amount of green areas per person will accomplish this. Furthermore, smart Almaty intends to execute projects for smart street lighting, municipal garbage collection and disposal, and the integration of utilities and electricity management platforms in buildings. To enhance security in crowded places and prevent crimes and fires, smart Almaty is implementing smart video monitoring and response systems. The city is also embarking on various projects to digitize and enhance systems of education, social inclusion, and health care via online resources and platforms.

Data Analysis

Qualitative analysis

In the comparative study of the role of engineering in ensuring sustainable development of urban infrastructure facilities in Ukraine and Kazakhstan, thematic analysis is used to identify patterns in engineering approaches and policy frameworks in both countries.

Quantitative analysis

Also, the application of metrics like carbon footprint ($kgCO_2e$), energy efficiency (kWh/m^2), and resource consumption is utilized to compare environmental impacts. Specific projects based on the SDG 11 goals in the selected cities of Ukraine and Kazakhstan are compared based on criteria such as innovation level, scalability, cost, and environmental outcomes.

A comparison of the carbon footprint of GBs in the city of Lviv and that of Astana is illustrated in **Table 1**. The comparative illustration in **Table 1** highlights the shared aim of both cities' projects to reduce environmental impact while improving the quality of life for residents.

Limitations of the Study

Although this study offers insightful information, there are a few important constraints to be aware of. The study is based

Table 1. Comparison of carbon footprints of GBs in Lviv and Astana

	Ukraine (Lviv)	Kazakhstan (Astana)
Innovation	The modernization of sewage treatment facilities in Lviv is expected to urgently reduce the amount of nutrients in the discharge by 50%, as well as reduce electricity consumption by 30% and allow generating heat energy from the sewage to heat the homes of more than 50,000 residents of the northern part of the city	Astana has developed a smart street lighting system that utilizes energy-conserving LED lamps, offering an energy conservation capacity of 35 to 40 percent more than conventional types
Cost-effectiveness	Highly cost-effective	Moderately cost-effective
Environmental impact	Low GHG emissions (kgCO_2e & methane) and global warming potential	Significantly reduces GHG emissions (kgCO_2e) compared to conventional systems
Scalability	Highly scalable	Highly scalable

on the data that is accessible, and challenges like incomplete data, language barriers, or differences in reporting standards between Ukraine and Kazakhstan. However, to ensure data transparency, consents were obtained from relevant authorities before interviews were conducted. Regression and correlation analyses (e.g., the high correlation between waste recycling and carbon footprint) are based on small datasets (only four cities), which severely limits statistical validity and is therefore a major limitation of this study; consequently overgeneralizing findings based on such a small sample should also be avoided.

Also, potential biases in data from government sources cannot be ruled out, which could affect the study's conclusions. Particularly in larger or more diversified areas, the level of the municipal analysis may mask regional differences. Moreover, Ukraine's focus on post-conflict reconstruction and Kazakhstan's emphasis on smart technologies make direct comparison less consistent. Notwithstanding these drawbacks, the study offers a useful starting point for comprehending regional sustainability in Kazakhstan and Ukraine and can become the basis for future, more focused studies and policy formulation.

RESULTS AND DISCUSSION

Key Findings

Ukraine

Large-scale, sustainable development of Kyiv's underground space, moving major highways underground, shortening and speeding up transportation routes, and diverting and treating (cleaning) vehicle emissions in tunnels can all help to reduce exhaust gas emissions into the atmosphere by 20-30%, improve the health of city dwellers, improve the environment, and lessen the greenhouse effect. The ability to redirect and treat (clean) exhaust emissions in tunnels, guarantee high travel speeds via tunnels (no junctions, traffic congestion, etc.), and reduce vehicle routes (tunnels follow the shortest trajectory) will all have an impact on emission reductions (Panchenko et al., 2022). Reducing surface road congestion will also help since it increases travel speed, which lowers emissions.

Also initiated is the construction of 20 MW of solar power generation at an estimated cost of 10 million euros, within the Lviv energy hub. In Lviv, electric transport is anticipated to replace diesel buses. Expected savings on public transport alone are expected to be 2 million euros per year. Sewage treatment facilities of Lviv receive 350,000 cubic meters of sewage per day. In the human equivalent, pollution is 2 million and consumes about 20 MWh of electricity per day. The modernization of sewage treatment facilities in Lviv is expected to urgently reduce the amount of nutrients in the discharge by 50%, as well as reduce electricity consumption by 30%. The 15 MW heat pump at the sewage treatment facilities of Lviv will allow the generation of heat energy from sewage to heat the homes of more than 50,000 residents of the northern part of the city. It is one of the most relevant areas in the development of heat generation in the context of decarbonization, electrification, and the development of RES.

Kazakhstan

Over the last 20 years, Astana has seen a boom in building, significant economic expansion (fueled by the oil and gas sectors and investments in cutting-edge technology), and population increase. It created several initiatives to hasten the achievement of the SDGs, such as smart street lighting that encourages climate neutrality and energy efficiency, and smart health clinics that enhance the standard of medical care by automating internal and external procedures. Through the creation of the smart Astana mobile app and the digitization of governmental services, Astana increased accessibility. Other crucial elements in transforming Astana into a sustainable smart city include the implementation of affordable housing initiatives and programs, as well as energy-efficient policies and technology. To organize and minimize traffic, which in turn lowers GHG emissions, a system called Sergek was implemented to monitor vehicle movement throughout the city's transportation arteries as more and more energy-efficient and contemporary buildings are constructed. Additionally, Astana unveiled a smart street lighting system that uses LED lights, which are 35-40% more energy-efficient than conventional ones. The city has also taken actions to enhance trash management, such as monitoring city landfills, removing rubbish, and educating citizens about recycling and waste separation. In addition to implementing projects for smart street lighting, municipal garbage collection and disposal, Smart Almaty intends to integrate energy and utilities management systems in buildings.

Regression analysis

The data displayed in **Table 2** are mean values for the years 2021 to 2024 as a result of the paucity of specific and reliable data for the selected cities of both countries. Approximated data values were obtained from various sources ranging from UNECE, World Bank, Qazinform.com, Bureau of National Statistics of the Republic of Kazakhstan, ScienceDirect.com, Astana News, etc.

Table 2. Environmental impact metrics for the selected cities of Ukraine and Kazakhstan

City	Energy efficiency (kWh/m^2)	Waste recycling (%)	Water consumption (m^3/capita/year)	Carbon footprint (kgCO_2e/capita/year)
Kyiv	55.4	6.0	1,280.0	3,610
Lviv	61.5	4.0	1,005.6	3,610
Astana	162.0	30.0	752.3	17,500
Almaty	90.0	25.8	109.5	17,500

Note. Carbon footprint = 5,009 + 2.752 × energy efficiency + 489.4 × waste recycling - 3.506 × water consumption

Table 3. Pairwise Pearson correlations coefficients

Sample 1	Sample 2	Correlation	p
Waste recycling	Energy efficiency	0.863	0.137
Water consumption	Energy efficiency	-0.351	0.649
Carbon footprint	Energy efficiency	0.798	0.202
Water consumption	Waste recycling	-0.732	0.268
Carbon footprint	Waste recycling	0.990	0.010
Carbon footprint	Water consumption	-0.821	0.179

From the dataset outlined in **Table 2**, the regression equation, as shown in equation 1, was obtained through a multiple linear regression analysis using the Minitab software.

Correlation analysis

A (Pearson) correlation coefficient analysis was executed via Minitab software based on the data in **Table 2**. The results obtained are presented in **Table 3** via a pairwise Pearson correlation format. Based on the data from **Table 2**, results from both the regression and correlation analyses indicate that energy-efficient systems and waste management practices have significant positive relationships with carbon footprint output, while waste recycling has a strong negative relationship for the cities of both countries, respectively. Furthermore, the correlation between carbon footprint and waste recycling is 0.990, indicating a statistically significant relationship ($p = 0.010$), while the other correlations are not significant ($p > 0.05$).

DISCUSSION

Ukraine's post-conflict reconstruction needs are the main driving force for sustainable and resilient urban infrastructure development. The various engineering solutions initiated in several cities are very effective towards these objectives. The modernization of the sewage treatment plant in Kyiv is an outstanding example. This innovative approach not only reduces nutrient discharge by 50%, decreases electricity consumption by 30%, but also provides heating for 50,000 residents in the city. Additionally, extensive subterranean space development in Kyiv, the underground relocation of key roads, the reduction and acceleration of transportation routes, and the diversion and treatment (cleaning) of vehicle emissions in tunnels (Lutsenko et al., 2023; Pavlovskyi, 2024; Ratov et al., 2022) all contribute to a considerable reduction in exhaust gas emissions (by 20-30%) into the atmosphere (Kisselyova et al., 2022), and these underground tunnels that simultaneously also serve as underground bunkers (bomb shelters) are a testament to their engineering solutions being more effective to a more resilient and sustainable Ukraine post-conflict reconstruction needs.

Ukraine does not have a strong methodology for social and economic growth planning centered on the SDGs, alongside an effective organizational framework. Despite the presence of a strategic document such as the sustainable development strategy Ukraine-2030, its implementation remains insufficiently effective due to limited funding, political instability, and low priority given to environmental issues. Ukraine's increased cooperation with international organizations and donors on sustainable development issues, European integration, serves as an incentive for the implementation of sustainable development standards, and developing comprehensive national and regional strategies.

Kazakhstan's regional growth is extremely unequal, with the majority of the population living in the south and a labor deficit in the north. Additionally, the oil-producing western areas, the towns of Astana (formerly Astana) in the heart of the nation, and Almaty in the south were the centers of economic activity. To correct this imbalance, the Kazakhstan Vision 2050 is formulated to accelerate and meet Kazakhstan's urban expansion needs.

To improve security in crowded places and prevent crimes and fires, smart Almaty is implementing smart video monitoring and response systems. The Almaty master plan 2040 envisions a polycentric and digitally smart city development. Additionally, Astana unveiled a smart street lighting system that uses LED lights, which are 35-40% more energy-efficient than conventional ones. Thus, Kazakhstan's engineering solutions are more effective in smart cities to meet its urban expansion needs. In an effort to more effectively deliver urban investments, the Kazakh government has made significant strides toward coordinating budgetary and strategic planning. It took action to enhance inter-budgetary ties, increase the effectiveness of public debt management, and broaden the scope of public-private partnership instruments and strategies.

Nonetheless, the nation has difficulties in guaranteeing access to sustainable financing. The public budget provides very little money for urban services and infrastructure. Nearly two-thirds (65.6%) of the activities in 2024 focused on driving progress towards SDG 3 (28.9%), SDG 16 (13.5%), SDG 5 (7.8%), SDG 8 (7.3%), and SDG 4 (6.2%). According to the UN annual report 2024 on Kazakhstan, of the 17 SDGs, SDG 11 (sustainable communities and cities), with a 3.4% funding gap, is among the top five SDGs with the highest funding gaps in Kazakhstan, indicating lower priority and funding challenges with regard to SDG 11. The chart in **Figure 7** shows the top 5 SDGs with the highest funding gap in 2024, based on the difference between required and available resources. The funding gap is expressed as a percentage of the total required funding for each SDG.

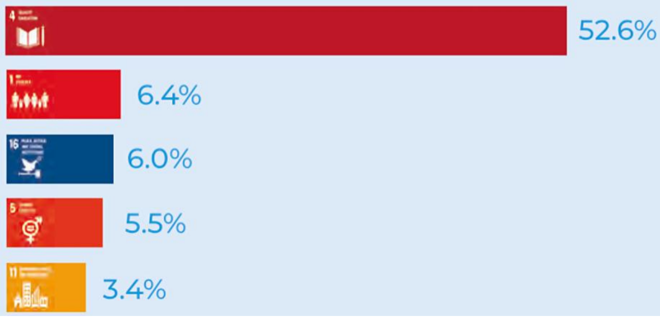

Figure 7. Top 5 SDGs with the highest funding gap (https://kazakhstan.un.org)

From the chart in **Figure 7**, SDG 4 (quality education) incurred the highest funding gap at an estimated 52.6%, while SDG 11 (sustainable cities and communities) had the lowest funding gap of 3.4%. Persistent inflationary pressures and the depreciation of its currency against the US dollar by 15.25% over the year 2024, increased fiscal pressures, lower-than-expected revenue collection, and increased spending to mitigate the severe floods that affected 10 regions and displaced 118,200 people resulted in the share of debt servicing and repayment in total expenditures increasing from 16.8% to 19.4%. The above-listed concerns together with the aforementioned national policy priorities, were some of the mitigating factors that contributed to the underfunding and relegation of other SDGs, especially SDG 11 in Kazakhstan.

The installation of smart street lighting is part of the Kazakhstan 2050 development strategy and the Astana smart city initiatives, which aim to advance climate neutrality and energy efficiency. Additionally, the creation of the smart Astana mobile app and, more broadly, the conversion of governmental services into a digital format have improved accessibility. The creation of housing initiatives and infrastructure projects is a further crucial milestone in transforming Astana into a sustainable and smart capital city.

From the comparative overview of the sustainable urban infrastructure development goals between Ukraine and Kazakhstan carried out in this article, there are visible and viable lessons learned that could be shared between countries: Kazakhstan's impressive organization, innovation, and implementation of the SDGs framework and Ukraine's resilient post-conflict infrastructure rebuilding. Also, as shown in **Table 2**, Kazakhstan's cities produced higher carbon dioxide emissions compared to the Ukrainian cities, probably due to differences in energy consumption patterns or prevailing economic conditions. While Kazakhstan emphasizes smart city development, its per capita carbon footprint remains significantly higher than Ukraine's. To align smart city initiatives, Kazakhstan can implement strategies such as integrating RES, such as wind power, promoting energy efficiency, investing in green infrastructure, leveraging green financing mechanisms, and establishing robust monitoring systems. While Ukraine's focus on post-conflict reconstruction is essential for meeting the immediate needs of affected communities, Kazakhstan's emphasis on smart technologies presents a proactive strategy for sustainable development. Ukraine's approach facilitates rapid response and infrastructure rebuilding, but it may not necessarily incorporate sustainable practices. In contrast, Kazakhstan's smart city initiatives promote long-term sustainability and efficiency, yet they may not address the urgent needs of communities in crisis. These differing approaches reflect the unique contexts and priorities of each country, with Ukraine responding to ongoing conflict while Kazakhstan invests in future growth. A balanced approach that integrates elements from both strategies could potentially provide a more comprehensive path to sustainability.

However, a balanced approach that integrates elements of both strategies could provide a more comprehensive pathway to sustainability. Both Kazakhstan and Ukraine can benefit from investing in energy-efficient systems (Arabov et al., 2023; Atynian et al., 2019), Kazakhstan can leverage wind power and other RES to reduce its carbon footprint. Both countries can invest in energy-efficient systems, such as net-zero buildings, to reduce energy consumption and GHG emissions. Net-zero energy buildings represent a groundbreaking approach to architecture, generating as much energy over the course of a year as they utilize. These structures are crucial for promoting sustainable development and enhancing energy efficiency. By integrating cutting-edge technologies such as solar panels, high-performance windows, heat pumps, combined heat and power systems, and energy storage solutions, net-zero energy buildings can significantly reduce energy consumption and limit GHG emissions, all while contributing to a more sustainable future (Rosen et al., 2025).

Also, investing in green infrastructure, such as green roofs and urban parks, can enhance sustainability and mitigate the urban heat island effect. Establishing robust monitoring systems can help track progress, identify areas for improvement, and ensure accountability. Thus, by sharing lessons learned and integrating elements from both approaches, policymakers in post-Soviet states of Ukraine and Kazakhstan can foster environmentally friendly and efficient urban development by integrating resilient infrastructure, innovation and digitalization, as exemplified by Ukraine's sewage treatment modernization and Kazakhstan's smart city initiatives, and ultimately contributing to a more sustainable future.

CONCLUSIONS

The study conducted reveals that the various engineering solutions adopted in Ukraine highlight the country's focus on resilient post-conflict recovery efforts. The modernization of the sewage treatment plant in Lviv reduces nutrient discharge by 50%, decreases electricity consumption by 30%, and also provides heating for 50,000 residents in the city. Also, the sustainable large-scale development of Kyiv's underground space for transportation improvements resulted in the reduction of gas emissions, e.g., $kgCO_2e$ (by 20-30%), into the atmosphere, and these underground tunnels simultaneously serve as bomb shelters. The conflict between Ukraine and the Russian Federation, along with its negative effects on the country's economy and governance, has played a crucial role in shaping Ukraine's performance in sustainable urban infrastructure development.

By contrast, Kazakhstan's emphasis is on innovation, influenced by its urban expansion needs arising from imbalances in regional developments, uneven population concentration, and migration. Astana started smart street-lighting projects to encourage climate neutrality, energy efficiency, and the use of smart health clinics, which led to better medical care, easier access to public services through the smart Astana mobile app, and the digitization of public services. The creation of housing initiatives and infrastructural projects is aimed at transforming Astana into a sustainable and smart capital city. Based on the ONAY! The card system, the City of Almaty created a digital urban transportation model that aims to improve public transit connectivity as well as mobility through real-time commuter monitoring and the use of synchronized video surveillance. Areas for further study could involve a comparative study of the role of engineering in ensuring the sustainable development of urban infrastructure facilities, utilizing longitudinal impact assessment methodology. Furthermore, a comparative analysis could be carried out with other post-Soviet states, such as Kazakhstan versus Uzbekistan, Azerbaijan versus Georgia, Latvia versus Lithuania, etc.

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AI statement: The authors stated that during the preparation of this manuscript, the authors did not use Generative AI and AI-assisted technologies and takes full responsibility for this declaration.

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