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INFRASTRUCTURE RESILIENCE AMID CRISES

Amid escalating global and regional crises – such as wars, economic upheavals, climate disasters, and pandemics – infrastructure resilience is becoming increasingly vital for economic stability, social security, and economic recovery. The relevance of this research is determined by the need to explain how different infrastructure policy models affect a country's ability to withstand crises. Ukraine, amid a full-scale war, faces severe challenges in the infrastructure sector, while Portugal, despite political stability, regularly deals with natural disasters, including large-scale wildfires. The research is based on the hypothesis that infrastructure resilience is

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ІНФРАСТРУКТУРНА СТІЙКІСТЬ В УМОВАХ КРИЗОВИХ ЯВИЩ

На тлі загострення глобальних і регіональних криз – таких як війни, економічні потрясіння, кліматичні катастрофи та пандемії – інфраструктурна стійкість набуває все більшого значення для економічної стабільності, соціальної безпеки й економічного відновлення. Актуальність цього дослідження зумовлена необхідністю пояснити, як різні моделі інфраструктурної політики впливають на здатність країни протистояти кризам. Україна, перебуваючи в умовах повномасштабної війни, стикається із серйозними викликами в інфраструктурному секторі, тоді як Португалія, попри політичну стабільність, регулярно має справу зі стихійними



determined by the ability of critical infrastructure to function effectively, adapt, and recover after emergencies through strengthening coordination among public, private, and international institutions. To achieve the goal, a combination of general scientific and special methods has been applied. Methods of systematization and generalization – to identify the key factors of infrastructure resilience in Portugal and Ukraine. Comparative analysis – to assess the infrastructure environment of both countries. The tabular method has been used to organize data regarding the effectiveness of infrastructure functioning and resilience policies. The infrastructure environment of Portugal and Ukraine was assessed using the CMS Infrastructure Index data for 2023. Portugal's position reflects a mature institutional system and stable public policy in the field of infrastructure development. Ukraine, despite significant difficulties, has the potential to improve its position through international support, structural reforms, and targeted restoration of critical infrastructure. Despite the different levels of infrastructure development, both Portugal and Ukraine face common challenges such as cyber threats, energy security, water resource scarcity, and risks associated with urban infrastructure operation. An integrated approach is needed to overcome these challenges, which includes coordination between government structures, the private sector, and international partners to enhance resilience and effectively respond to modern threats.

Keywords: critical infrastructure, resilience, institutional conditions, risks, crisis situation.

лихами, зокрема масштабними лісовими пожежами. Дослідження ґрунтується на гіпотезі, що інфраструктурна стійкість визначається здатністю критичної інфраструктури ефективно функціонувати, адаптуватися та відновлюватися після надзвичайних ситуацій завдяки зміцненню координації між державними, приватними і міжнародними інституціями. Для досягнення мети використано комбінацію загальнонаукових і спеціальних методів. Методи систематизації та узагальнення – для виявлення ключових факторів інфраструктурної стійкості в Португалії й Україні. Порівняльний аналіз – для оцінки інфраструктурного середовища обох країн. Табличний метод – для впорядкування даних щодо ефективності функціонування інфраструктури та політики стійкості. Оцінка інфраструктурного середовища Португалії й України проводилася на основі даних CMS Infrastructure Index за 2023 р. Позиція Португалії відображає зрілу інституційну систему та стабільну державну політику у сфері інфраструктурного розвитку. Україна, незважаючи на значні труднощі, має потенціал для підвищення своєї позиції завдяки міжнародній підтримці, структурним реформам і цільовому відновленню критичної інфраструктури. Попри різний рівень інфраструктурного розвитку, як Португалія, так і Україна стикаються зі спільними викликами: кіберзагрозами, енергетичною безпекою, дефіцитом водних ресурсів і ризиками, пов'язаними з функціонуванням міської інфраструктури. Для подолання цих викликів необхідний інтегрований підхід, що містить координацію між державними структурами, приватним сектором і міжнародними партнерами задля посилення стійкості й ефективного реагування на сучасні загрози.

Ключові слова: критична інфраструктура, стійкість, інституційні умови, ризики, кризова ситуація.

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Introduction

In the context of an increasing number of global and regional crises – including armed conflicts, economic shocks, climate disasters, and pandemics – the issue of ensuring infrastructure resilience is becoming particularly important. Modern infrastructure is a crucial factor not only for the functioning of the economy but also for social stability, security, and rapid post-crisis recovery. The experience of various countries in strengthening infrastructure's capacity to adapt and respond to challenges makes it possible to develop effective approaches to building resilient systems.

The relevance of this research is primarily driven by the need to understand how different models of infrastructure policy management influence a country's ability to withstand crises. Ukraine, currently facing a full-scale war, is encountering unprecedented challenges across its entire infrastructure system, including energy, transport, and social sectors. At the same time, Portugal, despite its political stability, has its own experience in dealing with natural disasters, particularly regular large-scale wildfires. These not only cause significant ecological damage but also destroy infrastructure assets such as roads, power lines, housing, and communication systems. This requires the country to develop effective mechanisms for prevention, response, and recovery.

A comparison of the two countries, with their different historical, economic, and security contexts, enables a deeper understanding of the structural factors behind infrastructure resilience and helps identify the strengths and weaknesses of management decisions. Furthermore, the research topic aligns with the priority directions of modern European policy, particularly the Green Deal, digital transformation, and strategic autonomy.

The issue of ensuring infrastructure resilience to external and internal shocks has been widely discussed in academic circles. Theoretical research and classification of existing approaches to understanding the infrastructure resilience has been made by Liu et al. (2022). The conceptual framework to assess the resilience of critical infrastructure by integrating existing best practices in organizational governance, enabling cross-sector and cross-border cooperation has been proposed by Cadete et al. (2017). Resilience curves in infrastructure resilience have been assessed by Poulin and Kane (2021). Methodology that assesses both technical and organizational resilience, using statistical analysis for evaluating the resilience of critical infrastructure elements has been proposed by Rehak et al. (2019).

Focus on improving the resilience of interconnected critical infrastructures in Europe, addressing systemic risks posed by natural hazards and complex cyber-physical-human threats has been made by Giunta et al. (2025) aiming to ensure the continuity of vital operations, reduce cascading disruptions, and protect populations and the environment.

The resilience of Ukraine's critical infrastructure examination in the face of Russia's invasion, highlighting the impact on energy, transportation, and communication sectors, with insights on the role of legislation, international aid, and domestic efforts in maintaining essential services during conflict has been made by Aebi et al. (2024). The study of energy security system of Ukraine and the policy to stimulate its development has been made by Mazaraki and Melnyk (2024).

Research on the importance of human capital in ensuring national security, that focuses on development of a multi-level national security and resilience system for critical infrastructure has been made by Nikolaienko et al. (2024).

The financial aspects of infrastructure resilience have been explored by Moghimi and Kashani (2025) who have proposed the framework for financing resilience improvements by taxing sectors that benefit from reduced losses due to improved infrastructure resilience.

The connection between cybernetics and resilience has been explored by Demmer et al. (2025) demonstrating how control theory can be used to enhance infrastructure resilience.

The study of resilience-building dynamics in response to climate variability has been made by Bizer et al. (2025). The findings suggest that experiencing disruptions alone is not enough to drive transformative adaptation, and emphasize the importance of eliminating silos, fostering networks, and reducing barriers to action to support climate resilience in critical infrastructure.

The study of macroeconomic impacts of infrastructure investment in Portugal from 1980 to 2019, underlining the importance in investing in sectors such as airports, ports, health, highways, water and railroads was made by Pereira and Rodrigues (2024).

The aim of the study is to characterize the factors and directions for ensuring infrastructure resilience in the context of crises, using the cases of Ukraine and Portugal.

The article's hypothesis is that infrastructure resilience is determined by the ability of critical infrastructure to function effectively, adapt, and recover after emergencies through enhanced coordination among public, private, and international institutions.

To achieve the aim of the research, a combination of general scientific and specific methods was used: methods of systematization and generalization were employed to identify the key determinants of infrastructure resilience across various sectors, as well as the organizational and legal frameworks governing resilience in Portugal and Ukraine. Comparative analysis was used to assess the infrastructure environments of Portugal and Ukraine. Tabular method was applied to organize and analyse data on the infrastructure systems in both Portugal and Ukraine, including infrastructure performance, historical disruptions, and existing resilience policies. This method facilitated a clear comparison between the two countries.

The structure of the article is as follows: the determinants of infrastructure resilience have been analysed in the first section; the infrastructure environment of Portugal and Ukraine has been assessed in the second section; the challenges and directions for ensuring infrastructure resilience in Portugal and Ukraine have been identified in the third section.

1. Determinants of infrastructure resilience

Infrastructure represents a functional and territorial combination of economic sectors that serve material production, the non-productive sphere, and the population directly. Economically, infrastructure is an intersectoral formation whose operation within the economy is aimed at meeting the diverse service needs of various sectors and the population.

A well-developed infrastructure promotes proportionality, balance, and efficiency in regional production, facilitates intersectoral linkages, and supports the resolution of environmental and social issues. At the same time,

it is a key factor in the development of industrial and social facilities, the state of demographic potential, and the rationality of settlement systems. The main task of infrastructure is to promote the further development of economic sectors, the integration of industries, and the improvement of population welfare.

From a territorial perspective, infrastructure is divided into national, regional, and local levels. *National infrastructure* in the framework of national resilience includes sectors and services that support the functioning of the economy as a whole such as unified transport systems, energy networks, telecommunications etc. (Umantsiv & Shkuropadska, 2023). *Regional infrastructure* includes facilities located within a specific territory that provide services such as product transport and storage, information transmission, mobility of people, and supply of material resources – such as water, heat, gas, and electricity – to enterprises, organizations, and the local population. *Local infrastructure* refers to services and facilities necessary for the productive activities of enterprises and organizations that are too costly for individual enterprises to develop independently and are thus provided by the state (water and electricity supply, freight transport etc).

Considering the territorial aspect of infrastructure development, *infrastructure resilience* can be understood as the ability of national, regional, and local infrastructure elements to maintain essential operational and developmental parameters under the influence of various factors at different levels. In general, infrastructure resilience encompasses a system's ability to adapt, recover, and maintain functionality during and after crises. As Liu et al. (2022) note: "A resilient infrastructure system is supposed to minimize the probability of failure, possess redundant connectivity, shrink the recovery time, and limit impact propagation, which corresponds to four properties including robustness, redundancy, rapidity, and resourcefulness".

Infrastructure resilience is the result of the interaction of numerous factors that determine a country's ability to ensure the uninterrupted operation of critical systems under extreme conditions, adapt quickly to change, and recover from shocks. In the cases of Portugal and Ukraine, these determinants differ significantly due to the specific geopolitical context, security situation, economic models, and institutional development (*Table 1*).

Table 1

Determinants to ensure infrastructure resilience in Ukraine and Portugal

Determinants	Ukraine	Portugal
Security environment	The main challenge to infrastructure resilience is the constant threat of destruction of critical facilities due to military actions	The main security challenges are natural disasters, primarily large-scale wildfires, which annually destroy significant infrastructure
Investment environment	The country financially unstable and depends on international aid, but shows strong potential for developing partnership projects and is committed to post-war reconstruction in line with European standards	The country has a stable macroeconomic environment, access to EU funds, and developed public-private partnership mechanisms that ensure sustainable infrastructure investment

End of Table 1

Determinants	Ukraine	Portugal
Political stability and institutional capacity	Despite extraordinary conditions, the country is implementing reforms, building institutions, and forming a new management architecture for critical infrastructure	A high level of political stability and effective governance supports long-term infrastructure development planning
The degree of digitalization and innovation	The country emphasizes digital transformation, particularly in monitoring systems, online services, and critical resource management	The country actively implements "smart" solutions in transport, energy, and urban infrastructure
Private sector involvement	Institutional foundations are being formed to engage business in reconstruction projects, particularly through PPP mechanisms and foreign capital attraction	Portugal has successful experience in attracting private capital for the construction and management of highways, hospitals, and energy facilities. The private sector is actively investing in renewable energy, especially solar and wind power

Source: composed by the authors.

The security environment is a key characteristic of a state's condition, reflecting the level of threats, risks, and challenges to its national security. Ukraine is facing one of the most severe security challenges in its history – a full-scale armed aggression by Russia. Accordingly, the main challenge to infrastructure resilience is the constant threat of destruction of critical facilities. This requires rapid response, the creation of backup capacities, logistics diversification, and the implementation of dual-use solutions (civil-military infrastructure).

Portugal, as an EU and NATO member state, enjoys a stable geopolitical position, yet it faces growing climate-related challenges that affect its internal security environment. Wildfires in the country pose a serious ecological and socio-economic problem, regularly intensifying during the summer months. Portugal is one of the European countries most affected by forest fires. Hot, dry summers contribute to the ignition and spread of fires. Eucalyptus and pine trees – highly flammable species – are widespread in Portugal and accelerate the spread of fire, while frequent winds complicate firefighting efforts. In September 2024, Portugal faced some of the largest wildfires in recent decades (Copernicus report, 2024).

Despite climate-related challenges, Portugal has a stable and mature investment environment supported by its participation in the EU and Eurozone. As a result, the investment environments of Ukraine and Portugal are at different stages of development. Portugal offers predictable conditions for investors and actively encourages capital inflow, while Ukraine is working to create new opportunities despite high risks. In the longer term, Ukraine's post-war reconstruction may become one of the largest investment

projects of the 21st century, but this will require further strengthening of the country's institutional capacity and security guarantees for investors.

Overall, political stability and institutional capacity are key factors that determine a state's ability to function effectively, implement infrastructure policy, and ensure stable economic development. Portugal's political stability is rooted in its strong democratic traditions established after the Carnation Revolution of 1974, which ended the dictatorship and launched the country's democratic transformation (UN News, 2024). Its institutional capacity is supported by an effective judicial system, a stable civil service, and EU membership, which drives continuous improvement in governance standards. Notably, the Council of the EU adopted the Directive on the Resilience of Critical Entities (effective as of January 16, 2023), which provides a framework to support member states in ensuring that critical entities can prevent, resist, absorb, and recover from disruptive incidents, including those caused by natural disasters, terrorism, insider threats, sabotage, public disorder, and public health emergencies.

In the case of Ukraine, the legal framework for critical infrastructure and its protection includes the Constitution of Ukraine, the Law of Ukraine "On Critical Infrastructure", the Cabinet of Ministers' resolution "On the Approval of the National Plan for the Protection, Security, and Resilience of Critical Infrastructure", and relevant international treaties. Overall, Ukraine's National Critical Infrastructure Protection System largely depends on the level of political stability in the country. Political stability ensures predictable decision-making, coordination among government bodies, an effective regulatory framework, and timely response to threats.

In Ukraine, political stability remains under constant pressure due to external aggression and reform-related challenges. However, institutional capacity has significantly improved since 2014 due to reforms in public administration, anti-corruption policy, and the judiciary. Nevertheless, it remains insufficient in many sectors.

Despite the ongoing war, Ukraine has demonstrated remarkable achievements in digital development. Since the start of the full-scale invasion, around 70 digital services have been launched, along with various tools under the "Diia" platform, used by about 20 million Ukrainians. These tools facilitate access to critical services, including (Diia Business, 2025):

- business registration and updating entrepreneur information;
- online vehicle re-registration;
- use of "resilience maps" showing shelters and resilience hubs;
- purchasing government bonds to support the economy;
- acquiring or upgrading digital skills, changing professions, and job searching through "Diia. Education" for those affected by the war;
- buying housing under preferential conditions for citizens who lost homes due to military action.

A notable digital initiative supporting Ukraine during the war is the fundraising platform United24, created for centralized donations from anywhere in the world. It unites charitable organizations, international partners, donors, and public figures. United24 ensures transparency in fund usage and allows resources to be rapidly directed toward the most urgent needs – defense, humanitarian aid, healthcare, and the restoration of critical infrastructure (RISE, 2025).

Digital technologies not only optimize governance but also serve as a foundation for post-war recovery in Ukraine. Portugal, in turn, demonstrates a sustainable model of integrating digital and green solutions in infrastructure development. The country actively implements smart energy grids, expands the network of electric vehicle charging stations, and modernizes ports using digital technologies for cargo flow management. The "Portugal Digital" program promotes the digitalization of small and medium-sized enterprises, while investments in green hydrogen and renewable energy enhance energy independence and environmental resilience (Portugal Digital, n. d.). Thus, Portugal aligns digital transformation with climate goals, ensuring long-term benefits for the economy and society.

Development of modern infrastructure is also impossible without active private sector involvement. Public-private cooperation mobilizes additional resources, enables the implementation of innovative solutions, and increases the efficiency of large-scale project execution. Private investment in infrastructure is particularly relevant for countries undergoing modernization or post-crisis recovery, like Ukraine, and for countries seeking to enhance their global competitiveness, like Portugal.

2. Assessment of the infrastructure environment

The assessment of the infrastructure environment is the process of analysing and determining the level of development and efficiency of a country's infrastructure based on various criteria. For example, the international law firm CMS Cameron McKenna Nabarro Olswang calculates the Infrastructure Index (the CMS Infrastructure Index – further on), which evaluates the attractiveness of 50 countries for infrastructure investment. The goal of the CMS Infrastructure Index is to help investors understand the environment they may encounter in different jurisdictions and to identify potential advantages and opportunities for the successful implementation of investment projects.

The CMS Infrastructure Index is measured on a scale from 0 to 100, where 100 represents the best possible performance and 0 the worst. The data from 50 jurisdictions using nine key criteria have been analysed in the index in 2023:

- economic status (21%);
- political stability (15%);
- private participation (13%);
- infrastructure environment (10%);

- protectionism (10%);
- ease of doing business (10%);
- market size (9%);
- sustainability and innovation (6%);
- tax environment (6%).

A country's overall score is calculated by summing the scores for each indicator, weighted according to its importance. In this way, the index presents a comprehensive picture of a country's attractiveness for infrastructure investment.

The CMS Infrastructure Index covers various regions of the world (Europe, Asia, North and South America, Africa). The countries at different levels of economic development are included – from highly developed economies (such as Germany and the United Kingdom) to developing countries (such as India and Brazil). In 2023, the CMS Infrastructure Index also includes countries that are actively developing national infrastructure strategies, implementing large-scale projects, and attracting foreign investment (*Table 2*). For example, Ukraine is mentioned in the report due to the urgent need to rebuild its infrastructure following the war aftermath.

Table 2

The CMS Infrastructure Index in 2023

Rank	Country	Score	Rank	Country	Score
1	Germany	77.0	26	Hungary	56.3
2	Netherlands	75.8	27	Chile	56.2
3	United States	74.5	28	Kuwait	54.6
4	United Kingdom	74.4	29	Saudi Arabia	53.4
5	Singapore	73.6	30	Bulgaria	53.0
6	Finland	72.2	31	India	51.2
7	Japan	72.0	32	Malaysia	50.8
8	Australia	71.8	33	Romania	50.7
9	Canada	71.5	34	Philippines	50.6
10	France	71.4	35	Indonesia	50.4
11	Sweden	69.8	36	Thailand	49.4
12	Austria	68.4	37	Oman	49.4
13	Czech Republic	68.4	38	Peru	48.0
14	Norway	67.3	39	Colombia	47.8
15	Hong Kong	67.1	40	Mexico	47.7
16	South Korea	65.9	41	South Africa	43.8
17	Belgium	64.9	42	Morocco	43.2
18	UAE	64.7	43	Brazil	42.2
19	Slovakia	63.7	44	Uzbekistan	41.2
20	China	62.3	45	Turkey	38.8
21	Portugal	62.1	46	Ukraine	38.0
22	Spain	62.1	47	Kenya	37.0
23	Italy	61.3	48	Egypt	33.2
24	Poland	58.0	49	Angola	28.3
25	Qatar	56.4	50	Mozambique	28.0

Source: CMS LEGAL (2023, November 7).

Leaders in Infrastructure Development scored over 70 points. The top of the ranking is dominated by advanced economies with robust infrastructure: Germany, the Netherlands, the United States, the United Kingdom, Singapore, Finland, Japan, Australia, Canada, and France. These countries demonstrate balanced development across all infrastructure sectors, including transport, energy, IT, and finance. Their high scores indicate institutional maturity, a favourable regulatory environment, and well-developed public-private partnerships.

Countries with Stable Medium Attractiveness received between 60 and 69 points. These are mostly European nations and highly developed Asian economies: Sweden, Austria, the Czech Republic, Norway, Hong Kong, South Korea, Belgium, the UAE, Slovakia, China, Portugal, Spain, and Italy. These countries have a solid level of infrastructure development but may face regulatory and environmental challenges.

Countries with Growing Potential scored between 50 and 59 points: Poland, Qatar, Hungary, Chile, Kuwait, Saudi Arabia, Bulgaria, India, Malaysia, Romania, the Philippines, and Indonesia. Most of these countries are experiencing dynamic growth and have developed government programs for infrastructure modernization; however, they may need to improve administrative transparency and financial resilience.

Countries with Developing Infrastructure scored between 40 and 49 points: Indonesia, Thailand, Oman, Peru, Colombia, Mexico, South Africa, Morocco, Brazil, and Uzbekistan. These countries are gradually improving their infrastructure by attracting foreign capital, but they still need to address legal security and institutional effectiveness.

Countries Facing Infrastructure Challenges scored below 40 points. These are mostly nations with limited resources or socio-political instability: Turkey, Ukraine, Kenya, Egypt, Angola, and Mozambique. Their low levels of infrastructure development are due to political instability, lack of funding, corruption risks, or the consequences of armed conflicts. In particular, Ukraine shows a significant decline due to the full-scale war and requires large-scale reconstruction with the support of international partners.

An analysis of the Infrastructure Index for Portugal and Ukraine by structural components is presented in *Table 3*. Comparing Ukraine with Portugal is appropriate, as both countries are located on the geopolitical periphery of Europe – one on the western coast, the other on the eastern frontier. Both play strategic roles as transport and logistics hubs and as "gateways" to broader regions: Portugal to the Atlantic, and Ukraine to the Black Sea basin. Both also have relatively limited domestic markets, which encourages them to focus on exports, attract foreign investment, and develop infrastructure aimed at international integration.

Table 3

The CMS Infrastructure Index for Portugal and Ukraine in 2023

Infrastructure Index	Portugal		Ukraine	
	Score	Rank	Score	Rank
Overall	62.1	21	38.0	46
Economic status	68.5	23	9.3	50
Sustainability & innovation	64.6	24	55.7	27
Tax environment	27.7	47	76.9	6
Ease of doing business	73.8	19	41.2	45
Infrastructure environment	64.3	23	45.0	38
Private participation	70.1	12	51.6	37
Political stability	73.5	15	31.5	47
Protectionism	79.4	2	75.3	10
Market size	3.8	44	5.5	36

Source: CMS LEGAL (2023, November 7).

The CMS Infrastructure Index overall score for Portugal is 62.1 (ranked 21st), while Ukraine scores only 38.0 (ranked 46th). This clearly reflects Portugal's significant advantage in terms of overall infrastructure development. Portugal is characterized by a stable economy with a well-established governance system, developed transport, energy, and digital infrastructure, and a favorable environment for attracting private investment. Ukraine, by contrast, is undergoing deep socio-economic transformations in the context of a full-scale war, which explains its lag across most critical indicators.

One of the most striking contrasts is in the Economic Status indicator, where Portugal scored 68.5 points (23rd place), while Ukraine scored only 9.3 points (50th place). This gap is explained by differences in GDP per capita, the stability of macroeconomic policy, and the extent of financial support from the state and external partners. Ukraine's economy has suffered a significant blow due to industrial and agricultural losses, internal displacement, and the destruction of logistics infrastructure caused by Russian military aggression.

Nonetheless, Ukraine shows a competitive position in the area of sustainability and innovation, scoring 55.7 points compared to Portugal's 64.6. Ukraine's performance reflects the preservation of its scientific and technological potential, the activation of the digital sector, and progress in energy efficiency and environmental initiatives. Even during wartime, the Ukrainian government is implementing policies to support innovative businesses, the IT sector, and digital services.

Ukraine received its highest score in the tax environment – 76.9 points (6th place), significantly outperforming Portugal's 27.7 points (47th place). This reflects Ukraine's investor-friendly conditions, including a simplified tax system for small and medium-sized enterprises, numerous tax incentives for relocated businesses, and deregulatory efforts. Portugal's tax system, despite its overall stability, remains complex for small businesses and foreign companies.

In the Ease of Doing Business category, Portugal ranks 19th with 73.8 points, while Ukraine ranks 45th with 41.2 points. A challenging regulatory environment, frequent legislative changes, unpredictability in

government decisions, and corruption risks affect confidence in Ukraine's business climate. However, in recent years, Ukraine has actively reformed permitting procedures, digitized public services, and launched initiatives such as Diia City.

In terms of the infrastructure environment – which includes accessibility of logistics routes, energy capacity, and utility services – Portugal scores 64.3 points, while Ukraine scores 45.0. A significant portion of Ukraine's infrastructure has been destroyed or damaged due to hostilities, and many regions face urgent needs to modernize rail connections, energy systems, and communication networks.

Private participation in infrastructure projects is supported in both countries, but Portugal scores significantly higher – 70.1 points (12th place) versus Ukraine's 51.6 (37th place). Despite martial law, Ukraine has seen a rise in public-private partnerships, particularly in the energy, construction, and IT infrastructure sectors.

Political stability remains a critical factor, where Portugal (73.5 points, 15th place) clearly outperforms Ukraine (31.5 points, 47th place). Security risks, external aggression, martial law, and a lack of predictability in domestic politics undermine investor confidence in Ukraine's long-term projects.

On a positive note, both countries received high scores in openness to foreign trade. Portugal ranks 2nd with 79.4 points, while Ukraine ranks 10th with 75.3. Both are actively integrating into international economic structures, opening their markets to investment and technology. For Ukraine, this is especially crucial in the context of post-war recovery.

The market size indicator remains relatively low for both countries: Portugal scores 3.8 and Ukraine 5.5. This is due to limited domestic demand. However, Ukraine's market has higher potential owing to its larger population and strategic location at the crossroads of key transport corridors.

In conclusion, Portugal currently demonstrates a well-balanced infrastructure policy characterized by high stability, effective private sector engagement, and a favorable business environment. Ukraine, despite severe challenges, retains potential for recovery and growth – especially in innovation, tax flexibility, and openness. To improve its position in global infrastructure rankings, Ukraine should focus on enhancing political stability, safeguarding investor rights, modernizing logistics, and actively attracting private capital to support post-war reconstruction.

3. Challenges and directions for ensuring infrastructure resilience

Infrastructure resilience is a key factor in ensuring national security and sustainable development. Portugal, as a country with diverse geographical and economic characteristics, faces a number of challenges in this area. The main challenges include climate change, seismic risks, energy dependence, cyber threats, aging transport and urban infrastructure, and water supply issues (*Table 4*).

Table 4

Challenges and directions for ensuring infrastructure resilience in Portugal

Challenges	Directions for Enhancing Resilience
Cyber threats and attacks on critical infrastructure	Expanding cybersecurity within the NIS2 framework, strengthening cooperation with ENISA
Climate change (wildfires, droughts, sea level rise)	Investing in sustainable energy infrastructure, developing water-saving technologies, wildfire prevention programs
Seismic risks and tsunamis	Strengthening building standards, developing early warning systems, improving evacuation plans
Energy security (dependence on energy imports)	Developing renewable energy sources (wind and solar), creating strategic energy reserves
Water supply and scarcity	Optimizing water supply systems, constructing desalination plants, improving water conservation infrastructure
Urban infrastructure risks (aging buildings, increasing urbanization)	Building renovation programs, "smart" urban planning, development of Smart Cities concepts

Source: composed by the authors.

With the digitalization of society, cyber threats are becoming a serious issue. There was a historic surge in cyberattacks, intensifying threats to critical infrastructures around the globe in 2024. Portugal, too, was shaken by one of the EU's most severe ransomware incidents when cybercriminals breached the Agência para a Modernização Administrativa (AMA). This attack disrupted essential platforms like Autenticação.gov and Gov ID – services integral to Portuguese citizens and businesses for authenticating on government systems. Their temporary shutdown stalled the delivery of vital public digital services, underscoring the critical role these platforms play. Cybersecurity risks are not limited to ransomware alone; state-sponsored groups, often linked to countries like China and Russia, also pose severe threats to critical infrastructures (Vasconcellos, 2024). The response to these challenges includes strengthening cybersecurity measures under the NIS2 directive, as well as cooperation with the European Union Agency for Cybersecurity (ENISA).

Portugal is increasingly affected by extreme weather events, including wildfires, droughts, and sea level rise. To mitigate these risks, the country is investing in sustainable energy infrastructure, developing water-saving technologies, and implementing wildfire prevention programs. As part of its wildfire response strategy, Portugal established the Integrated Fire Management Agency (AGIF), which brings together representatives from nature conservation, the police, the military, and private forestry companies to optimize wildfire prevention and suppression efforts. Portugal's efforts to reform its fire management system have attracted interest from other regions facing similar challenges, including California, South Africa, and Australia (Gill, 2022, July 15).

Portugal lies near the boundary between the Eurasian and African tectonic plates, making the region prone to seismic activity. High-risk areas include the Azores and Madeira islands, as well as the southern part of mainland Portugal, including the Algarve region. Both municipal and national authorities are working to improve infrastructure and early warning systems to minimize potential future losses. Key safety measures include

strengthening building standards, developing early warning systems, and enhancing population evacuation plans (The Lisboner, n. d.).

Due to its significant dependence on energy imports, Portugal is actively expanding its use of renewable energy sources, particularly solar and wind power, and is creating strategic reserves of energy resources. Portugal has achieved a historical milestone in the production of renewable energy, since it supplied 89% of consumption in 2024, while it supplied 61% of electricity consumption in 2023. Portugal's sources of renewable energy for the first quarter of 2024 were composed of 47% from hydroelectric power, 31% from wind power, 6% from photovoltaic power, and 5% from biomass. It is to be noted that, in 2024, Portugal ranks 6th EU country using the highest share of renewable energy according to Eurostat. Portugal's success story in the renewable energy sector is such that the country's energy sector is no longer the main source of CO₂ emissions, since the main source of carbon emissions is now the transport sector (AICEP Portugal Global, 2024, April 3).

It is worth noting that within the framework of REPowerEU, EU countries are updating their recovery and resilience plans with new measures for energy saving and diversification of the EU's energy supply. Accordingly, reforms and investments in the plan of Portugal, approved by the Council on 13.07.2021, help it become more sustainable, resilient and better prepared for the challenges and opportunities of the green transition and digital transition (European Commission, n. d. a).

Water quality plays a crucial role in public health and environmental sustainability. In recent years, water quality in Portugal has attracted increasing attention due to environmental issues, aging infrastructure, and growing concerns about climate change. According to recent reports, approximately 98.5% of the population has access to safe drinking water that meets the standards established by EU regulations. However, there are still some disparities in water quality between urban and rural areas. While cities like Lisbon and Porto have well-developed water supply systems, some rural regions still face issues with access and water quality. This disparity highlights the need for continuous improvement of infrastructure and water treatment processes to ensure that all communities in Portugal benefit from the same level of water safety and cleanliness (Ion Exchange, n. d.). The main measures include the construction of desalination plants, optimization of water conservation systems, and the development of water supply infrastructure.

It is worth noting that the European Regional Development Fund (ERDF) supports projects aimed at improving water efficiency, digitalizing water infrastructure, and mitigating the effects of desertification in accordance with the "Urban Waste Water Treatment Directive". This emphasis on water resource management acknowledges that future challenges cannot be overcome without effective water infrastructure.

Housing also remains a key issue for many EU citizens – 23% of respondents in the latest Eurobarometer survey identified the lack of affordable housing as an urgent problem (European Commission, 2025, April 2). Aging housing stock and increasing urbanization rates create additional

challenges in Portugal. To address them, building renovation programs, smart urban planning, and the development of the Smart Cities concept are being implemented (European Commission, 2022, December 9). Urban renewal involves the reconstruction of areas within the city, often to address urban decay or meet new economic and social needs. Numerous urban renewal projects have been implemented in Portugal, aimed at revitalizing cities, improving infrastructure, and enhancing the quality of life for residents (Talkpal, n. d.).

It is worth noting that international partnerships, public programs, and innovative technologies play a significant role in the process of ensuring Portugal's infrastructure resilience. In particular, industrial innovations depend on greater investment in critical technologies – such as those identified through the Strategic Technologies for Europe Platform (STEP): clean technologies, biotechnologies, and deep-tech innovations (European Commission, n. d. b). Considering the central role of large enterprises in the development of innovation and technology transfer, the European Commission offers them cohesion policy support in critical sectors such as defense, strategic technologies, and decarbonization. This support helps businesses build local supply chains and technological clusters, equipping the EU with infrastructure and technological capacity to face future challenges.

Overall, the European Commission actively responds to the new challenges faced by EU Member States in the context of dynamic geopolitical changes – particularly the war of Russia against Ukraine, climate change, and the energy crisis. The adaptability and flexibility of EU policy means that Ukraine, in forming its own national infrastructure policy, should take into account modern European approaches and new priorities. The challenges and directions for ensuring Ukraine's infrastructure resilience are presented in *Table 5*.

Table 5

Challenges and directions for ensuring Ukraine's infrastructure resilience

Challenges	Directions for Ensuring Resilience
Military threats and shelling of critical infrastructure	Development of protected infrastructure, restoration of facilities based on resilience standards, diversification of energy supply
Cyber threats and attacks on critical infrastructure	Strengthening cybersecurity of critical infrastructure, expanding cooperation with NATO and the EU, implementation of NIS2 standards
Energy security (dependence on external suppliers, attacks on the energy system)	Decentralization of energy grids, development of RES, integration into ENTSO-E, strengthening protection of energy facilities
Destruction of transport infrastructure (roads, bridges, railways due to war)	Restoration of transport routes, modernization of rail transport, development of alternative logistics routes
Water supply and water shortage	Construction of backup water intakes, modernization of water supply systems, implementation of water-saving technologies
Financial risks and lack of funds for urban recovery	Expansion of international aid, attraction of investment, creation of funds for the recovery of cities and critical infrastructure

Source: composed by the authors.

One of the greatest challenges for Ukraine is military threats and the destruction of critical infrastructure. Russian aggression has caused significant damage to energy, transport, communication, and housing infrastructure. Their restoration requires the usage of modern resilience standards, the creation of backup electricity and water supply systems, as well as diversification of energy supplies and logistics routes. Currently, more than 100 cities and communities in Ukraine are restoring municipal infrastructure under two European Investment Bank (EIB) recovery programs after the Ukrainian government allocated EUR 161 million to local budgets. These funds open the path to recovery, including: 155 projects under the "Ukraine Recovery Programme" and 66 projects under the "Emergency Credit Programme for the Recovery of Ukraine". The projects focus on restoring social infrastructure: hospitals, educational institutions, social housing, water supply and sewage systems in de-occupied and frontline territories, particularly in Kyiv, Odesa, Sumy, Kharkiv, Mykolaiv, and Zaporizhzhia regions.

Since the beginning of the full-scale invasion, the EIB has provided Ukraine with EUR 2 billion in support for the urgent repair of infrastructure damaged by Russian bombings (European Investment Bank, 2024, March 8). Through the "EU for Ukraine" initiative and the "EU for Ukraine Fund", the EIB is committed to scaling up its activities in Ukraine in close cooperation with the European Commission, the European Parliament, EU Member States, and international partners.

Countering cyber threats is now considered one of the top security priorities and a key factor in ensuring infrastructure resilience. Massive cyberattacks on critical infrastructure networks, telecommunications, and financial institutions since the start of Russia's invasion have heightened awareness of these threats. However, the implementation of best practices into national cybersecurity legislation and information protection remains fragmented, which also hampers the development of an overall cybersecurity culture in both the private and public sectors. To strengthen cyber resilience, it is necessary to implement international security standards, deepen cooperation with NATO, the EU, and ENISA, and increase investment in cybersecurity technologies and personnel training.

Energy security remains another strategic aspect, as attacks on Ukraine's energy system threaten the stability of electricity and heat supply. During the Ukraine Recovery Conference in London, Ukraine's "Energy Strategy to 2050" was presented. It envisions the restoration of the sector using cutting-edge technologies, enhancing the resilience of the system, and strengthening energy security for both Ukraine and Europe. A key objective is to transform Ukraine into a European energy hub, enabling full independence from Russian fossil fuels through the replacement with clean energy generated in Ukraine. The strategy highlights the existing capacity for expansion: solar power – up to 94 GW; specialized storage – up to 38 GW; nuclear power – up to 30 GW; thermal power and bioenergy – up to 18 GW; hydropower – up to 9 GW. In total, the strategy estimates investment

opportunities for new generation facilities at USD 383 billion. Simultaneously, the "Economic Strategy of Ukraine until 2030" also identifies decarbonization and the development of renewable energy as major priorities in line with the European Green Deal and efforts to improve energy efficiency (YC Market, 2024, February 2).

In the transport infrastructure sector, the war has caused destruction of bridges, roads, and railways, complicating logistics and export. More than 26 000 kilometers of roads have been damaged or destroyed, amounting to losses of USD 28.3 billion. Railway losses total USD 4.3 billion, port infrastructure – USD 0.85 billion, and the aviation sector – USD 2 billion. Direct losses of private vehicles are estimated at USD 2.2 billion – with 260 000 cars destroyed or damaged (Hromadske, 2025). To restore critical transport routes, it is necessary to construct new infrastructure considering security risks, expand alternative routes, and increase the role of multimodal transportation. The World Bank Board of Directors has approved a support package "Building Resilient Infrastructure in a Vulnerable Environment in Ukraine (DRIVE)" worth USD 432 million (Burych, 2025, March 31).

The war has also severely impacted critical water infrastructure. Currently, about 8.5 million Ukrainians face limited access to quality water (Ministry of Environmental Protection and Natural Resources of Ukraine, 2025, March 25). This crisis not only endangers public health but also has serious environmental consequences. Addressing it requires building backup water intakes, introducing modern water purification and conservation systems, and using water recycling technologies.

International cooperation, technological innovation, and effective resource management remain to be the key priorities in ensuring infrastructure resilience. An implementation of these measures will determine the future stability and development of Ukraine as a whole.

Conclusions

The study of infrastructure resilience in the context of crisis phenomena, based on the examples of Ukraine and Portugal, has shown that ensuring the continuous functioning of critical infrastructure depends on a number of factors. Among them, the security environment, investment attractiveness, political stability, and institutional capacity of state authorities play a decisive role. Equally important are the levels of digitalization and innovation in infrastructure development, as well as the active involvement of the private sector in processes aimed at ensuring infrastructure resilience.

In the cases of Portugal and Ukraine, the influence of these factors differs significantly: for Ukraine, the main challenge remains ensuring infrastructure resilience in the context of military aggression, while Portugal is primarily focused on strengthening its infrastructure in the context of natural disasters.

The assessment of the infrastructure environment in Portugal and Ukraine was conducted through analysis of the CMS Infrastructure Index.

Portugal's position in 2023 reflects a mature institutional system and consistent public policy in the field of infrastructure development. High scores in indicators such as political stability, private sector involvement, ease of doing business, and openness to international trade show the country's ability to effectively manage long-term investment processes. However, relatively low scores in the tax environment and the small size of the domestic market highlight the need to further improve conditions for small and medium-sized enterprises and to work more actively on attracting foreign capital. It is important for Portugal not only to maintain its current achievements but also to focus on digitalization, environmental sustainability, and adapting infrastructure to new global challenges.

Ukraine belongs to the group of countries facing infrastructure difficulties and scored 48 out of 100 possible points. Despite the challenging situation, Ukraine has the potential to improve its position through international support, reforms, and targeted rebuilding of critical infrastructure. The CMS Infrastructure Index analysis also indicates that Ukraine scores relatively high in certain indicators – particularly in the tax environment, openness to investment, and sustainable development – creating a unique "window of opportunity" for the structural transformation of the country. If an adequate level of security, political predictability, and an effective recovery strategy are ensured, Ukraine has every chance to become an attractive center for international infrastructure projects in Eastern Europe. This would require not only the restoration of what has been destroyed, but also an innovative approach to the development of a new, resilient, and competitive infrastructure that meets modern European standards.

Despite the differences in infrastructure development levels, both countries face common challenges, including cyber threats and cyberattacks on critical infrastructure, energy security, water supply and water scarcity, and risks related to urban infrastructure functioning. Therefore, ensuring infrastructure resilience in both countries requires an integrated approach that involves coordination between government institutions, the private sector, and international organizations to respond effectively to contemporary threats and strengthen the capacity of infrastructure systems. Thus, the findings confirm the research hypothesis.

In the context of future scientific inquiry, studying the adaptability of urban infrastructure to multi-crisis situations, characterized by the simultaneous impact of military, energy, and climate threats, will be of particular relevance.

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DIGITALISATION AS A FACTOR OF INCREASING ECONOMIC RESILIENCE IN THE PUBLIC SECTOR

The increase in the frequency of crisis phenomena caused by both internal and external shock influences intensifies the need for the formation of a resilient public sector of the national economy. The digitalization of the public sector is considered as one of the factors capable of enhancing adaptability, flexibility, and ability to recover in response to shock influences. In this context, there is a need for a deeper study of the role of digital technologies in strengthening the functional efficiency of the public sector. The research is based on the assumption that digitalization positively affects the level of public sector resilience, and that countries with a higher level of digitalization are able to cope more effectively with current shock impacts. To verify the hypothesis, the countries of the European Union are studied for comparative analysis, 27 EU countries are grouped according to their level of digitalization based on the E-Government Development Index (EGDI). In addition, the research uses correlation and regression analysis to determine the relationship between the indicators of digitalization and the public sector resilience. The obtained results indicate that a positive relationship between digitalization and the public sector resilience indeed exists, however, its significance is small (for countries with a low level of digitalization, the relationship is even weaker). The research suggests that the public sector digitalization can have a greater impact on the resilience of the household sector, which is confirmed by further results. Since households are direct consumers of public services, the digital transformation of the public sector has an impact on their social and economic resilience, particularly due to the increased adaptability to

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ЦИФРОВІЗАЦІЯ ЯК ФАКТОР ПІДВИЩЕННЯ ЕКОНОМІЧНОЇ СТІЙКОСТІ ДЕРЖАВНОГО СЕКТОРУ

Зростання частоти кризових явищ, спричинених як внутрішніми, так і зовнішніми шоківими впливами, посилює потребу у формуванні стійкого державного сектору національної економіки. Цифровізація державного сектору розглядається як один із факторів, спроможних підвищити адаптивність, гнучкість і здатність до відновлення у відповідь на шоківі впливи. У цьому контексті постає необхідність глибшого дослідження ролі цифрових технологій у зміцненні функціональної ефективності державного сектору. Дослідження ґрунтується на припущенні, що цифровізація позитивно впливає на рівень стійкості державного сектору, а країни з вищим рівнем цифровізації здатні ефективніше справлятися із сучасними шоківими впливами. Для перевірки гіпотези розглянуто країни Європейського Союзу: для порівняльного аналізу 27 країн ЄС згруповано відповідно до їх рівня цифровізації за Індексом розвитку електронного врядування (EGDI). Окрім цього, в дослідженні використовується кореляційно-регресійний аналіз – з метою визначення взаємозв'язку між показниками цифровізації та стійкості державного сектору. Отримані результати свідчать про те, що позитивний взаємозв'язок між цифровізацією та стійкістю державного сектору дійсно існує, проте його значення невелике (для країн, що мають низький рівень цифровізації, взаємозв'язок є ще слабшим). У ході дослідження припускається, що цифровізація державного сектору здатна мати більший вплив на стійкість сектору домогосподарств, що і підтверджується подальшими результатами. Оскільки домогосподарства є прямими споживачами державних послуг, цифрова трансформація



sudden economic shock effects. The results of the research can be used to improve digital transformation strategies in the public sector, especially in addressing issues related to digital inequality (both age and geographical), social resilience, and digital inclusion.

Keywords: economic resilience, resilience of the public sector, digitalisation, digital transformation.

JEL Classification: O33, O52, C50.

державного сектору має вплив на їх соціальну й економічну стійкість, зокрема внаслідок збільшення адаптивності до раптових економічних шоків впливів. Результати дослідження можуть бути використані для вдосконалення стратегій цифрової трансформації державного сектору, особливо в роботі над питаннями, що стосуються цифрової нерівності (як вікової, так і географічної), соціальної стійкості та цифрової інклюзії.

Ключові слова: економічна стійкість, стійкість державного сектору, цифровізація, цифрова трансформація.

Introduction

The resilience of the public sector, like organizational resilience, is determined by its ability to absorb shocks (minimize disruptions to public services), adapt (adjust the functioning of the entire apparatus to new conditions), and recover (ensure full functionality at the pre-shock level). In fact, the public sector is capable of cross-sectoral resilience, as it must not only adapt, but also guarantee the provision of quality services to the household and business sectors, and develop policies for all sectors of the economy affected by the shock (Profiroiu & Nastacă, 2021). Therefore, the main challenges in ensuring public sector resilience are maintaining a balance between flexibility and adaptability and stable, predictable functioning of the sector (Leite & Hodgkinson, 2021; Duit, 2016).

The economic resilience of the public sector is determined by its level of financial liabilities. It is widely believed that countries with lower liabilities, such as a low debt-to-GDP ratio, a stable domestic budget, and low external debt, will be able to regulate the economy and respond effectively to economic shocks when they arise. At the same time, there is a wider list of indicators of the economic sustainability of the public sector. In particular, within the framework of the integrated approach, the following indicators are distinguished:

- the level of GDP redistribution through the consolidated budget;
- the ratio of the deficit (surplus) of the state budget to GDP;
- coverage of the deficit of the consolidated budget by external borrowing;
- the volume of transfers from the state budget;
- the share of the public sector in current revenues;
- the level of state and state-guaranteed external and internal debt;
- the adequacy ratio of international reserves to service external debt;
- the level of implementation of the plan for revenues of the consolidated budget;
- the level of implementation of the consolidated budget expenditure plan (Shkuropadska, 2017).

However, ensuring economic sustainability requires not only control over key macro indicators, but also the ability to flexibly respond to changes in the economic environment (Geets et al., 2020). In this case, it is the use of digital tools that helps to increase flexibility, ensuring more effective management of public resources and better coordination of actions in conditions of shock impact. Digitalization is already one of the key factors of change at the macroeconomic level and at the level of individual economic agents (Grytsenko & Burlay, 2020; Novikova & Azmuk, 2023).

The aim of the research is to identify the relationship between the level of digitalization of the public sector and its resilience to shock impacts using the example of the European Union countries. To achieve this aim, the following tasks were set: to conduct a quantitative assessment of the level of digitalization of the public sector of the EU countries using statistical and mathematical methods; to conduct a correlation-regression analysis to identify the relationship between digitalization indicators and the level of resilience of the public sector; to formulate practical conclusions on the possibilities of strengthening the resilience of the public sector through digital transformation.

The research is based on the hypothesis that, firstly, the digitalization of the public sector can positively affect its economic sustainability; secondly, countries with a higher level of digitalization of the public sector are able to demonstrate greater sustainability, unlike countries with a lower level of digitalization. Mathematical and statistical research methods were used to test the hypothesis.

The quantitative distribution of countries by their level of digital development of the public sector was carried out on the basis of the quartile distribution of the values of the Digital Governance Development Index (as discussed in the first section of the main part of the article). The second section presents the results of the study of the impact of digitalization on the sustainability of the public sector of the EU countries, for which correlation and regression analysis is used, in particular, the construction of a paired linear model. The results of the research indicate that the relationship between digitalization and the sustainability of the public sector exists, but its significance is small, and economic factors still influence the sustainability of the sector to a greater extent. It is assumed that the digitalization of the public sector can have a greater impact on the household sector; therefore the third section contains a deeper study using the mathematical modeling method, the purpose of which is to establish the impact of the use of digital public services on the readiness of the household sector to sudden shocks.

1. Identification of digital development level of the public sector in EU countries

When assessing the effects of the use of digital technologies in the public sector, we can divide them into two categories: effects from practical

activities and effects from normative activities. In the first case, the digitalization of the government sector makes it possible to promote the development of digital infrastructure (in turn, this affects the equal access of all other sectors to digital technologies), implement digital technologies (thereby reducing public sector costs and increasing productivity) and digitize public services (which increases their efficiency and accessibility for other sectors). As for the second, the legal competences of the public sector provide the opportunity to disseminate the regulatory rules for the development of digitalization, form a strategic vision and stimulate innovative activity. We can determine the impact of digitalization on economic sustainability by applying a pair correlation-regression model and analyzing the development of digitalization of the public sector. Since statistical data on the national economy are limited and do not sufficiently reflect the manifestation of digitalization processes, we will consider EU countries to test the hypothesis.

It is worth identifying EU countries with a high level of public sector digitalization and those with a low level. One of the most convenient methods to establish the level of each of the 27 European Union countries is to refer to the already developed integrated indices. This has its advantages, since such indices usually contain data on each country and create a rating system. Currently, there are three global indices that measure the level of public sector digitalization: the e-Government Development Index proposed by the UN (World Bank Data, n. d.), the Digital Economy and Society Index (DESI), developed by the European Commission (The Digital Economy and Society Index, n. d.) – its purpose is not to directly assess the digitalization of the public sector, but the index contains a separate component "Digital Public Services" – the Digital Government Index (proposed by the OECD) (2023 OECD Digital Government Index, 2024, January 30). As we can see, only two of them specialize in assessing the public sector, but the OECD Digital Government Index does not cover all EU countries (data is available only for key ones – France, Germany, Spain, etc.). Given that using the European Commission's Digital Economy and Society Index will require additional quantitative methods of processing and collecting statistical data, we will use the e-Government Development Index. This Index contains information on all EU countries, specializes in assessing the public sector, and is updated every two years.

The index measures the level of development of digital governance by assessing three components: the volume of electronic services provided and their quality (Online Services Index); the state of telecommunications infrastructure (Telecommunication Infrastructure Index); and human capital (Human Capital Index). *Table 1* presents the results of calculating the Index for the 27 EU countries, from the worst to the best (which is close to 1).

Table 1

Classification of EU countries based on the results of calculating their e-Government development index, 2022 and 2024

Country	2022	2024	Level of development of governance digitalization
Romania	0.7619	0.7636	Low
Bulgaria	0.7766	0.8145	
Hungary	0.7827	0.8043	
Slovakia	0.8008	0.8021	
Czech Republic	0.8088	0.8239	
Croatia	0.8106	0.8818	
Belgium	0.8269	0.8121	Below average
Portugal	0.8273	0.8415	
Italy	0.8375	0.8356	
Poland	0.8437	0.8648	
Greece	0.8455	0.8674	
Ireland	0.8567	0.9138	
Latvia	0.8599	0.8852	
Cyprus	0.866	0.8619	
Luxembourg	0.8675	0.8466	
Lithuania	0.8745	0.9110	
Germany	0.877	0.9382	Above average
Slovenia	0.8781	0.8759	
Austria	0.8801	0.9065	
France	0.8832	0.8744	
Spain	0.8842	0.9206	
Malta	0.8943	0.8886	
Netherlands	0.9384	0.9538	
Estonia	0.9393	0.9727	High
Sweden	0.941	0.9326	
Finland	0.9533	0.9575	
Denmark	0.9717	0.9847	

Source: compiled by the author based on (Regional e-Government development and the performance of country groupings, September, 2024).

We can group countries by their level of digitalization, using quartiles as a measure of location. First, we should determine the median, which will divide the data set "in half". Since we have 27 observations in total, we can assume that the median value is between 14 and 15. Accordingly, we have:

$$\frac{0.866 + 0.8675}{2} = 0.8667.$$

Therefore, the level of all values less than 0.8667 is below the average. However, in order to divide the countries into more equal groups, it is also

worth defining quartiles 1 (Q_1) and 3 (Q_3) (with the median being quartile 2 (Q_2)). Accordingly, Q_1 is the average value of the lower half of the data and is equal to 0.8218 (the values of all countries less than 0.8218 belong to the low level). Q_3 is the average value of the upper half of the data, which is 0.9096. As we can see, the countries with a low level of digitalization of governance are Romania, Bulgaria, Hungary, Slovakia, the Czech Republic, and Croatia. On the other hand, the group with a high level includes Estonia, Sweden, Finland, and Denmark.

2. The correlation between digitalization and the level of sustainability of the public sector

In order to determine the relationship between digitalization and the economic sustainability of the public sector, we will use regression mathematical modeling. When building the model, we will consider the following form of the equation:

$$Y = a + bX, \quad (1)$$

where: Y – is the dependent variable that reflects the economic sustainability of the public sector (gross value added (GVA) indicator in the field of public administration, defense, education, healthcare and social work);

X – is the independent variable that characterizes the level of digitalization of the public sector (the percentage of people who used digital public services (website or application) during the last 12 months);

a – is the expected value of Y at a zero value of X (regression constant);

bX – is the deterministic part of the model that reflects the change in Y depending on X .

As a dependent variable expressing the economic sustainability of the public sector, we will consider the indicator of gross value added (GVA) in the sphere of public administration, defense, education, health care and social work. As already noted, the most common indicators expressing the purely economic sustainability of the public sector are public sector GDP (as a % of total GDP), budget deficit/surplus, government spending, and employment level in the public sector. However, unlike the indicated indicators, GVA in the sphere of public administration is sensitive to changes in productivity in the public sector, namely productivity – what is most affected by digitalization (for example, automation of public services, optimization of management and costs). In addition, attempts to determine the correlation-regression relationship between budget deficit/surplus indicators, government spending and public sector GDP (as a share of total GDP) and digitalization factors have revealed that such mathematical models are not statistically significant, and therefore, there is no relationship between the data.

As an independent variable, we will consider the percentage of people who used digital government services (website or application) during the last

12 months. The availability and use of digital government services is an indicator that reflects the optimization of government processes, in particular, reducing operating costs (for example, by replacing physical branches with an online application/website), accelerating the provision of administrative services and reducing the level of corruption. It would be quite logical to also investigate the impact of the number of digital government services provided (depending on the EU country), but currently there is no statistical measurement of this indicator.

The proposed study also contains a number of limitations. In particular, the biggest drawback at the moment is the time period used. Digitalization is a dynamic phenomenon, the development of which intensifies over the years, so the logical choice is a medium-term time period (5–7 years) or a long-term one (10–15 years). But, unfortunately, in addition to dynamism as one of the main characteristics of the digitalization process, it is also characterized by the complexity of its assessment and measurement by specific indicators (which are due to the lack of a clear and stable system for collecting statistics). Therefore, the study covers only a comparison of the impact of the digitalization factor on the sustainability of the public sector in 2022 and 2023. The data that will be used in the future are given in *Table 2*.

Table 2

Input data for building a regression model of the impact
of the public sector digitalization factor on GDP in the field of public
administration in EU countries, 2022–2023

EU country	2022		2023	
	GDP*, % of total	Share of users**, %	Share of users**, %	Share of users **, %
	Y	X	Y	X
Belgium	21.3	83.27	21.8	81.78
Bulgaria	15.2	26.38	16.1	29.72
Czech Republic	15.8	78.81	15.6	71.12
Denmark	18.7	96.98	19.4	97.68
Germany	19.6	51.24	19.4	58.07
Estonia	15.1	85.83	16.6	88.74
Ireland	8.7	80.83	9.9	85.56
Greece	18.2	67.64	17.6	68.69
Spain	17.7	79.75	17.4	79.68
France	21.9	82.64	21.2	85.17
Croatia	16.4	56.98	17.0	74.62
Italy	16.1	65.69	15.4	60.11
Cyprus	18.2	89.74	18.2	66.12
Latvia	18.2	70.98	18.7	73.18
Lithuania	14.9	73.49	15.5	71.82
Luxembourg	17.3	89.40	18.7	88.90
Hungary	16.6	72.68	15.9	75.63

End of Table 2

EU country	2022		2023	
	GDP*, % of total	Share of users**, %	Share of users**, %	Share of users **, %
	Y	X	Y	X
Malta	15.6	76.41	14.8	81.34
Netherlands	20.5	92.50	20.5	94.78
Austria	17.9	73.88	18.1	75.60
Poland	14.6	55.38	15.3	58.54
Portugal	18.8	68.72	18.3	69.63
Romania	13.2	20.93	13.2	22.56
Slovenia	17.1	73.09	16.5	71.14
Slovakia	16.5	73.58	15.7	71.69
Finland	20.3	94.78	21.1	95.49
Sweden	20.1	93.07	20.5	94.58

* Gross value added in public administration, defense, education, health care, and social work;

** people who used digital public services (website or app) in the last 12 months.

Source: compiled by the author based on (Eurostat, n. d. a, Eurostat, n. d. b).

To determine the parameters of equation (1), we will use the method of least squares. Let x_i and y_i be the corresponding values of the independent (X) and dependent (Y) variables for the i -th observation ($i = 1, 2, \dots, n$). In this case, the estimates of the parameters a and b are calculated using formulas (2), (3).

$$a = \frac{n \cdot \sum_{i=1}^n x_i y_i - (\sum_{i=1}^n x_i) \cdot (\sum_{i=1}^n y_i)}{n \cdot \sum_{i=1}^n x_i^2 - (\sum_{i=1}^n x_i)^2}, \quad (2)$$

$$b = \frac{1}{n} \cdot \sum_{i=1}^n y_i - a \cdot \frac{1}{n} \cdot \sum_{i=1}^n x_i. \quad (3)$$

Accordingly, the parameters for 2022 will be as follows:

$$a = \frac{(27 \cdot 34500.75) - (1974.67 \cdot 464.5)}{(27 \cdot 153347.08) - 1974.67^2},$$

$$a = 0.0593,$$

$$b = \frac{464.5}{27} - 0.0593 \frac{1974.67}{27},$$

$$b = 12.8692.$$

We have the function $Y = 12.8692 + 0.0593 X$, with the standard error of the model (E) being 2.582, the coefficient of determination (R^2) being 0.158, and the F-criterion being 4.702.

When constructing the primary regression model, a low coefficient of determination ($R^2 = 0.158$) was found, which indicates a weak explanatory power of the model. To check its stability, an analysis of residuals and influential points was performed. In particular, several observations were found that deviated significantly from the general trend. In order to increase the adequacy of the model, these observations were excluded from further analysis. In this case, the model parameters will be:

$$a = \frac{(18 \cdot 22763.451) - (1303.55 \cdot 308.6)}{(18 \cdot 99487.09) - 1303.55^2},$$

$$a = 0.08157,$$

$$b = \frac{308.6}{18} - 0.0815 \frac{1303.55}{18},$$

$$b = 11.2365.$$

In order to increase the adequacy of the model, these observations were excluded from further analysis. In this case, the model parameters will be:

Taking into account the updated sample, it was found that the coefficient of determination increased to 0.568, and the standard error of the model decreased to 1.2669, which indicates a significant improvement in the accuracy and reliability of the regression model (Table 3).

Table 3

Parameters of the impact of digitalization on the GVA of the public sector in EU countries, 2022

a_1	0.0815798	11.236484	a_0
S_{a1}	0.0177681	1.3209532	S_{a0}
R^2	0.5685082	1.2669922	E
F	21.080659	16	$n-k$
$S_{2reg.}$	33.840135	25.684309	$S_{2gener.}$

Source: calculation results generated using the LINEST function in Excel.

Therefore, the standard error of the model is 1.27, which in percentage terms is 7.4% of the mean value of the dependent variable. This indicates sufficient accuracy of the model, since the error value does not exceed 10%. The F-test was used to check the statistical significance of the model. With the number of observations $n = 18$ and the number of model parameters $k = 2$, the degrees of freedom are: $m_1 = 1$ and $m_2 = 16$. The calculated value of F is 21.04, which exceeds the tabular value $F_{table} = 4.49$ at the significance level $\alpha = 0.05$. Therefore, the model is considered statistically reliable (Table 4).

Parameters for the 2023 model:

$$a = \frac{(18 \cdot 23157.963) - (1319.95 \cdot 309.3)}{(18 \cdot 101613.106) - 1319.95^2},$$

$$a = 0.0989,$$

$$b = \frac{309.3}{18} \cdot 0.0989 \frac{1319.95}{18},$$

$$b = 9.9297.$$

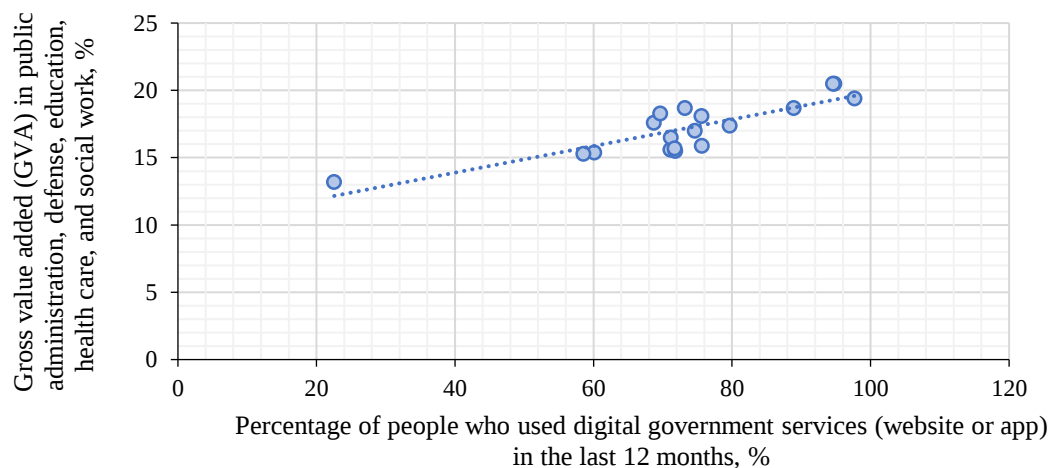
Table 4

Parameters of the regression model of the impact of the digitalization factor of the public sector of EU countries on its sustainability (2023)

a_1	0.09891675	9.92971344	a_0
S_{a1}	0.01567035	1.17738177	S_{a0}
R^2	0.71349666	1.08798274	E
F	39.8457718	16	$n-k$
$S_{2reg.}$	47.1656969	18.9393031	$S_{2gener.}$

Source: calculation results generated by the author using the LINEST function in Excel.

The standard error of the model $E = 1.09$, which is 6.32% as a percentage of the mean value of the dependent variable, indicates a fairly high quality of the model. The value of the coefficient of determination R^2 is 0.7, which indicates that most of the variation in the dependent variable is explained by changes in the independent variable (*Figure*). This is a significant improvement compared to the model of the previous year. The value of the Fisher test $F = 39.85$ exceeds the table value $F_{table} = 4.49$ so the model is considered statistically adequate and significant.



Correlation between digitalization and the sustainability of the public sector in EU countries, 2023

Source: compiled by the author.

We can draw the following conclusions:

- a higher level of digitalization does indeed strengthen the correlation between the economic sustainability of the public sector (in this case directly with the GVA of the sector), but this correlation is quite low;
- in countries with a low level of digitalization, the connection is even weaker (virtually imperceptible);
- accordingly, digitalization may be one of the factors contributing to the economic sustainability of the public sector, but we assume that economic factors have a greater impact.

Thus, the economic sustainability of the public sector largely depends on budget policy, the level of debt burden, tax revenues and external economic factors, while the digitalization of the sector should be considered as a tool used to increase operational efficiency, increase the productivity of the work of state bodies themselves and speed up decision-making processes. All of the above digitalization processes are observed at the micro-level of each state body separately, which significantly complicates quantitative modeling and mathematical measurement of its impact on the economic sustainability of the sector.

3. Impact of public sector digitalization on the sustainability of the household sector

At the same time, the digitalization of the public sector is not limited to internal management processes, but also encompasses the transformation of mechanisms for providing public services, which has a broader macroeconomic impact: in particular, its impact is indirectly manifested through ensuring the sustainability of other sectors – the household sector and the business sector – as a result of the implementation of digital public services. Moreover, if the public sector thus performs administrative and regulatory functions in relation to the business sector, we assume that the impact on the sustainability of the household sector is greater. This can be explained by the fact that the digitalization of public services directly affects the social and economic security and adaptability of households, since they are the main consumers of such services. In addition to faster access to medical services, social payments, and other administrative services, the public sector, thanks to digitalization, is also able to ensure the social sustainability of vulnerable segments of the population – such as people on the verge of poverty, IDPs, people with disabilities, the elderly, or veterans. Unlike the business sector, for which the digitalization of public services manifests itself mainly in the form of simplification of permitting procedures, tax administration, and registration processes, for households it is a factor of social resilience that directly affects the quality of life, well-being, and the ability to adapt to economic shocks.

In order to clarify the impact of the digitalization of public services on the household sector, we can also use a linear correlation-regression model.

The dependent variable is the share of individuals who may face unforeseen financial costs. The chosen indicator characterizes the ability of the household sector to adapt during a shock, which is a characteristic feature of

resilience. Under the independent variable, we will consider the share of individuals who used digital public services (website or application) during the last 12 months, i. e. those who performed the following actions: interacting with government authorities, submitting tax returns online, submitting requests for financial benefits or rights, obtaining information about services, benefits, rights and laws. The model hypothesis is based on the assumption that all of the above actions and online access to them can improve the adaptability of the household sector: in the event of a shock, the use of digital public services allows for faster receipt of financial assistance (benefits or other social support), provides access to transparent and clear information, and reduces the time gap in communication and interaction with government agencies. The statistical data that will be used are given in *Table 5*.

Table 5

Statistical data for creating a regression model of the impact
of the digitalization factor of public services on the sustainability
of the household sector in EU countries, 2023

EU country	Share of persons, %	
	who may face unexpected financial expenses	who have used digital public services (website or app) in the last 12 months
	Y	X
Belgium	78.6	81.78
Bulgaria	53.3	29.72
Czech Republic	80.3	71.12
Denmark	76.9	97.68
Germany	65.0	58.07
Estonia	69.6	88.74
Ireland	65.7	85.56
Greece	55.7	68.69
Spain	62.8	79.68
France	70.6	85.17
Croatia	58.6	74.62
Italy	71.2	60.11
Cyprus	62.4	66.12
Latvia	55.2	73.18
Lithuania	59.5	71.82
Luxembourg	75.9	88.90
Hungary	65.8	75.63
Malta	84.1	81.34
Netherlands	84.1	94.78
Austria	77.2	75.60
Poland	74.3	58.54
Portugal	69.5	69.63
Romania	53.6	22.56
Slovenia	77.3	71.14
Slovakia	70.7	71.69
Finland	74.0	95.49
Sweden	78.2	94.58

Source: (Eurostat, n. d. a; Eurostat, n. d. c).

We will use the same pairwise linear regression model and the least squares method as a way to calculate the coefficients. Assuming that outliers are discarded, the results of the calculations are as follows:

$$a = \frac{(15 \cdot 88588.558) - (1105.41 \cdot 1007.7)}{(15 \cdot 88588.558) - (1105.41)^2},$$

$$a = 0.3016,$$

$$b = \frac{1007.7}{15} - 0.3016 \frac{1105.41}{15},$$

$$b = 44.954.$$

We have the function $Y = 44.954 + 0.3016X$. In order to determine the quality of the model, we will pay attention to the value of its error (E). In our case, it is equal to 4, which is 6% as a percentage of Y_c , therefore, the constructed model is qualitative.

We will find the table value of F at a significance level of 0.95 and degrees of freedom $m_1=1$ and $m_2=13$ to check the model for reliability. $F(40.02) > F_{table}(4.67)$, therefore, we can consider the model reliable.

The coefficient of determination of the model (R^2) is 0.75 (or 75%). This indicates that 75% of the variation of the dependent variable is explained by changes in the independent variable. This means that the constructed model has high explanatory power and quite effectively describes the relationship between digitalization and the economic sustainability of the household sector.

As we can see, the hypothesis was partially confirmed: the digitalization of the public sector does have an impact on the sustainability of the household sector and helps to improve its adaptability. Moreover, the impact of digitalization on the household sector is greater than the direct impact on the sustainability of the public sector itself (75% compared to 71%). However, the impact is still not significant. It should be noted that the impact of digitalization usually manifests itself with a certain delay, which creates a lag effect. Therefore, even with a high level of digitalization of the public sector, its real impact on the economic sustainability of households may only manifest itself after a few years.

Conclusions

The research results showed a statistically significant relationship between the level of digitalization of the public sector (quantitative measurement – the percentage of people who used digital public services (website or application) in the last 12 months) and its economic resilience in the face of shocks. In particular, in European Union countries with high indicators of digital transformation of public administration, a higher level of adaptability and resilience is observed. At the same time, in countries with a low level of digitalization of the public sector, such a relationship is weak.

In addition to the direct impact of digitalization on the public sector, it also has an indirect effect through ensuring digital inclusion of the household sector. This indicates the systemic and intersectoral nature of digital transformation as a tool for increasing overall economic resilience.

The scientific novelty of the research lies in the combination of cluster analysis (through quartile grouping) with correlation-regression estimation to determine the relationship between digitalization and economic sustainability of the public sector based on a comparison of EU countries. The proposed approach can be adapted to other sectors of the economy and used to develop strategic directions for digital development in conditions of shock impacts.

The practical significance of the results obtained lies in the possibility of using the identified patterns to form recommendations for the digital transformation of the national economy. Further research should be directed at studying the role of digitalization in ensuring the sustainability of the household sector: to analyze the possible digital vulnerabilities of the sector (digital inequality, level of digital skills, cybersecurity), as well as its level of digital transformation.

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IMMIGRANT EMPOWERMENT AND INCLUSIVE SOCIAL COMPETITIVENESS

Amid accelerating global shifts, geopolitical instability, demographic transitions, technological disruption, and economic fragmentation, Europe faces the urgent challenge of sustaining competitiveness while safeguarding social cohesion. Migration intensifies this challenge, making immigrant empowerment central to long-term resilience. This paper investigates microfinance as a strategic lever for inclusive competitiveness, hypothesizing that access to financial tools enhances immigrants' entrepreneurial capacity, financial autonomy, and civic participation, thereby reinforcing institutional trust and contributing to host economies' adaptive competitiveness. A PRISMA-guided systematic literature review (2010–2025) across Scopus, Web of Science, and Google Scholar identified 973 records, of which 31 peer-reviewed studies met the inclusion criteria. Bibliometric mapping with VOSviewer revealed three thematic clusters: entrepreneurship, financial literacy, and institutional trust-linking microfinance to immigrant empowerment and systemic resilience. Evidence from Spain, Germany, and France shows that microfinance programs foster business formalisation, reduce welfare dependency, and increase civic participation, while adaptive innovations during COVID-19, such as repayment moratoria and digital lending, enhanced household stability and sustained local demand. The findings confirm the hypothesis across three levels: at the micro-level, microfinance strengthens individual entrepreneurship and resilience; at the

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РОЗШИРЕННЯ ПРАВ І МОЖЛИВОСТЕЙ ІМІГРАНТІВ ТА ІНКЛЮЗИВНА СОЦІАЛЬНА КОНКУРЕНТОСПРОМОЖНІСТЬ

На тлі прискорення глобальних зрушень, геополітичної нестабільності, демографічних переходів, технологічних потрясінь та економічної фрагментації Європа стикається з нагальним викликом підтримки конкурентоспроможності та одночасного захисту соціальної згуртованості. Міграція посилює цей виклик через розширення прав і можливостей іммігрантів центральним фактором довгострокової стійкості. У цій статті досліджується мікрофінансування як стратегічний важіль інклюзивної конкурентоспроможності, висувається гіпотеза, що доступ до фінансових інструментів підвищує підприємницький потенціал іммігрантів, фінансову автономію та громадянську участь, тим самим зміцнюючи інституційну довіру та сприяючи адаптивній конкурентоспроможності економік країн, що приймають. Систематичний огляд літератури під керівництвом PRISMA (2010–2025) у Scopus, Web of Science та Google Scholar виявив 973 розробки, з яких 31 рецензоване дослідження відповідало критеріям включення. Бібліометричне картування за допомогою програми VOSviewer виявило три тематичні кластери: підприємництво, фінансова грамотність та інституційна довіра, що пов'язують мікрофінансування з розширенням прав і можливостей іммігрантів та системною стійкістю. Дані з Іспанії, Німеччини та Франції показують, що програми мікрофінансування сприяють формалізації бізнесу, зменшують залежність від соціального забезпечення та підвищують громадянську участь, тоді як адаптивні інновації під час COVID-19, такі як мораторії на погашення боргів та цифрове кредитування, посилили стабільність домогосподарств та сталий місцевий попит. Результати дослідження підтверджують гіпотезу на трьох рівнях: на мікрорівні мікрофінансування зміцнює



meso-level, it builds social networks and trust; and at the macro-level, it contributes to inclusive competitiveness and systemic stability. The scientific novelty of this study lies in bridging migration, finance, and competitiveness within a unified multi-level analytical framework. Policy recommendations include dismantling credit barriers, embedding financial literacy into microfinance schemes, and expanding inclusive digital finance as integral components of Europe's competitiveness agenda.

Keywords: immigrant empowerment; microfinance; social inclusion; competitiveness; resilience.

JEL Classification: F22; J15; G21; M13.

індивідуальне підприємництво та стійкість; на мезорівні будує соціальні мережі та довіру; на макрорівні сприяє інклюзивній конкурентоспроможності та системній стабільності. Наукова новизна цього дослідження полягає в поєднанні міграції, фінансів та конкурентоспроможності в рамках єдиної багаторівневої аналітичної системи. Рекомендації щодо політики включають ліквідацію кредитних бар'єрів, впровадження фінансової грамотності в схеми мікрофінансування та розширення інклюзивного цифрового фінансування як невід'ємних компонентів порядку денного Європи щодо конкурентоспроможності.

Ключові слова: розширення прав і можливостей іммігрантів; мікрофінансування; соціальна інтеграція; конкурентоспроможність; стійкість.

Introduction

Global disruption, climate change, demographic transitions, technological shifts, and geopolitical instability place pressure on Europe to sustain competitiveness while maintaining cohesion. Scholars argue competitiveness must now extend beyond GDP growth to embrace inclusiveness and resilience (Rodrik, 2021; Aiginger & Guger, 2014). Migration intensifies this challenge, reshaping labor markets and institutions (Castles et al., 2021; OECD, 2023).

Immigrants contribute to innovation and human capital development (Nathan, 2014), yet exclusion from financial and entrepreneurial opportunities risks entrenching marginalization and undermining long-term stability (UNHCR, 2023). Addressing this tension requires mechanisms that simultaneously promote immigrant inclusion and reinforce Europe's competitiveness.

Financial inclusion and microfinance in particular, has emerged as one such pathway. Initially developed as a poverty alleviation tool in the Global South (Yunus & Jolis, 2003; Ledgerwood et al., 2013), microfinance is now applied in Europe to empower marginalized groups, including immigrants. Empirical studies demonstrate its benefits: in Spain, microfinance improved entrepreneurial survival rates among migrant women (Álvarez & Ruíz, 2023); in Germany, loans reduced welfare dependency and supported immigrant-led enterprises (Bruder et al., 2011); and in France, targeted microfinance expanded access to formal credit markets (Evers & Reifner, 1989).

Despite these insights, important gaps remain. Migration research emphasizes cultural and legal integration, while financial inclusion studies often treat immigrants as a secondary category within broader vulnerable groups (Guérin et al., 2013). Few works explicitly link microfinance to systemic outcomes such as competitiveness or institutional resilience. The European Investment Bank's (2022) FINCLUDE initiative is a rare exception, yet most studies remain nationally bounded and fragmented.

The aim of this article is to synthesize global evidence on the role of microfinance in fostering immigrant empowerment and inclusive social competitiveness. Specifically, it aims to: (i) examine how microfinance

enhances immigrants' entrepreneurial capacity, financial literacy, and social participation; (ii) evaluate its contribution to systemic outcomes such as trust in institutions, cohesion, and resilience; (iii) situate these outcomes within debates on Europe's competitiveness under conditions of global disruption.

The central hypothesis is that microfinance strengthens immigrants' entrepreneurial capacity, financial autonomy, and civic participation, thereby reinforcing inclusive competitiveness in host economies. To test this hypothesis, the research applies a PRISMA-guided systematic literature review (2010–2025) across Scopus, Web of Science, and Google Scholar. After rigorous screening, 31 peer-reviewed articles were retained for analysis. Bibliometric mapping with VOSviewer identified thematic clusters and conceptual gaps. While limited to English-language studies, the review's comparative scope across Europe and the Global South provides a unique cross-contextual perspective.

The novelty of this paper lies in bridging migration, finance, and competitiveness studies within a unified analytical framework.

The paper is structured as follows: Section 1 develops the conceptual foundations linking microfinance, empowerment, and competitiveness. Section 2 outlines the methodology. Section 3 presents and discusses the findings across mechanisms such as access to capital, financial literacy, and trust-building. The conclusion summarizes contributions, confirms the hypothesis, and offers policy recommendations for embedding microfinance into Europe's competitiveness strategies.

1. Conceptual and theoretical foundations

This section develops the framework for analyzing how microfinance contributes to immigrant empowerment and inclusive social competitiveness. It situates microfinance as a financial innovation with transformative potential, explores its role in shaping immigrant agency, and integrates these insights into debates on Europe's competitiveness under global disruption.

1.1. *Microfinance as empowerment*

Microfinance provides small-scale financial services to those excluded from banks (Ledgerwood et al., 2013). Originating in the Global South as a poverty alleviation tool (Yunus, 2003), it has evolved into an instrument addressing financial exclusion, fostering entrepreneurship, and enhancing participation. Its relevance in Europe has grown as immigrants face barriers such as non-transferable credit histories, lack of collateral and restrictive regulations (Guérin et al., 2013).

Evidence highlights its transformative effects. In Spain, programs improved business survival rates and confidence among migrant women (Álvarez & Ruíz, 2023). In Germany, loans reduced welfare dependency and supported immigrant-led enterprises (Bruder et al., 2011). In France, targeted initiatives expanded access to credit markets (Evers & Reifner, 1989). Beyond

Europe, East African evidence shows microfinance groups foster trust and resilience (Munene & Onyango, 2024), underlining global transferability.

1.2. Immigrant empowerment and agency

Empowerment is the expansion of capacity to make strategic life choices (Kabeer, 1999). For immigrants, this means not only economic independence but also agency in host-country institutions. Financial access reduces dependency and fosters autonomy (D'Ignazio et al., 2024). Microfinance-supported entrepreneurs create jobs beyond ethnic networks, driving inclusive growth (Matei & Sandu, 2022).

Yet empowerment is relational. Welfare regimes, labor markets, and legal rights mediate opportunities (Castles et al., 2021). Fragmented governance often limits local initiatives (Scholten et al., 2017). Thus empowerment must be understood at micro, meso, and macro levels.

1.3. Inclusive social competitiveness

Competitiveness is increasingly framed in terms of inclusiveness, resilience, and cohesion (Aiginger & Guger, 2014). Inclusive institutions strengthen societies' ability to withstand disruption (Rodrik, 2020; Acemoglu & Robinson, 2023). Empowered immigrants are active contributors to competitiveness: diversity drives innovation and productivity (Nathan, 2014). Microfinance enables immigrant entrepreneurship to evolve from survival to systemic competitiveness by linking individual agency with trust and cohesion.

This aligns with EU strategies. The Social Economy Action Plan (European Commission, 2023) identifies microfinance as a growth driver, while the Green Deal and Recovery Plan implicitly rely on immigrant labor and entrepreneurship. Strengthening the EU's social dimension is tied to competitiveness and cohesion (Bilbao-Ubillos, 2022). At the same time, different mechanisms illustrate how microfinance translates into systemic competitiveness (*Table 1*).

Table 1

Pathways from microfinance to inclusive social competitiveness

Mechanism	Micro-Level Impact	Macro-Level Outcome
Access to capital	Entrepreneurial start-ups, asset building	Increased business activity, job creation
Financial literacy	Better budgeting, improved financial autonomy	Stronger household and community resilience
Trust in Institutions	Greater civic participation, reduced exclusion	Reinforced democratic legitimacy
Community cohesion	Stronger networks between immigrants and locals	Enhanced social stability and cohesion

Source: compiled by the author based on (European Commission, 2023; Bilbao-Ubillos, 2022) and related studies.

1.4. Gaps and hypothesis

Despite promising evidence, research on microfinance and immigrant integration remains fragmented. Migration studies emphasize cultural/legal aspects (Triandafyllidou, 2018), while financial inclusion research seldom addresses immigrant-specific barriers (Evers & Reifner, 1989). Few works link microfinance to competitiveness or institutional resilience. The European Investment Bank's (2022) FINCLUDE program is a rare exception.

2. Research methodology

2.1. Methodological rationale

This study employs a systematic literature review (SLR) to examine the nexus between microfinance, immigrant empowerment, and inclusive social competitiveness. The SLR method is appropriate for two main reasons. First, the field is interdisciplinary, spanning development economics, migration studies, entrepreneurship, and institutional theory.

Fragmentation across these domains necessitates synthesis to produce a coherent and integrated understanding (Tranfield et al., 2003; Snyder, 2019). Second, SLRs are widely recognized as rigorous approaches that enhance transparency, replicability, and credibility when addressing complex social challenges, making them highly relevant for evidence-based policymaking (Booth et al., 2016; Xiao & Watson, 2017).

2.2. Research hypothesis and questions

The central hypothesis guiding this study is that microfinance strengthens immigrant empowerment and, through mechanisms such as capital access, financial literacy, trust-building, and community cohesion, contributes to inclusive social competitiveness. This assumption builds on prior work linking financial inclusion to entrepreneurship, resilience, and long-term development outcomes (Kabeer, 2002; Ledgerwood et al., 2013; Guérin et al., 2013).

To operationalize this hypothesis, three research questions were formulated. The first (RQ1) asks how microfinance influences immigrants' entrepreneurial, financial, and integration outcomes. The second (RQ2) explores the mechanisms through which financial inclusion connects to systemic outcomes such as competitiveness, resilience, and institutional trust. The third (RQ3) addresses the gaps that remain in the current literature and consider how future studies might resolve them.

2.3. PRISMA-Guided procedure

The review followed PRISMA 2020 guidelines (Page et al., 2021) to ensure methodological rigor. Searches were conducted in Scopus, Web of

Science, and Google Scholar between 2010 and 2025, using Boolean combinations such as "microfinance AND immigrants", "financial inclusion AND migration", and "entrepreneurship AND refugees". The initial search produced 973 records. After duplicate removal and screening titles/abstracts, 216 remained. Applying strict inclusion criteria (peer-reviewed, English-language, explicitly addressing immigrants and microfinance) and excluding reports, dissertations, or purely descriptive policy notes resulted in 31 eligible studies.

These studies were coded and analyzed using a three-level framework. At the micro-level, the analysis focused on outcomes such as entrepreneurship, financial literacy, and household resilience. At the meso-level, it examined community trust networks, civic participation, and institutional engagement. Finally, at the macro-level, it considered broader systemic outcomes including competitiveness, resilience, and social cohesion.

Bibliometric mapping with VOSviewer (Van Eck & Waltman, 2010) revealed thematic clusters and citation networks that illustrate the intellectual structure of the field (*Figure 1*).

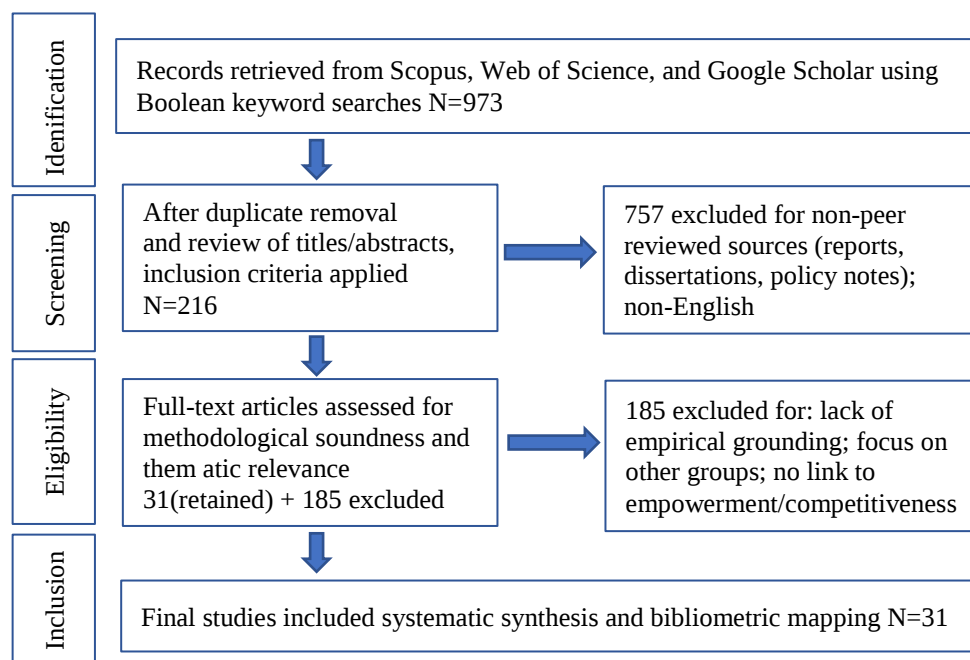


Figure 1. Bibliometric mapping of thematic clusters and citation networks

Source: compiled by the author based on (Van Eck & Waltman, 2010).

2.4. Hypothesis testing and analytical strategy

Testing the hypothesis required a mechanism-based approach (Hedström & Swedberg, 1998). Evidence from Spain, Germany, and France was compared with multi-country initiatives such as the European Investment Bank's FINCLUDE program (European Investment Bank, 2022). Converging findings, such as enhanced immigrant entrepreneurship, reduced

welfare dependency, and stronger business formalisation, were interpreted as support for the hypothesis.

Diverging findings, by contrast, underscored the role of institutional and contextual barriers, including rigid credit-scoring systems, legal uncertainty, and cultural mismatches that constrain immigrants' access to financial services (Scholten et al., 2017; Bruder et al., 2011).

These mechanisms, capital access, financial literacy, trust in institutions, and community cohesion, emerged as the mediating channels through which microfinance contributes to empowerment and, ultimately, inclusive competitiveness.

2.5. Limitations

Three limitations must be noted. First, restricting the review to English-language studies may underrepresent contexts such as Italy, Greece, or Eastern Europe. Second, immigrant-specific data availability varies, with Spain and Germany dominating due to stronger empirical documentation. Third, while SLRs provide robust synthesis, they do not establish causal inference; mechanisms remain indicative rather than definitive. These challenges echo findings by Evers and Reifner (1998) and Munene and Onyango (2024).

Nevertheless, the methodology ensures rigor, transparency, and replicability, making the findings relevant for both scholarly debate and policy design.

3. Findings and discussion

The review of 31 peer-reviewed studies reveals consistent but context-dependent evidence that microfinance fosters immigrant empowerment and contributes to inclusive social competitiveness. The discussion is organized across three analytical levels: micro, meso, and macro.

3.1. Micro-Level: individual empowerment and resilience

At the micro level, microfinance enhances financial autonomy, entrepreneurship, and self-reliance. In Spain, access to credit improved entrepreneurial self-efficacy among migrant women (Álvarez & Ruíz, 2023). In Germany, microloans enabled North African migrants to expand enterprises and reduce welfare dependence (Bruder et al., 2011). Financial literacy programs further strengthened household budgeting and resilience (Guérin et al., 2013).

Despite these benefits, structural barriers remain. Legal status, lack of credit history, and cultural or linguistic challenges often restrict access (Matei & Sandu, 2022). These findings underscore that microfinance alone is insufficient without complementary institutional support.

3.2. Meso-Level: community cohesion and trust

At the meso level, microfinance fosters networks of trust and civic engagement. Group lending and rotating savings associations mitigate risk while promoting solidarity (Munene & Onyango, 2024). Participation also increases immigrant involvement in community associations and civic bodies (D'Ignazio et al., 2024). Yet, programs limited to ethnic enclaves risk reinforcing insularity rather than integration (Scholten et al., 2017). Balancing ethnic solidarity with cross-community networking is therefore critical.

3.3. Macro-Level: competitiveness and systemic resilience

At the macro level, microfinance contributes to competitiveness by stimulating entrepreneurship, job creation, and institutional resilience. The European Investment Bank's (2022) FINCLUDE program shows that microfinance fosters business creation and innovation while reducing unemployment.

This resonates with Rodrik's (2021) view that inclusive institutions support adaptive growth and Acemoglu and Robinson's (2023) argument that broad access underpins resilience. However, cross-national divergence persists: Spain and Germany demonstrate systemic impact by integrating microfinance into inclusion strategies, while weaker policy frameworks elsewhere limit outcomes (Bilbao-Ubillos, 2022). A synthesis of the multi-level findings is presented in *Table 2*.

Table 2

Multi-level findings on microfinance, immigrant empowerment, and competitiveness

Level	Mechanisms Identified	Key Impacts (Evidence)	Limitations/Barriers
Micro	Access to capital, financial literacy	Entrepreneurship, self-sufficiency, reduced welfare reliance (Álvarez & Ruíz, 2023; Bruder et al., 2011)	Legal restrictions, lack of credit history, cultural barriers
Meso	Group lending, community savings, trust-building	Civic engagement, social cohesion, immigrant–host trust (Munene & Onyango, 2024; D'Ignazio et al., 2024)	Risk of reinforcing ethnic enclaves (Scholten et al., 2017)
Macro	Institutional integration, inclusive growth strategies	Job creation, innovation, systemic resilience (European Investment Bank, 2022; Rodrik, 2021; Acemoglu & Robinson, 2023)	Uneven implementation across EU states (Bilbao-Ubillos, 2022)

Source: Compiled by the author based on (Álvarez & Ruíz, 2023; Bruder et al., 2011; Munene & Onyango, 2024; D'Ignazio et al., 2024; European Investment Bank, 2022; Rodrik, 2021; Acemoglu & Robinson, 2023; and Bilbao-Ubillos, 2022).

3.4. Cross-Cutting patterns and divergences

Three patterns emerge. First, microfinance consistently boosts entrepreneurship and resilience when paired with financial literacy (Guérin et al., 2022). Second, community lending fosters trust and civic participation but risks reinforcing enclaves if disconnected from mainstream institutions

(Scholten et al., 2017). Third, systemic outcomes are strongest where microfinance is integrated into national strategies, notably Spain and Germany (Álvarez & Ruíz, 2023; Bruder et al., 2011).

Divergences reflect institutional contexts. France, constrained by rigid credit systems, shows weaker results (OECD, 2023), while Spain's flexible credit models and municipal partnerships enable stronger outcomes (Evers & Reifner, 2023). EU policy frameworks are increasingly promoting digital tools for inclusion, creating space for digital microfinance, even if implementation remains uneven (OECD/European Commission, 2023).

3.5. Synthesis and policy implications

Overall, microfinance emerges as both a direct empowerment tool and an indirect driver of competitiveness. Its impact, however, depends critically on institutional design, supportive regulation, and program integration. Three main policy implications follow from the analysis.

First, the development of inclusive credit scoring systems at the EU level is essential; as such mechanisms would recognize informal economic activity and transnational financial histories, thereby reducing barriers for immigrants who lack conventional collateral. Second, the integration of financial literacy training and digital banking tools into microfinance programs would help ensure that beneficiaries fully leverage available services while avoiding debt-related risks. Third, aligning microfinance initiatives with broader policies on labor, education, and housing is necessary to prevent fragmentation and to maximize their contribution to systemic competitiveness. Together, these strategies would allow microfinance to evolve from a localized financial intervention into a cornerstone of Europe's competitiveness agenda, fostering resilience, diversity, and institutional trust.

Conclusions

This research confirmed that microfinance serves as a catalyst for immigrant empowerment and inclusive social competitiveness in Europe. A systematic review of 31 peer-reviewed studies demonstrated that microfinance enhances entrepreneurial capacity and autonomy at the micro-level, strengthens social cohesion and institutional trust at the meso-level, and contributes to competitiveness and resilience at the macro-level.

The central hypothesis was therefore confirmed. An additional, unanticipated finding was that microfinance also fosters civic participation and institutional trust, extending its role beyond entrepreneurship and financial access.

The novelty of this research lies in linking microfinance to a multi-level model of competitiveness, bridging individual empowerment with systemic performance. The paper contributes both theoretically, by integrating fragmented literatures, and practically, by offering policymakers guidance for embedding microfinance into Europe's competitiveness agenda.

The practical value is clear: by incorporating microfinance into labor market, financial inclusion, and social economy strategies, governments can

empower immigrant communities while enhancing overall economic performance. Future research should employ longitudinal and comparative methods to trace causal pathways and clarify how institutional contexts mediate outcomes.

In conclusion, when embedded in inclusive institutional frameworks, microfinance becomes a strategic lever for addressing the twin challenges of immigrant integration and sustainable competitiveness in an era of global shifts.

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STIMULATION OF REGIONAL COMPETITIVENESS

The article is devoted to the research of economic policy for stimulating regional competitiveness in conditions of macroeconomic instability, spatial polarization and the consequences of the full-scale war in Ukraine. The relevance of the topic is determined by the need to modernize regional development mechanisms in the context of global challenges, in particular the demographic crisis, institutional asymmetry, the digital divide, and structural depletion of peripheral regions. The research is based on the hypothesis that an effective policy to stimulate regional competitiveness is possible provided that the European development vector is integrated with the values of security, sustainable development, institutional capacity, digital transformation of public administration, and differentiated consideration of spatial asymmetries between regions. The research methodology is based on general scientific and specialized methods, including systemic, institutional, comparative, factorial, structural-logical, statistical, spatial, cluster, and graph analytical approaches. The research contains the results of a comparative analysis of the regions' competitiveness of Poland, Lithuania, and Ukraine in the Lublin Triangle architecture, it analyses geospatial differentiation, and identifies transformation vectors of regional development in the context of the war in Ukraine, in particular digital adaptation, demographic

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СТИМУЛЮВАННЯ РЕГІОНАЛЬНОЇ КОНКУРЕНТОСПРОМОЖНОСТІ

Досліджено економічну політику стимулювання регіональної конкурентоспроможності в умовах макроекономічної нестабільності, просторової поляризації та наслідків повномасштабної війни в Україні. Актуальність теми обумовлена необхідністю модернізації механізмів регіонального розвитку в контексті врахування глобальних викликів, зокрема демографічної кризи, асиметрії інституційного середовища, цифрового розриву й структурного виснаження периферії. У дослідженні висунуто гіпотезу, що ефективна політика стимулювання регіональної конкурентоспроможності можлива за умови інтеграції європейського вектора розвитку з цінностями безпеки, сталого розвитку, інституційної спроможності, цифрової трансформації державного управління та диференційованого врахування просторових асиметрій регіонів. Методологія дослідження ґрунтується на таких загальнонаукових і спеціальних методах: системному, інституційному, порівняльному, факторному, структурно-логічному, статистичному, просторовому, кластерному й графоаналітичному підходах. У статті представлено результати компаративного аналізу конкурентоспроможності регіонів Польщі, Литви та України в архітектоніці Люблінського трикутника, проаналізовано геопросторову диференціацію, визначено трансформаційні вектори регіонального розвитку



response, institutional mobilization, and mechanisms for stimulating innovation. A conceptual model for aligning sustainable development values with economic policy for managing competitiveness at the regional level is proposed. The results of the research made it possible to develop new conceptual approaches to assessing the effectiveness of economic policy for stimulating regional competitiveness and to justify directions for its further improvement.

Keywords: economic policy, competitiveness, local governments, public administration, region, territorial communities.

в умовах війни в Україні, зокрема цифрову адаптацію, демографічну реакцію, інституційну мобілізацію та механізми стимулювання інновацій. Запропоновано концептуальну модель узгодження цінностей сталого розвитку з економічною політикою управління конкурентоспроможністю на регіональному рівні. Результати дослідження дали змогу розробити нові концептуальні підходи до оцінки ефективності економічної політики стимулювання регіональної конкурентоспроможності й обґрунтувати напрями її подальшого вдосконалення.

Ключові слова: економічна політика, конкурентоспроможність, органи місцевого самоврядування, публічне управління, регіон, територіальні громади.

JEL Classification: R11, R12, R58, O25, O38, H70.

Introduction

In the context of macroeconomic instability, the processes of territorial asymmetry are intensifying, accompanied by increased competition between regions for human, financial, material resources, technologies, investments, and innovations. Ensuring the vector of sustainable regional development requires the introduction of effective mechanisms to support small and medium-sized businesses, implement investment projects, and develop cluster structures. Transformational digital and environmental challenges necessitate a revision of the conceptual framework of the policy of stimulating regional competitiveness. Managing regional competitiveness requires a strategic focus of territorial communities on human capital development, shaping a competitive environment, and strengthening institutional capacity.

Among the latest scientific studies, an important place is occupied by the scientific works of economists devoted to the development of conceptual and methodological approaches to the formation of economic policy and practical mechanisms for its implementation in conditions of macroeconomic instability.

In the report "The future of European competitiveness Part B. In-depth analysis and recommendations" presented to the European Commission, prepared by M. Draghi, the need to form a new institutional and innovative base to increase the competitiveness of the EU, particularly at the regional level, is emphasised. Given the fragmentation of the research and innovation system and the need to consolidate the economic potential of all European regions in this area, Draghi stresses that "The EU needs to set as one of its key priorities the establishment of a Research and Innovation Union" emphasising that "better coordination of public R&I expenditure across Member States is crucial to enhance innovation in the EU", which involves the consolidation of resources, the formation of common strategic directions and the implementation of interregional projects to ensure competitive advantages in the global market (Draghi, 2024).

European scholars Dijkstra et al. (2020) have made a significant contribution to the study of spatial imbalances, substantiating the phenomenon of the "geography of discontent", which manifests itself in the growing social and economic polarisation between dynamic urban centres and depressed peripheries. The researchers argued that regions that are losing economic dynamics are characterised by an increase in protest moods among the local population and growing distrust of government institutions. This confirms the need to develop inclusive economic policies that take into account territorial differences and minimise the risks of increasing regional polarisation.

In their research, Gianelle et al. (2020) emphasise that the concept of Smart Specialisation has become a key instrument of EU regional policy. The researchers note that the concept of the Smart Specialisation strategy is aimed at identifying and strengthening the unique competitive advantages of regions, which allows for the formation of innovative clusters, stimulates scientific and technological development, and increases the investment attractiveness of territories.

Recent studies by Ukrainian economists highlight key areas of economic, spatial and demographic development of regional competitiveness in the context of global challenges and European integration.

Danylyshyn (2024) reveals the strategic priorities for the restoration and development of communities and regions in Ukraine, emphasising the consistent strengthening of the administrative capacity of local authorities, the integration of European management practices, and the formation of a systematic approach to spatial management, taking into account regional disparities and mechanisms of international cooperation.

Varnalii et al. (2023) justify the system of assessing regional disparities using a spatial β -convergence model, which reveals the slow convergence and increasing divergence between regions, necessitating a correction of regional policy objectives.

Mazaraki and Umantsiv (2025) explain the institutional vectors for implementing economic policy in conditions of global instability, noting the need to review state regulation tools, develop incentives to ensure the stability of the national economy, and apply an institutionally oriented approach to economic modernisation in the context of post-war recovery.

Shkuropadska, et al. (2024), having analysed the impact of demographic stability on economic development using the example of the macro-regional association of the Visegrad Group countries, emphasise that declining birth rates, increased mortality and depopulation processes create structural risks for human capital and require comprehensive and effective state policy.

In their research, Ukrainian experts in public management and administration devote considerable attention to researching the problems

and opportunities of regional development in conditions of war and post-war reconstruction.

The authors of the collective monograph "Economic Security in Restoring Competitiveness of Ukraine" (Nadolenko et al., 2024) noted that Ukraine has seen a significant increase in the effectiveness of economic management, which ensures stability, competitiveness, and the development of entrepreneurial activity in the innovation space.

Zalizniuk and Lazebna (2024) indicate that the destruction of infrastructure, reduced tax revenues, demographic losses, and dependence on state transfers significantly limited the economic capacity of local communities.

Goncharenko, et al. (2023) define state regulation as a key instrument for ensuring sustainable development, emphasising its importance for infrastructure restoration, investment support and implementation of priority projects, as well as the need for transparent legal mechanisms and public participation.

Dynnyk (2024) analyses regional branding as an innovative tool for shaping a positive image, increasing competitiveness and attracting investment.

In addition, economic policies aimed at stimulating regional competitiveness must take into account the problems of rural areas, which, according to research by Levandivskyi, et al. (2025) are characterised by low living standards due to weak economies and insufficient development of social infrastructure.

The problem of developing strategies for restoring economic ties, strengthening the adaptive capacity of regional economies to external shocks, and forming new growth trajectories based on systemic approaches to regional development has been the subject of research conducted by scholars on the example of the Visegrad countries in the context of the impact of the crisis caused by the COVID-19 pandemic.

The study by Mitze and Makkonen (2021) provides a comprehensive analysis of research and innovation (R&I) financing as an economic policy tool that ensures the recovery of regional economic growth after the COVID-19 crisis. The researchers have shown that such investments create the basis for increasing productivity, revitalizing local enterprises, and generally strengthening the long-term competitiveness of regions.

Lithuanian scientist Vilpišauskas (2024) emphasizes the value-based approach of macro-regional European integration, which he considers a foreign policy success and a tool for economic modernization, including the regional dimension and integration into common EU policies, including energy policy.

Particular attention should be paid to the study by Polish scientist Kloska on the classification of Polish voivodeships by the level of socio-

economic development using the Ward's Method of clustering. The results obtained allowed the researcher to identify groups of regions with similar characteristics, which creates an analytical basis for the development of differentiated regional development strategies, taking into account the structural affinity of the territories (Kłoska, 2023).

Some EU scholars have also studied the tools of regional incentive policy in the form of GRW (Gemeinschaftsaufgabe Verbesserung der regionalen Wirtschaftsstruktur) grants, which are used to support areas with lower levels of socioeconomic development. Researchers have found that an increase in the share of project funding stimulates investment growth and job creation, especially in small businesses; in regions where grant support decreased, employment growth slowed (Alecke & Mitze, 2023).

Recognizing the undeniable scientific and practical significance of the research, we believe that the aspects of economic policy to stimulate regional competitiveness remain insufficiently developed at both theoretical and applied levels and require a separate in-depth study.

The aim of the research is to substantiate the conceptual foundations of the economic policy of stimulating regional competitiveness in the context of macroeconomic instability.

The authors hypothesise that an effective policy for enhancing regional competitiveness is possible provided that the European development vector is integrated with the values of security, sustainable development, institutional capacity, digital transformation of public administration, and differentiated consideration of spatial asymmetries between regions.

The algorithm for testing the hypothesis involves the theoretical formalization of the conceptual foundations of competitiveness; analysis of spatial differences between regions within the Lublin Triangle; checking whether the empirical data correspond to the expected consequences; and interpretation of the results obtained in the strategic context of post-war recovery.

To realize this aim, the following tasks have been identified:

- to study conceptual approaches to the economic policy of regional development;
- to analyze international experience in assessing regional competitiveness;
- to assess the spatial asymmetry of competitiveness of the regions of Poland, Lithuania, and Ukraine in the context of European integration;
- to identify the transformational factors of Ukraine's regional policy in the context of war and post-war recovery.

The methodological basis of the study consists of works by leading scholars on regional economics, spatial development, and public administration. The validity of the scientific results is based on the use of general scientific and special methods of cognition: systemic (for a comprehensive disclosure of the subject of research), institutional (for assessing the impact

of institutional factors on regional policy), comparative (for comparing indicators of different countries and regions), factorial (for identifying key determinants of regional development), structural-logical (for constructing analytical generalisations), statistical (for quantitative processing of indicators), spatial (for analysing territorial differences based on NUTS), cluster (grouping regions by level of development), and graph analytical (for visualising results and identifying trends).

The empirical basis consists of data from the European Commission, the OECD, the World Bank, the NUTS classification system, analytical reviews by Deloitte and McKinsey, and indicators from the State Statistics Service of Ukraine for the Regional Competitiveness Index (RCI) and the Digital Transformation Index for the regions of Ukraine. The analytical part of the study covers the period from 2010 to 2024. The spatial coverage includes the countries of the Lublin Triangle at the macro level (national economy), meso level ("Oblasti" in Ukraine, "Województwa" in Poland, "Apskritys" in Lithuania) and micro level (territorial communities).

The limitations of the research are related to the incompleteness of Ukraine's statistical data on the temporarily occupied territories in connection with the hybrid war of 2014 and the start of full-scale war on 24 February 2024. Statistical data sources in Ukraine and EU countries differ in their methodologies for calculating indicators. The use of expert assessments and analytical reviews expands the factual basis of the study but at the same time limits the possibilities for quantitative comparisons. At the same time, a multi-component methodology and a wide range of verified sources ensure the robustness of the results obtained.

The structure of the article, which consists of three sections, focuses on analyzing the challenges of regional development, assessing the effectiveness of the current policy and the development of tools for its improvement. The main part of the article is structured in the following areas: conceptual understanding of the essence of the competitiveness promotion policy; comparative assessment of the regional potential of Poland, Lithuania and Ukraine; analytical study of the transformational vectors of Ukrainian regional policy in the context of war and its impact on the institutional, digital, demographic and innovative parameters of regional development.

1. Conceptual framework of the policy to stimulate regional competitiveness

The formation of an effective policy to stimulate regional competitiveness is based on an interdisciplinary approach that combines the provisions of macroeconomic theory, institutional economics, spatial organization of the economy, and human capital theory. The change in the paradigm of regional development from centralized financial redistribution to spatially oriented strategies has necessitated a rethinking of the conceptual foundations of economic policy.

1.1. Macroeconomic approaches for stimulating regional development

The formation of an effective policy to stimulate regional development is impossible without understanding the evolution of macroeconomic approaches that have defined the basic principles of government intervention in the face of spatial asymmetry.

The origins of macroeconomic policy to stimulate regional development can be found in the work of Keynes "The General Theory of Employment, Interest and Money", where the key concept is the need for state regulation of the economy in conditions of insufficient aggregate demand. The scientist argues that private investment is not always able to provide full employment, and therefore the state should compensate for the deficit of effective demand by making budget expenditures that should have a multiplier effect, activating employment, income, and domestic demand (Keynes, 1936).

The Keynesian approach became the basis for a centralized policy of supporting depressed areas (LFRS, Less-Favored Regions and Spaces), which was implemented through subsidizing enterprises, infrastructure investments, and social transfers. This concept was the basis for post-war regional development strategies in Western Europe, focused on active state involvement in spatial equalization.

Critically assessing the Keynesian approach to stimulating regional development, Amin (1999) emphasizes its limitations in the implementation of spatial mechanisms of economic policy, primarily due to the dominance of centralized transfers and macroeconomic regulation that does not take into account local institutional specifics. Instead, the scientist develops an institutional approach, according to which the long-term competitiveness of regions depends on deeply rooted social structures, norms of trust, interaction, and the ability to learn and develop. In this perspective, incentive policies should focus not only on economic incentives, but also on creating a sustainable institutional environment that ensures effective interaction between the state, business, and civil society.

The developer of the "national diamond" model of competitiveness, Porter, argues that no country is able to dominate most industry markets, as each country forms its own specific structure of competitive advantages. Competitive advantages of macroeconomic systems are formed as a result of localized processes caused by a combination of national values, resource potential of territories, cultural factors, historical background, and institutional environment. Therefore, the key determinants of the competitiveness of the country and its regions are the development of highly productive industries, rational use of production factors, formation of competitive strategies of enterprises, availability of institutional support, development and implementation of effective economic incentive policies (Porter, 1990).

According to M. Porter, economic policy instruments can significantly transform the structure of sectoral competition, determining the conditions for entering or exiting sectoral markets, which directly affects the dynamics of regional competitiveness. The scientist emphasizes that economic policy functions as an "exit barrier" or as an "entry barrier", and such restrictions "include governmental entry bans or opposition to entry out of concern for possible unemployment growth or regional economic effects: these are particularly common outside the United States" (Porter, 1998).

Thus, the modern macroeconomic policy of stimulating regional development is the result of a theoretical evolution from centralized state intervention to concepts that take into account local institutional preconditions, competitive advantages and strategic interaction of actors.

1.2. Institutional vector of regional policy

Modern regional policy is formed in the context of global institutional guidelines that define the principles of spatial development and competitiveness of territories. A special role in this process is played by international institutions such as the OECD, the World Bank, and the European Commission, which form the analytical framework, methodological foundations, and regulatory standards for regional development policy with a focus on institutional capacity, multi-level governance, and public administration efficiency.

In the early 1990s, the Organization for Economic Cooperation and Development (OECD) formulated the concept of "*learning regions*", defining human capital, training and skills development as strategic resources for regional economic growth. According to this concept, a region is viewed as a dynamic space of institutional development. Its logic is based on the integration of knowledge development policies with the needs of regional economies, providing for the formation of sustainable partnerships between educational organizations, business, and government. However, despite its theoretical attractiveness, the implementation of this model has been limited due to a lack of coherence between educational programs and market demands, insufficient development of multilevel institutional interaction, and fragmented cross-sectoral cooperation (OECD, 2001).

The current paradigm of regional policy is characterized by a shift to spatially oriented, place-based approaches that take into account the socio-economic heterogeneity of territories and adapt policy instruments to local challenges. According to OECD analytical findings, regional competitiveness is assessed on the basis of a number of measurable indicators, among which labor productivity, employment, innovation dynamics, quality of human capital, and public administration efficiency are

of key importance (OECD, 2019). This approach creates the basis for the formation of a regional policy capable of activating the internal development potential and ensuring the socio-economic sustainability of the territories. In this regard, human capital, professional training, and the development of professional competencies are recognized as key factors in regional competitiveness.

The integration of economic, social and environmental vectors of the policy of stimulating regional competitiveness is consistent with the Sustainable Development Goals (SDGs). Since about 2/3 of the SDGs cannot be achieved without the active participation of territorial communities and coordination of local governments, the OECD has developed a localized indicator framework that allows measuring progress in achieving the SDGs, identifying regional disparities, and adapting strategic policy instruments to realize the internal potential of territories, develop human capital, and modernize infrastructure to stimulate innovation in accordance with the principles of social inclusion and environmental sustainability (OECD, 2020).

The OECD Council Recommendation on Regional Development Policy outlines a holistic concept of spatial development based on the following basic principles: strategic planning, relevance to the territorial scale, joint policy-making, sustainability, analytical framework, multi-level governance, institutional capacity, resource provision, integrity, and result orientation. The proposed framework allows policy to be adapted to spatial heterogeneity, ensuring its coherence, effectiveness and sustainability in response to regional development challenges (OECD, 2023).

According to the analytical work of the OECD Competition Committee, the effective implementation of a spatially differentiated competitiveness policy requires the introduction of clear principles of competition policy: market neutrality, removal of barriers to market access, and support for fair competition. An important area of economic policy to stimulate regional development is to ensure consistency between the institutional regulatory mechanism and local economic characteristics, which allows unlocking the potential of regions in the context of innovative renewal, productivity growth, and increased efficiency of public administration through competitively oriented solutions (OECD, 2024).

The OECD report "*Place-Based Policies for the Future*" states that the effectiveness of regional policy depends on the following prerequisites:

- focus on mobilizing regional potential by clearly defining policy objectives based on an in-depth analysis of market failures and institutional barriers;
- ensuring policy coherence through effective management of interactions between sectors, institutions and policy frameworks, in particular in relation to macroeconomic and structural strategies;

- ensuring effective implementation through scalably relevant tools for transparent resource allocation and implementation of feedback mechanisms;
- strengthening multi-level governance through the development of coordination mechanisms for fiscal and institutional capacity, leadership, and inclusive participation at the local level (OECD, 2025).

In the context of the modern paradigm of regional development, the European Commission is actively implementing the concept of "Smart Specialisation", which is the methodological basis for strategic planning in the EU. This approach involves identifying regional priorities based on existing competitive advantages in order to further strengthen them through the development of innovation potential and technological upgrading of the economy. At the center of this concept is the idea of territorial innovation as a driver of economic growth, quality of life and sustainable development at the national, regional and local levels. The implementation of Smart Specialisation policies is aimed at creating dynamic entrepreneurial ecosystems, supporting transformational innovations, and implementing strategies adapted to the specific needs of individual territories. The concept is implemented in practice through the Smart Specialisation Community of Practice network, which provides methodological support, strategic advice, and a platform for the exchange of experience between stakeholders. This promotes the implementation of innovation-oriented approaches to spatial transformation, in particular in the context of digital, environmental and social transitions. The concept is also closely linked to the implementation of the Sustainable Development Goals (SDGs) by integrating science and technology roadmaps into local research and innovation policies. The transnational projection of this model is also important, as Smart Specialisation mechanisms are gradually being implemented in the EU's neighborhood, which demonstrates the universality and adaptability of this model to different institutional and socio-economic contexts (European Commission, n. d.).

In the context of current challenges to regional development, the World Bank emphasizes the need to transform competition strategies into a systemic policy to stimulate regional competitiveness. The main directions of such a policy are the implementation of institutional reforms, infrastructure modernization and support for small and medium-sized businesses as key factors in enhancing regional growth; it is emphasized that insufficient competition hinders productivity, innovative development and social mobility, and therefore the formation of an effective competitive environment is considered a fundamental prerequisite for ensuring sustainable economic development of regions (World Bank Live, 2024).

Therefore, the institutional direction of regional development policy increasingly depends on the influence of international institutions, which is manifested in the standardization of approaches, the transfer of public

administration tools, and the integration of sustainable development goals into strategic planning. Taking into account OECD practices, World Bank recommendations, and European Commission directives ensures that regional policy is more adaptable and effective in the face of spatial asymmetry and growing global challenges.

1.3. Assessment of regional competitiveness in the geospatial coordinate system of the European Union

The geospatial dimension of the competitiveness of EU regions reflects the systemic asymmetry of social and economic development between the western, northern and eastern territories, which forms a stable geo-economic space of uneven growth. Spatial disparities are caused by different levels of access to resources, variations in the institutional capacity of the regions, the impact of agglomeration effects, structural inertia of development, and unequal degree of integration of the regions into the EU internal market.

The study by Duranton and Venables, commissioned by the World Bank, proves that spatial disparities are a stable phenomenon of economic development. Moreover, the elimination of regional development asymmetries does not occur automatically, firstly, due to the limited mobility of production factors such as land, labor, and capital, which hinders the realization of competitive advantages, causes depopulation of territories, and reduces investment; secondly, the tendency of economic activity to spatial concentration due to agglomeration effects and the difficulty of launching new centers of economic development. This increases inequality and creates barriers for regions that are not integrated into the economic core. Under such conditions, the expediency of economic policies to stimulate regional development is explained not only by the need to eliminate market failures, but also by the consequences of depopulation, social decline, and the risks of growing territorial inequality, which threatens the stability of the macroeconomic system (Duranton & Venables, 2018).

The parameters of regional competitiveness within the European space are determined through the Regional Competitiveness Index (RCI), developed by the European Commission as an analytical tool for assessing the ability of regions to provide an attractive environment for doing business, innovative development and social well-being of the population. The RCI represents the spatial differentiation of the development of administrative-territorial entities in the EU countries (*Figure 1*).

The methodology for assessing the competitiveness of EU regions is based on the NUTS classification, the official system of territorial division for statistics established by Regulation (EC) No 1059/2003 and updated by

Regulation (EU) No 2016/2066. The use of NUTS 2 and NUTS 3 levels provides a detailed analysis of the economic, social and institutional structure of regions, and also allows identifying disparities between agglomerations and peripheries (NUTS, 2016).

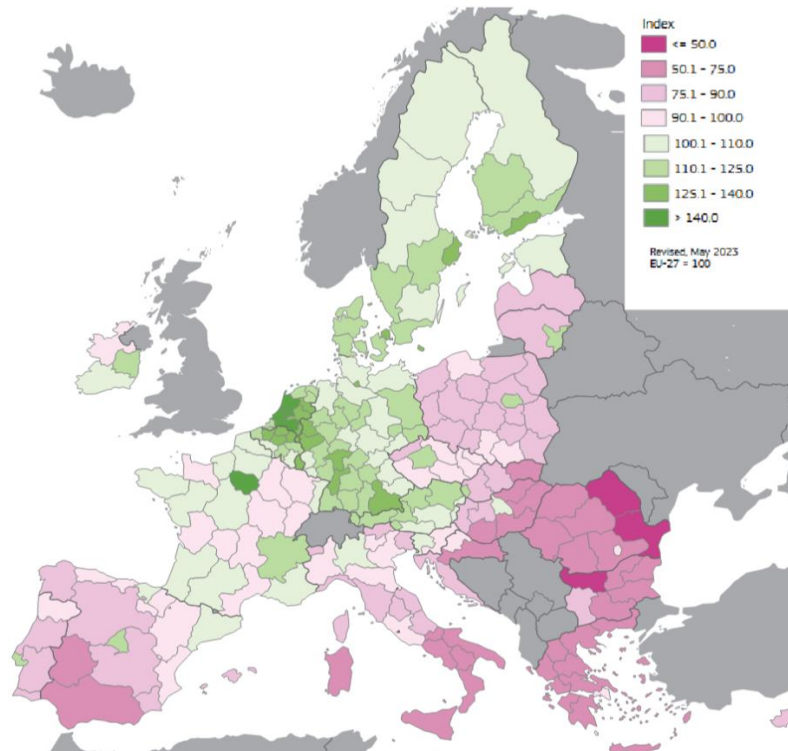


Figure 1. Regional competitiveness index

Source: based on the materials of the European Commission (Dijkstra et al., 2023).

The Regional Competitiveness Index, updated in version 2.0 in 2022, contains 68 indicators grouped into sub-indices: "Basic Factors, Efficiency, and Innovation. Based on the model of the World Economic Forum, RCI 2.0 allows comparing regions with each other, identifying leaders and identifying areas that are lagging behind. The combination of NUTS and RCI 2.0 analysis forms an evidence-based basis for policies to promote regional competitiveness (Dijkstra et al., 2023).

As shown in *Figure 1*, the regions of the Benelux, Northern Europe, Austria, and Germany are characterized by a level of competitiveness that exceeds the EU average. At the same time, most Eastern European regions, with the exception of metropolitan areas, have lower values. A similar situation is observed in the southern EU member states, except for such regions as Catalonia, Madrid, Basque Country (Spain), Lombardy (Italy), and the Lisbon metropolitan area (Portugal), which represent successful competitiveness results. Ireland and France are characterized by a mixed profile, with regions with different levels of competitiveness. In most EU member states, metropolitan regions have the highest competitiveness scores,

especially in Spain, France, Portugal, and Eastern Europe, which can exacerbate imbalances between regions. At the same time, in Germany, Italy, and the Netherlands, the highest results were recorded not in the capitals, but in economically powerful regions: Utrecht (151% of the EU average) and South Holland (142%) in the Netherlands, Lombardy (103%) in Italy, and Oberbayern (130%) in Germany, which exceed the respective indicators of Berlin, Rome and Amsterdam.

Thus, the global policy of stimulating regional competitiveness is based on the principles of spatially oriented development, which involves taking into account the importance of human capital, environmental responsibility, inclusiveness, intellectualization of economic processes, modernization of regional infrastructure, support for small and medium-sized businesses, strategic planning, and focus on achieving sustainable development goals. At the same time, it envisages the introduction of multi-level governance, strengthening the institutional capacity of the regions, development of innovative ecosystems, and ensuring inter-sectoral cooperation.

2. Assessment of regional competitiveness in the architectonics of the Lublin Triangle

The Lublin Triangle is an intergovernmental platform for economic, political, security and regional cooperation between Poland, Lithuania and Ukraine, launched during a meeting of foreign ministers in Poland, in Lublin on 28.07.2020. The format of the Lublin Triangle reflects the institutionalization of a strategic partnership between Poland, Lithuania and Ukraine, based on a common historical and cultural heritage and focused on deepening regional integration. The focus of the partnership initiative is to coordinate cooperation between European and Euro-Atlantic structures, support reforms, and strengthen Ukraine's European integration in the face of Russia's armed aggression. In this context, the border regions of the three countries are seen as key geospatial platforms for the implementation of common strategic priorities, which involves strengthening their role in transforming the security architecture, strengthening economic resilience, and developing the institutional capacity of the territories (Lublin Triangle, 2025).

2.1. Competitiveness of Polish regions in the context of European integration

European integration has become a catalyst for significant shifts in Poland's regional policy, causing a revision of approaches to territorial management, stimulating economic growth and reducing interregional disparities.

Ślugocki (2019) believes that the key factor in the development of regional policy was Poland's accession to the EU on May 01, 2004. Accordingly, Poland gained access to financial resources and institutional support through the European Cohesion Policy.

Since EU membership has opened up new financial, institutional and political opportunities for Poland, it is of particular importance to analyze spatial differences, factors of regional competitiveness and the effectiveness of implemented policies. Assessment of these parameters makes it possible to identify structural features of socio-economic development of voivodeships, to identify areas of growth and vulnerability, and to justify the need for a differentiated approach to stimulating competitive advantages at the territorial level.

According to Poniatowicz (2000), the regional competitiveness of the economy is influenced by the following factors: the level of economic development of the country; the level of interregional differentiation; legal and economic status of the regions and the related territorial organization of the state; the degree of openness of the regions and their integration with the European space; location of the region; transport accessibility; availability of research institutions; level of investment in research and development; level of higher education; effective system of vocational education and training.

In her study, Chrobocińska conducts a comparative analysis of the level of competitiveness of Polish regions based on the Regional Competitiveness Index (RCI), which allows identifying spatial patterns of development and assessing the effectiveness of the implemented regional policy. The researcher emphasizes that the highest competitiveness indicators are demonstrated by the Mazovian, Silesian, Greater Poland, and Lower Silesian Voivodeships. These regions are characterized by a stable economic structure, established cluster formations, a high level of investment attractiveness, significant scientific and educational potential, and developed infrastructure, which indicates the presence of long-term competitive advantages, in particular investment attractiveness and high productivity. They are "growth engines" because they have the highest concentration of production, innovation, and human capital. On the other hand, the eastern voivodeships (in particular Podlaskie, Lubelskie, and Świętokrzyskie) are characterized by low values of the index, which indicates the need for targeted support from regional policy (Chrobocińska, 2021).

In the context of the implementation of the sustainable development vector, the results of the comparative cluster analysis of the regions of Poland are presented in the form of a dendrogram (*Figure 2*).

The analysis of the dendrogram, built with the STATISTICA software package using the Ward's hierarchical agglomerative clustering method (Murtagh & Legendre, 2014), allows us to distinguish two groups of Polish regions:

Higher level of competitiveness: Mazowieckie, Silesian, Lesser Poland, Lower Silesian, Greater Poland, Pomeranian and Lodz voivodeships. The closest in terms of characteristics were Lower Silesian, Greater Poland and Silesian Voivodeships, as well as Lodz and Pomeranian Voivodeships.

Lower level of competitiveness: West Pomeranian, Warmińsko-Mazurskie, Świętokrzyskie, Podlaskie, Podkarpackie, Opolskie, Lubuskie, Lubelskie and Kujawsko-Pomeranian Voivodeships. Within this group, smaller clusters were observed, in particular: Lubuskie and Opolskie; Lubelskie and Podkarpackie; Podlaskie, Świętokrzyskie and Podlaskie; Kujawsko-Pomeranian and West Pomeranian.

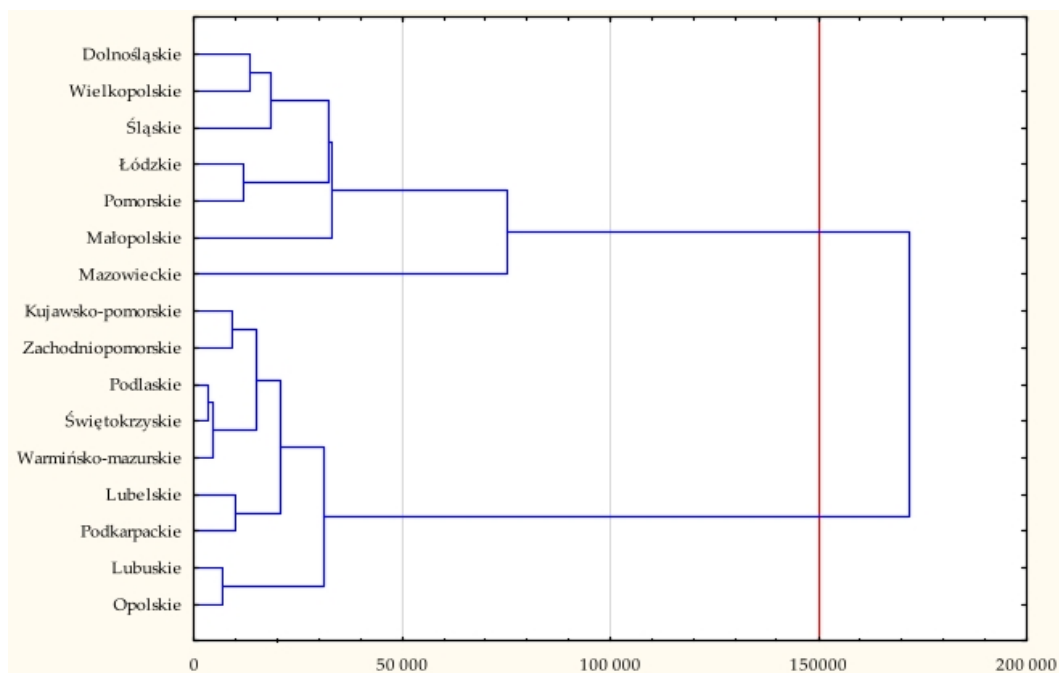


Figure 2. Typology of competitiveness of Polish regions

Source: based on the materials of the research (Chrobocińska, 2021).

The empirical results obtained indicate a clear spatial polarization of regional competitiveness in Poland, which is formed under the influence of institutional, economic, educational, and innovative factors. Within the framework of the European Cohesion Policy, Poland was able to mobilize external resources to strengthen the potential of individual voivodeships, but structural inequalities persist, especially between the western and eastern regions. This necessitates further improvement of the mechanisms of territorial equalization, development of cluster structures, support for human capital, and formation of an institutional environment capable of ensuring long-term competitiveness of the regions in the context of internal and external challenges.

In this context, a new geo-economic factor is worthy of attention: the impact of the war in Ukraine on the regional development of Poland. Russia's invasion of Ukraine and the massive inflow of human capital have led to significant shifts in the demographic and economic structure of individual Polish regions.

Data from an analytical study commissioned by the UN Refugee Agency and conducted by Deloitte show that the competitiveness of certain regions of Poland has increased due to the integration of labor resources from Ukraine, the restructuring of logistics chains, and the growth of entrepreneurial activity. In 2024, the economic contribution of Ukrainian Internally Displaced Persons (IDPs) amounted to 2.7% of Poland's GDP. The high level of labor integration – 69% among people of working age – led to an increase in employment, higher labor productivity, and expanded consumer demand, without causing any negative effects on the labor market for the local population (Deloitte, 2025).

The economic activity of military migrants in Poland has had a multiplier effect: tax revenues, contributions to social and health insurance systems, and overall consumption have increased. Thus, the Polish policy of openness towards the integration of refugees from Ukraine contributed to the growth of regional competitiveness and ensured sustainable economic development of the Polish territories.

2.2. Assessment of regional competitiveness in the context of social and demographic challenges in Lithuania

In the context of modern spatial transformations caused by the demographic crisis, internal migration and external social and economic challenges, in particular the war in Ukraine, the issue of assessing Lithuania's regional competitiveness is an important management problem. The state's regional policy should take into account not only traditional macroeconomic indicators, but also the depth of social and demographic changes that significantly affect the economic dynamics of the territories. In this context, the Regional Competitiveness Index (RCI) acts as an integral tool capable of identifying the strengths and weaknesses of individual regions and providing a comparative assessment based on relevant indicators.

The analytical effectiveness of the regional competitiveness index is substantiated in the works of Snieszka and Brunetskene (Snieška & Bruneckienė, 2009). The empirical application of the index on the example of Lithuanian regions shows its ability to identify key determinants of competitiveness, in particular the demographic structure, level of economic activity, development of institutional and educational infrastructure, degree of clustering and intensity of interaction between science and business. At the same time, there are a number of methodological limitations of the index: its static nature, limited to quantifiable parameters, and insensitivity to qualitative characteristics such as the quality of governance, social capital, and cultural values. In this context, it would be appropriate to supplement the RCI with qualitative indicators for correct interpretation of data in strategic planning of regional development.

In the scientific work of Zhitkus (2015), regional competitiveness is considered as a comprehensive analytical tool for the formation of regional

development policy, which goes beyond the narrow economic paradigm. According to the scientist, an effective policy should be focused not on the formal equalization of interregional disparities, but on the activation of internal drivers of economic growth. These factors include the development of human capital, modernization of the infrastructure base, strengthening of inter-institutional cooperation, and the ability of regions to adapt to structural and technological transformations. The author emphasizes the need to reorient Lithuania's regional policy from the passive distribution of financial resources to the strategic positioning of regions in accordance with their unique competitive advantages. Such an approach allows creating preconditions for the growth of economic efficiency and long-term social sustainability of regional systems.

In the context of Lithuania's regional development, the study of key macroeconomic indicators at the level of territorial units by NUTS 3 allows for a comparative analysis of regional competitiveness. Lithuania, as an EU member state with a relatively recent institutional involvement in pan-European integration processes, demonstrates high rates of macroeconomic growth. At the same time, there is a threatening structural polarization between urbanized centers and demographically vulnerable peripheries (*Table 1*).

Table 1

Competitiveness indicators of Lithuanian regions

Region	GDP		Productivity (GVA PPS per person employed) EU27=100, 2021	Real productivity growth	Population growth
	per head (PPS) EU27=100, 2021	per head growth; Avg % change on previous year, 2011–2020			
Vilnius county	126	4.27	89	0.71	3.60
Alytus county	53	3.80	56	2.54	–17.36
Kaunas county	89	5.02	94	4.06	–5.88
Klaipėda county	81	2.93	83	2.78	–3.70
Marijampolė county	54	4.02	61	2.96	–18.55
Panevėžys county	65	4.73	71	3.71	–19.08
Siauliai county	67	4.76	78	3.89	–13.89
Tauragė county	48	4.93	52	3.43	–20.65
Telšiai county	60	2.86	61	0.32	–16.60
Utena county	52	2.90	62	2.35	–20.73
European Union	100	0.59	100	0.25	–
Lithuania	88	4.49	82	2.48	–8.80

Source: based on the reports of the (European Commission, n. d.).

The analysis of the above data demonstrates a significant socio-economic polarization between the capital region (Vilnius) and other Lithuanian territories. Vilnius County significantly exceeds both the national and EU averages in terms of GDP per capita (126% of the EU average) and labor productivity (89%). Moreover, this region demonstrates positive demographic dynamics: population growth of +3.6% and positive migration of +4.4%. It is the only region with a systematic population growth, which indicates its attractiveness in the socio-economic dimension.

In contrast, peripheral regions such as Tauragė, Utena, and Marijampolė demonstrate extremely low GDP per capita (48% to 54% of the EU average) and low labor productivity (52% to 62%). Despite relatively high GDP growth rates (about 4–5% per year), these regions are experiencing an intense demographic decline: population growth ranges from –18% to –21%, which indicates that economic growth in these regions does not compensate for the structural outflow of human capital. Other large urbanized regions, such as Kaunas and Klaipėda, are doing much better: their productivity levels are above the national average, and their growth rates (4.06% in Kaunas) are the highest among all regions. However, even in these regions, the demographic situation remains negative.

Thus, the regional economic dynamics of Lithuania demonstrates the concentration of growth in urbanized destinations, primarily in Vilnius, while the periphery faces systemic challenges of demographic depletion and insufficient labor productivity. This situation calls for a revision of spatial development policy with a focus on stimulating human capital, increasing regional attractiveness, and supporting decentralized economic growth.

In the context of the policy of stimulating regional competitiveness, it is important to take into account the consequences of migration flows caused by the war in Ukraine. Russia's full-scale invasion of Ukraine has resulted in a significant inflow of labor to EU countries, in particular to Lithuania, where more than half of the Ukrainians of working age who arrived in the country are employed. Despite the rapid integration of some migrants, the overall situation on the labor market was ambiguous: the unemployment rate among unskilled workers in Lithuania increased from 14.9% in Q1 2022 to 15.5% in Q4, which was significantly higher than the EU average (6.5%) (European Commission, n. d.).

These trends point to problems of labor market sustainability and the need for an adaptive policy of public administration in the regions. In particular, an effective regional policy should not only facilitate the integration of internally displaced persons, but also ensure a balance between the demand for skilled labor and the employment structure. Supporting vocational training, stimulating small businesses, and developing local employment infrastructure are key areas for reducing regional inequality and strengthening the competitiveness of territories in the face of socio-economic turbulence.

An assessment of Lithuania's regional competitiveness through the prism of socio-demographic transformations revealed a significant polarization between urbanized centers and peripheries, indicating a systemic imbalance in the development of territories. The high economic performance of the Vilnius region contrasts with the demographic decline of most other administrative units. This necessitates a rethinking of the country's spatial development strategy with a focus on supporting human capital, integrating internal and external migrants into the local socio-economic environment, developing the institutional capacity of the regions, and ensuring social sustainability as a basis for building competitive potential in the long term.

2.3. Transformational policy vectors to stimulate regional competitiveness in the context of war and post-war recovery of Ukraine

Russia's full-scale armed aggression against Ukraine has become a determining factor in the profound transformations of regional socio-economic systems. The war caused not only the loss of infrastructure, production and human potential, but also exacerbated the asymmetries of regional development, making it necessary to rethink strategies for managing the competitiveness of territories. In such circumstances, regional competitiveness policy becomes critical as a tool for adapting to crisis challenges, mobilizing domestic resources, and providing the basis for post-war recovery and economic sustainability.

2.3.1. Geospatial transformation of the competitive positions of regions under martial law in Ukraine

The policy of stimulating regional competitiveness is a key factor in Ukraine's economic recovery. The war, which Russia started in a hybrid format in 2014 with the annexation of the Autonomous Republic of Crimea and transformed into a full-scale invasion on February 24, 2022, caused significant losses of national wealth, large-scale destruction of infrastructure, displacement of logistics hubs, and deepening asymmetries in regional development.

According to the World Bank, Ukraine's real GDP declined by 28.8% in 2022, while in 2023 it grew by 5.3% (World Bank, 2025). According to the State Statistics Service of Ukraine, in 2024, Ukraine's real GDP grew by only 2.9% compared to the previous period. The slowdown in its growth rate was caused by the consequences of the war and attacks on system-forming enterprises and regional infrastructure facilities (State Statistics Service of Ukraine, 2025, March 31).

It is clear that the economic growth of GDP in the year following Russia's full-scale invasion of Ukraine was made possible by the processes of

adaptation of regional socio-economic systems to martial law, which was manifested through the intensification of business activity in the western and central regions, the relocation of production facilities from the war zones, and the support of international partners. These processes demonstrate the ability of the regions to adapt and structurally transform their economic activities in the face of limited access to resources and growing security risks.

The war has devastated the economy of Ukraine and exacerbated regional disparities: frontline regions have lost their industrial and manufacturing potential, while western regions have gained new opportunities for development thanks to business relocation, changes in trade routes and a stronger role in European economic integration. The primary and secondary sectors have suffered the greatest losses, while the social services and trade sectors remained relatively stable even in frontline territories. Recovery requires taking into account regional specifics and forming competitive advantages. The key challenge is to create an investment climate: international assistance remains crucial in the initial stage, while in the long term, it is necessary to attract private and, in particular, foreign capital, develop entrepreneurship, and stimulate exports and investments (Lyvch & Diakiv, 2025).

The asymmetry of social and economic development necessitates the formation of an economic policy to stimulate regional competitiveness aimed at eliminating structural imbalances, restoring the potential of the territories liberated from Russian occupation and strengthening their economic capacity. Some regions are now acting as internal donors of economic stabilization through the formation of new production clusters, intensification of housing construction, development of trade and services, and job creation. The existence of regional imbalances requires a systematic approach to the development of economic policy aimed at restoring the production base, mobilizing internal resources and increasing the competitiveness of the territories.

2.3.2. Sustainable development values in regional competitiveness management

In the scientific discourse, there is an ambiguous interpretation of the concept of sustainable development in the context of its application in the management of regional competitiveness.

Ecological integrity, economic well-being, and social justice are a triad of values, each of which is a necessary but not sufficient condition for sustainable development (Our Common Future, 1987).

In the context of macroeconomic instability, the challenges of war, post-war recovery, resource depletion, climate change, and social disparities, the concept of sustainable development is seen as a methodological basis for strategic management of regional competitiveness. In this context, the values

of sustainable development serve as a methodological basis for the formation of management decisions, ensuring the integration of economic, social, environmental, and institutional dimensions into a holistic system of regional economic policy.

Taking into account the methodological approach (Dmytruk & Humeniuk, 2022), the values of sustainable development acquire the status of objectively verifiable and measurable characteristics that reflect the ability of the regional socio-economic system to respond adaptively to external and internal challenges. If values are integrated into the management decision-making system (if values are real, not abstract declarations), they serve as integral indicators that synthesize the results of strategic and tactical management actions. In this context, values express the level of coherence of economic, social, environmental, and institutional components within the sustainable life cycle of a region's development, transforming into a means of analytical assessment of the effectiveness of economic policies to improve competitiveness.

Therefore, it is appropriate to interpret them as the result of synchronization of strategic and operational management decisions in the context of a sustainable life cycle of generating relevant values. To formalize this approach, we will use the function of the integral value of sustainable development of the region:

$$VR(t) = \alpha_{(1)} R(t) + \alpha_{(2)} S(t) + \alpha_{(3)} E(t) + \alpha_{(4)} I(t) + \alpha_{(5)} D(t), \quad (1)$$

where: $VR(t)$ – the integral function of the value of sustainable development of the region at time t ;

$R(t)$ – the resource potential, which includes balanced use;

$S(t)$ – social integration, which reflects equitable access to opportunities and inclusion of vulnerable groups in the development of the region;

$E(t)$ – environmental quality, which takes into account ecosystem sustainability, resource recovery, and pollution control;

$I(t)$ – institutional capacity, which includes governance effectiveness, adaptability of regional institutions, and strategic coherence;

$D(t)$ – management actions that accumulate the results of policy coordination, goal setting, and response to external challenges;

$\alpha_{(1)}, \alpha_{(2)}, \alpha_{(3)}, \alpha_{(4)}, \alpha_{(5)}$ – weighting coefficients that determine the relative importance of each component in accordance with the priorities of regional development.

The conceptual model under consideration is consistent with the "Matrix of Sustainable Development Values in the Regional Competitiveness Management Coordinate System", where each value is specified through economic, social, environmental, and institutional dimensions (*Figure 2*).

Values	Dimension			
	Economic	Social	Environmental	Institutional
	Transdimensional			
	An environment mindful of future generations' needs	Balancing short- and long-term needs	Accounting for ecosystem parameters	Planning with a horizon of post-war recovery
	Equity			
	Competitive conditions for access to resources and infrastructure	Real opportunities for community development	Distribution of environmental risks without prejudice	Involvement of key stakeholders in business processes
	Rationality			
	Maximizing value rent in the context of sustainable development	Responsible organization of regional clusters	Optimization of the use of the region's productive forces	Monitoring of the situation, intellectualization of regional policy
	Ecologization			
	Support for the environmental vector	Raising environmental awareness	Restoration and conservation of resources	Implementation of environmental management
	Inclusiveness			
	Facilitating economic inclusion of persons with disabilities and veterans	Real community participation in regional governance	Protection of natural resources of the territories	Participatory public management and administration
	Innovation			
	Technological modernization of production	New forms of employment in the region	Development of environmental technologies	Support for regional regional innovations
	Sustainability			
	Decarbonization policy in region	Formation of a culture of frugality	Transition to circular economy	Limitation of eco-risk practices
	Synergy			
	Harmonization of regional priorities	Integration of social effects	Systematic consideration of risks	Coordination of regional policy coordination

Figure 2. Matrix of sustainable development values in the coordinate system of regional competitiveness management

Source: compiled by the authors.

The above conceptual model forms the information and methodological basis for substantiating the policy of stimulating competitiveness, as it allows assessing the values of sustainable development of territories, ensuring a balance of economic, social, environmental, and institutional mechanisms.

2.3.3. Digital transformation as a factor of regional sustainability

Digital transformation shapes the structure of modern regional policy, defining new governance principles, mechanisms of interaction, and competitive advantages of territories. In the context of war and post-war

recovery, digital solutions play not only a technological but also a strategic role as a catalyst for adaptation, institutional stability, and economic activity at the regional level. The importance of studying this problem is outlined in the following vectors:

- in the current economic environment, regions compete not only at the national but also at the cross-border and international levels, which necessitates the development of effective competitiveness management strategies taking into account trends in the international sectoral concentration of business entities and economic specialisation of territories;
- globalization processes and the rapid development of digital technologies are radically changing traditional models of regional governance, putting forward new requirements for flexibility, innovation, and digital integration of regional systems in the face of increasing macroeconomic instability;
- the digital transformation of sectoral markets increases the responsibility of local authorities in ensuring the economic sustainability of regions, the integration of digital technologies into public administration practices, the modernization of local government mechanisms, and the strengthening of the institutional capacity of territorial communities.

In the context of the implementation of the EU's macro-regional strategy (Sytnyk et al., 2020), the key factors in these processes are the development of human capital, the development of modern digital infrastructure, ensuring inclusive digital accessibility, and the integration of digital solutions into the practice of managing regional competitiveness.

Today, sectoral digital transformation determines the institutional sustainability and competitiveness of regions. According to the report "Digital Transformation Index of Ukrainian Regions. Results of 2024", the Sectoral Digital Transformation sub-index reflects the level of integration of digital technologies in the areas of cybersecurity, healthcare, civil protection, and e-democracy. The assessment covers the implementation of information security measures, modernization of alert systems, and the introduction of digital tools for the participation of local communities in regional development decision-making. Due to security restrictions in the context of martial law in Ukraine, no data on cybersecurity and civil protection are detailed, instead the focus is on the development of e-democracy (Index of Digital Transformation of the Regions of Ukraine, 2024).

The results of the analysis of the sectoral digital transformation of Ukraine's regions show significant territorial disparities. The highest values of the Sectoral Digital Transformation sub-index were recorded in Lviv (0.964), Ternopil (0.792), Poltava (0.694), Volyn (0.664), Vinnytsia (0.652), and Dnipro (0.650) regions. At the same time, Zaporizhzhia (0.243), Mykolaiv (0.292), and Ivano-Frankivsk (0.357) regions have lower scores (Index of Digital Transformation of the Regions of Ukraine, 2024).

The overall range of values of the Sectoral Digital Transformation sub-index (from 0.243 to 0.964) indicates the presence of digital asymmetry in the development of territorial communities. In such circumstances, the priority of regional policy should be to stimulate digital modernization and develop effective mechanisms for managing regional competitiveness in the digital environment. In this context, sectoral digital transformation serves as a public management and administration tool that ensures the integration of digital technologies into the strategic planning processes of territorial communities.

The problem of managing regional competitiveness in the context of sectoral digital transformation is particularly acute in Ukraine, where, as a result of large-scale armed aggression, certain territories have been temporarily occupied, critical infrastructure destroyed, production potential lost, and economic activity reduced. Targeted attacks on energy infrastructure facilities (power plants, substations, distribution networks) have complicated the functioning of business entities in sectoral markets, destabilized the transport and logistics infrastructure, and worsened the socioeconomic conditions of the population in certain territorial communities.

Under such conditions, the management of the competitiveness of regional socio-economic systems is determined not only by the ability to create a favorable environment for doing business, attracting investment and rational use of resources, but also by the ability to restore critical infrastructure, reintegrate the affected territories, and guarantee the vector of sustainable development of territories in the period of post-crisis transformations.

Thus, digital transformation in Ukraine is gradually moving from the status of an auxiliary tool to the plane of methodological principles of public management of regional competitiveness. Its level already correlates with economic sustainability, business activity, investment attractiveness, and social inclusion, and in the medium term will be crucial for the country's post-war recovery and European integration.

2.3.4. Stimulating the innovative competitiveness of regions in the perspective of post-war economic recovery

The innovative competitiveness of a region is formed as a result of the active implementation of innovative solutions in the economic activities of enterprises and the development of an institutional environment that ensures sustainable growth of the region's economy. Innovations play a key role in improving the efficiency of business entities, creating new or improving existing products, services and technologies, as well as in the ability to adapt to dynamic changes in the market environment.

Effective management of the region's innovation competitiveness involves a set of economic policy measures aimed at creating favorable conditions for the development of innovation. In particular, financial incentives in the form of subsidies, tax breaks, and grants significantly reduce barriers to the introduction of new technologies. This allows companies to overcome the risks associated with innovation activities faster and increases

the investment attractiveness of relevant projects. An example of such an impact is the growing number of renewable energy projects under the influence of government subsidies, which reduce the financial burden and create an impetus for the region's innovative competitiveness.

A special role in stimulating the innovation activity of enterprises is played by the innovation rent, which is an economic incentive for business and the development of territorial communities. The innovation rent allows enterprises that introduce new technologies and developments to receive excessive profits due to a temporary monopoly on unique innovations.

The innovation rent of industry segments of the regional economy is one of the key indicators characterizing the economic effect of implementing innovative solutions within certain sectors of the region. It is formed in the form of additional cash flow generated by the growth of added value and increased competitiveness. Given that this effect is realized over a certain period of time, for its adequate assessment it is necessary to apply discounting of future income, which allows to determine the present value of the innovation rent:

$$RI = \sum [\Delta EVA_{jt} / (1 + ik)^t], \quad (2)$$

where: RI – the innovation rent of industry segments of the regional economy;

ΔEVA_{jt} – increase in economic value added in the j industry segment of the regional economy in year t due to the innovation component;

ik – discount rate, expressed as a decimal as the weighted average cost of capital directed to the development of innovations;

t – year number of the innovation life cycle.

Thus, the management of the region's innovation competitiveness involves an integrated system of measures that combines financial support, regulatory policy, and the development of innovation infrastructure. Creating conditions for obtaining innovation rents serves as an important motivational factor for business, contributing to the economic dynamics and social well-being of the region.

The analysis of the transformational vectors of Ukraine's regional competitiveness policy in the context of the war and post-war recovery shows significant changes in the priorities, mechanisms, and institutional approaches to regional development. The spatial challenges caused by the war have actualized the need for an adaptive and differentiated management solution that take into account the asymmetry of the social and economic situation of the regions, their resource base, and infrastructure potential.

Conclusions

This research has established an interdisciplinary theoretical and analytical basis for rethinking policies to stimulate regional competitiveness in conditions of spatial asymmetry, structural transformations, and security threats. The results confirmed the hypothesis that effective policies to stimulate regional competitiveness are possible provided that the European development

vector is integrated with the values of security, sustainable development, institutional capacity, digital transformation of public administration, and differentiated consideration of spatial asymmetries between regions.

A comprehensive study of theoretical approaches, indicator assessment, and empirical analysis of Poland, Lithuania, and Ukraine in the coordinate system of the Lublin Triangle has shown that modern economic policy of regional development requires a transition from unified models to adaptive, spatially differentiated strategies based on the principles of sustainable development, digital transformation, and innovation dynamics.

It is substantiated that the determinants of regional competitiveness are not only productivity, investment attractiveness and human capital, but also the ability of territories to adapt to demographic pressure, security risks, infrastructure losses and challenges of digital inequality.

An approach to an integrated assessment of the effectiveness of strategic management of regional development through the prism of sustainable development values is proposed. Such a model allows synthesizing economic, social, environmental and institutional factors within a single analytical framework suitable for monitoring the competitive potential of territories in the dynamics.

The research is limited by incomplete statistics on temporarily occupied territories and differences in the methodologies used to calculate indicators in Ukraine and the EU. The use of expert assessments and analytical reviews broadens the factual basis but complicates quantitative comparisons. However, the multi-component research methodology and the reliability of sources ensure the robustness of the results.

The scientific novelty lies in the interdisciplinary generalization of approaches to measuring the competitiveness of regions, covering social, institutional and digital factors, as well as in the development of functional models that ensure the formalization of strategic decisions.

The practical significance of the results lies in the possibility of their use in the development of regional development policies in conditions of limited resources, increased turbulence and asymmetry of post-war recovery.

Further research should focus on economic and mathematical modelling of the stability of regional systems, taking into account demographic and security factors, as well as on developing scenarios for the adaptation of regions to external shocks during wartime and post-war periods.

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EU ENERGY SECURITY AMID GEOPOLITICAL CHANGE

The European Union has long faced significant energy security challenges due to its high dependence on external fossil fuel imports. The Russian-Ukrainian war exacerbated these vulnerabilities, prompting urgent policy shifts toward energy diversification, renewables, and greater energy sovereignty. This article hypothesises that while national interests have historically hindered the full integration of EU energy policy, the crisis has catalysed transformative policy changes aimed at enhancing energy security and expediting the transition toward sustainable energy sources. To verify this hypothesis, a qualitative content analysis of EU legislative documents, political strategies, and scientific research have been conducted, combined with a comparative analysis of previous and current energy crises. The findings confirm that EU energy policy has undergone a fundamental shift, particularly the reduction of dependence on Russian fossil fuels and the increase in liquefied natural gas (LNG) imports from the United States and Norway. The share of Russian gas imports has decreased from 45% in 2021 to just 15% in 2023, while renewable energy production has reached record

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ЕНЕРГЕТИЧНА БЕЗПЕКА ЄС В УМОВАХ ГЕОПОЛІТИЧНИХ ЗМІН

Європейський Союз протягом тривалого часу стикається зі значними викликами у сфері енергетичної безпеки через високу залежність від імпорту викопного палива. Ця вразливість посилює російсько-українська війна, спонукаючи терміново змінити політику в напрямі диверсифікації енергетики, відновлюваних джерел енергії та більшого енергетичного суверенітету. Висунуто гіпотезу, що, хоча національні інтереси історично перешкоджали повній інтеграції енергетичної політики ЄС, криза стала каталізатором трансформаційних політичних змін, спрямованих на посилення енергетичної безпеки та прискорення переходу до стійких джерел енергії. Для перевірки цієї гіпотези проведено якісний контент-аналіз законодавчих актів ЄС, політичних стратегій та наукових досліджень, а також порівняльний аналіз попередніх і сучасних енергетичних криз. Результати підтверджують фундаментальні зміни в енергетичній політиці ЄС, зокрема зниження залежності від російського викопного палива, збільшення імпорту скрапленого природного газу (СПГ) зі США та Норвегії. Частка російського газу в імпорті ЄС скоротилася із 45% у 2021 р. до лише 15% у 2023 р., тоді як виробництво відновлюваної енергії



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levels – in 2023, wind energy surpassed the volume of electricity generation on natural gas for the first time. The growing role of renewable energy sources, supply diversification, and the challenges related to national policy fragmentation has been emphasized. Despite significant progress, further efforts are needed to align energy sovereignty with sustainable development goals and long-term economic stability. Promising directions for further research include the development of hydrogen energy, energy storage technologies, and regulatory mechanisms to strengthen the energy resilience of the EU.

Keywords: EU energy security, dependence on fossil fuel, transition to renewable sources, energy supply diversification, policy integration, geopolitical challenges.

JEL Classification Q48, Q42, Q41, H56, F52.

Introduction

Ensuring energy security has long been a strategic priority for the European Union (EU), given its high dependency on external fossil fuel supplies and the geopolitical risks associated with energy trade. The Russian-Ukrainian war has further underscored the fragility of the EU's energy system, accelerating the need for diversification, policy coordination, and a shift towards sustainable energy sources. The crisis has not only exposed the vulnerabilities of existing energy infrastructures but has also tested the resilience of EU energy governance, revealing the persistent challenge of balancing national interests with collective security objectives.

Recent scholarly works have explored various dimensions of this issue. LaBelle (2024) and Mišík and Nosko (2023) highlight the shift from energy interdependence to energy sovereignty and solidarity, arguing that the EU's response to the crisis has led to a reassessment of traditional energy security paradigms. Prisecaru (2022) examines the challenges of supply diversification, particularly regarding the feasibility of reducing dependence on Russian gas through alternative sources such as liquefied natural gas (LNG). Meanwhile, Banas and Melnyk (2024) and Streimikiene et al. (2023) analyse the acceleration of the green transition as an essential component of long-term energy security. Additionally, Nicoli et al. (2023) provide insights into public perceptions of energy cooperation, demonstrating that while public support for an integrated energy strategy is strong, political constraints remain a significant barrier.

Given the breadth and significance of existing research, an extensive systematic overview of the literature is presented in a dedicated section of this article, where the key scholarly contributions are analysed and synthesised in detail.

досягло рекордних рівнів – у 2023 р. вітрова енергетика вперше перевищила обсяги виробництва електроенергії на природному газі. Акцентовано увагу на зростаючій ролі відновлюваних джерел енергії, диверсифікації постачання та труднощах, пов'язаних із фрагментацією національних політик. Попри значний прогрес, необхідні подальші зусилля для узгодження енергетичного суверенітету з цілями сталого розвитку та довгострокової економічної стабільності. Перспективними напрямками подальших досліджень є розвиток водневої енергетики, технологій зберігання енергії та регуляторних механізмів для зміцнення енергетичної стійкості ЄС.

Ключові слова: енергетична безпека ЄС, залежність від викопного палива, перехід на відновлювані джерела, диверсифікація енергопостачання, інтеграція політики, геополітичні виклики.

This article identifies the main stages in the evolution of the EU energy security policy and outlines the key legislative and strategic instruments that have determined its current framework.

The research hypothesises that, while national interests have historically hindered the full integration of EU energy policy, the ongoing crisis has catalysed significant policy changes aimed at enhancing energy security and promoting a transition toward renewable sources. This dual hypothesis will be tested through qualitative content analysis of EU legislative documents, policy papers, scholarly articles, and expert assessments, complemented by a comparative analysis of past and present energy crises.

Methodologically, the study applies qualitative content analysis to EU legislative documents, strategic communications, and academic literature in order to identify key policy shifts and trends. This is complemented by a comparative analysis of EU responses to past and present energy crises to assess policy continuity and change.

The article is organised into three main sections. It begins by exploring the historical context and evolution of EU energy security policies, establishing a foundation for understanding how earlier developments have influenced current strategies. The second section presents a systematic review of scholarly contributions on the topic, highlighting significant themes and insights related to recent challenges and responses. Finally, the article examines the legislative frameworks and key initiatives that have emerged, assessing their effectiveness and the implications for EU energy security amidst ongoing geopolitical shifts.

By addressing these aspects, this study provides a comprehensive understanding of the EU's energy security framework and evaluates its effectiveness in achieving long-term resilience and stability goals. The findings will contribute to the broader discourse on European energy governance and inform future policy directions.

1. EU energy security: historical background and policy shifts

The importance of the European energy security strategy was first recognised during the oil crisis of the 1970s. In November 1974, the International Energy Agency (IEA) was established to ensure global oil supply security (IEA, 2022). The EU's efforts to develop a common energy policy began in the early 2000s, with the European Commission's Green Paper highlighting the increasing external energy dependence of the EU (European Commission, 2000, November 29).

Following this initiative, public debates on EU energy security were reflected in the Final Report on the Green Paper (European Commission, 2002, June 26), which highlighted demand management and energy efficiency as strategic priorities. This shift in focus underscored the need for a coordinated European approach to energy policy, particularly as individual member states faced growing external vulnerabilities.

The necessity for a unified external energy policy became increasingly evident after the 2006 Russia-Ukraine gas dispute, which exposed the EU's dependence on Russian energy supplies and the political risks associated with it (European Parliament Committee on Foreign Affairs, 2007). In response, the European Commission's 2007 energy strategy identified three core principles for European energy security policy: sustainability, security of supply, and competitiveness (European Commission, 2007, November 20). However, as Closson (2008) noted, despite these advancements, many EU member states remained reluctant to cede sovereignty over energy policy to Brussels, posing a significant challenge to deeper integration.

The 2009 Russia-Ukraine gas crisis further reinforced the urgency of revising the EU's energy security framework. In response, the EU adopted the Regulation on Security of Gas Supply (2010), which introduced mandatory risk assessments, emergency preparedness plans, and reverse flow capabilities to mitigate supply disruptions (European Parliament & Council of the European Union, 2010). Additionally, the Treaty of Lisbon (2007) formally enshrined energy policy as a shared competence within EU primary law, with Article 194 of the Treaty on the Functioning of the European Union (TFEU) outlining key objectives such as energy market integration, supply security, efficiency, and renewable energy development (Treaty of Lisbon, 2007; Huhta, 2021).

By 2014, the EU took further steps to reduce its dependence on Russian energy imports. The European Energy Security Strategy prioritised supply diversification and energy infrastructure development, aiming to strengthen energy resilience across the bloc (European Commission, 2014). These efforts were reinforced by the Energy Union Strategy, which expanded focus beyond energy security to include market integration, decarbonisation, and innovation (European Commission, 2015). Recognising the strategic importance of natural gas and oil, the EU introduced the Gas Supply Regulation, which enhanced regional cooperation and crisis response mechanisms (European Parliament & Council of the European Union, 2017).

Additionally, the EU established the Trans-European Networks for Energy (TEN-E) policy, which defined nine priority corridors and three thematic areas to improve cross-border energy integration and efficiency (Ciucci, 2021). Meanwhile, energy efficiency was increasingly viewed as a key energy security measure, with studies emphasising its role in reducing the EU's dependence on external suppliers (Ghantous, 2022, March 8).

Russia's invasion of Ukraine in February 2022 prompted urgent and specific actions from the European Union (EU) to reduce its dependency on Russian energy sources. Some academicians and economists have referred to the economic situation resulting from the Ukrainian-Russian conflict as either an asymmetric shock (Redeker, 2022) or stagflation (Canuto, 2022).

The European Commission, in its Communication, aims to make Europe independent from Russian fossil fuels well before 2030 (European

Commission, 2022). This plan outlines measures to mitigate retail prices, support companies, and ensure sufficient gas storage as preparations for the coming winter. The RePowerEU initiative seeks to diversify gas supplies, accelerate the rollout of renewable gases, and replace gas usage in heating and power generation through ten key actions, including increasing biogas production, enhancing energy efficiency, and boosting solar energy capacity (European Commission, 2022, March 8).

In March 2022, the International Energy Agency published a plan to reduce the EU's imports of russian natural gas by more than one-third within a year, aligning with the objectives of the European Green Deal to support both energy security and affordability (IEA, 2022, March 3). On March 14, 2022, High Representative/Vice President Josep Borrell stated in his blog that "EU leaders agreed... to bolster European economic resilience, radically reduce our energy imports from russia and move ahead with a serious strengthening of European defence" (Borrell, 2022, March 14).

Furthermore, on March 25, 2022, the President of the European Commission emphasised the support of the United States in "strengthening Europe's energy security and independence from russian fossil fuels". This initiative aims to eliminate dependency on russian energy supplies through investments in renewables and additional gas supplies from trustworthy and reliable suppliers. The United States also committed to providing the EU with an additional 15 billion cubic meters of liquefied natural gas (LNG) in 2022 (European Commission, 2022, March 25).

2. Systematic review of scholarly contributions on the topic

The evolving landscape of EU energy security has been widely examined in recent scholarship, with researchers analysing the geopolitical, economic, and policy dimensions of the crisis. This section provides a structured review of key contributions, highlighting major themes such as the end of energy interdependence, diversification efforts, the acceleration of the green transition, and policy effectiveness in securing long-term energy resilience.

2.1. End of energy interdependence and the rise of sovereignty and solidarity

Before the war, EU-russia energy relations were built on interdependence, where natural gas and oil flows were integral to both economic and geopolitical stability (Tichý & Dubský, 2024). However, as Yakoviyk and Tsvelikh (2023) emphasise, russia weaponised its energy exports by demanding payments in roubles, reducing Nord Stream gas supplies, and leveraging its energy dominance for political influence. The resulting energy crisis forced the EU to rethink its strategic approach, prompting a shift from interdependence to energy sovereignty and solidarity (LaBelle, 2024).

While solidarity mechanisms such as joint gas purchases and collective energy security measures have been proposed, Mišík and Nosko (2023)

highlight the paradox of EU energy security: although greater integration would enhance resilience, individual member states resist collective decision-making, prioritising short-term national energy security interests. This reluctance was evident in negotiations over gas-sharing agreements, where some states hesitated to reduce consumption to support more affected regions. Nonetheless, as Nicoli et al. (2023) demonstrate through an extensive cross-national survey, public support for a unified Energy Union is high, particularly in Western European countries, indicating political feasibility for deeper cooperation in the future.

In this context, Zubko (2023) provides an important perspective on how international cooperation, particularly with the EU, has shaped the resilience of Ukraine's energy sector. The analysis emphasises that EU assistance and the integration of Ukraine's energy system into the ENTSO-T network played a pivotal role in stabilising energy governance during the war. This reinforces the broader argument that energy solidarity and interconnectivity are vital not only within the EU but also with neighbouring partners seeking alignment with EU energy frameworks.

2.2. Energy diversification: LNG, alternative suppliers, and hydrogen solutions

The war also intensified efforts to diversify energy sources, reducing reliance on Russian fossil fuels. Prisecaru (2022) outlines the challenges of energy diversification, noting that while the EU imposed sanctions on Russian energy, finding alternative suppliers for LNG, coal, and oil remains difficult due to global supply constraints.

Beyond LNG, the Middle East has emerged as a potential alternative energy partner. Al-Saidi (2023) questions whether the region will become a "white knight" in EU energy security or merely another supplier within a broader diversification strategy. Meanwhile, Liu et al. (2023) propose hydrogen infrastructure as a long-term replacement for fossil fuels, arguing that by 2060, hydrogen-based energy systems could fully substitute Russian imports, except for oil. These solutions, however, require massive infrastructure investments and regulatory adjustments.

2.3. Acceleration of the green transition and energy security measures

While immediate energy security concerns dominated EU policy-making in 2022, the crisis also accelerated the green transition. Banas and Melnyk (2024) analyse how the REPowerEU plan has redefined the EU's energy landscape, emphasising renewable energy integration, infrastructure modernisation, and regulatory frameworks to reduce fossil fuel dependence. Similarly, Streimikiene et al. (2023) propose a comparative framework to measure energy security across EU regions, identifying that while some states (e.g., Scandinavia) already demonstrate high energy security, Eastern

and Southern European nations remain vulnerable due to lower diversification levels.

Osička and Černoch (2022) highlight the paradigm shift in European energy policy, where natural gas—previously considered reliable—is now seen as expensive and politically volatile, further reinforcing the urgency of transitioning towards renewables. However, as they caution, a poorly coordinated transition could trigger economic instability, particularly in industrial sectors reliant on traditional energy sources.

Mazaraki and Melnyk (2024) offer a complementary view, examining the broader implications of the fourth global energy transition for national and regional security frameworks. They argue that managing energy security under the pressures of war, climate change, and economic crises demands a conceptual recalibration of policy. Their work emphasises the role of systematisation and scenario planning in neutralising new threats during the green transition, thereby supporting the case for more adaptive and multi-layered policy mechanisms in the EU and its neighbourhood.

2.4. Assessing EU Energy Security: Policy Effectiveness, Governance Challenges, and Future Integration

To assess the effectiveness of EU policy responses, multiple studies have examined quantitative indicators of energy security. Brodny and Tutak (2023) employ a multi-criteria decision-making (MCDM) model to rank the energy security levels of EU-27 countries, revealing significant regional disparities. Their analysis confirms that Scandinavian countries exhibit the highest levels of resilience, while Eastern European nations face greater risks due to infrastructural and economic limitations.

Similarly, Sadowska (2022) assesses the EU's policy adjustments following the Russian invasion, evaluating measures taken to secure gas supplies and suggesting additional steps for enhancing energy resilience. Her findings align with Prisecaru's (2022) argument that while sanctions effectively reduced Russian imports, the EU still struggles to fully replace these energy flows without price volatility and supply disruptions.

Finally, the war has reshaped discussions on EU energy governance. Nicoli et al. (2023) provide empirical evidence that European citizens support stronger institutional mechanisms for energy security, favouring policies that include joint procurement, centralised governance, and enhanced regulatory coordination. However, as Mišík (2022) and Mišík and Nosko (2023) argue, achieving consensus among member states remains a major obstacle, given the persistent fragmentation of national energy policies.

Moreover, Yakoviyk and Tsvelikh (2023) stress that energy security is now deeply intertwined with geopolitical stability, as rising transportation costs and inflation have broader implications for EU economic and political dynamics. In this regard, Atamanenko and Piddubnyi (2023) argue that while the EU has successfully reduced hydrocarbon imports from Russia, this

diversification process has introduced new risks, including price instability and supply chain vulnerabilities.

To summarise, the Russian-Ukrainian war has reshaped the EU's energy security, driving a shift towards resilience, diversification, and sovereignty. Studies highlight that the future of EU energy security will depend on balancing diversification, sustainability, and economic stability, with further research needed on the role of hydrogen, nuclear, and advanced renewables in ensuring long-term resilience.

3. EU energy dependency: trends, challenges, and policy shifts

The European Union (EU) has long been dependent on energy imports, with its energy import dependency rate steadily increasing over the past few decades. As early as 1990, the EU imported approximately 50% of its total energy needs, a figure that continued to rise due to declining domestic production and growing demand (Eurostat, n. d. a). By 2022, energy dependency reached 62.5%, underscoring the EU's structural reliance on external energy sources, particularly crude oil (97.7%) and natural gas (97.6%) (Eurostat, n. d. b).

Natural gas imports more than doubled between 1990 and 2022, with Russia historically serving as the EU's primary supplier. The trend was further exacerbated by the progressive decline in domestic fossil fuel production, especially natural gas (−64.9%) and coal (−38.7%) over the past decade (Eurostat, n. d. b). Although the EU had begun investing in renewables, fossil fuels remained dominant in its energy mix well into the early 2020s, leaving the bloc vulnerable to geopolitical disruptions and supply shocks.

3.1. Impact of the Russian invasion and the decline of fossil fuel imports

The Russian invasion of Ukraine in 2022 served as a turning point in the EU's energy strategy, prompting an urgent reassessment of energy security. In response, the EU implemented gas-saving measures, diversified its energy imports, and significantly ramped up renewable energy production. As a result, gross available energy in the EU decreased by 4.5% in 2022, while natural gas consumption dropped by 13.3% compared to 2021 (Eurostat, n. d. a).

Natural gas, once the backbone of the EU's energy system, saw a 14.6% decline in net imports in 2023, marking the continuation of a downward trend. Inland gas consumption also fell by 7.4% from 2022 and 19.4% from 2021, reflecting a strategic shift away from Russian supplies. Russia's share of EU gas imports plummeted from 45% in 2021 to just 15% in 2023, as the EU increasingly turned to Norway, the United States, and Qatar for liquefied natural gas (LNG) (Eurostat, n. d. b).

Coal and oil imports also followed a downward trajectory. After a temporary rise in 2021 and 2022 due to post-pandemic energy demand, coal

consumption fell to record lows in 2023, with lignite use declining by 24.2% and hard coal by 25.8%. Similarly, oil dependency declined, with refinery demand for crude oil dropping by 1.7% in 2023, reinforcing the EU's long-term strategy to reduce fossil fuel reliance (Eurostat, n. d. a).

3.2. Role of renewables in reducing energy dependency

A key driver of the EU's decreasing reliance on fossil fuel imports is the rapid expansion of renewable energy. In 2023, for the first time, electricity generated from wind exceeded that from natural gas, marking a major milestone in the energy transition. Renewables accounted for 44.7% of total electricity production, surpassing fossil fuels (32.5%) (Eurostat, n. d. b). This transition aligns with the REPowerEU plan, which prioritizes energy diversification, efficiency, and clean energy technologies such as hydrogen and solar power.

Despite these achievements, the EU remains highly dependent on energy imports, particularly natural gas, with 88% of its gas supply in 2023 still coming from external sources. The long-term success of the EU's energy strategy will hinge on further investments in renewable energy infrastructure, energy storage capacity, and alternative fuel development (Eurostat, n. d. a).

3.3. EU energy policy shifts amid geopolitical crisis

According to Birol and von der Leyen (2024), Europe has significantly reduced its dependence on Russian energy, with the share of Russian fossil fuels in the EU's total energy supply dropping from 45% before the war to just 5% in 2023. The rapid expansion of alternative suppliers, such as Norway, the United States, and Qatar, has been a key driver of this shift. At the same time, the EU's transition towards renewable energy reached a major milestone in 2023 when, for the first time, electricity generated from wind exceeded that from natural gas.

Before Russia's invasion of Ukraine, 20% of the EU's energy came from Russian fossil fuels, whereas today, that figure has dropped to just 5%. Additionally, Russian gas imports have plummeted from 45% before the war to 15% in 2023. The shift has been supported by an increase in LNG imports from the United States and Qatar, with global LNG supply expected to rise by 50% in the second half of the decade. While this may lead to lower gas prices, the EU remains committed to its decarbonisation goals, aiming for near-zero methane emissions and further scaling up renewable energy, clean hydrogen, and energy efficiency (Birol & von der Leyen, 2024).

Despite its progress, Europe faces new challenges, including balancing energy security with affordability and sustainability. While LNG has become the EU's baseload gas supply, policymakers stress that cheaper gas should not slow the transition to a net-zero economy. Future efforts will focus on clean energy technologies and industry cooperation, as demonstrated by the Clean Transition Dialogues initiated by the European Commission. The EU's ability to navigate energy crises and restructure its market demonstrates a long-term commitment to energy sovereignty, sustainability, and economic resilience (Birol & von der Leyen, 2024).

Conclusions

The Russian invasion of Ukraine in 2022 marked a profound and transformative moment in the energy landscape of the European Union (EU), catalysing a shift away from dependency on Russian fossil fuels and fostering a renewed emphasis on energy sovereignty, diversification, and sustainability. Scholarly analyses underscore the multifaceted nature of this transformation, encompassing the dismantling of traditional energy interdependence with Russia, the emergence of alternative energy suppliers, the expedited transition towards greener energy sources, and the complexities of policy coordination among member states.

The findings affirm the dual hypothesis that the ongoing crisis has catalyzed significant policy changes aimed at enhancing energy security while simultaneously exposing the hindrances posed by national interests to the full integration of EU energy policy. Key results reveal a drastic reduction in natural gas imports from Russia, accompanied by a notable increase in LNG imports from alternative suppliers. Investment in renewable energy sources and hydrogen technology has accelerated, with historic milestones achieved, such as wind energy production surpassing that of natural gas for the first time. These results underscore the success of the EU's efforts to transition toward a more resilient energy framework.

This study thoroughly examines the evolution of EU energy security policy against the backdrop of geopolitical shifts stemming from the Russian-Ukrainian war. While it confirms that national interests continue to present challenges in achieving a unified energy security framework, it also highlights a strong public support for deeper cooperation and integration within the EU. Despite this support, member states frequently prioritize their short-term energy security needs over collective goals, underscoring the need for further efforts to navigate the complexities of national interests in pursuit of a cohesive energy strategy.

The research contributes to the existing literature by providing a comprehensive analysis of the systemic shifts in energy policy following the crisis. Notably, it identifies a significant move away from energy interdependence towards energy sovereignty and solidarity among EU member states. This transition highlights the necessity for a coordinated approach to energy security that balances national priorities with collective resilience. Additionally, the findings point to the enhanced emphasis on diversifying energy sources and the accelerated push for renewable energy, which are crucial for long-term sustainability.

Further, the study reveals additional, unplanned outcomes such as the relative decline of Russian fossil fuel imports, which decreased dramatically from 45% to 15% within a span of two years. This surprising trend underscores the EU's ability to adapt amidst crises, with a notable shift towards energy sources from the United States, Norway, and other reliable partners. The role of public sentiment, as evidenced by various surveys, indicates a growing consensus on the need for a unified Energy Union, despite the political fragmentation that currently inhibits this process.

Looking ahead, the research highlights several practical implications for policymakers. Investing in renewable energy infrastructure and developing new regulatory frameworks will be critical for ensuring energy security while transitioning towards a low-carbon economy. Future research should focus on exploring the potential of hydrogen and advanced renewable technologies in strengthening energy resilience, alongside further investigations into the economic impacts of energy policy shifts on EU member states.

In conclusion, this study not only sheds light on the present dynamics of EU energy security but also emphasises the need for ongoing evaluation and adjustments in policy frameworks to adapt to an evolving geopolitical landscape. The pursuit of energy sovereignty must be harmonised with sustainability efforts to achieve long-term energy security and stability within the EU.

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BIORESOURCES IN THE TRANSFORMATION OF UKRAINE'S ENERGY SYSTEM

The growing volatility of global energy prices increases energy insecurity in importing countries, necessitating the development of adaptive strategies that consider local resource potential. In Ukraine, which is facing the consequences of war and partial destruction of its energy infrastructure, the development of bioenergy has become particularly relevant as an alternative path to strengthening energy security. The hypothesis of the research assumes that rising global prices for conventional energy carriers enhance the economic feasibility of local bioenergy projects, provided there is a sufficient resource base, regional support mechanisms, and effective tariff regulation.

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БИОРЕСУРСЫ У ТРАНСФОРМАЦИИ ЭНЕРГЕТИЧЕСКОЙ СИСТЕМЫ УКРАИНЫ

Зростання волатильності світових цін на енергоносії зумовлює нові виклики для енергетичної безпеки країн, що залежать від імпорту. В Україні, яка перебуває під впливом зовнішніх загроз та внутрішніх інфраструктурних втрат внаслідок повномасштабного вторгнення росії, особливої актуальності набувають локальні енергетичні рішення. Розглянуто потенціал біоенергетики як ефективний інструмент диверсифікації джерел енергії, підвищення енергетичної стійкості регіонів та зменшення залежності від традиційних енергоносіїв. Гіпотезою дослідження є припущення, що глобальні цінові коливання стимулюють зростання економічної доцільності реалізації



The research methodology is based on a combination of comparative analysis, expert assessments, a cost-element approach to energy pricing, and indicative ranking of biofuel alternatives using techno-economic criteria: cost, calorific value, profitability, and payback period. Using the Polissia region as a case study, the paper evaluates the potential of wood-based, agricultural, and peat biomass. The findings reveal that baled straw and wood chips are the most balanced heat sources in terms of cost-effectiveness, availability, and supply stability. A technical and economic comparison of various energy sources is provided, and key barriers to scaling bioenergy solutions are identified. Particular attention is paid to limitations in the current tariff policy and investment incentives. The research results are relevant for shaping regional energy transition strategies, supporting investment initiatives in the renewable energy sector, and advancing national decarbonization goals. Bioenergy is therefore positioned as a critical component of Ukraine's pathway toward energy autonomy and sustainable economic development in the context of global energy price fluctuations.

Keywords: bioenergy, price volatility, biomass, thermal energy, investment feasibility, energy policy.

JEL Classification: E30, F29, Q42.

місцевих біоенергетичних проєктів за умов наявності стабільної ресурсної бази та помірного рівня інвестицій. Методологія дослідження базується на поєднанні порівняльного аналізу, експертного оцінювання, індикативного ранжування альтернативних джерел тепла за критеріями собівартості, теплотворної здатності, інвестиційних витрат, терміну окупності та рентабельності. У ході дослідження проаналізовано ситуацію Поліського регіону, зокрема Житомирської області, яка має сприятливі умови для використання біомаси деревного, аграрного та торф'яного походження. На основі узагальнення результатів дослідження встановлено, що туюкована солома та деревна тріска є найбільш збалансованими джерелами з погляду ефективності, доступності й тарифної конкурентоспроможності. Водночас виявлено інституційні бар'єри, зокрема недосконалість тарифного регулювання, які стримують впровадження відповідних проєктів. Результати дослідження можуть бути використані при формуванні регіональних стратегій енергетичної трансформації, залученні інвестицій у відновлювану енергетику та підтримці цілей декарбонізації економіки України.

Ключові слова: біоенергетика, коливання цін, біомаса, теплова енергія, інвестиційна доцільність, енергетична політика.

Introduction

Global energy markets are experiencing periods of increasing instability, accompanied by high price volatility, which affects international energy trade and the energy security of states, creating new challenges for countries with a high level of import dependence. In conditions of external instability, especially during Russia's military aggression against Ukraine and the partial destruction of its energy infrastructure, there is an objective need to adopt adaptive local solutions aimed at strengthening energy self-sufficiency. One such solution is a reorientation to renewable energy sources, in particular to biomass, which can become a real tool for increasing the energy sustainability of regions.

The relevance of the research is due to the need for a systematic analysis of the relationship between global fluctuations in energy prices and the adoption of economically sound decisions in the field of bioenergy. Despite numerous initiatives to develop renewable energy, most of the existing solutions in Ukraine remain reactive, do not rely on a deep economic assessment of the efficiency of biomass use and do not take into account the broader global context. While in the European Union countries bioenergy is actively integrated into energy policy, thanks to predictable targets and stable incentives, in Ukraine fragmented regional projects dominate, requiring strategic rethinking in the face of global price pressure.

The scientific basis for analyzing the potential of bioenergy and its role in the energy transition is the subject of active research in a number of scientific works; in particular Scarlat et al. (2015) consider bioenergy as a central component of the EU energy transformation through an interdisciplinary approach. In the domestic discourse, important developments are the studies of Geletukha et al. (2023), as well as Oliynyk (2024), who carried out a thorough analysis of the potential of biomass, barriers to its use, and the economics of biofuels. At the same time, the issue of adapting local energy strategies under the influence of global price fluctuations, taking into accounts the technical and economic characteristics and investment attractiveness of alternative energy sources, remains insufficiently covered.

The aim of the research is to substantiate bioenergy solutions in the context of global fluctuations in world energy prices. The research focuses on analyzing the impact of international price volatility on local technical and economic decisions regarding the use of biomass as a source of thermal energy. Special emphasis is placed on substantiating the conditions and prospects for implementing bioenergy projects in regions of Ukraine with an existing raw material base, in particular on the example of Polissia.

The hypothesis of the research is the assumption that fluctuations in world prices for traditional energy carriers create the prerequisites for increasing the attractiveness of bioenergy solutions at the local level, especially in the presence of a stable resource base and moderate investment costs for equipment installation.

The methodological basis of the research is analytical and comparative methods, the expert assessment method, an elemental approach to calculating the cost of energy, as well as an indicative ranking of solutions according to the criteria of cost, efficiency, payback period and profitability. The information base was made up of statistical data from the State Statistics Service of Ukraine, official tariffs of the National Commission for the Regulation of Energy and Utilities of Ukraine, analytical reports of the Bioenergy Association of Ukraine, scientific publications from the international Scopus database and technical and economic parameters of implemented projects in the Zhytomyr region. The limitations of the research are due to the instability of the energy market, the lack of systematic accounting of agricultural waste at the local level, and the complexity of predicting changes in the regulatory and tariff environment.

The article consists of three main sections. The first section examines the dynamics of global wood and natural gas markets and their impact on local solutions. The second section analyzes the resource potential of biomass in Ukraine using the example of the Polissia region, taking into account technical capabilities, raw material base and operating enterprises. In the third section, a technical and economic comparison of thermal energy sources (wood chips, straw, pellets, natural gas, and electricity) is carried out with an assessment of investment feasibility, tariff efficiency and payback periods.

At the final stage, the results are summarized and recommendations are proposed for the formation of local policies to support bioenergy projects in the context of global energy pressure.

1. Global price fluctuations in the energy market

The global energy market over the past decade has been characterized by increased volatility, due to the influence of a wide range of geopolitical, economic, climatic and technological factors. The process of forming the price environment is influenced by the complex interaction of supply and demand, existing infrastructure constraints, as well as the regulatory policy of leading market participants. Additional determinants of price fluctuations have been the global crises of recent years, in particular the COVID-19 pandemic, the energy shock caused by the full-scale military aggression of the Russian Federation against Ukraine, as well as the sanctions policy of the EU and the USA, which significantly affected the transformation of the current pricing mechanisms. In these conditions, the analysis of the dynamics of world prices for key energy carriers, namely: natural gas, coal and oil, acquires particular importance. Identification of key price trends makes it possible to identify critical factors influencing local energy strategies, taking into account decisions on the development of renewable energy, including the use of biomass as an alternative source of thermal energy.

1.1. Dynamics of world prices in the natural gas market

In view of the holistic diagnosis of the price situation on the global energy market, it is important to analyze the situation and quotation trends on the natural gas market, which remains a key element of the global thermal energy architecture. In order to ensure the purposefulness, comprehensiveness and systematicity of the assessment, information and analytical data from leading exchange platforms that perform the function of global indicators of the price for natural gas were used. The main representatives of the exchange infrastructure that form guidelines for price positioning for gas include:

- gas hub Title Transfer Facility (hereinafter referred to as TTF);
- London Stock Exchange ICE (Intercontinental Exchange);
- New York Mercantile Exchange NYMEX (New York Mercantile Exchange).

Each of the above market infrastructure entities trades in its own currency and specific units of measurement of natural gas (Ministry of Finance, p. 11).

One of the largest gas hubs, the TTF, located in the Netherlands, is a key European trading center where prices are set in a freely convertible currency and are considered an indicator of the formation of free market prices for gas in Europe, measured in euros per megawatt hour (MWh). The

correspondence between energy and volume indicators is: 1 MWh = 95.31 m³ of natural gas, or 1000 m³ = 10.49 MWh. The London ICE exchange as a regulatory quotation platform, where the exchange price level is set in the national currency of Great Britain (GB p/thm), is 1/100 of a pound sterling per Therm, which approximately corresponds to 2.7933 m³ of natural gas, or 1000 m³ $\approx$ 358 Therms. The NYMEX futures market is an indicator of gas prices in the Western Hemisphere, where natural gas is traded in US dollars per Henry Hub, a benchmark gas grade in MMBtu = 1 million Btu = 1.000.000 Btu = 27.933 m³. A Btu is a British thermal unit (BTU), which is 252 cal, or 1.055 J. A BTU is the amount of heat required to raise the temperature of 1 pound of water (a mass of water equal to 0.45359 kg) by 1° Fahrenheit (Department of Finance, 2025).

The price situation in the natural gas market demonstrates similar trends among the three main exchange platforms that form global quotes (Figure 1).

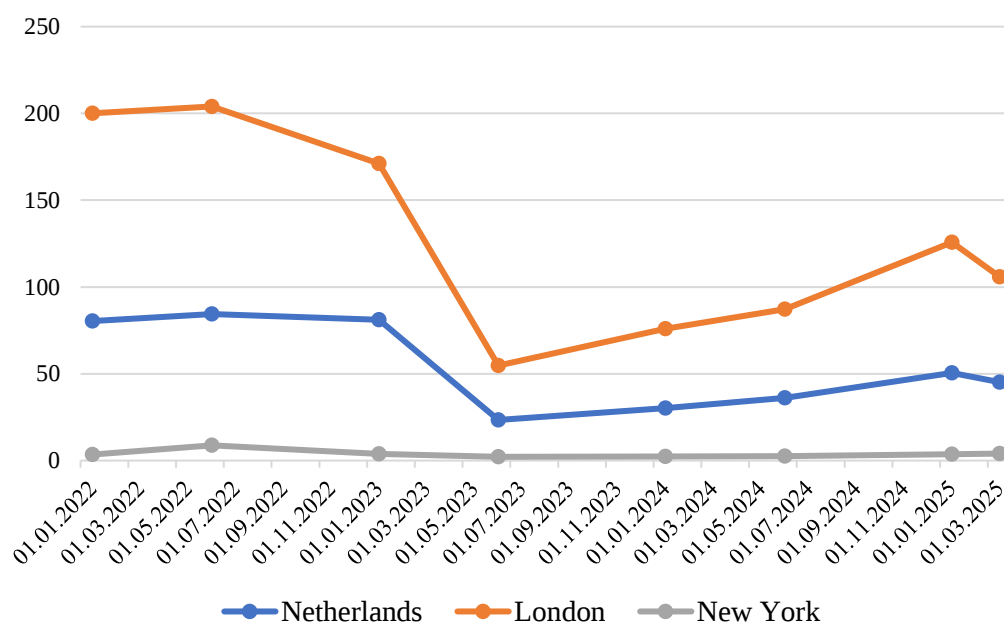


Figure 1. Dynamics of world prices for natural gas, USD per ton

Note: units of measurement: Netherlands (Gas Hub) – EUR/MWh; London Stock Exchange – pence/Therm; New York Mercantile Exchange – USD/million BTU.

Source: compiled by the authors based on (Ministry of Finance, n. d.).

The highest price level was recorded in March–May 2022. Subsequently, a gradual decline was observed, reaching a minimum level in July 2023. From the second half of 2023, prices began to increase again, reaching a new maximum in early 2025. Price volatility emphasizes the need to diversify energy sources and intensify the transition to more sustainable and renewable energy solutions, in particular based on the use of biomass as a strategic direction of energy security.

1.2. Dynamics of global prices on the coal market

Coal, as a traditional energy source, plays a significant role in the global energy balance, especially in the context of providing electricity and heat in economic activity. Despite the gradual transition to low-carbon technologies and international obligations to reduce greenhouse gas emissions, demand for coal remains, in particular in countries with energy-intensive economies.

The price situation on the global coal market is determined by leading exchanges that provide futures quotes based on market expectations and contractual agreements. World coal prices are set in USD per ton on such platforms as the aforementioned New York Mercantile Exchange NYMEX and the Intercontinental Exchange (ICE), as well as at the Newcastle Coal Terminal in Australia. Prices take into account both over-the-counter transactions and contracts for difference (CFDs). The results of coal trading on international commodity exchanges are shown in *Figure 2*.

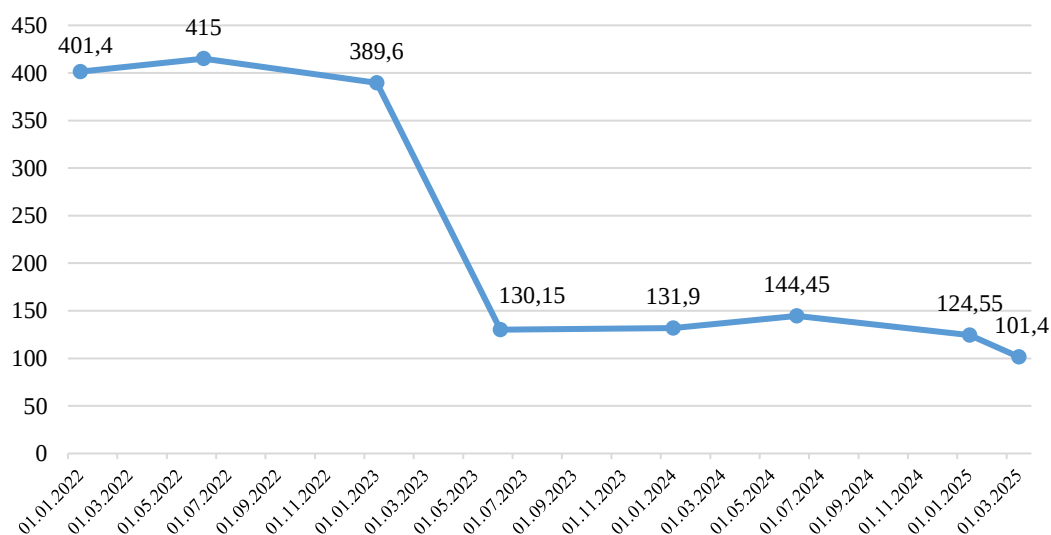


Figure 2. Dynamics of world coal prices, USD per ton

Source: compiled by the authors based on (Ministry of Finance, n. d.).

To ensure the comparison of the research results, the same time period of observation was used as in the case of the analysis of the natural gas market. Therefore, the dynamics of world coal prices demonstrate similar trends and phases of fluctuations. The highest price values were observed in March–June 2022, which coincides with the period of geopolitical tension and energy instability. Subsequently, a gradual decrease was noted, with a temporary sharp decline in May–June 2023 and reaching a minimum level in March 2025. Such price fluctuations indicate a high sensitivity of the coal market to global economic and political factors, which necessitates the diversification of energy sources.

1.3. Dynamics of world prices on the oil market

The world oil market demonstrates exceptional sensitivity to global economic, political and environmental changes. In particular, as a key source of energy, oil determines the pace of development of national economies, affects the structure of the balance of payments of exporting countries and forms a significant part of the cost component for importing countries. Its pricing is based not only on the ratio of demand and supply, but also on the qualitative characteristics of the resource, the geography of deposits, supply logistics, as well as on geopolitical stability in the regions of production.

The establishment of world market prices for oil, in particular for its individual types, which differ in the content of heavy hydrocarbons, sulfur, alkanes and other impurities, as well as the location of the deposit, is carried out according to three main reference grades: American WTI (West Texas Intermediate) – mainly for the American market; European Brent (Brent Crude) – as a reference for Europe and OPEC countries; russian Urals is the benchmark grade for russian oil. Monitoring of world prices recorded on the above international commodity exchanges is presented in *Figure 3*.

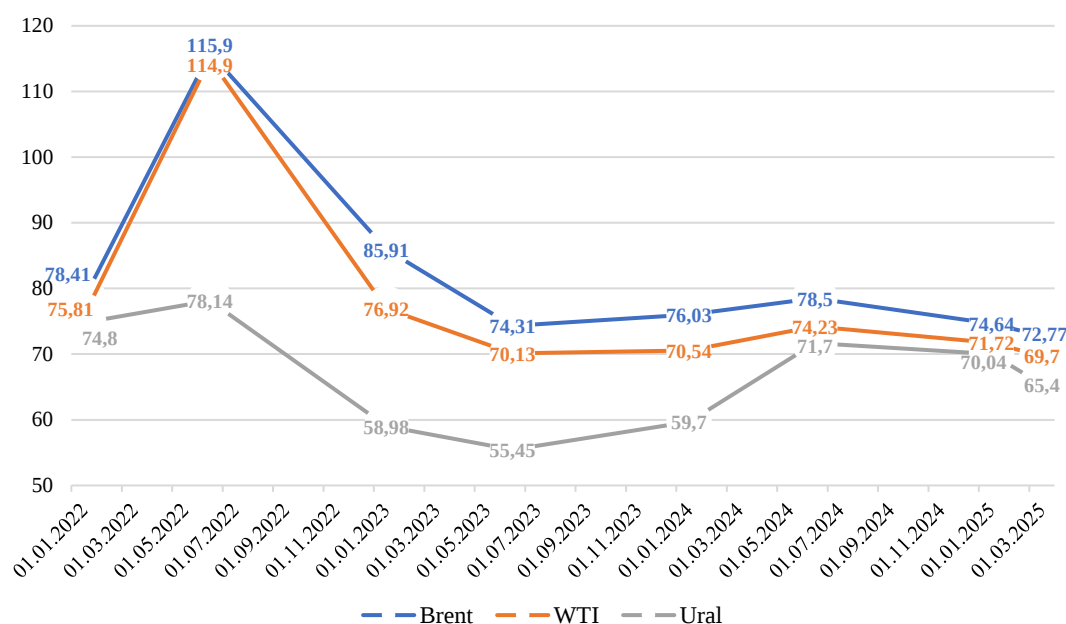


Figure 3. Dynamics of world oil prices, USD per barrel

Source: compiled by the authors based on (Ministry of Finance, 2025).

Monitoring of world oil prices reveals trends that are largely correlated with trends in the natural gas market. The highest level was recorded in May–June 2022, which is directly related to the beginning of Russia's full-scale invasion of Ukraine and the introduction of sanctions against the aggressor country. However, the re-election of the US president and changes in the foreign policy of this state led to the fact that after Trump's

inauguration in February–March 2025, prices for Russian Urals oil did not show significant volatility, as in 2022–2023.

Therefore, price trends in the world market for natural gas, coal and oil are interconnected and have similar vectors of change. The current stabilization of world prices for major thermal energy resources is seen as a positive factor that contributes to reducing uncertainty in energy markets, providing more predictable conditions for the formation of national energy strategies and investment decisions in the bioenergy sector.

1.4. Dynamics of world prices on the timber market

Price monitoring and assessment of the timber market situation is a rather complex task given the diversity of the product range, its grades, quality characteristics and final destination. In industry classification, experts distinguish two main types of wood: industrial and energy. Industry differentiation makes it possible to carry out an accurate analysis of demand, supply and pricing, since each of the segments has its own specific market price dynamics and influence factors.

According to experts from the Association of Woodworking Enterprises of Ukraine, "the global lumber market has been demonstrating a steady downward trend over the past two years. There is a decrease in demand for coniferous lumber in key regions, which is due to a number of interrelated factors, in particular, a decrease in housing construction, a decrease in the scale of repair work and a general decrease in the level of consumption of goods" (Association of Woodworking Enterprises of Ukraine, 2025). Based on information and analytical data provided by experts, the main global trends in the wood market have been systematized (*Table 1*).

Table 1

Characteristics of the global timber market by major regions

Market Characteristics	Northern and Central Europe	North America	China and the Middle East and North Africa Region
Condition	Wood prices in Scandinavian countries reach highest level in a decade	Colombia is facing a timber shortage, high production costs and other issues that are reducing production. In 2024, production was less than half of what it was a decade ago	China's lumber imports fell 7% year-on-year in the first ten months of 2024. In the Middle East and North Africa, imports fell 4% in the first nine months of 2024.
Price	Rising raw material prices are putting pressure on sawmills as the increase in raw material costs outpaces lumber prices, reducing their profitability	Roundwood prices in the US South have fallen to their lowest level in 30 years, a trend that could potentially spur new investment in the region's sawmills	Uneven demand and pricing across regions

End of Table 1

Market Characteristics	Northern and Central Europe	North America	China and the Middle East and North Africa Region
Forecast	In Northern Europe, controlling production costs becomes critical due to rising raw material prices	Low roundwood prices in the US South could make the region attractive to investors in 2025 and beyond	Trends will affect businesses differently in different regions. The decline of the sawmill sector in British Columbia is an example of how changing demand, regulation and global competition can transform the industry

Source: compiled by the authors based on (Association of Woodworking Enterprises of Ukraine, 2025, January 8).

Therefore, the analysis of the current situation on the world timber market reveals significant regional differences in the market situation, price dynamics and forecast indicators, which necessitates a differentiated approach to strategic planning. In particular, in Northern and Central Europe, a steady trend of increasing timber prices to record levels over the past decade is recorded, which negatively affects the profitability of sawmills due to the outstripping growth in the cost of raw materials. This fact emphasizes the critical importance of optimizing production costs to ensure competitiveness.

Meanwhile, in North America, despite a shortage of wood and high production costs that have led to a significant decline in production volumes (less than 50% of the level of a decade ago), the decline in roundwood prices in the southern USA states to a 30-year low creates the potential to attract new investments in the sawmill industry starting in 2025. In the regions of China, the Middle East and North Africa, a decrease in sawn wood imports is observed (by 7% and 4%, respectively, in 2024), which is accompanied by uneven demand and pricing due to regional specific market conditions and increased sensitivity to global economic changes.

Thus, for international companies operating in the timber market, regional differences in roundwood prices highlight the strategic value of geographical diversification as a mechanism to reduce the impact of market volatility. In addition, the growth of European sawn wood exports to the US can be seen as a new opportunity to expand supply in foreign markets. In general, the industry demonstrates sensitivity to changes in demand, regulatory frameworks and global competition, which requires constant adaptation and flexibility of business models.

Analyzing the prices of the region closest to us – Western Europe – it was found that the average European prices for wood, mainly industrial, fluctuate between 75–115 euros per cubic meter (*Table 2*).

Table 2

Prices for spruce and pine saw logs in selected European countries in 2024,
euros per cubic meter (excluding VAT)

Country	Minimum	Maximum
Austria	75	115
Latvia	85	100
Germany	103	115
Finland	79.96	90

Source: compiled based on data (Association of Woodworking Enterprises of Ukraine, 2025, March 28).

The results of monitoring the global timber market indicate a steady trend towards an increase in prices for industrial timber, even in conditions of declining demand. In particular, according to 2024 data, despite a decrease in overall demand, the average price for timber increased by 7%. Price dynamics in this segment are largely due to the development of the construction industry, the growth in demand for repair and construction services, as well as the level of solvency of the population.

At the same time, prices for low-quality energy wood are forecast to stabilize or even decrease due to an excess of existing stocks. This objective factor complicates the sale of wood chips and other waste from the forestry industry. As of today, real stocks of firewood exceed their consumption. Demand for them has decreased due to the high level of prices for the population and state regulation of natural gas tariffs. Sales volumes of wood chips remain low, and the price situation in this market segment is stable without signs of significant growth.

Thus, the global timber market situation demonstrates differentiated price dynamics depending on the quality and purpose of the resources. At the same time, it remains an important factor influencing the adoption of economically sound decisions at the local level, in particular regarding the diversification of energy sources, forest resource management and stimulation of biomass use.

2. The impact of global trends on local decisions

Local decisions are shaped by external macroeconomic trends, including fluctuations in global energy prices and increasing environmental requirements. The above-mentioned factors necessitate adaptation of local strategic decisions in the energy, forestry and agricultural sectors. The search for sustainable and affordable energy sources is becoming increasingly relevant, with biomass playing a significant role as an energy resource, especially in the context of the need to rethink energy consumption models and national energy security priorities.

2.1. The potential of biomass as an energy resource in Ukraine

Biomass is one of the most promising renewable energy sources for Ukraine, given the existing agricultural potential, the volume of forestry waste and the high level of dependence on imported fossil fuels. For the production of thermal and electrical energy in Ukraine, it is planned to attract biomass of forest, wood, agricultural, agricultural and other relevant origin. Three main groups of resources are most often used as solid fuel at thermal power plants (TPP) and combined heat and power plants (CHPP): peat biomass; plant biomass (including energy crops and agricultural residues); wood (Figure 4).

Peat group	Plant group	Wood group
• pellets • peat chunks • milled peat • peat briquettes	• sunflower husks • buckwheat husks • rice husks • corn husks, • straw, chaff • miscanthus • switchgrass • sedge	• firewood • wood chips • wood shavings • sawdust • pellets • granules • energy willow

Figure 4. Main types of solid fuel from renewable energy sources used to produce heat and electricity

Source: constructed by the authors.

This diversification of the raw material base for energy purposes provides flexibility, allowing for consideration of regional characteristics, seasonality, logistical costs, and the level of infrastructure development. At the same time, the effective use of biomass as an energy source requires a detailed analysis of the available volumes and the features of its spatial distribution.

2.2. Resource potential of biomass for energy purposes in the Polissia region: the example of Zhytomyr region

The Polissia region of Ukraine, in particular the Zhytomyr region, has significant potential for the development of bioenergy due to the presence of a wide biomass resource base, which is due to natural and climatic conditions and the structure of land use, especially in the forest and agricultural sectors. One of the determining factors of the biomass energy potential in the region is the significant forest cover of the territory. The area of Zhytomyr region is about 29.8 thousand km² and has a forest cover level of 35.2%, which provides it with the fourth place among all regions of Ukraine in this indicator. The total area of the forest fund of the region is 1094.4 thousand hectares. Such a level of forest cover creates a stable raw material base for

obtaining wood biomass, in particular firewood, wood chips, wood chips, sawdust, wood granules, pellets, etc. In addition, the region has significant areas of peatlands, which can serve as an additional source of peat biomass.

Along with forest resources, agricultural waste is a significant source of biomass in the region. According to the State Statistics Service of Ukraine, in 2023, Zhytomyr region produced 2.418 million tons of grain and leguminous crops, 934 thousand tons of sugar beets, 361 thousand tons of sunflower seeds, 1.902 million tons of potatoes and 400 thousand tons of open ground vegetables (Statistical Yearbook of Ukraine for 2023, 2024). Accordingly, the by-products of these productions, in particular straw, husks, stalks, husks and other agricultural waste, form a significant potential for the production of solid biofuels in the form of briquettes, pellets or for direct combustion in appropriate boiler rooms.

An important element of realizing the biomass potential in the Zhytomyr region is the presence of three generation facilities that are already operating on the basis of bioenergy technologies. For example, LLC "Poliska TPP" (Ovruch city), which operates a thermal power plant on solid biofuel, the main types of wood residues from the woodworking industry and energy willow. Two more power plants operate on biogas: LLC "LNK", which combines seven biogas plants, and LLC "Dionys Biogas Energy". The activities of these enterprises indicate the practical feasibility and economic viability of using biomass for energy needs within the Polissia region. This gives grounds to assert that favorable conditions have been formed in the Zhytomyr region for the large-scale use of biomass for energy purposes. The combination of wood, peat, and agricultural biomass sources creates a powerful resource base for the implementation of regional strategies for the development of renewable energy, which will become an important component of energy security, decarbonization of the economy, and sustainable development of territories.

3. Technical and economic comparison of heat energy sources

To make strategically sound decisions on the effective use of the available resource potential for energy purposes, a technical and economic assessment of alternative sources of thermal energy is important. Therefore, the study carried out a comparative analysis of technical and technological parameters and economic efficiency of thermal energy production from various types of solid biofuels and natural gas in the conditions of Ukraine.

As of the beginning of 2025, in accordance with current legislation in Ukraine, differentiated prices for natural gas have been established depending on the categories of consumers, which significantly affects their energy consumption and competitiveness (Law of Ukraine "On Natural Gas Markets", 2015). The lowest price is for households and is UAH 7.96 per m³. At the same time, the cost of gas for budgetary institutions is 2.1 times higher, which creates an additional financial burden on social infrastructure

facilities. For industrial enterprises, the price of gas exceeds the tariff for the population by 2.5 times, which significantly reduces the competitiveness of domestic products, taking into account the constant growth of the energy component in the cost structure (*Table 3*).

Table 3

Technical characteristics and assessment of thermal energy production from solid fuels (2025)

Technical data	Average cost with transport and VAT	Units of measurement	Heat capacity	Units of measurement	Cost of energy unit, UAH
Natural gas for the population	7960	UAH/ thousand m ³	33.5	MJ/m ³	238
Natural gas for the budget sector	16554				494
Natural gas for industry	20250				604
Natural gas imported by Ukrtransgaz	31000				925
Electricity for the population	4.36	UAH/kWh	—		1211
Electricity for the population consumed through a heat pump with COP ¹ =2.7					449
Electricity for households consumed through a heat pump with COP =3.5					346
Electricity for non-household consumers	2778				
Electricity for non-household consumers consumed through a heat pump with COP =2.7	10				1029
Wood chips	2500	UAH/t	10.5	MJ/kg	238
Wood pellets	9000		17		529
Husk pellets	7000		17.5		400
Bale of straw or corn stalks	2000		14.6		137

Source: compiled by the authors based on (Oliinyk, 2024).

The price level of natural gas under import contracts, supplied through the operations of JSC Ukrtransgaz, is particularly indicative. Its cost is UAH 31 per m³, which is 3.89 times higher than the tariff for household consumers, 1.87 times higher than the tariff for budget institutions, and approximately 1.5 times higher than the tariff for industry (Ministry of Energy of Ukraine, 2024). Such price disparities need to be taken into account when developing an energy policy aimed at expanding the use of alternative, economically

¹ COP (a coefficient of performance) is an indicator of the energy efficiency of equipment that works on heat, for example, heat pumps or air conditioners. It shows the ratio of the thermal power produced by the device to the electricity consumed.

viable heat sources, in particular biomass. Electricity as a source for generating heat energy in Ukraine is regulated differently for two main groups of consumers: household and non-household. According to the Ministry of Energy of Ukraine, as of the beginning of 2025, the tariff for household consumers with value added tax is UAH 4.32 per kWh, including in cases of using electricity for heat pumps with a coefficient of performance (COP) of 2.7 or 3.5. However, for non-household consumers, i.e. business entities, the cost reaches UAH 10 per kWh, which is 2.3 times higher than the tariff for the population (National Commission for State Regulation in the Spheres of Energy and Utilities, n. d.). Such price differentiation significantly affects the competitiveness of products of national producers, as the energy component continues to grow, increasing the total cost of goods and services.

To justify the choice of the optimal source of thermal energy in the conditions of Ukraine, a comparative characteristic of four main types of solid biofuels presented on the Ukrainian market was carried out:

- wood chips, wood chips, which are used (for example) in LLC "Clear Energy-Zhytomyr", but belong to the low-price category (approximate price – UAH 2500 per t);
- wood pellets, pellets – the most expensive solid fuel (9000 UAH per t);
- sunflower husk pellets – belong to the higher-than-average price category (UAH 7000 per t);
- baled straw or corn stalks, the cheapest solid fuel (2000 UAH per t).

After converting the specified types of biofuels into the corresponding calorific equivalents, it is advisable to analyze the cost of thermal energy produced from them.

According to calculations by Yevhen Oliinyk, an expert at the Public Union "Bioenergy Association of Ukraine", the cost of thermal energy from various types of solid biofuels (in UAH/MJ) is: wood pellets – UAH 529/MJ (the most expensive option), sunflower husk pellets – UAH 400/MJ, wood chips – UAH 238/MJ, baled straw and corn stalks – UAH 137/MJ (the cheapest option). This indicates that wood chips, which are actively used in Clear Energy projects for energy production, combine a relatively high calorific value with an affordable market price, making it one of the most effective and economically feasible renewable energy sources for heat generation (Clear Energy, n. d.).

Separate studies conducted by specialists in the heat and power sector, including expert Yevhen Oliinyk, also took into account the economic efficiency and return on investment in the implementation of bioenergy technologies. The most expensive type of biofuel in terms of purchase price remains wood pellets from waste from the logging and woodworking industries – UAH 6.500/t, while the cost of biofuel from wood chips, wood chips (non-marketable crushed wood) and baled straw is practically the same – UAH 1.700/t and UAH 1.667/t, respectively (*Table 4*).

Table 4

Investment efficiency in the production of thermal energy
from various types of solid fuel

Technical data	Units of measurement	Wood chips	Baled straw	Pellets
Thermal capacity of biofuel boilers	kW	1000		
Calorific value of biofuel	MJ/kg	8.4	14.2	17.2
Production of thermal energy from biofuel	thousand Gcal	3.45		
Consumption of fuel raw materials	thousand tons	2.0	1.18	0.98
<i>Prices and tariffs</i>				
Electricity without VAT	UAH/kWh	6.5		
Chemically treated water without VAT	UAH/m ³	15		
Maintenance, repairs, materials	UAH/Gcal	32		
Biofuel with delivery, excluding VAT	UAH/t	1700	1667	6500
Thermal energy tariff (population), excluding VAT	UAH/Gcal	1500		2500
Investment activity expenses	UAH million	5.4	8.1	2.7
Operating activity expenses	UAH million	5.1	3.4	8.7
<i>Investment efficiency</i>				
Internal rate of return	%	13	28	54
Net present value	UAH million	3.0	12.9	9.5
Payback period	Years	6.4	4.2	2.8

Source: compiled by the authors based on (Oliinyk, 2024).

Due to the systematic damage to Ukraine's energy infrastructure as a result of Russia's armed aggression, there is an objective need to diversify energy sources and strengthen the role of local initiatives. In this context, it is advisable to consolidate the efforts of the Zhytomyr City Council, the Zhytomyrteplokomunenergo municipal enterprise, as well as to attract the experience, material and technical base, and high professionalism of specialists from Clear Energy-Zhytomyr LLC and its parent company Clear Energy to implement a new promising project for the production of electricity from renewable sources, which will increase the energy sustainability of the region, reduce dependence on imported energy carriers, and contribute to the development of a low-carbon economy in the region (Zhytomyr City Council, p. 1).

Tariffs for thermal energy for the population, including VAT, vary depending on the type of biofuel used. In particular, for cheaper sources such as wood chips and baled straw, the cost is about UAH 1.500/Gcal, while for heat produced from wood pellets, it reaches UAH 2.500/Gcal. According to the above calculations, the highest costs were for the implementation of

investment projects involving the use of wood pellets as an energy source (UAH 8.7 million). The capital costs for projects using baled straw are somewhat lower (UAH 8.1 million), and the lowest costs are typical for projects based on wood chips (UAH 5.4 million).

At the same time, the operating costs for the installation and operation of equipment demonstrate an inverse relationship: for wood chips they are the largest – 5.1 million UAH, for baled straw – UAH 3.4 million, and the project using wood pellets requires the least costs – UAH 2.7 million. The highest level of profitability from the point of view of economic efficiency is demonstrated by the project based on wood pellets – 54%, with a payback period of 2.8 years and an average income of UAH 9.5 million. The most attractive in terms of overall financial results is the investment project based on baled straw, since the net present value is UAH 12.9 million, the payback period is 4.2 years, and the level of profitability is 28%. Accordingly, the above indicators indicate the high potential of the project for generating profit and a quick return on invested funds. Taking into account the above financial indicators, the project based on baled straw deserves attention as a promising long-term investment. Its implementation can be ensured through combined financing, which includes state support, attracting international grants and using own funds of enterprises in the thermal energy sector. This approach will allow diversifying sources of financing and reducing the risks associated with the implementation of the project.

The generalized results of the technical and economic comparison of thermal energy sources confirm that the use of biomass is an economically feasible alternative to traditional energy carriers in the conditions of Ukraine. Among the studied types of biofuels, the highest profitability is demonstrated by projects based on wood pellets; however, they require the highest investment costs. At the same time, the highest net present value is the project on the use of baled straw, which indicates its high investment attractiveness in the medium term. Wood chips, as a resource with moderate cost and stable operational characteristics, provide an optimal balance between efficiency, availability and cost level. Overall, the results of the analysis confirm the need to form differentiated approaches to the implementation of bioenergy solutions at the local level, taking into account the resource base, economic parameters, and technical capabilities.

Conclusions

In the context of global price fluctuations in energy markets and the need to strengthen energy security, Ukraine is faced with the urgent task of diversifying energy sources. The analysis confirms that bioenergy solutions can become an effective tool for increasing the energy autonomy of regions, in particular Polissia, by combining forest, agricultural and peat resources. Zhytomyr region has an appropriate resource base and implemented examples of effective use of biomass in energy.

The feasibility study of various types of fuel allowed us to identify economically profitable areas for potential investments. In particular, baled

straw and wood chips turned out to be the most balanced in terms of cost, efficiency and availability. Provided that the state, municipalities and international donors support, biomass-based thermal energy production projects have a high potential for implementation. Thus, the development of bioenergy is an important component of the national energy transformation and a key direction in the country's sustainable development strategy.

The results of the research confirm the hypothesis that global fluctuations in prices for traditional energy carriers create the prerequisites for increasing the economic feasibility of implementing local bioenergy projects, especially in the presence of a stable resource base and a moderate level of investment support. The conducted feasibility study of various biofuel options (wood chips, baled straw, pellets) confirmed their competitiveness compared to natural gas and electricity, which indicates the significant potential of such solutions in the conditions of the modern energy market. Thus, the hypothesis of the study has been empirically confirmed.

The methodological platform for further research is the development of models for integrating bioenergy solutions into regional energy strategies, which will allow increasing the energy sustainability of territories, minimizing dependence on imported energy carriers and ensuring the achievement of the goals of decarbonization of the Ukrainian economy.

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ESG AS A DRIVER OF COMPETITIVENESS AND BUSINESS VALUE

Integrating Environmental, Social, and Governance (ESG) factors into corporate strategies has become a central theme in management, finance, and accounting research. However, the literature on the "value relevance" of ESG disclosure and its relationship with performance and valuation remains fragmented, with divergent theories and results. Mapping this field is essential to systematize conceptual foundations, highlight dominant research streams, and identify gaps shaping the debate on ESG as a driver of corporate value. The aim of this study is to explore the evolution of academic research on ESG, disclosure, performance, and valuation, focusing on how ESG has been conceptualized as a factor of competitiveness and long-term value creation. The hypothesis that underlies research is that the relevance of ESG in determining the market value has expanded since the global financial crisis, with literature shifting from descriptive approaches to analytical and performance-based assessments. Hence, the ESG factors are assuming growing attention in business valuation domain. Methodology: a bibliometric analysis was conducted using Web of Science; with

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ESG ЯК ДРАЙВЕР КОНКУРЕНТОСПРОМОЖНОСТІ ТА БІЗНЕС-ЦІННОСТІ

Інтеграція екологічних, соціальних та управлінських (ESG) факторів у корпоративні стратегії набула статусу ключової теми досліджень у галузі управління, фінансів та бухгалтерського обліку. Водночас наукова література щодо "значимості для вартості" розкриття інформації про ESG та її взаємозв'язок з результатами діяльності та оцінкою вартості залишається фрагментарною, з розбіжними теоріями та результатами. Картування цієї галузі є необхідним для систематизації концептуальних основ, виокремлення провідних напрямів досліджень та виявлення прогалин, що формують дискусію про ESG як чинника створення корпоративної вартості. Метою дослідження є вивчення еволюції академічних досліджень з питань ESG, розкриття інформації, ефективності та оцінки з акцентом на тому, що ESG було концептуалізовано як фактор конкурентоспроможності та створення довгострокової вартості. Гіпотеза, що лежить в основі дослідження, полягає в тому, що релевантність ESG у формуванні ринкової вартості зростає після світової фінансової кризи, а дослідницький фокус поступово змістився від описових підходів до аналітичних та заснованих на ефективності оцінок. Отже,



VOSviewer, the study maps co-citation networks, co-occurrence of keywords, and semantic clustering to identify main theoretical streams, influential journals, authors, and emerging topics in the ESG-value relevance debate. Findings reveal distinct research clusters showing that ESG integration enhances reputation and market valuation, especially when supported by strong governance and incentives. Key themes include double materiality, impact investing, and executive compensation tied to ESG metrics, with evidence that ESG-linked pay fosters measurable improvements in sustainability outcomes, though short-term financial effects remain mixed. ESG strategies, steadily evolving from a voluntary practice aimed at legitimization of the firm to a determinant of competitiveness and business value. Such evolution is reshaping academic inquiry and corporate valuation models while enhancing long-term value creation philosophy.

Keywords: ESG, competitiveness, market value, business valuation, sustainability reporting, corporate governance, EU regulation.

JEL Classification: C55, M14, M41, G32, Q56.

фактори ESG привертають дедалі більше уваги в галузі оцінки бізнесу. Методологія дослідження базується на бібліометричному аналізі, проведеному з використанням наукометричної платформи Web of Science. За допомогою програмного забезпечення VOSviewer у дослідженні відображено мережі спільних цитувань, спільну появу ключових слів та семантичне кластеризування для виявлення основних теоретичних напрямів, впливових журналів, авторів та нових тем у дебатах щодо значущості ESG для вартості. Результати дослідження показують, що інтеграція ESG покращує репутацію та ринкову оцінку, особливо за умови підтримки сильного управління та стимулів. Ключові теми включають подвійну суттєвість, інвестиції з соціальним впливом та винагороду керівників, пов'язану з показниками ESG, з доказами того, що винагорода, пов'язана з ESG, сприяє помітному поліпшенню результатів у сфері сталого розвитку, однак короткострокові фінансові ефекти залишаються неоднозначними. Стратегії ESG поступово еволюціонують від добровільної практики, спрямованої на легітимізацію компанії, до визначального чинника конкурентоспроможності та бізнес-цінності. Така еволюція змінює академічні дослідження та моделі корпоративної оцінки, одночасно посилюючи філософію створення довгострокової цінності.

Ключові слова: ESG, конкурентоспроможність, ринкова вартість, оцінка бізнесу, звітність про сталий розвиток, корпоративне управління, регулювання ЄС.

Introduction

The pursuit of sustainable development capable of meeting present needs without compromising the ability of future generations to satisfy their own has progressively reshaped business, finance, and accounting systems worldwide. Climate change, social inequalities, and corporate governance failures have heightened the urgency to embed sustainability principles into corporate strategies and valuation models (United Nations, 2015a, 2015b; European Commission, 2018). The European Green Deal, the EU Taxonomy, and the Corporate Sustainability Reporting Directive (CSRD) represent milestones in this process, positioning Environmental, Social, and Governance (ESG) disclosure as a key tool for market transparency, capital allocation, and competitiveness (European Commission, 2022).

The concept of ESG, originally introduced in the report Who Cares Wins (Compact, 2004), has evolved from voluntary corporate practices into a framework shaping investor decisions, regulatory requirements, and academic inquiry. Firms with strong ESG performance benefit from reputational advantages, enhanced stakeholder trust, and lower capital constraints (Cheng et al., 2014; Fatemi et al., 2018; Eliwa et al., 2021). Moreover, ESG

disclosure reduces information asymmetry, strengthens governance mechanisms, and supports more accurate valuation practices (Suhartati et al., 2024). However, the relationship between ESG and firm performance remains contested, with studies reporting positive (Friede et al., 2015; Albuquerque et al., 2020), negative (Di Giuli & Kostovetsky, 2014; Busru, 2021), or insignificant effects (Chauhan & Kumar, 2018; Kartal et al., 2024). More recently, Bruna et al. (2022) highlighted that the relationship is not linear but curvilinear (U-shaped), showing a marginal effect: while in the initial stages ESG investments may negatively affect financial performance due to the costs of non-financial objectives, beyond a certain turning point these efforts translate into improved performance.

Controversial results emerged over time has fostered an expanding body of literature aimed at clarifying the "value relevance" of ESG disclosure, defined as the extent to which sustainability information explains variations in firm valuation (Francis & Schipper, 1999; Natale, 2015). In this context, bibliometric approaches have proven particularly effective in mapping the intellectual development of ESG research, identifying leading authors, journals, and theoretical clusters (Jain & Tripathi, 2023; Senadheera et al., 2022; Wan et al., 2023; Zeng et al., 2024).

Recent reviews highlight four dominant streams: ESG investing, ESG disclosure and integrated reporting, ESG performance and firm value, and corporate governance and ESG (Jain & Tripathi, 2023; Galletta et al., 2022). The COVID-19 pandemic has further intensified interest, with ESG funds outperforming conventional funds in times of crisis (Nofsinger & Varma, 2014; Takahashi & Yamada, 2021). Emerging themes include double materiality, ESG-linked executive compensation, assurance of non-financial information, and the role of ESG standards in reducing greenwashing risks (Galletta et al., 2022; Zeng et al., 2024).

Against this backdrop, the present study contributes by systematically mapping the academic debate on ESG, disclosure, performance, and valuation through bibliometric analysis of Web of Science publications. The objective is to provide a comprehensive understanding of how ESG has been conceptualized as a driver of competitiveness and long-term value creation, while highlighting areas where theory and evidence remain fragmented.

Based on this aim, the following research questions guide the study:

RQ1: What is the intellectual development and knowledge structure of the ESG literature concerning disclosure, performance, and valuation?

RQ2: How have research streams on ESG and corporate value evolved over time, and what dominant clusters can be identified?

RQ3: Which authors, journals, and institutions have most influenced the debate on ESG as a determinant of competitiveness and business value?

RQ4: What are the main gaps and unresolved controversies in the literature regarding the value relevance of ESG disclosure?

RQ5: Which future research directions emerge from the bibliometric analysis of ESG-related studies in management, accounting, and finance?

The research rests on the hypothesis that the relevance of ESG in business valuation has significantly expanded after the global financial crisis. To test this hypothesis, a bibliometric methodology was employed using data retrieved from Web of Science. VOSviewer was used to map co-citation networks, keyword co-occurrences, and thematic clusters, while performance analysis identified influential authors, journals, and countries. The dataset covers peer-reviewed journal articles, excluding grey literature, with the time frame spanning from 1999 to 2025. Limitations concern the restriction to two databases and the reliance on bibliometric indicators, which may not fully capture qualitative contributions or practitioner insights.

The paper is structured as follows: Section 1 presents the data collection procedures and methodology; Section 2 provides the bibliometric results and cluster analysis; Section 3 discusses the main findings in light of existing literature; and Section 4 concludes by outlining implications, limitations, and directions for future research.

1. Research design

1.1. Data sources and sample characteristic

To explore the academic debate on ESG, disclosure, performance, and corporate valuation, this study employs a bibliometric analysis. The data were collected from one of the most comprehensive and internationally recognized bibliographic databases, Web of Science (WoS). This platform was chosen for his extensive coverage of peer-reviewed journals in management, finance, accounting, and sustainability, and their reliability in providing citation and co-citation information (Baas et al., 2020; Donthu et al., 2021).

The search strategy was designed to capture publications that explicitly address the intersection of ESG with corporate performance and value creation. Keywords included variations of "ESG", "environmental, social and governance", "sustainability disclosure", "firm value", "corporate valuation", and "performance". The search was applied to the title, abstract, and author keywords fields to ensure relevance. Only journal articles and reviews were considered, while grey literature such as conference papers, book chapters, and editorials was excluded to guarantee the academic robustness of the dataset (Wan et al., 2023; Senadheera et al., 2022).

The time frame spans from 1999 to 2025. The retrieval was conducted in 2025, yielding an initial sample of 982 records. After a screening process to exclude irrelevant subject areas, and non-English publications, the final dataset consisted of 796 records.

The bibliometric dataset was subsequently processed using VOSviewer to generate co-citation maps, keyword co-occurrence networks, and cluster visualizations (Aria & Cuccurullo, 2017; van Eck & Waltman, 2010). These tools allow the identification of intellectual structures, dominant research streams, and emerging topics in the ESG-value relevance debate.

Table 1 summarizes the rationale, objective, eligibility criteria, and scope of the selected dataset.

Table 1

Sample criteria and data collection strategy

Indicator	Description
Rational and objective	The paper analyses the evolution of academic research on ESG disclosure, performance, and corporate valuation, investigating its role as a driver of competitiveness and long-term value creation. The aim is to investigate how ESG has been conceptualized as a driver of competitiveness and long-term value creation, highlighting its role in shaping corporate strategies and financial performance. Particular attention is devoted to the evolution of the literature, the identification of dominant research streams, and the gaps that persist in linking ESG disclosure to firm value
Study design	The study applies a bibliometric analysis to systematically review and map the literature on ESG, disclosure, performance, and corporate valuation. The process relies on rigorous selection criteria and quantitative science-mapping techniques to ensure objectivity and reproducibility
Eligibility criteria	Only peer-reviewed journal articles and reviews written in English were included to ensure academic rigor. Grey literature such as conference proceedings, book chapters, editorials, and non-scholarly documents was excluded. The search was restricted to publications indexed in Web of Science, covering the period 1999-2025, and focused on the intersection of ESG, disclosure, performance, and corporate valuation
Publication time frame	All years
Language	English
Search strategy	We selected the following codes to be searched in the source database: TS = ("ESG" AND "value relevance") TS = ("Environment*" AND "value relevance") TS = ("Governance*" AND "value relevance") TS = ("Social" AND "value relevance")
Sample	Results found: 796 Sum of the Times Cited: 39919 Average Citations per Item: 50.15 H-index: 86

Source: compiled by the authors.

1.2. Methodology

This research employs a bibliometric analysis to systematize the literature on ESG, disclosure, performance, and corporate valuation, following established approaches in recent research (Paltrinieri et al., 2019; Bahoo et al., 2020a; Ahmad & Naz, 2021; Soeryanto Soegoto et al., 2022). As argued by Bahoo et al. (2020b), bibliometric methods present several advantages compared to traditional systematic reviews: (i) they reduce sample selection bias through rigorous and transparent data collection; (ii) they combine quantitative mapping with qualitative interpretation; and (iii) they allow researchers to handle large datasets and detect emerging topics objectively (Naciti et al., 2022).

For the analysis and visualization, we relied on VOSviewer (van Eck & Waltman, 2010), which enables the construction of co-citation, co-authorship, and keyword co-occurrence networks. The clustering of bibliometric networks was based on the "unified approach" proposed by Waltman et al. (2010), which groups items according to both distance and the strength of their connections. In this framework, the prominence of a keyword is determined by the number of publications in which it appears, while the strength of the link between two keywords is measured by their frequency of co-occurrence across titles, abstracts, and author keywords.

To capture the intellectual development of the field, we performed:

Keyword analysis, aimed at identifying the most frequent terms and their temporal evolution. A chronological distribution was computed using the weighted average year of occurrence for each keyword, in order to trace how academic interest has shifted over time.

Co-citation analysis, which clustered references cited together in the sampled publications, thus revealing the theoretical foundations underpinning the ESG-value relevance debate.

Network visualization, where nodes represent items (keywords, authors, or journals) and edges represent the strength of their relationships, enabling the detection of dominant research streams and emerging themes.

Country analysis, conducted to map the geographical distribution of publications and the collaboration networks across nations.

Finally, to complement the mapping, we examined the most frequently cited articles and journals in the dataset (*Figure 1*). These results were combined with cluster analysis to uncover the main conceptual pillars of ESG research and to assess how disclosure and performance have been linked to firm value and competitiveness.

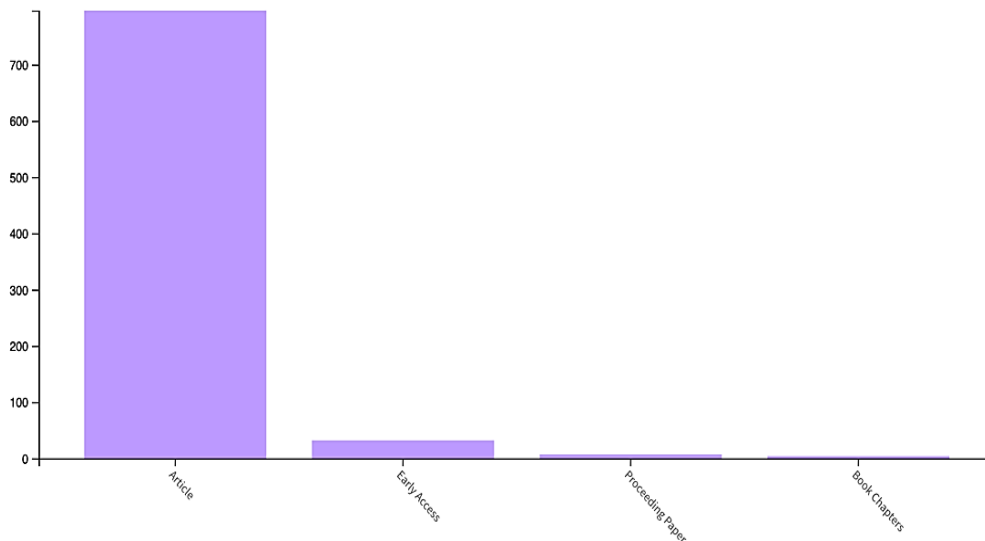


Figure 1. Distribution of document types in ESG-related publications (2001–2025)

Source: authors' elaboration from Web of Science.

2. Results

2.1. Descriptive analysis

Early access papers constitute a smaller but growing share, showing the dynamism of current research activity, while conference proceedings and book chapters remain marginal. This indicates that the debate on ESG disclosure, performance, and valuation is largely anchored in high-quality journal outlets.

Figure 2 shows the annual number of publications and citations from 1999 to 2025. The trend confirms a progressive growth of interest, with an initial phase of sporadic contributions until the early 2000s, a first acceleration after the global financial crisis of 2008, and a significant surge after 2015, coinciding with the UN 2030 Agenda and the Paris Agreement.

The peak in 2020 reflects the impact of the COVID-19 pandemic, when ESG was increasingly explored as a resilience factor.

Citations also grew steadily, confirming the consolidation of ESG as a mainstream research field in accounting, finance, and management.

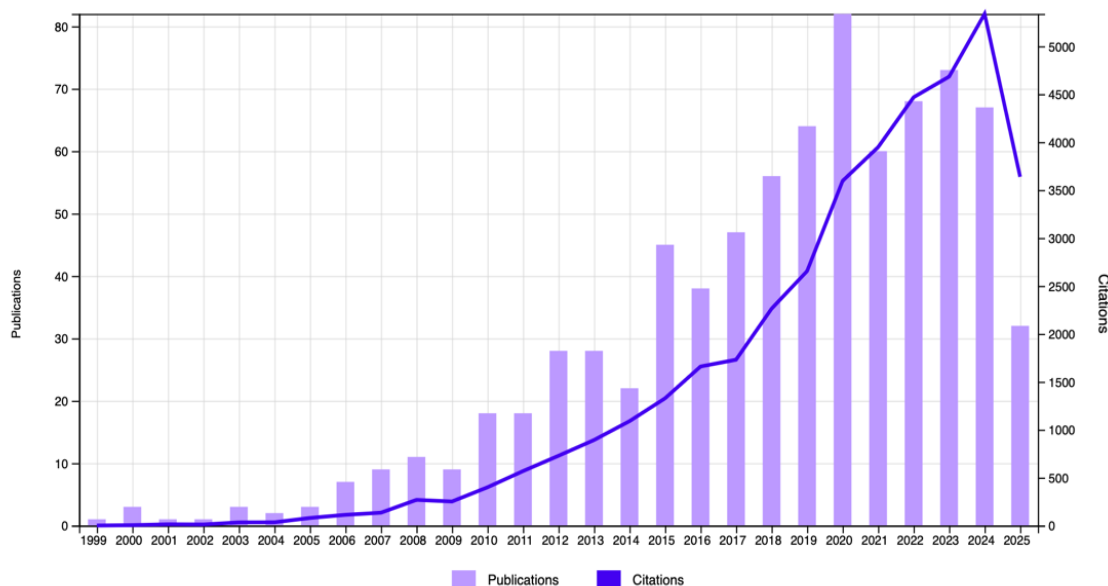


Figure 2. Annual number of publications on ESG, disclosure, performance, and corporate valuation (1999–2025)

Source: authors' elaboration from Web of Science.

2.2. Country analysis

Figure 3 shows the geographical distribution of publications. The United States dominates, followed by England, Australia, Italy, and China, confirming the centrality of Anglo-Saxon and European contexts. Countries

such as Canada, New Zealand, and South Korea also contribute actively, while emerging economies (India, Indonesia, South Africa) remain underrepresented, despite facing significant sustainability challenges.

Overall, the distribution highlights a globalization of ESG research, but with persistent geographical imbalances in scholarly production.

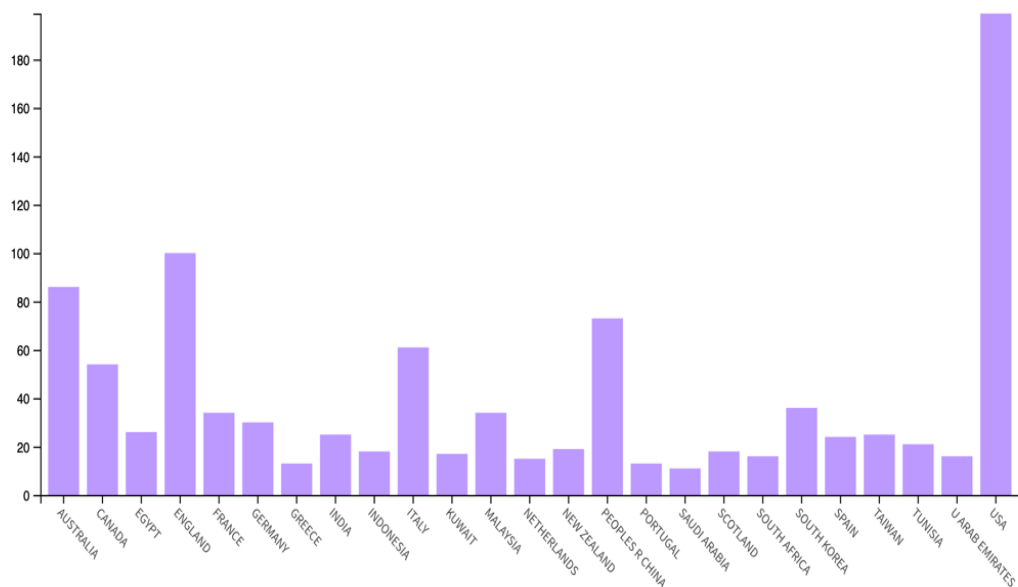


Figure 3. Geographical distribution of ESG-related publications by country

Source: authors' elaboration from Web of Science.

2.3. Journal analysis

Table 2 reports the most active journals in the field. The analysis shows a concentration of publications in a limited number of academic outlets, with leading contributions from Journal of Financial Reporting and Accounting (3.2%), Business Strategy and the Environment (2.3%), Journal of Accounting and Public Policy (2.2%), Corporate Social Responsibility and Environmental Management (2.1%), and Journal of Applied Accounting Research (2.0%).

These journals represent the core platforms where ESG-related studies are most frequently disseminated. Specialized outlets such as Journal of Business Ethics, Journal of Cleaner Production, and Corporate Governance: An International Review also play a pivotal role in shaping the debate, while broader accounting, finance, and management journals (e.g., Accounting Review, International Journal of Accounting, Journal of Business Finance & Accounting) provide significant complementary contributions.

The wide range of journals highlights the multidisciplinary nature of ESG research, which spans across accounting, finance, business ethics, and management studies.

Journal	Record count	% of 796
Journal of Financial Reporting and Accounting	26	3.2
Business Strategy and the Environment	19	2.3
Journal of Accounting and Public Policy	18	2.2
Corporate Social Responsibility and Environmental Management	17	2.1
Journal of Applied Accounting Research	16	2.0
Accounting Review	16	2.0
International Journal of Accounting	15	1.8
Journal of Business Finance Accounting	15	1.8
Contemporary Accounting Research	15	1.8
Journal of Business Ethics	14	1.7

Figure 4 presents the keyword co-occurrence network. "Value relevance" is the most central concept, strongly linked to corporate social responsibility, financial reporting quality, earnings management, and climate change.

Other clusters emphasize governance issues (e.g., audit committees, board diversity, agency problems), social dimensions (e.g., trust, social media, customer satisfaction), and environmental themes (e.g., greenhouse gas emissions, pollution).

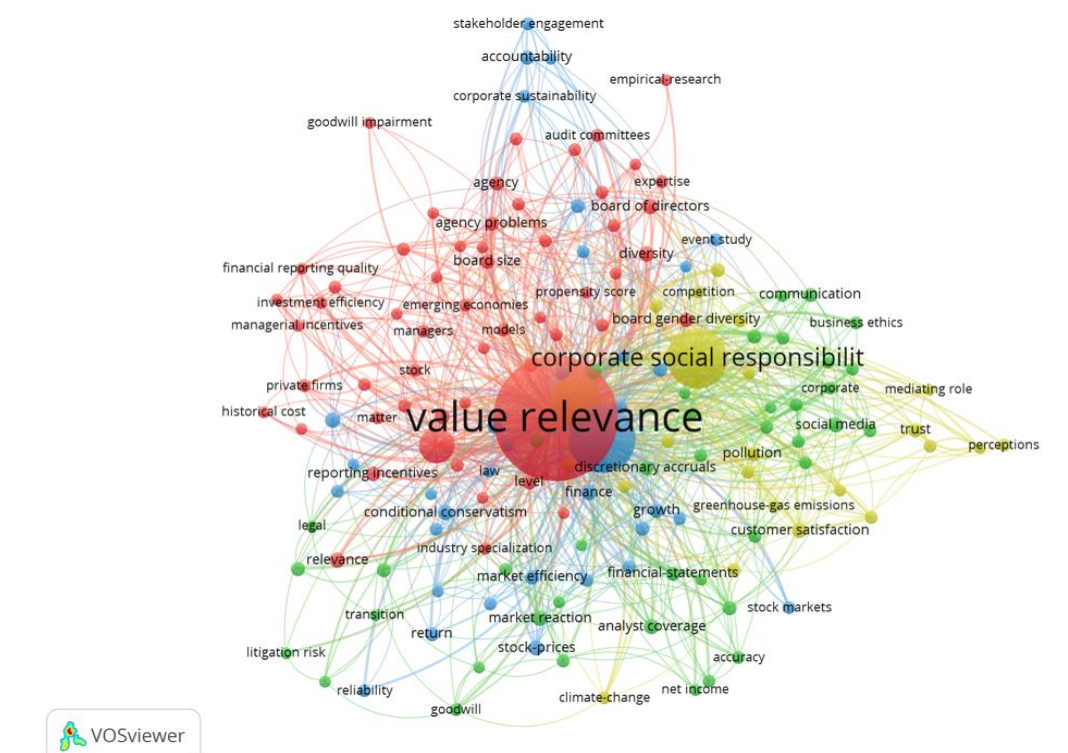


Table 3

Top five most cited publications on ESG, disclosure, performance, and valuation

Rank	Reference	Journal	Year	Total citation	Avg. per year
1	Healy, P. M., & Palepu, K. G. (2001). Information asymmetry, corporate disclosure, and the capital markets: A review of the empirical disclosure literature. <i>Journal of accounting and economics</i> , 31(1-3), 405–440	Journal of Accounting & Economics	2001	3.677	147.08
2	Dechow, P., Ge, W., & Schrand, C. (2010). Understanding earnings quality: A review of the proxies, their determinants and their consequences. <i>Journal of accounting and economics</i> , 50(2-3), 344–401.	Journal of Accounting & Economics	2010	1.839	114.94
3	Ball, R., Kothari, S. P., & Robin, A. (2000). The effect of international institutional factors on properties of accounting earnings. <i>Journal of accounting and economics</i> , 29(1), 1–51.	Journal of Accounting & Economics	2000	1.587	61.04
4	Larcker, D. F., & Rusticus, T. O. (2010). On the use of instrumental variables in accounting research. <i>Journal of accounting and economics</i> , 49(3), 186–205.	Journal of Accounting & Economics	2010	1.505	68.72
5	Barth, M. E., Landsman, W. R., & Lang, M. H. (2008). International accounting standards and accounting quality. <i>Journal of accounting research</i> , 46(3), 467–498.	Journal of Accounting Research	2008	1.237	68.72

Source: compiled by the authors.

3. Discussion

The bibliometric results provide several insights into the evolution of the ESG-value relevance debate. First, the descriptive analysis confirms the exponential growth of academic interest in ESG disclosure and performance after the global financial crisis and, more prominently, after the adoption of the UN 2030 Agenda and the Paris Agreement. This pattern is consistent with prior studies that documented the shift of sustainability from a voluntary practice to a mainstream determinant of competitiveness and firm value (Friede et al., 2015; Wan et al., 2023). The surge observed during the COVID-19 pandemic also corroborates findings that ESG-oriented firms and funds exhibit greater resilience in times of crisis (Nofsinger & Varma, 2014; Takahashi & Yamada, 2021).

The country-level analysis highlights the dominance of Anglo-Saxon and European contexts, with the United States, England, and Italy among the leading contributors. This distribution mirrors both the strong regulatory emphasis of the European Union (European Commission, 2022) and the investor-driven dynamics in the US (Cheng et al., 2014). However, the underrepresentation of emerging economies indicates a structural gap in the literature, despite the fact that sustainability challenges are often more acute in those contexts. Similar concerns have been raised by previous bibliometric studies (Galletta et al., 2022; Zeng et al., 2024), suggesting the need for broader internationalization of ESG research.

The journal analysis confirms that ESG scholarship is concentrated in a limited set of outlets, such as *Journal of Business Ethics*, *Journal of Cleaner Production*, and *Business Strategy and the Environment*. These journals bridge management, accounting, and sustainability, reinforcing the multidisciplinary nature of the debate (Jain & Tripathi, 2023; Senadheera et al., 2022). The strong role of publishers such as Emerald, Elsevier, and Wiley reflects their capacity to act as hubs for the consolidation of this field, while the presence of smaller publishers indicates fragmentation and the coexistence of diverse perspectives.

Keyword and cluster analysis reveal that "value relevance" and "corporate social responsibility" represent the core conceptual anchors, surrounded by streams focusing on governance mechanisms, financial reporting quality, and climate-related risks. These findings resonate with prior evidence that ESG performance and disclosure are closely tied to reputation, stakeholder trust, and access to finance (Fatemi et al., 2018; Eliwa et al., 2021). At the same time, the overlay visualization suggests a progressive thematic shift: early studies focused on accounting constructs such as earnings quality and conservatism, while recent contributions engage with double materiality, stakeholder engagement, and greenwashing (Suhartati et al., 2024). This transition indicates that ESG has become a key factor shaping corporate legitimacy and long-term competitiveness.

Finally, the analysis of the most cited works demonstrates that ESG research is deeply rooted in the traditional accounting and disclosure literature, particularly the seminal works on information asymmetry (Healy & Palepu, 2001), earnings quality (Dechow et al., 2010), and international accounting standards (Barth et al., 2008). This confirms that the debate on ESG value relevance cannot be detached from the broader evolution of financial reporting research (Francis & Schipper, 1999). By building upon these conceptual foundations, the ESG literature has expanded the scope of accounting inquiry, integrating environmental, social, and governance dimensions into firm valuation models.

Recent developments of research open to a diverse way to interpret the relationship between financial performance and ESG performance. In this regard, Bruna et al. (2022) emphasize that mandatory disclosure regimes and

institutional support are crucial in transforming ESG from a cost into a source of financial value, especially for smaller firms. Their findings suggest that regulation can play a decisive role in ensuring that sustainability commitments translate into tangible economic outcomes.

Taken together, these findings suggest that ESG disclosure has evolved from a marginal and voluntary initiative to a central determinant of competitiveness and corporate value creation. However, the fragmentation across countries, journals, and methodological approaches still limits the consolidation of a unified theoretical framework, leaving room for future contributions that bridge existing gaps.

Conclusions

This research explored the evolution of ESG-related research with a focus on disclosure, performance, and corporate valuation. By applying bibliometric methods to a dataset of 796 publications indexed in Web of Science, the analysis revealed the intellectual foundations, thematic clusters, and emerging trends that characterize the debate on the value relevance of ESG. The findings confirm that ESG has evolved from a voluntary practice to a mainstream determinant of competitiveness and long-term value creation, with research activity intensifying after the global financial crisis, the Paris Agreement, and the COVID-19 pandemic.

Implications

The results highlight the multidisciplinary nature of ESG research, spanning accounting, finance, and management. The centrality of "value relevance" and "corporate social responsibility" underscores the integration of traditional accounting constructs with broader sustainability concerns, encouraging scholars to further investigate the link between disclosure quality, governance, and corporate value.

For companies, the growing body of evidence suggests that ESG disclosure is increasingly scrutinized by investors and regulators, affecting market valuation and access to capital. Firms that integrate ESG into their strategies can strengthen their reputation, mitigate risks, and attract sustainable investment.

The dominance of European and US contributions reflects the role of regulatory frameworks such as the CSRD. Policymakers should continue to promote harmonization of standards and comparability of non-financial information to reduce greenwashing and enhance the reliability of ESG data.

Limitations

Despite its contributions, this study is not without limitations. First, the dataset is limited to the Web of Science database, excluding potentially relevant publications indexed in Scopus or other repositories. Second, the analysis considered only English-language publications, which may bias the

geographical scope. Third, bibliometric methods focus on quantitative mapping and citation analysis, without fully capturing the qualitative depth and theoretical nuance of individual studies.

Future research

Future studies could address these limitations by integrating multiple databases and including non-English literature to capture a more global perspective. Moreover, sector-specific analyses (e.g., banking, energy, technology) could provide insights into how ESG value relevance differs across industries. Methodologically, combining bibliometric mapping with systematic reviews or meta-analyses could yield a more comprehensive understanding of ESG-performance linkages. Finally, greater attention should be given to emerging markets, investor perspectives, and the impact of evolving regulations on the adoption and effectiveness of ESG disclosure.

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GREEN LOGISTICS STRATEGIES

The strategic importance of green logistics in supply chain management has been proven, leading to a reduction in the negative impact of companies' activities on the environment and ensuring a balance between economic efficiency, environmental safety, and social impact. A hypothesis has been formulated regarding the presence of synergy between green marketing and green logistics for fostering environmental awareness, implementing green initiatives, and ensuring the sustainable development of trade enterprises. The areas for implementing green logistics strategies have been identified, including the optimization of transportation routes, the introduction of energy-efficient technologies, the use of alternative energy sources, waste management, and the reuse of packaging materials. Particular emphasis is placed on fostering environmental awareness among supply chain participants through the synergistic interaction of green communications and green logistics solutions, which contributes to the increasing sustainable consumer preferences, enhancing partner awareness, and encouraging responsible behaviour. The conditions for the effective implementation of green logistics strategies have been considered, including the development of unified assessment standards, the formation of standardized indicators, the monitoring of indirect environmental impacts, and the integration of economic, environmental, social, and technological criteria into the supply chain management system. The proposed approach will enable trading

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СТРАТЕГІЇ ЗЕЛЕНОЇ ЛОГІСТИКИ

Доведено стратегічне значення зеленої логістики в управлінні ланцюгами постачання, що призводить до зменшення негативного впливу діяльності підприємств на довкілля та забезпечує баланс між економічною ефективністю, екологічною безпекою й соціальним ефектом. Сформульовано гіпотезу про наявність синергії між зеленим маркетингом і зеленою логістикою для формування екологічної свідомості, реалізації зелених ініціатив і забезпечення сталого розвитку підприємств торгівлі. Визначено напрями реалізації стратегій зеленої логістики, зокрема оптимізація транспортних маршрутів, впровадження енергоефективних технологій, застосування альтернативних джерел енергії, управління відходами та повторне використання пакувальних матеріалів. Особливо акцентовано на формуванні екологічної свідомості учасників ланцюгів постачання через синергетичну взаємодію зелених комунікацій та логістичних зелених рішень, що сприяє підвищенню стійких споживчих переваг, посиленню обізнаності партнерів та стимулюванню відповідальної поведінки. Розглянуто умови ефективної реалізації стратегій зеленої логістики, включаючи розроблення єдиних стандартів оцінювання, формування уніфікованих показників, моніторинг непрямих екологічних впливів та інтеграцію економічних, екологічних, соціальних і технологічних критеріїв у систему управління ланцюгами постачання. Запропонований підхід



companies to minimise environmental risks, improve the efficiency of logistics processes, strengthen competitive positions, and create additional value for all participants in the supply chain.

Keywords: strategy, green logistics, supply chains, logistics systems, supply chain adaptation, green distribution, environmental awareness, sustainable development.

дозволить підприємствам торгівлі мінімізувати екологічні ризики, підвищити ефективність логістичних процесів, зміцнити конкурентні позиції та створити додаткову цінність для всіх учасників ланцюга постачання.

Ключові слова: стратегія, зелена логістика, ланцюги постачання, логістичні системи, адаптація ланцюгів постачання, зелена дистрибуція, екологічна свідомість, сталий розвиток.

JEL Classification: D21, D62, L81.

Introduction

In the context of globalization of trade, environmental safety plays a key role in the development and implementation of green logistics strategies in supply chains. These processes are particularly significant within the framework of the European Green Deal, which guides countries and enterprises towards achieving climate neutrality and developing a sustainable economy. The effectiveness of their implementation determines the possibilities for improving the environmental condition through energy consumption, emissions of harmful gases, waste generation, and other environmentally significant aspects. Therefore, green logistics strategies in trade enterprises, aimed at integrating environmental principles into the planning, organization, execution, and control of logistics operations, are highly relevant.

The issues of selecting, unifying, and developing an integrated system of evaluation indicators, as well as ways to increase the efficiency of green logistics, are particularly important for the formation of effective logistics systems, the construction of optimal logistics chains, ensuring the competitiveness of trading enterprises in the long term, and achieving their strategic target goals. In view of the growing global environmental challenges, such areas of green logistics as optimization of transportation flows to reduce emissions, efficient distribution and recycling of waste, environmentally safe disposal of materials, the use of renewable energy sources, and rational consumption of natural resources are gaining significant importance. Moreover, the integration of environmental standards into logistics processes leads not only to a reduction of negative environmental impact but also to an increase in the resilience of logistics systems.

The effectiveness of green logistics encompasses a set of indicators that characterize the level of greenhouse gas emission reductions, the rational use of energy and material resources, the reduction of the negative impact of logistics processes on the environment, as well as the improvement of companies' environmental responsibility. In other words, it is an integral indicator of the performance of logistics systems, combining economic, environmental, and social aspects of the functioning of their elements within supply chains.

The issues of green logistics, its ecological, economic, and organizational components, as well as the processes of assessing efficiency in all areas of society's functioning, are actively studied by both foreign and Ukrainian researchers. The article (Bondarenko et al., 2024) notes that environmental problems, the socially responsible orientation of the world's population, and the promotion of a healthy lifestyle necessitate the implementation of the concept of "green smart cities", within which green marketing and green logistics play a key role. Indeed, today the interconnection between green marketing and green logistics creates an integrated impact on the strategic development of both cities and enterprises. Scholar Salo (2023) notes that the achievement of logistical activity goals is ensured through the synthesis of economic, social, and environmental components, which form the framework of "green logistics" and provide the unity of interaction of resource-saving technologies. Researchers Reznik and Marynina (2024) also emphasize that the combination of these components contributes to achieving both quantitative and qualitative goals of logistical activity, enhancing the impact of green logistics on sustainable development.

On her part, Kalycheva (2023) focuses on the interrelation between the concept of 'green logistics' and the concept of sustainable development, and also argues that the effective implementation of green logistics principles should be based on technical, organizational, and environmental factors. According to Dorosh (2024), the future of green logistics is directly linked to the automation of the supply chain, while the critical role in achieving its objectives and overcoming barriers to implementing green logistics lies in cooperation between companies, the government, and society. The empirical results of research by Sarkis and Zhu (2024) justify that regulatory pressure (economic, consumer pressure, and government support) is the strongest driver for the adoption of green logistics practices, emphasizing the importance of complying with environmental regulations and standards. Seuring and Müller (2025) analyze the evolution and current state of research in the field of Green Logistics Management (GLM). They pay particular attention to the integration of environmental aspects into supply chains, sustainability measurement, reverse logistics, waste management, and recycling. The research findings indicate that GLM is strategically important for achieving ecological stability and sustainable development in logistics operations.

Research conducted by scientists on the example of about five hundred manufacturing companies in Indonesia (Rizki et al., 2022) allowed them to conclude that green procurement, green marketing, green manufacturing, and green design as key elements of Green Supply Chain Management (GSCM), together with environmental awareness, are decisive in the performance indicators of sustainable enterprise development. At the

same time, eco-design, internal environmental management, environmental education, cooperation with customers, and green information systems do not affect sustainable development indicators. Meanwhile, Fransoo and Winkenbach (2024) reveal the specifics of the impact of digital technologies on the sustainable development of global supply chains through the prism of green logistics management. They analyze how the use of big data, the Internet of Things (IoT), and artificial intelligence contributes to reducing CO₂ emissions, optimizing routes, and improving waste management. The authors also emphasize the importance of integrating environmental criteria into digital platforms to achieve sustainable development in supply chains.

Visualization of scientific connections between publications (*Figure 1*) using Connected Papers (n. d.) allows us to establish that:

- green logistics is rapidly developing as a scientific field (the number of publications has significantly increased in 2023–2025);
- the central research cluster integrates various directions (ecological transport, sustainable supply chains, green technologies, green strategies, green initiatives, environmental awareness);
- the visualized network presents both foreign and domestic authors, indicating the inclusion of national research in the global discourse;
- some articles are devoted to general concepts of logistics, while others focus on specialized issues of supply chains;
- the most cited works are scientific studies related to the integration of ESG approaches into green logistics.

Despite the active development of scientific research in the field of green logistics, for trading enterprises the problem of determining the components for evaluating the effectiveness of implementing "green" practices in supply chains and strategic enterprise development remains unresolved. The efforts of theorists and practitioners are focused on studying conceptual models or mechanisms for implementing green logistics. There is no unified system of indicators for evaluation that would allow for a comprehensive consideration of: environmental outcomes (emission reduction, energy efficiency, waste disposal); economic feasibility (costs and benefits for the business); social impacts (working conditions, community influence); managerial responsibility (compliance with ESG approaches, transparency and strategic decision-making); and the possibilities of digital technologies (to enhance supply chain efficiency). This complicates the development of practical recommendations for integrating green logistics into sustainable supply chain development.

The purpose of the article is to justify the mechanism for implementing a green logistics strategy in supply chains and to reveal its role in ensuring economic efficiency, environmental safety, and the social impact of trade enterprises' operations.

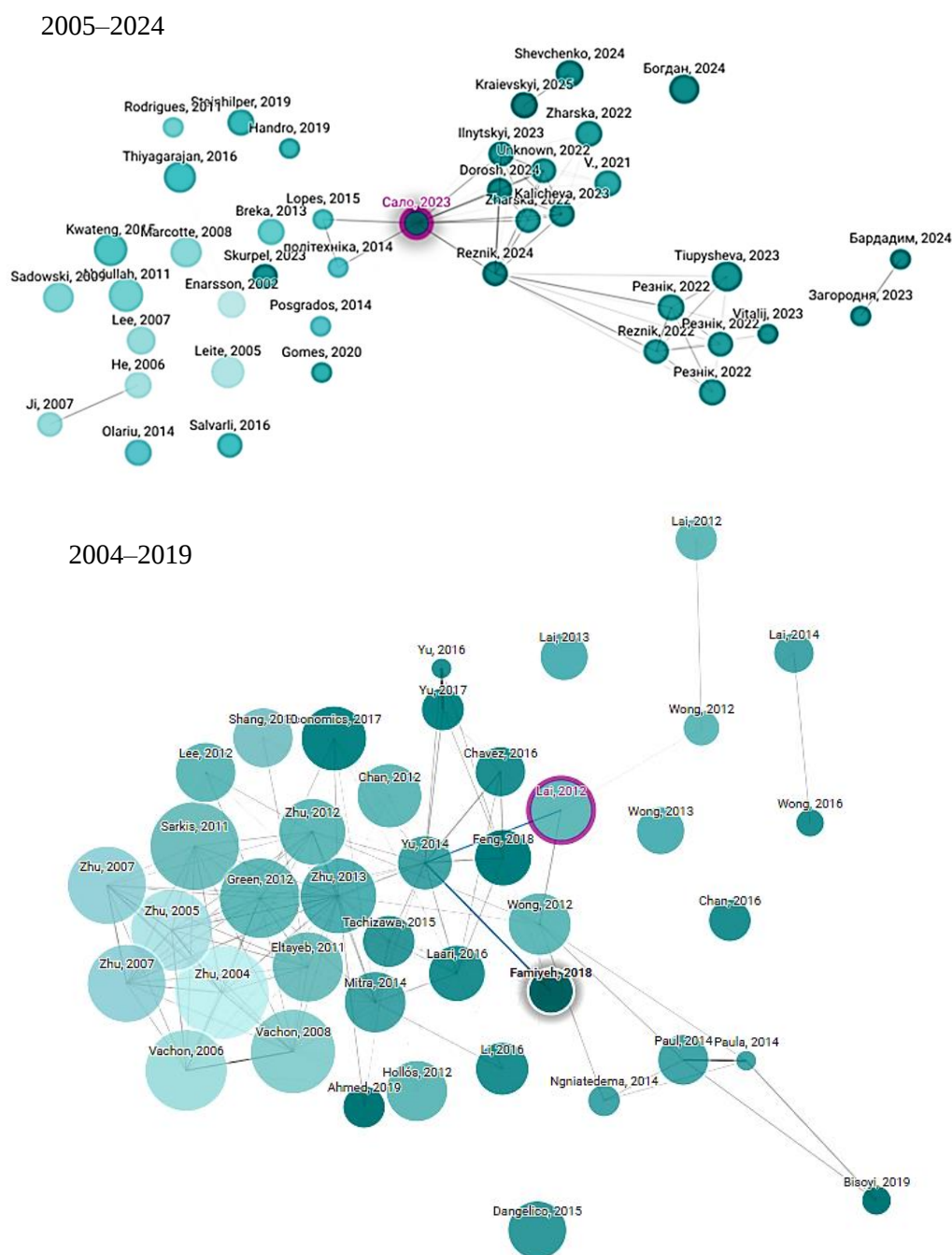


Figure 1. A fragment of the visualization of scientific connections between publications of foreign and domestic researchers

Source: compiled by the authors based on (Connected Papers, n. d.).

A hypothesis has been proposed regarding the presence of synergy between green marketing and green logistics for the formation of environmental awareness, the implementation of green initiatives, and the provision of sustainable development for trade enterprises.

The research methodology is based on the use of systemic and interdisciplinary approaches, which allow for the integration of the principles

of sustainable development, the concept of green marketing, and green logistics. Methods of theoretical generalization, comparative, and structural-logical analysis were also applied for the author's interpretation of the interrelationship between marketing and logistics green solutions.

The three sections of the main part of the article examine the essence and role of green logistics in trade enterprises, outline the key aspects of green logistics, and the environmental initiatives and strategies used by trade enterprises to enhance consumer loyalty. It is proved that green logistics is a concept of strategic development that ensures a balance between economic performance, environmental safety in supply chains, and social impact. The article analyzes the green initiatives of trade enterprises and substantiates the operational and strategic aspects of green logistics. The conditions for the effective implementation of green logistics strategies in supply chains are defined, and their impact on the economic, environmental, and social components of supply chains is studied. Special attention is paid to the methods and directions of forming environmental awareness in supply chains and the synergistic effect ensured by the interaction of green communications and green logistics, which is manifested in the formation of sustainable consumer preferences, increased environmental awareness of partners, and the stimulation of responsible behavior among supply chain participants.

1. The essence and role of green logistics in trade enterprises

For trading enterprises, green logistics has special strategic significance. Effective green logistics strategies not only enhance the efficiency of supply chain operations but also help shape a positive company image, strengthen consumer trust in the brand, and meet modern sustainable development requirements.

Ukrainian researchers, in particular Zharska (2022), establish a connection between the concept of green logistics and the concept of sustainable development, emphasizing the expediency of implementing green practices in enterprises such as green warehousing, green transportation, green packaging, and green management. The authors Skupeiko et al. (2022) note that green logistics is a kind of tool for combining the economy and ecology, which ensures increased efficiency of business activities and meeting consumer needs without harming the environment, with the main objects being material, informational, and financial flows. Researcher Salo (2023) identifies three goals of green logistics: reducing traffic, limiting pollutant gas emissions, and minimizing waste. The authors Dorosh et al. (2024) reveal the advantages of green logistics for the company, its suppliers and partners, clients, and society.

Foreign researchers Nagy and Szentesi (2024) note that companies prioritizing green logistics can significantly enhance brand reputation and meet consumer expectations. At the same time, the regular support of the government and environmental organizations in implementing green logistics is important.

The results of Khayyat's (2024) research have demonstrated that environmental awareness, organizational culture, technological readiness, government regulation, and financial support significantly influence the implementation of green logistics practices in enterprises. In turn, Kim (2024), using mathematical modeling methods, proves that the implementation of green logistics strategies ensures a combination of environmental principles and profitability, as well as coordination between the private and public sectors.

Research by scientists allows for the identification of the following common features in the implementation of green logistics tasks: minimizing the negative impact of logistics operations on the environment (reducing greenhouse gas emissions, energy efficiency, use of alternative energy sources, and waste management); optimizing supply chains (aimed at improving the efficiency of all stages of the supply chain (from raw material procurement to delivery to the end consumer), route optimization, warehousing, and packaging in accordance with environmental standards); integrating economic and social aspects (green logistics simultaneously performs economic, environmental, and social functions); forming a positive company image and consumer trust; and having a connection with the concept of sustainable development and ESG.

The distinctive features in the works of researchers on the implementation of green logistics strategy are: emphasis on different levels of application (focusing on the entrepreneurial and national levels, paying attention to global and systemic approaches; concentrating on the integration of green logistics into international supply chains and the use of innovative technologies); detailing of tools and technologies (describing specific technologies in detail, such as carbon-free transport, electric vehicles, AI logistics optimization models, or focusing on general principles, standards, and management approaches, not always resorting to specific technological solutions); different levels of emphasis on the social component (highlighting social responsibility, image, and consumer trust, or focusing on economic and environmental efficiency, with the social aspect mentioned less in detail, except for the general principles of ESG); defining the role of the circular economy and closed loops (closing resource and circular economy cycles or limiting it to waste management and material reuse, without a broad analysis of the circular economy).

The analysis results prove that green logistics in supply chains is a comprehensive concept of flow process management that ensures the integration of economic, environmental, and social principles at all stages of the movement of goods and services, starting from procurement planning and transportation and ending with the disposal or reuse of products and packaging. For trading enterprises, green logistics acquires specific characteristics dictated by the particular nature of their activities. First of all, this involves the use of environmentally safe packaging materials and the minimization of packaging waste; optimization of transport routes and implementation

of energy-efficient types of transport; application of "green" technologies in warehouses and retail spaces; introduction of energy-saving measures and reduction of carbon emissions; development of reverse logistics, which includes collection, return, reuse, and recycling of products and containers; the need to combine economic benefits, environmental responsibility, and social priorities, which allows achieving long-term competitive advantages. Operational and strategic levels of green logistics are presented in *Table 1*.

Table 1

Operational and strategic levels of green logistics

Analysis criterion	Green logistics as:	
	operational approach	strategic development concept
Purpose of implementation	Reduction of operational costs and optimization of current logistics processes	Formation of long-term resilience of logistics systems and competitive advantages
Planning level	Short-term and medium-term planning	Long-term planning
Focus	Transport, storage, packaging, energy saving	Integration of economic, environmental, and social goals into business strategies
Tools and technologies	Energy-saving technologies, route optimization, waste reduction	Eco-supply strategies, investments in renewable energy, "green" partnerships, socially responsible policy
Function for enterprises	Performs an auxiliary function in daily processes	Is a key element of strategic development and positioning
Implementation results	Resource savings and improved operational efficiency	Improving corporate reputation, attracting investors and loyal consumers, sustainable development of logistics systems

Source: developed by the authors.

Thus, green logistics in trade enterprises serves not only as a direction of operational management but also as a strategic development concept that ensures a balance between economic efficiency, environmental safety in supply chains, and social impact, which is manifested in improving consumers' quality of life, promoting responsible consumption, and strengthening reputation. It involves a set of measures and actions aimed at minimizing negative environmental impact. It encompasses logistics solutions in the areas of reducing CO₂ emissions through the use of environmentally friendly transportation, optimizing delivery routes to reduce mileage and fuel costs, implementing energy-efficient warehouse solutions, transition to biodegradable and recyclable packaging, and digitalizing processes to enhance transparency and control at all stages of the supply chain.

Rational use of natural resources and the preservation of biodiversity in supply chains are key guidelines of green logistics strategy. This involves using environmentally safe materials, optimizing packaging, minimizing energy consumption, and implementing sustainable sourcing principles, which contribute to maintaining ecological balance and long-term environmental sustainability of commercial activities. These areas have found

practical implementation in the green initiatives of retail networks, which include measures for energy efficiency, resource reuse, waste recycling, and the development of environmentally responsible supply chains (*Figure 2*).

LLC "EPICENTER K" • Use of energy-saving technologies (installation of solar power plants and providing up to 30% of shopping centers' needs with "green" energy). • Implementation of charging stations for electric vehicles (development of its own network of EV charging hubs). • Recycling of waste paper (collection and sending of cardboard and paper packaging for recycling). • Recycling of used batteries (installation of battery collection containers). • Reduction of plastic packaging and containers consumption (implementation of large-scale projects (#BagForYou and #BreakingUpWithPlastic))	LLC "SILPO-FOOD" • Operation of the "ReCycling" supermarket (equipped with solar panels, heat pumps for heating and cooling, refrigeration equipment running on CO₂). • Implementation of the Silpo Recycling project "Silpo" (includes a network of collection stations for recyclables, where consumers receive eco-points on their loyalty card for returning paper, plastic, metal, glass). • Eco-friendly delivery (order delivery using electric scooters, eco-packaging for orders). • Organic product support program (joining the international initiative Organic September). • Reusable packaging programs
LLC "ATB-Market" • Implementation of a comprehensive eco-strategy aimed at reducing plastic use and promoting a culture of responsible consumption. • Encouraging consumers to use biodegradable bags and offering plastic bags for sale. • Collection and recycling of used batteries. • Greening and forest restoration (within the framework of social and environmental projects, 30 hectares of forest were donated to six regions of the country and over 180,000 seedlings were planted). • Use of reusable eco-boxes (introduction of eco-packaging technologies and the appearance of "shopping boxes" made of durable cardboard).	LLC "NOVUS Ukraine" • Launch of its own "green" logistics center in Kyiv (the logistics center built according to BREEAM eco-building principles) • Use of biodegradable bags (made from corn and potato starch and decomposing within three years). • Installation of solar panels and solar stations. • Sorting and recycling of waste (installation of sorting locations in the network, special containers for glass, paper, plastic, and other waste, recycling of waste and expansion of the range of recyclable items)

Figure 2. Green initiatives of trade enterprises

Source: developed by the authors.

For domestic trade enterprises, green logistics is becoming increasingly important. Its tools reduce the negative impact on the environment while also serving as factors that enhance the efficiency of logistics processes. Its implementation in trade enterprises is based on the principles of efficient resource use, waste minimization, transition to renewable energy sources, and the application of innovative technologies. In particular, green transportation logistics ensures a reduction in energy consumption and operational costs through route optimization, improved quality of transportation, and decreased losses during the transportation and storage of products. Green warehouse logistics involves energy-efficient lighting and heating of warehouses, the use of automated inventory management systems to minimize losses and optimize space; environmentally responsible packaging using biodegradable and recyclable materials, as well as minimizing packaging to reduce waste; a sustainable supply chain that includes selecting suppliers with environmental certifications, reducing transportation, and prioritizing local producers to lower the carbon footprint; as well as green information logistics, which includes the digitization of processes, electronic document management, and tracking environmental indicators in supply chains to increase transparency and control of environmental impact.

2. Conditions for ensuring the effective implementation of a green logistics strategy in supply chains

The implementation of green logistics strategies in trade enterprises is an important task that will create a solid foundation for the development of environmentally conscious brands, support consumer trust, and sustain ecological reputation. The strategic objectives of green logistics are aimed at ensuring sustainable development by integrating environmental initiatives into all stages of logistics processes. One of the priority areas is the reduction of greenhouse gas emissions (CO₂, CH₄, N₂O), which is achieved through the optimization of transportation routes, the implementation of energy-efficient technologies, and the transition to the use of alternative energy sources. Decarbonization of logistics operations helps reduce the impact on global warming, which is a key factor in maintaining climate stability. In addition to reducing the carbon footprint, green logistics aims to decrease environmental pollution, particularly of the air, water resources, and soil. This is achieved through the implementation of cleaner technologies, emission control, and efficient management of harmful waste generated during the storage, packaging, and transportation of goods.

The goal of developing and implementing a green logistics strategy is to ensure the development of logistics systems by harmoniously combining economic feasibility, environmental sustainability, and social responsibility. While traditional logistics often prioritizes cost and speed, green logistics pays significant attention to environmental preservation and social responsibility. An important component of green logistics in the trade sector is also reducing waste through recycling and reuse systems for packaging materials, which helps minimize waste generation, reduce the need for primary resources, and lessen the environmental impact on landfills. This is achieved through phased planning based on the selection of environmentally responsible suppliers and procurement optimization, the implementation of energy-saving and "green" technologies in transportation and warehouses, the organization of reverse logistics and product recycling, the development of environmental awareness among employees and consumers, as well as monitoring and evaluating the effectiveness of strategy implementation.

Despite the fact that each trade enterprise chooses its own approach to implementing green logistics strategies, a number of directions can be highlighted that define its unique opportunities, including: the use of electric and hybrid vehicles; optimization of delivery routes based on modern logistics software and real-time traffic data, taking into account road conditions, weather, and customer time windows; lean inventory management; creation of energy-efficient warehouses and heating and cooling methods; use of biodegradable, compostable, or recyclable packaging materials; development of waste reduction policies and responsible waste management practices; implementation of ethical standards and building environmentally responsible

supply chains with the harmonious functioning of all participants; and the use of reverse logistics technologies.

Let's consider the main conditions that contribute to the effective implementation of green logistics strategies in the supply chains of trade enterprises.

Taking into account the requirements of international certification standards (Bondarenko & Siazin, 2024). The application of internationally recognized certification standards (ISO 14001, Fair Trade Certified, Rainforest Alliance, GOTS and PEFC) ensures the credibility of companies' environmental statements and their adherence to greening principles. The use of these standards provides a systematic approach to controlling the environmental aspects of operations, optimizing resources, reducing negative environmental impact, and increasing corporate environmental responsibility. ISO 14001 certification promotes the formalization of environmental management systems, allowing companies to integrate sustainable development principles into logistics processes, including optimization of delivery routes, warehouse energy efficiency, and management of transport flows to reduce emissions and resource consumption. The Fair Trade Certified standard provides support for corporate social responsibility and ethical trade, enabling commercial enterprises to build responsible supply chains and reduce social risks. Rainforest Alliance certification focuses on biodiversity conservation and the implementation of sustainable agricultural practices, allowing companies to choose environmentally certified suppliers and minimize the negative impact of logistics operations on natural ecosystems. The GOTS standard ensures the use of organic materials and compliance with social standards in textile production, enabling the integration of environmentally friendly products into a company's logistics flows, supporting the concept of a closed loop and waste minimization. PEFC certification ensures the legality and sustainability of forest management, allowing responsible use of timber and packaging materials, optimizing resource conservation, and maintaining environmental standards in supply chains. Thus, the implementation of these standards not only increases the level of environmental responsibility of trading enterprises but also provides practical realization of the key components of green logistics: resource optimization, emission reduction, waste management, and the creation of sustainable supply chains.

Transparency of environmental processes in supply chains. Ensuring the transparency of environmental reporting involves systematic and regular informing of supply chain participants, partners, and end consumers about the company's environmental performance indicators and environmental initiatives. The information in the reports should reflect key environmental indicators, including: rational use of water, energy, and fuel; waste volumes and greenhouse gas emissions and their dynamics; expenditures on environmental protection measures and the results of their implementation; payment of environmental taxes and rent for subsoil use; renewal of fixed assets

considering their impact on energy efficiency and reduction of environmental load; and expenses for implementing environmental initiatives. This approach allows for increasing the transparency of logistics processes, strengthening the brand's reputation as a socially and environmentally responsible business entity, and also encourages partners and suppliers to adhere to the principles of green logistics.

Access to independent sources of control and audit. Ensuring access to independent sources of control and auditing is an important tool for implementing green logistics strategies in supply chains. This approach involves the introduction of external and internal systems for checking environmental practices, which allows for the assessment of the compliance of a company's actual activities with established standards and certification requirements. This area includes external audits, internal control and monitoring, transparency of audit results, and analytical use of audit report data.

The activation of the use of digital technologies by enterprises. This concerns the following areas:

- optimization of transportation routes: the use of Big Data and Artificial Intelligence (AI) allows for demand forecasting and selecting optimal delivery routes. This reduces vehicle mileage, lowers fuel costs, and cuts CO₂ emissions;
- ensuring intelligent warehouse and inventory management (warehouse management systems (WMS) with analytics help to plan inventory volumes more accurately and avoid excessive transportation. This will reduce the frequency of transportation and unnecessary cargo movements, which will lower energy consumption and greenhouse gas emissions;
- the integration of IoT (Internet of Things) and sensors allows real-time tracking of vehicle conditions, loading, and cargo temperature. As a result, it ensures more accurate planning, reduces losses and product returns, which decreases additional transportation and emissions;
- promoting "green" solutions in supply: digital platforms enable consideration of environmental criteria when selecting suppliers and transport operators. For example, by choosing a supplier with a lower carbon footprint or vehicles with low emissions, companies directly reduce the overall emissions of the supply chain.
- reverse logistics and recycling: digital technologies enable the efficient organization of reverse flows of goods and waste. This increases recycling rates, reduces the need for new materials, and lowers emissions associated with production and disposal.

Resource optimization and waste management. The rational use of materials, energy, and water resources, along with the implementation of policies for waste reduction, reuse, and recycling, ensures the minimization of environmental impact based on the creation of energy-efficient warehouses, optimization of packaging, sorting, and reuse of materials.

Partnership with environmentally responsible supply chain participants. Cooperation with participants who adhere to principles of sustainable development and ethical standards allows for the formation of a more

resilient supply chain. Assessing environmental practices and integrating environmental criteria into operations ensures that all stages of the logistics process are aligned with the principles of green logistics.

Increasing the environmental awareness of participants in supply chains. In this aspect, the participants include not only the enterprise's external contractors but also the employees of the enterprise, since their actions and decisions directly affect the effectiveness of implementing green logistics strategies. Regular training of personnel on the principles of green logistics, environmental standards, and ethical resource management practices contributes to the formation of a socially responsible corporate culture. This ensures the effective implementation of environmental initiatives in daily operational activities and supports the enterprise's strategic goals in the field of green logistics.

Thus, the effectiveness of green logistics strategies in commercial enterprises lies in their ability to integrate economic benefits, environmental feasibility, and social priorities, forming the foundation for long-term sustainable development.

3. Environmental awareness in supply chains

Environmental awareness in supply chains encompasses a range of aspects. In particular, it involves assessing environmental indicators, applying international certification standards to optimization of transportation flows, enhancing warehouse energy efficiency, managing waste, and implementing digital technologies for controlling and monitoring logistics processes. It ensures not only compliance with environmental regulations but also enhances brand reputation, strengthens consumer and partner trust, and creates preconditions for the economic, environmental, and social sustainability of the enterprise.

According to the Deloitte report (2025), environmental issues continue to shape the behavior of Generation Z and Millennials. The environment is a constant source of concern for these generations: about two-thirds of Generation Z (65%) and Millennials (63%) reported feeling worried or anxious about environmental issues over the past month. These concerns directly influence their consumer choices: for instance, nearly two-thirds of respondents indicate a willingness to pay more for environmentally sustainable products and services. Environmental considerations also affect career decisions – around 23% of Generation Z and 22% of Millennials report that they research a company's environmental impact or policies before accepting a job offer.

An important role in this process is played by green marketing, which encourages consumers to choose environmentally friendly products and services, as well as raises business partners' awareness of the need to comply with environmental standards. On the other hand, green logistics ensures the effective management of material and product flows taking into account environmental criteria, such as minimizing CO₂ emissions, optimizing transportation routes, and reducing waste. The integration of green supply

chain management (GSCM) practices and environmental consciousness significantly improves the sustainable performance of enterprises, particularly through the influence of green marketing and environmentally oriented processes (Rizki et al., 2022). At the same time, green logistics practices positively affect the operational and financial efficiency of companies while promoting the development of corporate environmental awareness (Sarkis & Zhu, 2024).

Therefore, the main areas for implementing effective green logistics strategies in supply chains are:

Organization of environmental activities. Organizing training sessions and seminars for employees and partners on green logistics practices, including energy-efficient transportation, route optimization, and waste and resource management. This will help align green logistics strategies with consumer expectations and the capabilities of companies to meet them.

Sponsorship and participation in environmental initiatives. This area concerns the support of environmental programs and partner projects. It promotes the development of sustainable environmental practices throughout the supply chain and is ensured through participation in environmental initiatives and the exchange of best green practices. The success of its implementation affects the enhancement of brand reputation by demonstrating its environmental responsibility.

Green distribution and transport. This area involves planning optimal delivery routes taking into account environmental criteria to reduce CO₂ emissions and fuel costs, using energy-efficient or alternative transport (electric vehicles, hybrid trucks, biofuels), using appropriate transport management systems to monitor and control the environmental performance of transportations; implementing reverse logistics and packaging management for recycling and reuse of resources.

Green procurement and production. Key actions include the rational selection of suppliers with certified environmental standards and low emissions, the use of materials with minimal environmental impact and energy-efficient equipment in production, and the implementation of Lean Green Logistics policies to reduce waste and optimize the resource use.

Digital monitoring and analytics. To track emissions, optimize logistics flows, and control energy consumption, it is reasonable to use IoT, big data, and analytical platforms. Monitoring the environmental indicators of supply chain participants is the foundation for ensuring compliance with corporate sustainability standards and supporting transparent communication.

Green marketing and communications. They foresee systematic informing of supply chain participants and end consumers about the environmental characteristics and benefits of products, including components of green logistics such as "green delivery", carbon footprint reduction, and rational use of resources. Effective implementation of green marketing strategies is aimed at stimulating demand for environmentally safe products, increasing consumer environmental awareness, and forming a positive perception of the brand as socially responsible and environmentally oriented.

For this, it is necessary to use comprehensive marketing measures, including green campaigns, educational programs, digital and social communication platforms, as well as transparent messages about the environmental initiatives of enterprises. In particular, green marketing initiatives and communication strategies that emphasize the environmental characteristics of products and the transparency of company actions motivate businesses to implement more efficient and environmentally safe logistics processes. This approach not only helps to enhance consumer loyalty but also strengthens brand reputation, ensuring its competitiveness in a market where environmental responsibility is becoming an important factor in consumer choice.

Green branding is becoming particularly significant as a key factor in ensuring sustainable business development and achieving leadership positions in the trade sector. In the context of growing consumer expectations and strengthened regulatory requirements for environmental processes, companies that integrate the principles of green branding into their activities are competitive. Brands that implement ecological values not only in their communication messages but also in their corporate culture are capable of ensuring high competitiveness and achieving successful development.

Clear formulation of a brand's green communications involves presenting the environmental characteristics of products and logistics practices in a straightforward and accessible manner in marketing messages, which helps build trust among consumers and partners and strengthens the image of a responsible brand. Green marketing communications convey the values of sustainable development to consumers and promote the practical implementation of eco-friendly logistics solutions in supply chains, while increasing environmental awareness among all participants in these processes becomes the foundation for their effective and responsible interaction.

Thus, under conditions of long-term strategic development, it is environmental awareness that will determine the level of competitiveness of enterprises, as consumers increasingly prefer brands with transparent and sustainable logistical practices. Furthermore, eco-consciousness contributes to the harmonization of economic, social, and environmental interests, ensuring balanced business development and the preservation of the environment.

Conclusions

The implementation of green logistics strategies in supply chains is an important task for trade enterprises that aim to build long-term relationships with consumers, create a positive customer experience, and ensure sustainable development. Applying the principles of green logistics and optimizing logistics operations will help reduce the negative impact of trade activities on the environment and decrease pollution of air, water, and soil. Effective waste management systems at the stages of storage, packaging, and transportation of goods allow for the reduction of harmful waste and ensure the efficient use of resources. Implementing practices for recycling and reusing packaging

materials reduces the need for primary resources and lessens the environmental burden on landfills.

Green logistics strategies should provide for the integration of environmental initiatives at all stages of the supply chain. One of the priority areas is the reduction of greenhouse gas emissions (CO₂, CH₄, N₂O), which can be achieved through the optimization of transportation routes, the implementation of energy-efficient technologies, and the transition to the use of alternative energy sources.

The formation of ecological awareness among participants in supply chains requires the coordination of green marketing initiatives with logistical solutions. The hypothesis of a synergistic effect from the interaction of green communications and green logistical solutions has been proven, manifesting in the development of sustainable consumer preferences, increased ecological awareness among partners, and the stimulation of responsible behavior among supply chain participants.

The implementation of green logistics strategies in trading enterprises requires the development of unified standards and methods for evaluating environmental indicators; the formation of a standardized system of indicators for an objective comparison of results between enterprises and types of economic activity; the assessment of indirect environmental impacts and the contribution of individual stages of the logistics chain to overall environmental performance; ensuring reliable information, systematic accumulation, monitoring, and reporting; and the integration of economic, environmental, social, and technological criteria into the overall supply chain management system.

The implementation of these measures will enable trading enterprises to reduce environmental risks, increase the efficiency of logistics processes, strengthen competitive positions, and create additional value for each participant in the supply chain.

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DRIVERS OF NEW PRODUCT ENVIRONMENTAL PERFORMANCE UNDER UNCERTAINTY

The impact of business income, innovations, and urban population on the environmental indicators of new products has been investigated. In this context, the uncertainty of economic policy and external shocks such as COVID-19 are taken into account as moderating factors to assess whether external shocks disrupt the sustainability of new products. The panel data from 30 Chinese provinces for the years 2013 to 2024 were analysed using a two-step GMM regression system. (GMM – Generalized Method of Moments in statistics and econometrics). The analysis results highlighted the negative role of income from the main business and urban population on the environmental

РУШІЙНІ СИЛИ ЕКОЛОГІЧНОЇ ЕФЕКТИВНОСТІ НОВОГО ПРОДУКТУ В УМОВАХ НЕВИЗНАЧЕНОСТІ

Досліджено вплив доходів бізнесу, інновацій та міського населення на екологічні показники нових продуктів. При цьому невизначеність економічної політики і зовнішні шоки на кшталт COVID-19 враховуються як пом'якшувальні фактори для оцінки того, чи порушують зовнішні шоки сталий розвиток нових продуктів. Проаналізовано панельні дані 30 китайських провінцій за 2013–2024 рр. за допомогою двоетапної системи регресії GMM (GMM – узагальнений метод моментів у статистиці й економетриці). Результати аналізу свідчать про негативний вплив доходів основного бізнесу та міського населення на екологічні показники нових продуктів,



indicators of new products, while innovations exhibit a positive influence. In addition, EPU (EPU – Economic Policy Uncertainty) plays a positive moderating role, but at the same time demonstrates a negative impact on the relationship between innovations and the environmental indicators of new products. It has been found that the moderating influence of COVID-19 is significantly positive. Considering the political implications, businesses should ensure that profitability does not come at the expense of sustainability. There should be a balance between financial goals and environmental issues. Additionally, the government should tackle uncertainty in economic policy, as stable policy can stimulate the development of green products.

Keywords: environmental indicators, urban population, innovations, economic policy uncertainty, two-step GMM system.

моді як інновації відбиваються позитивно. Крім того, EPU (EPU – невизначеність економічної політики) відіграє позитивну пом'якшувальну роль, але водночас демонструє негативний вплив на зв'язок інновацій з екологічними показниками нових продуктів. Встановлено, що пом'якшувальний вплив COVID-19 є доволі позитивним. З огляду на політичні наслідки, підприємствам слід переконатися, що досягнення прибутковості не відбувається через сталий розвиток. Має бути баланс між фінансовими цілями та заходами з вирішення екологічних проблем. Крім того, уряд має подолати невизначеність в економічній політиці, оскільки стабільна політика може стимулювати розвиток екологічних продуктів.

Ключові слова: екологічні показники, міське населення, інновації, невизначеність економічної політики, двоетапна система GMM.

JEL Classification: C12, D80, O47, Q21.

Introduction

Adopting environmentally sustainable methods in the products development has become paramount in today's business landscape. The growing concerns about climate change and environmental degradation have forced the businesses to adopt eco-friendly production (Fernando & Wah, 2017; Warner et al., 2009). Environmental performance of new products (EPNP) relates to the capability of newly developed products to influence the level of environmental sustainability at all stages of the product life cycle (Zhang et al., 2022; Xie et al., 2019). Achieving high EPNP is crucial from a compliance perspective to reduce environmental and respond to customers' increasing demand for sustainable products. The adoption of an environmental sustainability approach could therefore, be appealing to businesses who wish to introduce their new products in the market under the eco-friendly "green" label (D. Wang et al., 2023; Deng et al., 2022; Ranjbari et al., 2021). Businesses cannot make informed decisions regarding the environmental performance of new products without a reliable, cutting edge and advanced life cycle assessment (Xie et al., 2019). Otherwise, this could lead to financial burden for businesses, ambiguity for customers, and a potentially missed opportunity to endorse genuinely green products that uphold environmental integrity (Popp et al., 2011). Main business income (MBI) refers to measurements of revenues and profitability that determine the likelihood of businesses to finance sustainable initiatives and develop environmentally friendly product designs (Fernando & Wah, 2017; Guoyou et al., 2013). Liu et al. (2009, January) have pointed out that the EPNP is improved when environmental considerations are integrated into the product life cycle, and profitable businesses possess the resources and strategic direction necessary to do so. Previous studies argued that businesses with strong financial

positions have better environmental performance because these businesses can afford investments in green technologies and meet environmental standards (Deng et al., 2022; Farza et al., 2021).

Likewise, industrial innovations (INO) contribute to the improved efficiency and production of new products that have lesser ecological impacts (Blichfeldt & Faullant, 2021). The effective number of innovation patents and high R&D expenditures are the firm's long-term sustainable strategies for production and remaining market competitiveness. The literature highlights technological developments as critical to attaining better environmental performance because innovative businesses efficiently adopt eco-friendly technology and processes (Horbach et al., 2012; Cainelli et al., 2015). Similarly, the increase in population density in urban areas has both beneficial and deleterious effects on the EPNP. Urbanization is often linked with higher levels of product consumption and this may lead to environmental degradation if not appropriately managed. But there is also a positive side, as the urban areas are the sources of the ideas and practices related to sustainable product development (Stark et al., 2017). Therefore, these urban areas drive the economy of scale in sustainable production and distribution systems, which boosts the EPNP. Also, consumers in urban areas are more conscious and raise concerns about environmental causes, which in turn creates pressure on businesses to adopt sustainable practices (He et al., 2023; Gao et al., 2023; Hussain et al., 2020).

Economic policy uncertainty (EPU) can harm the management of businesses in the formulation of environmental strategies related to green innovations thereby, dissuading businesses from investing in sustainability programs. Because of unpredictability in policy changes, businesses may prioritize immediate financial stability rather than environmental objective (Latan et al., 2018). On the other hand, the COVID-19 pandemic increased awareness of global risks, which spurred businesses to make more concrete environmental pledges (Rume & Islam, 2020; Ranjbari et al., 2021). Therefore, CSR theory insists that businesses have a responsibility to benefit society and the environment beyond profit maximization. It proposes that businesses must incorporate social and environmental responsibilities into their management and production processes. Businesses with high financial performance should invest more capital in the research and development of green products that can prove their CSR commitment (Bhardwaj, 2016). Furthermore, according to real options theory, product innovations can be seen as the real options for the businesses. These innovations create the chances of responding to shifts in potential environmental regulations and consumer preferences. Consequently, the businesses with increased levels of innovative competence are likely to have the capability to create eco-friendly products, which in turn can be considered as the exercise of the real options.

We have selected China for empirical investigation because its social objectives (environmental and climatic conditions) were negatively impacted by its massive production-oriented focus during the early globalization phase. China's environmental crisis, which has been caused by several decades of

industrialization, does not only endanger people's lives and health in this country but also the global fight against climate change (Gao et al., 2023). The Chinese government is very active in encouraging innovation and production of new products, as evident in the "Made in China 2025" policy (Wübbeke et al., 2016; Zenglein & Holzmann, 2019). With the growing concerns over the effects of products on the environment, China has formulated sound environmental policies and measures to improve the environmental attributes of new products and services (Zhang et al., 2021; Liu et al., 2021) through its renowned slogans "Harmonious Society" and "Greener GDP". Chinese businesses are also increasing their investments towards research and development to create and introduce better innovative and sustainable products in the global markets (Hussain et al., 2025; Xu et al., 2020). However, China has started some actions that would help reduce emissions and halt further degradation of the environment like the ratification of the Paris Agreement on Climate Change 2015.

Thus, in this study, we examine the data of Chinese provinces to assess the outcomes of main business income, share of the urban population, and industrial innovations on the environmental performance of new products. Besides this, we innovatively introduced a unique concept by introducing EPU and COVID-19 as moderating factors.

Therefore, the purpose of our study is to determine whether EPU and COVID-19 can modify the above-mentioned relationships.

For our analysis, we methodologically relied on two-stage systematic GMM regression due to the panel nature of the data set of this study and to address the endogeneity problem. The results of this study will help enterprises formulate appropriate policies to improve the environmental performance of their new products.

In the current business research, the relationship between business income and environmental performance has gained significant attention. Implementing green production processes in new product development bring value and enhance business productivity. Eco-friendly innovation significantly improves the environmental performance of new products. Therefore, financially stable businesses inclined to invest more in green innovations (Deng et al., 2022). According to Fernando and Wah (2017), businesses with strong financial performance are better equipped to integrate green practices and technologies. This integration enables them to pursue environment strategies in product development. Guoyou et al. (2013) conducted a study on Chinese businesses and found that financially sound businesses often invest in R&D to manufacture products that meet environmental standards. Empirical studies suggest that businesses benefit from higher returns and improved reputation because of eco-friendly initiatives. Hence, according to Farza et al. (2021), businesses that engage in green practices in their operations enjoy increased customer loyalty and a better market image. It ultimately leads to increased sale of new products and profitability. Based on the following discussion, we hypothesize that:

H1. Main business income positively influences the environmental performance of new product.

The industrial innovations are instrumental in the development of products that are environmentally friendly. The green technologies and eco-innovations emphasize the integration of environmental aspects into R&D activities. These integrations make new green innovations highly effective in the reduction of the environmental impact of new products. Horbach et al. (2012) discussed that through their R&D activities, businesses possess the capability to produce lesser ecological harmful products. Also, Cainelli et al. (2015) found that businesses with strong R&D ingenuities and investments develop products that have high ecological efficiency R&D enables these businesses to set up new technologies and practices and manufacture products that have lower effects on the environment. Similarly, the firm's ability to innovations and commitment to environmental sustainability is assessed by the effective number of its invention patents. Green patents are especially essential because they highlight the firm's efforts for innovations to tackle ecological challenges (Popp et al., 2011). Oyebanji et al. (2022) focused on the Spanish industries and stated that if the businesses have innovation patent, they better perform environmentally. These green innovation patents have a very direct implications towards the environmental sustainability of the new products. These patents also include efficient energy utilization and the use of environmentally friendly resources. Based on the following discussion, we hypothesize that:

H2. Industrial innovations positively influence the environmental performance of new products.

Population density in urban areas causes an upsurge of resource utilization and the production of waste that puts pressure on the environment. He et al. (2023) revealed that environmental performance generally worsened since urbanization increases transport and industrial activities which, result in an increase in greenhouse gas emissions. Rapid urbanization accelerates the pressure and exploitation of natural resources and causes the environmental pollution. Cheng and Hu (2023) conducted a study on China and found that urban areas cause CO₂ emissions, especially developed and resource-based cities. But urbanization is also capable to diminish the negative impacts on ecology by promoting green innovations. Gao et al. (2023) experienced China's Innovation Pilot City (IPC) project and revealed that innovative city construction enhances environmental performance through stimulating technological advancements and restructuring industrial processes. Further, Pera (2020) investigated 153 published articles on the environmental sustainability performance of urban systems and revealed that green innovation initiatives in urban areas enhance environmental sustainability. The findings further indicate that urban growth, backed by strict ecological policies, can help to reduce the negative effects of urbanization on the environment. Based on the following discussion, we hypothesize that:

H3. Urban population positively influences the environmental performance of new products.

Economic policy uncertainty can impact businesses' operations and management, especially regarding environmental sustainability. High EPU may incline the businesses to focus more on short-term financial gains rather than long-term

sustainability projects. This situation also reduces efforts towards embracing sustainable green practices, hence developing products that could be a nuisance to the environment (Qureshi et al., 2023). Similarly, Jiang et al. (2019) concluded that when faced with EPU, businesses are willing to give up on projects for industrial innovations that would enhance environmental performance because of being directed to utilize such resources to manage uncertainty. He et al. (2020) noted that businesses cut their environmental investments during high EPU in order to concentrate their efforts on crucial business operations. Moreover, Demir and Ersan (2017) observed the BRIC countries and found that businesses hold more cash to shield against uncertainty hence leaving limited funds for environmental projects. Based on the following discussion, we hypothesize that:

H4. The moderating role of economic policy uncertainty is significant.

The ethical position adopted during the pandemic enables the businesses to perform better on the environmental front because stakeholders expect the businesses to be more environmentally responsible during crises (Al Amosh & Khatib, 2023; Obrenovic et al., 2020). Urban areas, because of dense population and resource utilization on a large scale have majorly impacted during COVID-19 pandemic. This has prompted the urban areas to adopt sustainable environmental policies. According to Gong et al. (2020), urban areas that have competent governance have done well economically and ecologically in the COVID-19 pandemic. In addition, during the pandemic, Rehman and Yaqub (2021) discovered that businesses increased their innovative abilities with the application of modern technologies, thereby helping to enhance environmental performance. Furthermore, Thomas et al. (2022) revealed that businesses that have adopted sustainable green innovations to manage their operations have been able to satisfy regulatory requirements and foster stakeholders' expectations. Based on the following discussion, we hypothesize that:

H5. The moderating role of COVID-19 is significant (Figure 1).

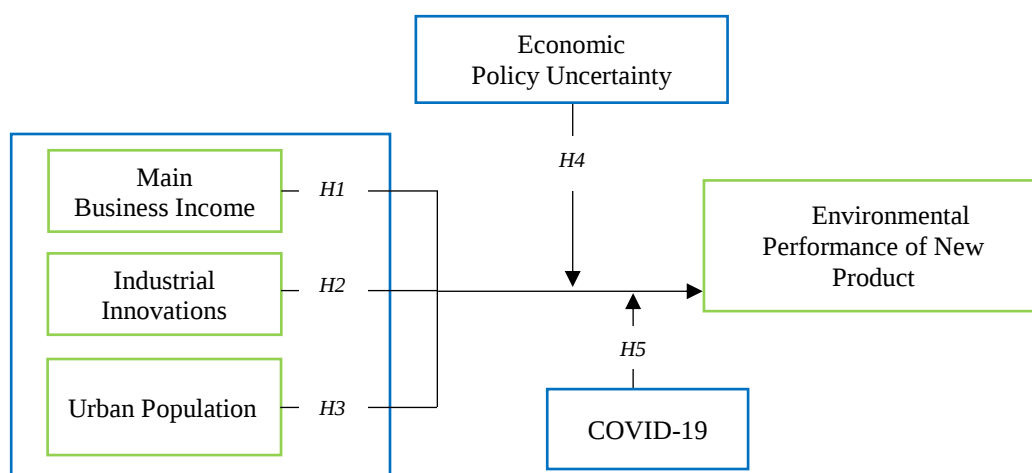


Figure 1. Conceptual Framework

Source: developed by the authors.

Research Methodology. To examine the nexus between the main business income, industrial innovations and urban population and new products' environmental performance, we have selected Chinese data over the years 2013 to 2024. The sample involves using panel data from 30 provinces, and data has been collected from China's Statistical Yearbook, High-tech Statistical Yearbook, and Energy Statistical Yearbook databases. The environmental performance of new products is an independent variable in this study, calculated as dividing the data of new product sales by total energy consumption. Further, the main business income, industrial innovations and urban population are the independent variables.

We included economic policy uncertainty and COVID-19 as moderator variables. The data of EPU was extracted from a news-based EPU index developed by Baker et al. (2016) based on the South China Morning Post. EPU is a national level variable. However, we have used it as panel data at the provincial level. We replicated the EPU values for each province by adhering to the method suggested by Adil et al. (2025). COVID-19 is included as a binary variable to gauge the impact of the COVID-19 pandemic on the environmental performance of new products. *Table 1* provides the further description of study variables along with their acronyms.

Econometric Model. By scrutinising the impact of main business income, industrial innovations and urban population on the environmental performance of new products, we used the following baseline regression models with year and region effects.

$$EPNP_{i,t} = \alpha + \beta_1(MBI_{i,t}) + \beta_2(INO_{i,t}) + \beta_3(UP_{i,t}) + \beta_4(EPU_{i,t}) + \beta_5(COVID - 19_{i,t}) + \varepsilon_t. \quad (1)$$

$$EPNP_{i,t} = \alpha + \beta_1(MBI_{i,t}) + \beta_2(INO_{i,t}) + \beta_3(UP_{i,t}) + \beta_4(EPU_{i,t}) + \beta_5(COVID - 19_{i,t}) + \beta_6(MBI \cdot EPU_{i,t}) + \beta_7(INO \cdot EPU_{i,t}) + \beta_8(UP \cdot EPU_{i,t}) + \varepsilon_t. \quad (2)$$

$$EPNP_{i,t} = \alpha + \beta_1(MBI_{i,t}) + \beta_2(INO_{i,t}) + \beta_3(UP_{i,t}) + \beta_4(EPU_{i,t}) + \beta_5(COVID - 19_{i,t}) + \beta_6(MBI \cdot COVID - 19_{i,t}) + \beta_7(INO \cdot COVID - 19_{i,t}) + \beta_8(UP \cdot COVID - 19_{i,t}) + \varepsilon_t. \quad (3)$$

Equation 1 highlights the impact of main business income, industrial innovations, urban population, economic policy uncertainty and COVID-19 on the environmental performance of new products. While equations 2 and 3 present the separate interaction terms of EPU and COVID-19 to gauge the moderating influence of economic policy uncertainty and COVID-19 on the relationship of main business income, industrial innovations, and urban population with environmental performance of new products. The main study model has been given in *Table 1*.

Table 1

Variables elucidation

Variable	Acronym	Description
Main business income	MBI	The primary revenue generated by enterprises within a province from their core business activities
Industrial innovations	INO	Advancements in technology and industrial processes based on R&D expenditures and effective number of innovation patents
Urban population	UP	The proportion of population residing in urban areas
Environmental Performance of new products	EPNP	The environmental efficiency of all newly developed products in industries, calculated as new product sales divided by total energy consumption
Economic policy uncertainty	EPU	Measures the level of uncertainty in economic policy based on South China Morning Post newspaper articles
COVID-19 pandemic	COVID-19	Binary variable indicating 1 during the pandemic and 0 otherwise

Source: developed by the authors.

The first section of the main part of the article presents the descriptive statistics used in the study; the second section presents their interpretation taking into account pairwise correlation and variance inflation factor; and the third section presents the main empirical results of the two-stage GMM regression.

Results

1. Descriptive statistics

Table 2 provides the descriptive statistics of all the variables being studied, including the number of observations, mean, median, standard deviation, and ranges of values (minimum and maximum).

Table 2

Descriptive statistics

Variable	Obs	Mean	Std.Dev	Min	Max
EPNP	360	0.087	0.732	0.000	11.960
MBI	360	7.207	1.703	2.708	10.823
INO	360	7.222	2.073	0	12.510
UP	360	57.048	12.773	29.89	89.6
EPU	360	178.712	102.282	92.114	390.388
COVID-19	360	0.166	0.373	0	1

Source: calculated by the authors based on the study data.

The balanced dataset consists of 360 observations from 30 provinces of China between the years 2013 to 2024. According to our analysis, the mean value of EPNP is 0.087, indicating the low environmental performance of new products because of insufficient focus on environmental factors during product development. The MBI has mean value of 7.207, suggesting

that businesses in all sampled provinces of China are generating a moderate level of revenue, which is a sign of sound profitability. The INO also has a moderate level mean value of 7.222, indicating a strong focus on innovations, which may be due to competitive pressure and technological progressions. Further, our findings show that the mean value of UP is 57.048, with a standard deviation of 12.773. The mean value of EPU is 178.712, indicating the strong influence of economic policy uncertainty on the strategic planning of the businesses due to unpredictability and instability of policy changes. Meanwhile, the mean value of COVID-19 is 0.166, showing a relatively low influence of the COVID-19 pandemic.

2. Pairwise correlation and variance inflation factor

Figure 2 reports the regression results of pairwise correlation analysis, showing the strength and direction of the linear relationship between study variables. Also, high correlation values between variables with large coefficients indicated the presence of multicollinearity. Tackling and managing high correlation between variables is crucial in order to obtain precise results and might involve omitting variables that exhibit high correlation.

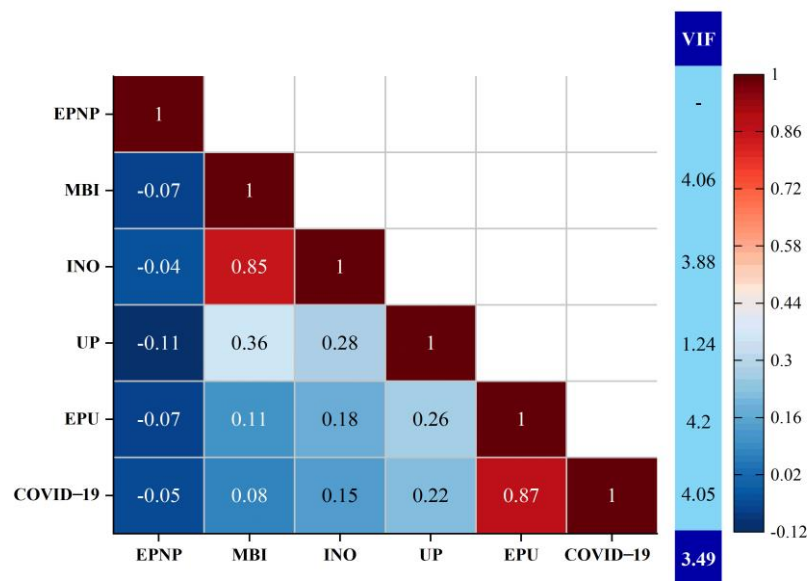


Figure 2. Pairwise correlation and VIF results from authors' computations

However, in our case, the correlation values between the study variables are within permissible limits, and there is no such issue of multicollinearity. In addition to our inspection of pairwise correlations, we also undertaken the VIF test to validate our apprehension about multicollinearity. Based on Studenmund (2014), a variable may face multicollinearity problems if its VIF value exceeds 10. The findings from our VIF test are encouraging, as the average VIF value for all variables is below 10. This result indicates that multicollinearity is not an issue in our model.

Further, *Table 3* notifies the outcomes of unit root analysis.

Table 3

Findings of unit roots tests

Variable	Im-Pesaran-Shin		Harris-Tzavalis	
	Level	First Difference	Level	First Difference
EPNP	−3.4740*	−8.3729*	0.2622*	−0.5020*
MBI	−3.5060*	−3.3868*	0.8362	0.2914*
INO	15.9795	−4.9827*	1.0870	0.4553*
UP	9.6746	−5.0645*	0.9981	−0.1282*
EPU	14.8911	−3.9339*	1.1018	0.5844*
COVID-19	7.3720	−7.1267*	0.9000	−0.1111*

Source: authors' own computations. Asterisk (*) denotes significance at the 1% level.

The findings confirm that all variables are stationary at first difference with significant p-values at 1%.

3. Main empirical results of two-step gmm regression

Table 4 reports the findings of the two-step system GMM regression. In Model 1, the MBI has been found to be negatively impacted the environmental performance of new products as indicated by coefficient ($\beta_{MBI} = -0.2417^*$).

Table 4

Findings of two-step sys

Variable	Model 1	
	Coefficient	p-value
L.EPNP ¹	−0.1086*	0.000
MBI	−0.2417*	0.000
INO	0.0473*	0.000
UP	−0.0022*	0.000
EPU	−0.0192*	0.000
COVID-19	0.0240*	0.000
Instruments	72	
Sargan test	29.284	0.819
AR (1)	0.057	
AR (2)	0.381	

Source: authors' own computations. Asterisk (*) denotes significance at the 1% level.

Ambec and Lanoie (2008) argued that the focus of high revenue in traditional business lines sometimes result in insufficient concentration in the development of eco-friendly products. Also, businesses choose cheaper and less environmentally friendly options in product design and manufacturing. It results in the introduction of products into the market that cause ecological

¹ "L" of the dependent variable in GMM regression typically refers to its lagged value.

problems during their lifecycle (Trumpp & Guenther, 2017). Upon this finding, we reject the initial hypothesis *H1*, which suggests a positive link. Moreover, industrial innovations have been found to be positive and significant impact on EPNP in the results, as indicated by the coefficient value ($\beta_{INO} = 0.0473^*$). Innovations contribute positively by forming the basis of green technologies and processes that help to manufacture eco-friendly products. For instance, Horbach et al. (2012) and Oyebanji et al. (2022) found that a rise in R&D expenses could lead to the attainment of energy-efficient manufacturing methods and the production of energy-efficient products. These findings also support our hypothesis *H2* which implies positive correlation between INO and EPNP. Further, the findings indicated the adverse impact of the urban population on the EPNP with a coefficient ($\beta_{UP} = -0.0022^*$). York et al. (2003) found that the higher resource consumption and waste generation urban areas cause environmental problems and also hinder eco-innovations. In a similar vein, Grimm et al. (2008) pointed out that the high demand pressures diminished the efficiency of sustainable product development. Based on this finding, we reject our hypothesis *H3* which suggests a positive association between UP and EPNP.

Table 5 reports the findings of interaction terms with EPU as a moderator.

table 5

findings of two-step system GMM with interaction of EPU

Variable	Model 2	
	Coefficient	p-value
L.EPNP	-0.1308*	0.000
MBI	0.0097	0.381
INO	-0.4797*	0.000
UP	0.0238*	0.000
EPU	-0.1494**	0.032
COVID-19	-0.0079*	0.000
MBI · EPU	-0.0539*	0.000
INO · EPU	0.1098*	0.000
UP · EPU	-0.0053*	0.000
Instruments	75	
Sargan test	23.431	0.781
AR (1)	0.090	
AR (2)	0.201	

Source: authors' own computations. Asterisk (*) denotes significance at the 1% level.

Our analysis discovered that EPU negatively moderates the relationship between MBI and EPNP, as indicated by the coefficient ($\beta_{MBI \cdot EPU} = -0.0539^*$). The findings show that the upsurge in EPU caused businesses to reduce their use of eco-friendly practices in product development. He et al. (2020) noted that businesses cut their environmental investments during high EPU in order to concentrate their efforts on crucial business operations. Moreover, Demir and Ersan (2017) observed the BRIC

countries and found that businesses hold more cash to shield against uncertainty hence leaving limited funds for environmental projects. However, we found the positive moderating role of EPU in the association between INO and EPNP, as indicated by the coefficient ($\beta_{\text{INO} \cdot \text{EPU}} = 0.1098^*$). Aghion et al. (2016) argued that during uncertain situations, businesses pursue eco-innovations to mitigate risks and gain a competitive edge in the market. Similarly, Lee et al. (2014) confirmed that businesses invest in sustainable product innovations to differentiate themselves and comply with evolving standards in times of EPU. While, we discovered that EPU has a negative moderating effect on the association between UP and EPNP, as demonstrated by the coefficient ($\beta_{\text{UP} \cdot \text{EPU}} = -0.0053^*$). According to Baker et al. (2016) EPU triggers decreases in R&D spending within environmentally sensitive sectors thus urban areas usually known for innovation show inferior environmental outcomes in times of policy unpredictability. Based on these above findings of EPU as a moderator, we accept our hypothesis *H4* that EPU's moderating role is significant.

Furthermore, *Table 6* reports the findings of interaction terms with COVID-19 as a moderator. Our analysis discovered that COVID-19 positively moderates the associations of MBI and INO with EPNP, as indicated by the coefficients ($\beta_{\text{MBI} \cdot \text{COVID-19}} = 0.0911^*$) and ($\beta_{\text{INO} \cdot \text{COVID-19}} = 1.5206^*$), respectively.

Table 6

Findings of two-step system GMM with interaction of COVID-19

Variable	Model 3	
	Coefficient	p-value
L.EPNP	-0.1235*	0.000
MBI	-0.2308*	0.000
INO	0.0284*	0.000
UP	0.0009	0.899
EPU	-0.0084*	0.000
COVID-19	-0.7163*	0.000
MBI · COVID-19	0.0911*	0.000
INO · COVID-19	1.5206*	0.000
UP · COVID-19	0.0013**	0.024
Instruments	75	
Sargan test	19.35	0.336
AR (1)	0.020	
AR (2)	0.151	

Source: authors' own computations. Asterisks indicate significance at 5% (**) and 1% (*), respectively.

Obrenovic et al. (2020) highlighted that COVID-19 pandemic heightened global awareness about the ecological challenges, and consumers became more conscious and demanded sustainability. This situation has put pressure on businesses to integrate eco-friendly processes in their operations

and manufacture green products that are less harmful to the environment. Similarly, Rehman and Yaqub (2021) indicated that the pandemic calamity has pushed the businesses to incorporate eco-friendly strategies into their operations to meet customers' expectations about sustainability and regulatory requirements. Therefore, businesses changed their business models and moved towards the adoption of green practices in their operations, which ultimately enhanced the environmental performance of new products (Amosh & Khatib, 2023; J. Wang et al., 2023). In the same way, we also revealed that COVID-19 positively moderates the association of UP with EPNP, as indicated by the coefficient ($\beta_{UP} = 0.0013^{**}$). Previous research supports our finding that environmental consciousness together with green innovation attained rapid growth during crises such as COVID-19 (Adil et al., 2024; Obrenovic et al., 2020). According to Sarkis et al. (2020), the pandemic functions as a trigger to provoke new perspectives on how sustainability should be applied in urban and industrial systems. Based on these above findings of COVID-19 as a moderator, we accept our hypothesis *H5* that COVID-19's moderating role is significant.

Conclusions

We have investigated the impact of main business income, industrial innovations and urban population on the environmental performance of new product. Further, we incorporated economic policy uncertainty and COVID-19 as moderating factors. To investigate the associations between the above-mentioned variables, we relied on the panel data of 30 Chinese provinces from 2013 to 2024. In our examination, we discovered a significant negative influence of main business income and urban population on the environmental performance of new product, while the impact of industrial innovations was significantly positive. In the moderation case of economic policy uncertainty, the results confirmed a significant positive moderating effect on the associations of main business income and urban population with environmental performance of new product. In contrast, a significant negative was found between industrial innovations and environmental performance of new product. Moreover, we also found that COVID-19 has a significant positive moderating role in the associations of main business income, industrial innovations, and urban population with environmental performance of new product.

The adverse impact of main business income on environmental performance of new product suggests that sometimes businesses focus on quick gains in the form of monetary profit instead of implementing eco-friendly measures. This situation leads to the creation of products that adversely influence environmental sustainability. Moreover, the positive association between urban population and environmental performance of new product revealed that consumers in such urban regions are more educated and better understand environmental concerns. They are willing to use products that have minimal adverse environmental impact. Besides, cities have the strongest environmental standards, forcing businesses to enhance

product quality. These reasons could result in the positive impact of urban population on the environmental performance of new product. Additionally, the positive link between industrial innovations and environmental performance of new product emphasizes that innovations serve as the foundation for green technologies and processes through which various environmentally friendly products can be created. In addition, the negative moderating role of economic policy uncertainty suggests that businesses prioritize immediate financial gains because of uncertainty and unpredictability in a business environment. Businesses also hold more cash to shield against uncertainty, hence leaving limited funds for environmental initiatives in product manufacturing. However, in the case of industrial innovations, the moderating role of economic policy uncertainty is surprisingly positive, which highlights that during uncertain situations, businesses pursue eco-innovations to mitigate risks and gain a competitive edge in the market. Enterprises invest in sustainable product innovations to differentiate themselves in the market and comply with evolving standards in time of economic policy uncertainty. While, the significant positive moderating role of COVID-19 indicates that the pandemic heightened global awareness about ecological challenges. Thus, consumers became more aware and demanded eco-friendly products. Pandemic calamity has pushed the businesses to incorporate eco-friendly strategies into their operations to meet customers' expectations about sustainability and regulatory requirements. Therefore, businesses changed their business models and moved towards the adoption of green practices in their operations. These initiatives enhanced the environmental performance of new products.

The findings of current study suggest several recommendations for policymakers. First, businesses should make sure that profitability does not come at the expense of environmental sustainability. Business managers should maintain a symmetry between financial pursuits and measures of environmental concerns. Second, policymakers should encourage a conducive environment for industrial innovations. It is because these innovations are crucial for developing green products with improved environmental performance. Third, sustainable urban planning should be indorsed to diminish ecological strain in urban regions. Beside this, government should enforce stricter eco-design regulations for products development and consumption. The government should also promote such policies that encourage the reuse and recycling of materials used in new product development. In addition, a stable and transparent economic policy environment is crucial for businesses to pursue green initiatives in product development. Therefore, the government should tackle down the ambiguity surrounding economic policies. Policymakers must come up with economic policies that are favorable for businesses and explicitly supportive of green business practices.

Despite a detailed examination, the research has certain limitations that could serve as a future research direction. Only one country is involved in the study, and it does not adequately represent other regions. Secondly,

since the research relies solely on provincial-level data, it imposes a generalization constraint on different regions. Further studies can extend the analysis to other areas in order to gain a more in-depth understanding. In addition, future research can also proceed beyond the provincial level analysis to a firm level. In this scenario, the utilization of case studies of those firms in China that have successfully integrated environmental performance of new product procedures may be advantageous. The role consumer awareness and demand for environmentally friendly new products should also be incorporated into the future studies.

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TOE-FRAMEWORK IN AI ADOPTION: A QUALITATIVE ANALYSIS OF SICILIAN SMES

This research examines the enablers and barriers to artificial intelligence (AI) adoption among small and medium-sized enterprises (SMEs) in Sicily, foregrounding how technological, organizational, and environmental factors interact in a peripheral regional context. Adopting a qualitative design, we conducted eight semi-structured, in-depth interviews with managers from digitally oriented and traditional SMEs. Data were analysed abductively through the Technology-Organization-Environment (TOE) framework. Findings reveal a pronounced

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КОНЦЕПЦІЯ TOE У ВПРОВАДЖЕННІ ШІ: ЯКІСНИЙ АНАЛІЗ СИЦИЛІЙСЬКИХ МАЛИХ ТА СЕРЕДНІХ ПІДПРИЄМСТВ

Це дослідження аналізує фактори, що сприяють та перешкоджають впровадженню штучного інтелекту (ШІ) серед малих та середніх підприємств (МСП) на Сицилії, висвітлюючи взаємодію технологічних, організаційних та екологічних факторів у периферійному регіональному контексті. Використовуючи якісний дизайн, було проведено вісім напівструктурованих глибоких інтерв'ю з менеджерами цифрових та традиційних МСП. Дані були проаналізовані за допомогою моделі "Технологія-Організація-Середовище" (TOE). Результати дослідження виявляють яскраво виражену різницю: цифрові МСП



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divide: digital SMEs treat AI as a strategic asset already embedded in daily workflows (e.g., code analysis, marketing, administrative support), reporting productivity gains and a shift toward higher value-added tasks; while traditional SMEs view AI as distant or overly complex, citing low awareness and unclear use cases. Organizational culture and leadership are pivotal—entrepreneurial, experimentation-friendly settings (often with dedicated "creative technologist" roles) accelerate adoption, whereas resistance among incumbent staff and weak change communication hinder progress. Environmental constraints specific to Sicily—fragmented incentives, uneven digital infrastructure, and limited knowledge networks—further dampen uptake, creating a risk of widening digital divides. The research offers actionable implications: staged, use-case-driven pilots with clear governance; leadership development and internal champions; continuous, modular training; and ecosystem interventions (innovation hubs, cluster initiatives, targeted vouchers/grants). Theoretically, we advance a socio-technical view of AI consolidation that links micro-organizational dynamics with territorially embedded conditions. Overall, the research contributes context-sensitive evidence and practical guidance to foster inclusive AI-enabled transformation in SMEs.

Keywords: Artificial Intelligence, SMEs, TOE-framework, digital transformation, qualitative research, regional innovation.

JEL Classification: O33, L26, M15.

розглядають ІІІ як стратегічний актив, який вже інтегрований у повсякденні робочі процеси (наприклад, аналіз коду, маркетинг, адміністративна підтримка), повідомляючи про підвищення продуктивності та перехід до завдань з вищою доданою вартістю; тоді як традиційні МСП вважають ІІІ віддаленим або надто складним, посилаючись на низьку обізнаність та нечіткі випадки використання. Організаційна культура та лідерство мають вирішальне значення – підприємницьке середовище, сприятливе для експериментів (часто з виділеними ролями "креативних технологів") прискорюють впровадження, тоді як опір серед діючих співробітників та слабка комунікація змін гальмують прогрес. Обмеження, характерні для Сицилії – фрагментовані стимули, нерівномірна цифрова інфраструктура та обмежені мережі знань, – це більше гальмують впровадження, створюючи ризик поглиблення цифрового розриву. Дослідження пропонує практичні рекомендації: поетапні пілотні проекти, орієнтовані на конкретні випадки використання, з чітким управлінням; розвиток лідерських якостей і внутрішніх лідерів; безперервне модульне навчання, а також втручання в екосистему (інноваційні хаби, кластерні ініціативи, цільові ваучери/гранти). Теоретично автори просувають соціально-технічний погляд на консолідацію ІІІ, який пов'язує мікро-організаційну динаміку з територіально вбудованими умовами. В цілому, дослідження надає контекстно-залежні докази та практичні рекомендації для сприяння інклюзивній трансформації малих і середніх підприємств за допомогою ІІІ.

Ключові слова: штучний інтелект (ІІІ), малі та середні підприємства, структура TOE, цифрова трансформація, якісне дослідження, регіональні інновації.

Introduction

In the actual digital world, Artificial Intelligence (AI) is escalating in interest (Ho et al., 2022), often regarded as the Fourth Industrial Revolution (Zhang et al., 2021). Academic work (Khalid, 2020; Dwivedi et al., 2021) portrays AI as a domain that merges computer science with extensive data, enhancing corporate decision-making. Dwivedi et al. (2021) state that AI replicates human cognitive processes using advanced tools like machine and deep learning. Scholarship (Awan et al., 2021; Sestino and De Mauro, 2022) confirms its synergy with Big Data analytics to convert raw data into actionable insights.

AI implementation yields multiple benefits: lower costs, greater accuracy (Agarwal et al., 2021), higher productivity (Acemoglu and Restrepo, 2018), enhanced product development (Babina et al., 2024), and accelerated business growth (Bag et al., 2021). Consequently, organizations are

increasingly deploying AI to bolster performance (Mikalef & Gupta, 2021), despite considerable obstacles (Yu et al., 2020). The strategic ramifications of AI are a vital research area (Sun & Medaglia, 2019), as its integration influences both financial and non-financial outcomes for Small and Medium-sized Enterprises-SMEs – (Baabdullah et al., 2021; Badghish & Soomro, 2024).

SMEs are principal drivers of economic growth (Gherghina et al., 2020) and are known for their agility and adaptability to technological shifts (Baeshen et al., 2021). They are increasingly using transformative technologies to scale operations (Rawashdeh et al., 2023). Despite these advantages, SMEs encounter barriers, including internal resistance, complexity, financial limitations (Venkateswarlu et al., 2022; Bakhtiari et al., 2020), and localized factors (Schwaeke et al., 2024).

This research focuses specifically on SMEs in Sicily, a region with a unique socio-economic context. Our purpose is to evaluate AI adoption by examining the awareness and requirements of local entrepreneurs. In particular, the objective of this research is to investigate the awareness, perceptions, and needs of entrepreneurs from Sicilian SMEs in relation to AI technologies and to identify the technological, organizational, and environmental factors that affect their readiness to adopt AI solutions.

We employ the Technology-Organization-Environment (TOE) (Baker, 2011) framework to propose a conceptual model that explains firm readiness for AI and its impact on performance within this specific setting.

1. Methodology

A qualitative approach was adopted, based on eight in-depth interviews with managers from both digital and traditional SMEs operating in Sicily. Data were analyzed using the Technology-Organization-Environment (TOE) framework to identify adoption drivers and barriers.

1.1. Research design and context

A qualitative design was adopted to generate an in-depth, contextually grounded understanding of enablers and barriers to AI adoption among small and medium-sized enterprises (SMEs) operating in Sicily. We conducted eight semi-structured, in-depth interviews with managers from both digital (e.g., software/IT services) and traditional sectors (e.g., construction equipment, manufacturing). The Technology-Organization-Environment (TOE) framework guided both data collection and analysis.

1.2. Research design and context

We used purposive, maximum-variation sampling to capture heterogeneity across sectors, firm sizes, and roles relevant to AI-related decision making. Inclusion criteria were: (i) SME status per EU definition; (ii) primary

operations in Sicily; (iii) managerial responsibility for technology, operations, or strategy; and (iv) at least nascent exposure to AI concepts or tools.

Participants were recruited via industry associations, professional networks, and snowball referrals. Initial invitations were sent by email with an information sheet; follow-ups were conducted by phone to confirm eligibility and schedule interviews. Recruitment continued until thematic sufficiency was indicated.

Participants provided informed consent prior to data collection and were reminded of their right to withdraw at any time. Data were anonymized; identifiers (name of the interviewed, and firm names) were replaced with codes. Only the research team had access to audio files and transcripts.

1.3. Data collection

Interviews were conducted between May and July 2025, either on-site at company premises or via secure video-conferencing (e.g., Microsoft Teams or Google Meet), according to participant preference. Conversations followed a semi-structured guide organized around four domains: company profile, digital maturity, current AI usage and perceptions, and perceived barriers/facilitators to adoption (aligned to TOE dimensions).

Interviews lasted approximately 60–90 minutes. With written informed consent, interviews were audio-recorded and supplemented with field notes on context, emergent topics, and nonverbal cues (for in-person sessions). Recordings were professionally transcribed verbatim in the original language (Italian). Where excerpts are reported in English, they were translated by a bilingual researcher to preserve meaning and tone.

Thematic saturation was assessed iteratively; by the eighth interview, no substantively new codes emerged within TOE dimensions and subsequent analysis showed increasing redundancy across cases, indicating adequacy of the sample for the study aims.

1.4. Data collection

We employed an abductive, framework-informed thematic analysis. First, an initial codebook was developed deductively from the TOE framework (technology, organization, environment) with provisional subcodes (e.g., perceived usefulness, compatibility, data readiness; leadership, culture, skills; regulatory pressure, ecosystem support), while allowing inductive codes to capture unanticipated themes (e.g., territorial embeddedness, vendor dependency).

Two researchers independently coded the same subset of transcripts in ATLAS.ti, discussed discrepancies, and refined code definitions to enhance coherence and transparency. The remaining transcripts were coded with the stabilized codebook, with periodic peer debriefs to interrogate emerging interpretations. The final themes are reported along TOE dimensions, distinguishing adoption drivers and barriers and illustrating mechanisms with anonymized quotations.

2. Results

The findings from the eight in-depth interviews revealed a clear divide between digitally oriented and traditional SMEs regarding the adoption and perception of AI. Among the more innovation-driven companies, AI tools were not only well known but actively integrated into daily business operations across various functions, from software development and marketing to creative production and internal administration. Participants from these firms described AI not as a threat or a tool for future use, but as a strategic asset already enhancing their productivity, accelerating workflows, and enabling a more meaningful engagement with complex creative and analytical tasks. One entrepreneur observed, "*We use it in various contexts – for code analysis, client quote evaluations, document summarization*" (Interviewee 6), highlighting the practical, day-to-day utility of these technologies.

Another emphasized the transformative role of AI in their work routines, stating, "*It speeds things up enormously... we spend less time on stupid tasks and more on what really matters*" (Interviewee 3), underscoring the shift toward a more value-added work model. In stark contrast, interviewees from more traditional SMEs reported a significantly lower level of technological awareness and application. For these companies, AI was often perceived as a distant or overly complex innovation, disconnected from their immediate operational needs and day-to-day challenges. A respondent openly admitted, "*I am aware of my lack of knowledge... I wouldn't even know how to apply it in my daily work*" (Interviewee 8), reflecting a widespread uncertainty and reluctance to engage with AI technologies. This sentiment reveals a profound knowledge gap that goes beyond simple lack of access, suggesting a fundamental disconnect between the perceived benefits of AI and the practical needs of these enterprises.

Organizational culture emerged as a critical determinant in the adoption process. In digital firms, an entrepreneurial and forward-thinking leadership style fostered a proactive attitude toward experimentation. These leaders not only encouraged the use of new tools but also created dedicated roles, such as a "Creative Technologist", to guide and evangelize AI integration within the company. This approach promoted a culture of continuous learning and adaptation. Conversely, more conventional businesses faced significant internal resistance, particularly from older staff members who were skeptical of change. As one interviewee noted, "*Some colleagues are just afraid of change. They think AI will make things more complicated, not easier*" (Interviewee 1). This resistance highlights the human element of digital transformation, where fear of the unknown and inertia can be as formidable an obstacle as technological or financial limitations.

Even among the more advanced firms, the fast pace of technological evolution presented challenges. One participant reflected, "*We need weekly updates... the tools evolve faster than our ability to adapt*" (Interviewee 4), demonstrating that even those who embrace AI must constantly invest in skills and training to keep pace.

Finally, the environmental context – especially the regional characteristics of Sicily – proved highly influential. Several respondents cited the lack of public incentives, weak infrastructure, and limited access to knowledge networks as major obstacles to innovation. These external factors create a difficult landscape for SMEs trying to embrace new technologies. As one entrepreneur remarked, "*Here in Sicily, we can't wait for the system to help – we must adapt ourselves*" (Interviewee 7), a quote that captures the spirit of resilience born from a lack of institutional support. The combined effect of these external constraints and internal challenges has led to a fragmented adoption landscape, where only the most forward-thinking SMEs appear equipped to harness the full potential of AI. One participant aptly captured this sentiment, warning of a coming divide: "*This revolution is enormous and definitive. Either you keep up, or you disappear*" (Interviewee 3).

These insights underscore the importance of viewing AI adoption not solely through a technological lens, but as a multifaceted process shaped by organizational culture and regional context. The variability in readiness and usage patterns among Sicilian SMEs reveals the need for tailored interventions, including targeted training, leadership development, and supportive policy frameworks, in order to ensure a broader and more inclusive integration of AI technologies.

The following *Table 1* distills qualitative insights from eight in-depth interviews with managers of Sicilian SMEs, contrasting digitally oriented and traditional firms across the Technology-Organization-Environment (TOE) dimensions. For each theme, it reports observed evidence by firm type, representative quotations that exemplify recurrent patterns, and actionable implications. The table highlights a marked divide in AI awareness, use, and strategic framing; the role of leadership, culture, and skills in shaping adoption trajectories; and the influence of environmental factors such as infrastructure, incentives, and knowledge networks. Together, these findings depict an uneven adoption landscape in which digitally mature SMEs leverage AI to streamline workflows and elevate value-added tasks, while more traditional firms face knowledge gaps, resistance to change, and limited ecosystem support. The implications column translates these insights into targeted interventions – ranging from awareness-building and change management to training, governance, and policy measures – intended to broaden and accelerate AI uptake in resource-constrained contexts.

Table 1

AI Adoption in Sicilian SMEs (TOE-Aligned)

Theme (TOE)	Digital SMEs – Evidence	Traditional SMEs – Evidence	Representative Quotes	Actionable Implications
AI Awareness & Current Usage (Technology)	High awareness; AI integrated across functions (code review, marketing, creative, admin). AI framed as strategic asset already in use	Low awareness; AI perceived as distant/complex; unclear practical applications	"We use it in various contexts—for code analysis, client quote evaluations, document summarization" (Int. 6); "I wouldn't even know how to apply it in my daily work" (Int. 8)	Targeted awareness-building; sector-specific use cases and demos to translate abstract benefits into concrete workflows
Perceived Value & Productivity (Technology)	AI accelerates processes, reduces rote tasks, frees time for higher-value work	Benefits remain abstract; fear of inefficiency or added complexity	"It speeds things up enormously... we spend less time on stupid tasks and more on what really matters" (Int. 3)	Show ROI through pilots; start with quick wins that automate low-value tasks
Organizational Culture & Leadership (Organization)	Entrepreneurial leadership; experimentation encouraged; dedicated roles (e.g., "Creative Technologist")	Conservative culture; change skepticism, especially among older staff	"Some colleagues are just afraid of change... They think AI will make things more complicated" (Int. 1)	Leadership development for digital transformation; internal champions; change management and communication plans
Skills, Training & Pace of Change (Organization/Technology)	Continuous upskilling needed; struggle to keep pace with fast-evolving tools	Foundational digital/AI literacy gaps; limited training routines	"We need weekly updates... the tools evolve faster than our ability to adapt" (Int. 4)	Modular training curricula; microlearning; vendor-supported enablement; time-bounded learning sprints
Internal Resistance & Human Factors (Organization)	Lower resistance due to culture of experimentation; clearer narratives on value	High resistance/inertia; fear of the unknown and job disruption	"Some colleagues are just afraid of change" (Int. 1)	Address anxieties; participatory design; involve skeptics early; emphasize augmentation, not replacement
Infrastructure, Incentives & Policy (Environment)	Operate despite weak external support; rely on internal initiative	More affected by lack of incentives, weak infrastructure, limited access to knowledge networks	"Here in Sicily, we can't wait for the system to help – we must adapt ourselves" (Int. 7)	Policy support for SME AI adoption; local innovation hubs; grants/vouchers; improved digital infrastructure
Ecosystem & Knowledge Networks (Environment)	Better connected to communities, vendors, and learning resources	Sparse networks; isolation from best practices and peer learning	Implicit across interviews (limited networks reported by several respondents)	Broker connections; cluster initiatives; peer cohorts; partnerships with universities and providers

Theme (TOE)	Digital SMEs – Evidence	Traditional SMEs – Evidence	Representative Quotes	Actionable Implications
Adoption Landscape & Digital Divide (Cross-cutting)	Poised to harness AI's potential; see AI as non-optional for competitiveness	Risk of falling behind; fragmented readiness and uptake	"This revolution is enormous and definitive. Either you keep up, or you disappear" (Int. 3)	Segmented interventions; prioritize lagging sectors with tailored roadmaps and support
Strategic Framing & Use-Case Selection (Organization/Technology)	Clear strategic framing; AI mapped to value-adding tasks and roles	Lack of strategic framing; unclear entry points; overwhelm from tool variety	"AI... a strategic asset already enhancing productivity" (synthesis from multiple interviews)	Use-case portfolio design; start small, scale fast; governance for tool selection and data readiness

Source: authors' elaboration.

3. Discussion and conclusion

This research provides a detailed account of how AI adoption unfolds within SMEs in a distinctive regional context like Sicily, offering valuable insights that reach far beyond local specifics. The main contribution is to demonstrate that the integration of AI is not a uniform or linear process but is profoundly influenced by regional socio-economic dynamics, the internal organizational culture of the firm, and its specific sectoral characteristics.

The application of the Technology-Organization-Environment (TOE) framework revealed that a firm's digital maturity and its managers' attitudes are decisive factors. For digitally advanced firms, these elements act as powerful enablers, allowing them to effectively translate AI opportunities into practical, day-to-day applications. Conversely, for more traditional enterprises, these same factors serve as significant barriers, creating substantial hurdles to adoption. From a theoretical perspective, this study emphasizes the critical importance of situating digital transformation research within specific territorial ecosystems.

The findings strongly suggest that regional conditions, such as the availability of training resources, the presence of supportive networks, and entrenched sectoral inertia, play a crucial and often underestimated role in shaping a company's readiness to adopt new technologies. In this sense, the research refines the TOE framework by highlighting the considerable influence of local embeddedness on technology adoption pathways.

On a practical level, the findings indicate that managerial interventions and public policies aimed at fostering AI adoption cannot be based on a "one-size-fits-all" approach. The observed heterogeneity among Sicilian SMEs necessitates the development of differentiated strategies. While digitally advanced enterprises may require sophisticated and structured training programs and ethical guidelines for responsible AI use, traditional sectors need more foundational initiatives. These should focus on raising basic awareness, demystifying AI, and reducing the ingrained resistance to change.

Innovation hubs and training institutions should, therefore, design multi-layered support systems that align with the varying degrees of digital maturity across the Sicilian SME population. The broader implication is that for SMEs, AI adoption is not just a matter of technological availability but also a process of profound cultural adaptation and organizational learning. Companies that successfully combine an openness to experimentation with deliberate investments in human capital will be better positioned to leverage AI for enduring innovation and enhanced competitiveness. Conversely, ignoring these crucial socio-organizational dimensions risks irrevocably widening the digital gap between advanced and lagging firms.

4. Implications and future research directions

This study contributes to the literature on digital transformation in SMEs and offers actionable guidance for managers, policymakers, innovation hubs, and training institutions. The findings underscore that the core challenge for SMEs is not merely adopting AI tools but embedding them into organizational routines in ways that enhance collective capabilities and elevate the value of work. The Technology-Organization-Environment (TOE) lens reveals a pronounced divide between digitally oriented and traditional firms: the former treat AI as a strategic asset already integrated into daily workflows, while the latter perceive it as distant, complex, and difficult to operationalize. This asymmetry is amplified by organizational culture and leadership – entrepreneurial, experimentation-friendly environments accelerate uptake – alongside environmental constraints specific to Sicily, including weak incentives, patchy infrastructure, and limited knowledge networks.

Managerially, the results point to a staged, use-case – driven approach. Firms should begin with "quick wins" that automate low-value tasks and demonstrate tangible ROI, then scale to more complex applications under explicit governance for tool selection and data readiness. Leadership development is pivotal: appoint internal champions (e.g., "creative technologists"), invest in change management and transparent communication, and frame AI as augmentation rather than replacement to reduce resistance – especially among older staff. Given the rapid progress of technological change, continuous capability-building is essential; modular curricula, micro-learning formats, and vendor-supported enablement can help teams keep pace without disrupting operations.

For the support ecosystem, implications are equally concrete. Innovation centers and business associations can broker access to sector-specific exemplars and peer cohorts, reducing isolation and shortening learning curves for traditional SMEs. Policy actors can mitigate environmental frictions through targeted instruments – SME vouchers or grants for pilot projects, tax credits tied to training outcomes, and investments in digital

infrastructure. Regionally rooted initiatives (local hubs, university – industry partnerships, cluster programs) can thicken knowledge networks and provide durable scaffolding for adoption, moving beyond one-off workshops toward sustained communities of practice.

Overall, theoretically, the study advances an integrated view of AI adoption as a socio-technical process shaped by the interaction of technological affordances, organizational culture and leadership, and territorially embedded conditions. Practically, it translates this view into a portfolio of tailored interventions: awareness-building with concrete use cases; leadership and change-management development; iterative pilots with clear governance; continuous, stackable training; and ecosystem-level supports that lower coordination and capability gaps.

Future research could extend these insights through longitudinal and cross-regional comparisons, examining how combinations of managerial practices and ecosystem supports enable durable consolidation of AI in diverse socio-economic environments.

Moreover, to extend and triangulate these qualitative insights, future research could incorporate a complementary quantitative phase using a survey administered to a probability sample of Sicilian SMEs drawn from the AIDA database (Analisi Informatizzata delle Aziende) – a comprehensive commercial information platform covering Italian firms. The sampling frame would consist of limited liability companies headquartered in Sicily that meet the EU definition of an SME (i.e., < 250 employees and either $\leq$ EUR 50 million in annual turnover or $\leq$ EUR 43 million in total assets). Recruitment could proceed via verified email and phone contacts listed in AIDA, with multi-wave reminders and mixed-mode administration to reduce nonresponse.

The survey grounded in the TOE framework and refined from the interview themes – would measure perceived AI utility, readiness (skills, data, governance), leadership and culture, environmental pressures/supports, and adoption outcomes; established multi-item scales would be adapted and pretested, followed by translation/back-translation and cognitive probing to ensure content validity. This design would offer a robust quantitative complement to the depth achieved qualitatively.

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CONDITIONS AND MECHANISMS OF IMPLEMENTING AI IN THE FINANCIAL SECTOR

The research analyses the process of adapting artificial intelligence in the financial sector, highlighting the key mechanisms of its implementation. The mentioned process was presented from the perspective of the development of

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УМОВИ ТА МЕХАНІЗМИ ВПРОВАДЖЕННЯ ШІ У ФІНАНСОВОМУ СЕКТОРІ

Дослідження обґрунтовує процес адаптації штучного інтелекту у фінансовому секторі, висвітлюючи ключові механізми його впровадження. Зазначений процес представлено з погляду розвитку Індустрії 4.0.



Industry 4.0. The research presents an overview of the conditions for the implementation of artificial intelligence in the financial sector. It does not pretend to be a study that would exhaustively present the research problem undertaken. Each of the partial issues presented in the following paragraphs requires development based on more in-depth research. The aim of the research is to show the process of adapting artificial intelligence in the financial sector and to highlight the mechanisms of its implementation. Instead of hypotheses, the following research questions will be formulated in this study: What is the importance of AI in the development of digital economy? What is the role of AI in the development of financial sector? What are the experiences with implementing AI in the financial sector of different countries? What are the lessons learned from using AI and ML in the financial sector so far? The study is based on the analysis and evaluation of literature and sectoral reports presenting the issues of digital transformation of the economy, highlighting the importance and possibilities of using artificial intelligence and related modern technologies. The above-mentioned analysis was complemented by the use of deductive and inductive reasoning. The use of artificial intelligence is an integral element of the process of digitization of the economy. The financial sector has widely adopted solutions based on the use of artificial intelligence and machine learning. They have become an important factor in increasing the efficiency of this sector and the financial system and its elements, the quality of services provided by financial institutions and, consequently, their competitiveness on the market. The development of the digital economy has created new opportunities for financial institutions to use artificial intelligence and information technologies related to it. This applies to the use of technologies such as autonomous robots, Big Data, cloud computing, system integration, additive production, Industrial Internet of Things, augmented reality, simulations, and technologies supporting cybersecurity. These technologies create new opportunities for financial institutions to improve their efficiency and the quality of the products they offer.

Keywords: artificial intelligence, financial sector, Industry 4.0, digital transformation.

JEL Classification: G2, O3.

Introduction

The free flow of economic resources, the development of digital technologies and the growing importance of intangible assets as components of enterprise resources have become the driving forces for the emergence of the fourth industrial revolution. Its symbol is Industry 4.0, focused on the

Розглянуто умови впровадження штучного інтелекту у фінансовому секторі. Проте воно не претендує на вичерпне висвітлення досліджуваної проблеми. Кожне з питань, представлених у статті, потребує розробки на основі більш глибоких досліджень. Мета дослідження – показати процес адаптації штучного інтелекту у фінансовому секторі та визначити механізми його впровадження. У межах цього дослідження сформульовано такі дослідницькі питання (без висунення гіпотез): Яке значення має ІІ у розвитку цифрової економіки? Яка роль ІІ у розвитку фінансового сектору? Який досвід впровадження ІІ у фінансовому секторі мають різні країни? Які уроки використання ІІ та МН у фінансовому секторі винесені на сьогоднішній день? Дослідження базується на аналізі та оцінці наукової літератури та галузевих звітів, що висвітлюють питання цифрової трансформації економіки, підкреслюючи важливість та можливості використання штучного інтелекту та пов'язаних з ним сучасних технологій. Вищезазначений аналіз був доповнений застосуванням дедуктивного та індуктивного міркування. Використання штучного інтелекту є невід'ємним елементом процесу цифровізації економіки. Фінансовий сектор широко застосовує рішення, засновані на використанні штучного інтелекту та машинного навчання. Вони стали важливим фактором підвищення ефективності цього сектору та фінансової системи і її елементів, якості послуг, що надаються фінансовими установами і, як наслідок, їх конкурентоспроможності на ринку. Розвиток цифрової економіки створив нові можливості для фінансових установ використовувати штучний інтелект та пов'язані з ним інформаційні технології. Це стосується застосування таких технологій, як автономні роботи, великі дані, хмарні обчислення, системна інтеграція, адитивне виробництво, промисловий Інтернет речей, доповнена реальність, симуляції та технології, що підтримують кібербезпеку. Ці технології створюють нові можливості для фінансових установ щодо підвищення своєї ефективності та якості продуктів, які вони пропонують.

Ключові слова: штучний інтелект, фінансовий сектор, Індустрія 4.0, цифрова трансформація.

digitization and mechatronization of production, and indicating a new approach to managing the efficiency of enterprises. The digital transformation taking place in the global economy is a factor stimulating the automation of business operations based on the use of artificial intelligence (AI). AI is the theory and practice of creating intelligent computer systems capable of supporting or replacing human mental work, as well as enabling a deeper understanding of human reasoning. This enables the processing of large amounts of data, which makes AI an important factor in increasing the efficiency of the financial sector and the financial system and its components.

This paper discusses the impact of the rapid adoption of artificial intelligence and machine learning (ML) in the financial sector. It highlights the benefits these technologies bring in terms of financial deepening and efficiency, while raising concerns about its potential in widening the digital divide between advanced and developing economies. The paper advances the discussion on the impact of this technology by distilling and categorizing the unique risks that it could pose to the integrity and stability of the financial system, policy challenges, and potential regulatory approaches. The evolving nature of this technology and its application in finance means that the full extent of its strengths and weaknesses is yet to be fully understood. Given the risk of unexpected pitfalls, countries will need to strengthen prudential oversight.

Therefore, the aim of the research is to show the process of adapting artificial intelligence in the financial sector and to highlight the mechanisms of its implementation. The implementation of this aim will be related to the exposure of the following partial research problems:

- artificial intelligence and the development of the digital economy;
- development and adaptation of artificial intelligence in the financial sector;
- good practices of the artificial intelligence implementation – perspectives of selected countries;
- analysis and evaluation of the artificial intelligence and machine learning in financial services.

1. Artificial intelligence and the development of the digital economy

The concept of the digital economy is intrinsically linked to the process of digital transformation of the economy (digitization of the economy) associated with the fourth industrial revolution exemplified by the concept known as Industry 4.0. This term originated in the German economy, where it is associated with the Federal Government's search for opportunities to mitigate the effects of the global financial crisis initiated in 2008 with the bankruptcy of Lehman Brothers. In 2011, the German government used the term Industrie 4.0 for the first time in a document indicating the high-tech

strategy formulated as part of the national development strategy for the German economy (Luck, 2022). Industry 4.0 is oriented towards the digitalization and mechatronization of production and indicating a new approach to business performance management with the blurring of boundaries between the physical, digital and biological spheres of manufacturing processes (Mączyńska, & Okoń-Chorodęńska, 2020; Jaśko et al., 2022). The digital transformation taking place in the global economy is driving the automation of the manufacturing environment as well as the creation of digital value chains that enable multi-directional communication within the enterprise and between the enterprise and its environment (Ślusarczyk, 2019). The development and dissemination of the Industry 4.0 concept has also recently led to the demand for its transformation into the Industry 5.0 concept, which is dictated mainly by the need to reveal the human role in cyber-physical systems (Saniuk et al., 2022).

The possibility of emergence of the digital economy as a result of revolutionary changes in the functioning of economies and in the management mechanisms of organizations was preceded by significant transformations that, over the last decades (since the 1980s), have become the driving forces of the fourth industrial revolution. Among these transformations, the following have been of key importance:

- the processes of globalization and economic, political and social integration stimulating the facilitation of economic resource flows and access to new markets, but at the same time increasing competition and demands of consumers and investors in regional and local markets;
- the growing importance of intangible resources as components of an enterprise's potential, creating new opportunities for the creation and use of unique economic resources and increase in the company's effectiveness and competitiveness on the market. As a result, intellectual capital has become a key driver of effectiveness-oriented changes in an enterprise (Bugarčić & Slavković, 2023);
- the rapid development of information technologies, especially the spread of the Internet from the point of view of its accessibility and multidimensional use.

Although the process of digital transformation is the result of the coincidental impact of the aforementioned revolutionary transformations, the emergence and spread of Internet use in the private and business spheres is of key importance here. This is because it has contributed to the following fundamental changes in the functioning of not only enterprises, but also other market actors:

- radical changes in terms of access to information and the speed of its flow, which has contributed, among other things, to an increase in the importance of information as an economic resource and market product and the emergence of information management as a business management concept;

- changes in the sphere of broadly understood communication – including the possibility to communicate online in real time using voice and video and using communication platforms such as Zoom, MS Teams and others;
- the use of the Internet as a channel for an enterprise to connect with its customers and distribute its products, in conjunction with both traditional business models and the creation of enterprises based solely on online sales of their products, resulting in new business models for enterprises based on the virtualization of their business;
- the use of the Internet in the field of education, enabling distance learning based on the use of real-time online communication platforms and professional learning platforms (e.g. Moodle);
- the emergence of technological solutions enabling digital authorization of documents through the use of an electronic signature, which has made it possible not only to facilitate the creation and transmission of formal and legal documentation, but also the provision of administrative services by public entities in the online system (e-governance);
- the emergence and spread of the use of information technologies in the medical services sector for issuing e-prescriptions and giving the physician online access to the patient's medical record and results of ordered tests, which has become an important factor stimulating the development of e-medicine with regard to the range of medical services that can be provided without the need for physical contact between the physician and the patient;
- the emergence of new ways of increasing the effectiveness of an enterprise and the quality of the products it offers and consequently increasing its competitiveness by reducing operating costs and the possibility of integrating dispersed economic resources with their sharing;
- the emergence and spread of hybrid products which, based on similar technological solutions, perform functions that were previously the domain of separate, unrelated products manufactured by separate economic entities, offered on separate markets and having their own, unrelated value chains – the hybridization of economic activity.

The emergence and implementation of technologies such as autonomous robots, Big Data, cloud computing, system integration, additive production, Industrial Internet of Things, augmented reality, simulations, and technologies supporting cybersecurity are associated with the development of the digital economy (Grabowska & Saniuk, 2022). In recent years, new areas for the use of artificial intelligence have been closely linked to the process of digitalization of the economy. The term "artificial intelligence" (AI) dates back as far as the mid-1950s, when it was defined by J. McCarthy and identified with the branch of computer science dealing with the construction of machines and algorithms, the operation of which has the hallmarks of intelligence (Winston, 1992). The connection of AI with the digital transformation of the economy, however, refers to its increasing implementation for business, economics, finance and management purposes. From the perspective of organization's operations, the utility of AI relates to the following three potential levels of its application (Korzynski et al., 2023):

strategic level – decision-making by managers based on the use of recommendations relating to specific decision-making problems, using of the organization's information resources for knowledge management purposes;

functional level – using for customer service, use for Human Resource Management;

administrative level – using to generate standard business documents and to automate and assist with various administrative tasks, such as scheduling appointments, booking travel arrangements, and managing calendars.

An important sector of the economy where technological solutions related to the use of AI have been used for many years is the financial sector. Research conducted in this area demonstrates not only the significant benefits generated from its use, but above all the very high potential relating to the future development of its applications for the growth of the activities of financial institutions. The financial sector is ranked third in the economy in this respect (after the information, communication and manufacturing sectors) (Fintech Poland, 2022). This is a natural consequence of the fact that this sector has been very quick to implement the achievements of digital transformation, the first stages of which were the provision of remote access to banking services for customers, followed by the creation of online banks based almost exclusively on the use of the Internet for the purpose of interacting with customers and their use of the services offered by the bank.

The research carried out demonstrates the feasibility and relevance of implementing AI-based technologies in the following areas of financial institutions' operations (Fintech Poland, 2022):

- functioning of the front office using machine learning, robotics, chatbots, biometrics and unique identity;
- functioning of the back office using text analytics tools, machine learning, robotics and chatbots;
- personalization of financial services using robotics and chatbots;
- risk management and compliance using text analytics tools, machine learning, biometrics and unique identity.

In the context presented, it becomes reasonable to present and exemplify the mechanisms for implementing AI in the financial sector, highlighting the determinants of its development and adaptation, presenting good practices applied in this field in different countries and carrying out an analysis and evaluation of the use of AI in the financial sector to date.

2. Development and adaptation of artificial intelligence in the financial sector

Artificial intelligence is the theory and practice of creating intelligent computer systems capable of supporting or replacing human mental work and enabling a deeper understanding of human reasoning. Machine learning, on the other hand, is the analysis of learning processes and the creation of systems that improve their performance based on past experience – through

the use of self-optimizing algorithms that stimulate the process of learning. In addition to their many practical applications, these technologies are increasingly used in the financial system. They are transforming the way financial market players make decisions on, among other things, transactions, capital allocation and lending. Therefore, there are many applications using artificial intelligence and machine learning technologies in the financial system. This is due to both supply-side factors (such as technological developments and the availability of data and infrastructure in the financial system) and demand-side factors (which may include issues of profitability, competition with other market players and regulatory requirements). These technologies are being used to assess the credit quality of business partners, price and sell insurance contracts, automate customer interactions, optimize capital utilization and commercial transactions as well as for risk management and fraud prevention, data quality assessment, regulatory compliance, among others.

With AI, machine learning and growing computing power, artificial intelligence is an increasingly effective mechanism to counter fraud. Financial institutions are using these solutions to detect payment fraud, credit fraud as well as social engineering fraud (phishing). Detection of inconsistencies or inaccuracies in payment, loan and application data is achieved through predictive analytics across multiple banking channels. By analyzing the data with a pre-trained algorithm, a transaction can be effectively assessed for fraud risk. Such a system can be extended to notify any deviations from the normal pattern by informing of different types of banking fraud vulnerability. Large-scale transaction verification is then performed in a matter of milliseconds, which reduces the risk of fraud in modern omnichannel banking.

The dynamic progress of artificial intelligence is fundamentally affecting the existing patterns operating in the financial sector. In the area of banking and insurance, AI is being used to automate processes, analyze complex data sets, detect fraud, personalize offers and create intelligent so-called robo-advisors. With AI, it becomes possible to gain a deeper understanding of customer preferences, enabling the delivery of better tailored products and services. Stock trading and investment are other areas where AI is playing an increasingly important role. AI-based models are able to analyze enormous amounts of data, predict trends in financial markets to aid investment decision-making. AI algorithms are also used for automated trading and identifying attractive investment opportunities. In the insurance sector, AI supports risk assessment, damage estimation, insurance portfolio management and the creation of personalized offers. AI-based chatbots are used for customer service and rapid response to queries.

The impetus for the use of AI and machine learning solutions in the automation of financial processes and in the replacement of human labor with algorithms was the deeply humanistic belief that human time, abilities and

intelligence can be used much more efficiently. It should also not be forgotten that AI systems do not get tired and therefore do not make potentially costly mistakes. Therefore, one can venture to say that full process automation would be the optimal solution for the financial sector. However, we will have to wait for such a scenario, mainly for legal reasons, although technology also imposes certain conditions in this case – such as that the automated process must be well defined and described.

At this point, it is worth mentioning that the financial sector and especially the financial markets have always been quick to adapt technological developments to their needs. This is no different with artificial intelligence solutions, especially with regard to deep learning. This type of data processing in the typical applications of financial institutions is far superior to other process automation methods. AI solutions are used, for example, in the preparation of stock market forecasts, in credit risk assessment or in the asset valuation process. However, it is worth remembering that the prospects opened up by the use of artificial intelligence in the financial sector are more promising. These include, among other things:

- automation of such complex processes as the planning and implementation of personalized and targeted marketing campaigns or complete strategies for both specific financial and banking products as well as entire brands;
- increasing transaction security, implemented while maintaining the flexibility of financial services and without compromising the usability of online tools or the quality of service in branch offices;
- preparation of complex demographic analyses in real time, without distracting customers from the financial operation being performed;
- analysis of customer behavior and the emotions they feel, based on their behavior in social networks;
- accurate real property valuation and optimized search for new locations for banking outlets.

These are just a few of the many new and not-so-obvious possibilities offered to financial institutions by artificial intelligence (Report, 2020).

Intelligent solutions can therefore be used in the financial sector in many aspects and areas of business. Robotization and automation of operational processes, mainly in the back-office area, are already an increasingly popular way to reduce costs and improve efficiency. AI is doing well in the case of handling large amounts of data, in automatic decision-making, where we are able to program a solution with the help of an algorithm. However, there are tasks where humans have the advantage. Decision-making there requires a comprehensive view of the problem, such as in the case of investment appraisal, which often requires talking to experts and drawing logical conclusions based on the data provided. However, the true potential will only become apparent when AI starts to support human capabilities and cooperate with humans. A contemporary example here is Morgan Stanley which has supported the work of its 16 000 financial

advisers with AI agents. An intelligent algorithm analyses customer data and supports advisers in finding investment options. The role of the adviser, who remains in contact with the customer, is to make an offer at the right time. With such a large number of customers and such a comprehensive portfolio of banks, it would not be physically possible for financial advisers to keep track of investment options for each individual customer. Through machine-human cooperation, additional possibilities have therefore been unlocked (Reworking the Revolution, 2019).

The aforementioned processes, however, require significant data sets that are subject to machine analysis. Of course, data has been collected by companies for years, but as a rule it was an unstructured collection, often in analogue form, collected unsystematically and without a clear purpose. Now, thanks to powerful computers and machine learning, systems are better able to read data sets and see regularities in them. Operations that currently take seconds would require several years of work by analysts. Big data therefore makes it possible to better advise customers on financial products, better manage risk and carry out a variety of projects that were not possible previously. It is no wonder that so many banks have created central credit registers for each customer and Data Science departments. Financial institutions know what their customers spend their money on, their habits and their needs. They can make predictions about future spending and create segmentations and personalized offers.

Current research on AI also focuses on reinforcement learning. This is a machine learning technique in which an AI model learns to make decisions by interacting with the environment and receiving feedback (reward or punishment) depending on the actions taken. Such AI model takes actions in a given environment and learns to improve its decisions based on the feedback it receives. In parallel, the development of large language models and learning from human interaction is noticeable. Nevertheless, there are still many obstacles in the way of AI freely "learning" and increasing its similarity to humans.

Taking all the aforementioned content into account, it is important to realize that artificial intelligence is no longer a distant future. It is being used today, often even without our knowledge. Sometimes we are confronted with the effects of AI without realizing that somewhere in the process concerning us an element of intelligent algorithm has been used. Various bots and algorithms are already assisting employees in the banking or insurance sector. Therefore, the financial sector should not be asking itself "should we implement?". The most important question now is "how to implement?", so as to catch up with competitors and not fall behind in the race of the digital revolution. The increasingly fierce competition caused by the low barrier to entry will make the progress of artificial intelligence solutions ever faster. Companies in the financial sector that underestimate the importance of AI will experience losses and their position on the market will be challenged.

For many companies in the financial sector, it is important that the implementation of AI involves a change in strategic approach or business model. AI is not only profitable if the aim is to cut costs. AI is a benefit on many levels at the same time (e.g. reducing costs or increasing customer and employee satisfaction). This is why it is important to take a holistic view of the implementation of solutions, also taking into account the impact on the organization and its customers. It is for this reason that any implementation should be preceded by idea testing. Already at this stage, it is necessary to measure success and potential profit and to determine whether the solution will bring the expected business value. It is also at this point that an organization should select the available technology options. How the implementation of artificial intelligence and the changes brought about by it are managed is also not without influence. This process should take into account the ethical approach to AI development and the organization's values.

In summary, to maximize the benefits of AI implementation, organizations in the financial sector should (Fintech Poland, 2022):

1. Move beyond simple automation, serving mainly to increase efficiency or reduce costs.
2. Focus on real, holistic growth.
3. Redefine the boundaries of the ecosystem in which the organization and its customers exist.
4. Propose and verify ideas (proof-of-concept) for AI that provide real, measurable business value and define a basic framework for building AI (e.g. it is important to identify activators, i. e. factors that will facilitate the development of AI in the organization).
5. Define the AI governance framework.

As for the specific benefits arising directly from the various applications of AI, these can be divided into the following categories:

Efficiency. Performing routine tasks thanks to well-defined rules, procedures and criteria.

Knowledge. Supporting the decision-making process will be facilitated by enhanced analytical capabilities.

Effectiveness. Activities performed by a personal assistant or agent will enhance human capabilities.

Innovation. Increasing creativity by identifying alternative possibilities and advising on optimal decisions.

The financial sector is therefore one of the key beneficiaries of advances in AI, which also translates into increased effectiveness, better customer service and more purposeful decision-making. However, the introduction of AI in the financial industry brings challenges such as liability, data security and regulatory issues. Therefore, it is important to maintain a balance between innovation and the protection of customer interests and the stability of the financial system.

It is natural that new technologies raise certain concerns. However, it is worth remembering that innovation has always helped to develop our skills. Calculators have not made us unable to count, but have made the process of calculation easier. Automated spell-checking has not replaced our ability to write, but aids its correctness. AI and automation aim to make work easier and more efficient and to extend our capabilities, not to replace humans. Nowadays, artificial intelligence that supports automation is becoming an important element influencing the ways in which both physical and mental work is done. The development of AI technology allows machines to take over routine and repetitive tasks, which initiates changes in the nature of work and reduces the direct involvement of humans in the stages of work that they have always complained about.

What aspects should the financial sector consider when preparing for AI implementation? First of all, AI should not be expected to replace employees. Artificial intelligence should be gradually improved, extended to then lead to automation. Over time, the proportion and nature of employee roles will change and there will be an increase in new roles related to AI training, explaining and maintaining AI-based solutions. It is also important to focus on identifying the areas of AI implementation that will have the most positive impact on driving business growth and increasing operational efficiency. It will be particularly important here to understand that the effect of AI implementation is the opportunities that will develop between human and machine. It is therefore important to give this a chance, rather than replacing humans with machines, as this will not deliver the expected benefits. From an organization-building perspective, it may be necessary to create an operational model that ensures ethical governance from the ground up as well as to acquire AI skills within the entire organization. Ethical and regulatory compliant governance must be integral to AI development. Also, cooperation with regulators, including by signaling loopholes or phenomena that require the creation of missing regulations, will ensure the success of AI implementation in the financial sector (Boost Tour AIQ, 2018).

In conclusion, it is worth noting that technological advances have helped to accelerate the integration of artificial intelligence and machine learning models with a growing number of processes in the financial sector. Today, financial institutions that do not exploit the potential of AI risk falling behind competitors who make strategic decisions using analytical systems. Intelligent algorithms learn from examples derived from historical data and are then used to discover patterns that are difficult for humans to identify. The use of machine learning in the financial sector is not new. In practice, this technology has been used for decades by banks and institutions offering financial services. It involves basic statistical methods and techniques, such as linear and logistic regression or rule-based modelling. Such traditional methods are relatively simple, easy to understand, explain and interpret. However, the price of their use tends to be lower efficiency compared to the possibilities offered by more advanced machine learning techniques.

With the increase in computing power of computers in recent years, analytical methods such as neural networks, decision tree-based algorithms and others have become increasingly popular. These methods tend to have higher efficiency compared to classical statistical methods, but the way they work is more complex and the influence of individual input variables on the final result is more difficult to interpret.

3. Good practices of the artificial intelligence implementation – perspectives of selected countries

Artificial intelligence may be one of the driving forces Polish economy. But in order for that to happen, we have to be right for it prepared now. The effective implementation of artificial intelligence is a challenge not only for entrepreneurs, but also for the broadly understood state.

A challenge not only of a strategic, technical or business nature, but also ethical and legal. AI solutions must be created because carefully, responsibly and ethically both at the level of the legal framework and processes in each organization using this technology. That is why in our paper we have devoted special attention to ethics in AI. We also reviewed national strategies in the field of AI so that the strategy finally implemented by Poland turns out to be effective. Entering the era of artificial intelligence must be an act not only conscious for all parties involved, but also systemic, because it is supported by an appropriate state strategy.

Polish financial institutions thanks to their technological advancement and the potential to use the huge amounts of data at their disposal, may be a critical part of the Polish artificial intelligence sector. At the same time, financial institutions have a special responsibility due to the scope of data they have and process and their role as an institution of public trust. It is estimated that the banks that will invest in AI and related solutions, may increase theirs in 2020–2025 revenue by more than 37%. And in the opinion of bankers, AI technology will be the one that will have the greatest impact on banking in the next couple of years.

The global race for position leader in the field of artificial intelligence is not limited only to leading companies. More and more countries are starting recognize the role of AI in development (Fintech Poland, 2022).

Governments are realizing how many changes driving their economy can be brought about by artificial intelligence. The Tech Vision trend report, prepared periodically by Accenture based on the opinions of key managers managing global companies, has been systematically showing for several years that that artificial intelligence is of interest to the most important players.

Those who do not adapt to the new conditions may pay a high price. That is why more and more countries recognize this and decide to create their own national AI strategy. The first such coherent and comprehensive strategy was presented by Canada in 2017. Also, in the international space, arrangements for cooperation between entities, countries, regions and

metropolises are being prepared. An example of the latter can be London, which in its strategy positions itself as a hub for the development of artificial intelligence. Also, in Poland, the dynamic development of innovative products based on AI was noticed, and the Ministry of Digital Affairs published assumptions for the AI strategy.

Such great interest from government, regional and local entities indicates the importance of artificial intelligence. They began to realize that maximizing the benefits of AI will only take place if we manage to strengthen cooperation between business, education and the public sector.

This ecosystem must have access to data and appropriate legal regulations must be ensured. Therefore, it is worth analyzing the approach of leaders to the subject of artificial intelligence. The UK, US, China, France and the EU are already in the midst of this transition.

Each strategy addresses issues such as:

- research and development;
- education;
- access to the data;
- financing;
- ethics and law;
- infrastructure.

These strategies also adjust the above issues to local realities. An interesting case is also the strategy of India, which – in addition to economic growth – is to take into account social problems.

There are some countries which have presented and already published a national strategy on AI: USA, Canada, Mexico, Tunisia, Kenya, United Arab Emirates, India, China, Taiwan, Japan, Australia, Great Britain, Italy, France, Denmark, Sweden, Finland, Lithuania, Germany. International strategies are also visible for the European Union, for Nordic-Baltic countries, for some countries of the UN, and a special agreement between United Arab Emirates and India (Fintech Poland, 2022).

The institutions of the European Union have been actively dealing with the subject of AI since 2016. In April 2018, the European Commission published a Communication Artificial Intelligence for Europe. This document describes the main goal for Europe: to become a global leader, providing state-of-the-art, ethical and safe human-centric AI solutions. The entire document emphasizes the anthropocentrism of the approach (Communication Artificial Intelligence for Europe, 2018).

The human being is to be at the center of the solution, despite the fact that development is associated with the development of artificial intelligence, i. e. algorithms, innovations and machines. This positions artificial intelligence and its role as ancillary to humans and its surroundings.

The European Union has the potential to develop artificial intelligence and recognizes the challenges it brings. The advantage of the European Union is undoubtedly its academic background in the form of scientists, research

and laboratories. Many AI startups are thriving in the EU and new ones are still being created.

Artificial intelligence solutions are already working well in many countries. For example, in Denmark there is a system that helps emergency services diagnose heart attacks based on the caller's voice. In Austria, on the other hand, X-ray images are analyzed to detect tumors by instantaneous comparison of medical data with X-ray images.

The great advantage of the Union is the Digital Single Market. This market is characterized by common rules, e.g. regarding data protection and flow, as well as security. The uniformity of these rules makes it easier for business and cooperation between entrepreneurs who, operating in other Member States, are subject to the same guidelines and regulations.

The European Union already has access to huge amounts of data on various industrial sectors, including the public sector. Access to this data and its processing may turn out to be crucial in the development of artificial intelligence.

The European Commission proposes a three-pronged approach to the development of artificial intelligence. Success is guaranteed here:

- increasing investment in AI in both the public and private sectors;
- preparation for socio-economic changes caused by AI;
- providing an ethical and legal framework.

The EU approach – in addition to investments – also analyzes changes in the human environment. AI causes and can cause further socio-economic changes that should be paid attention to. Not only the disappearance of entire professions, but also profound changes in the way they are performed can cause social tensions. They can only be mitigated by the coordinated policies of the Member States. For example, the introduction of the Uber application brought a wave of protests by taxi drivers. This will probably also be the case when fully driverless taxis are launched. That is why it is so important to introduce legal solutions on an ongoing basis that leave no room for doubt and over-interpretation. However, it will certainly be difficult, as most of the innovations introduced by enterprises are ahead of legal regulations.

In addition, the European Commission, together with the Member States, prepared and published in December 2018 a coordinated plan for AI (European Coordinated Plan on Artificial Intelligence, 2018, December 7). The plan provides for a number of actions to support the development and use of AI in Europe, including by:

- maximizing investment through public-private partnerships, increased funding for AI start-ups and small and medium-sized enterprises;
- creating and connecting digital innovation hubs that can help in the application of AI in small and medium-sized enterprises;
- adaptation of training programs and systems;
- creating European data spaces regulated by the GDPR (General Data Protection Regulation);
- ensuring that AI solutions are ethical and trustworthy.

The European Union's policy on artificial intelligence is also supported by a budget prepared for these purposes. The European Commission has so far planned significant sums of investment in AI in 2014–2020, including under two dedicated programs: Horizon and Digital Europe.

- Approximately EUR 1.1 billion is the budget allocated in 2014–2017 to areas related to artificial intelligence (robotics, big data, health, transport, new technologies) under the Horizon programme.

- As much as EUR 2.3 billion has been allocated – through the Structural Funds – to the development of digital skills (http://ec.europa.eu/newsroom/dae/document.cfm?doc_id=51610).

- Investments planned for the period 2018–2020 amount to EUR 1.5 billion for research and innovation.

- After 2020, as much as EUR 1 billion of expenditure per year was planned from the Horizon and Digital Europe programmes.

These amounts illustrate the importance of spending related to artificial intelligence in the Community budget.

On April 10, 2018, 24 member states, together with Norway, signed a declaration on cooperation in the field of artificial intelligence. This declaration aims to create a unified European approach to AI. As part of the declaration, all Member States committed themselves to develop their own national strategies by mid-2019, defining the approach to AI and the level of investment (European Commission, 2018, December 7).

The EU plans to monitor the implementation of the strategy in individual countries, introducing indicators necessary to analyze and evaluate the implementation of this initiative. Monitoring information will be published on the AI Watch portal (A hub for the JRC's scientific research on Artificial Intelligence).

Despite the anticipated benefits, AI also poses many risks. Therefore, the European Union places great emphasis on making AI solutions credible and ethical. The key here is to create an ethical and legal framework in which the EU's position as a leader in the implementation of innovative solutions in the field of artificial intelligence should be built. For this purpose, the European Commission's group of experts developed the Ethics Guidelines for Trustworthy AI². The document was published on 2019, April 8. and is a set of guidelines for building and implementing AI systems. The addressees of these guidelines are enterprises, organizations, public administration bodies, academia, individuals or other entities involved in the creation, implementation and use of AI in practice.

² Within the advisory bodies of the European Commission, a group of 52 high-level experts on artificial intelligence in the European Commission was established, consisting of academics, lawyers, politicians and business practitioners (High-level expert group on artificial intelligence)

As part of the "trustworthy AI" concept, the EC emphasizes that artificial intelligence should be used in compliance with applicable regulations and basic principles and values, and should be technically reliable. Reliable AI is defined by three determinants:

- should comply with applicable regulations;
- should respect basic ethical principles and values;
- it should be reliable – technically reliable while taking into account the social environment, so that it cannot cause even unintentional damage.

The guidelines are organized according to three levels of abstraction, from the most abstract (providing ethical AI) to the most practical (Assessing the AI's credibility). The document contains guidelines divided into 3 groups:

- ensuring ethical AI;
- implementing reliable AI;
- AI credibility assessment.

The first part is about ensuring the ethical purpose of AI by establishing the fundamental rights, principles and values necessary for AI solutions. The implementation, development and use of artificial intelligence systems should comply with ethical principles such as: respect for human autonomy, harmlessness, justice and responsibility.

Based on ethical principles, the second part outlines the seven principles necessary to achieve trustworthy AI (both in terms of ethical purpose and technical integrity):

Human leadership and oversight – supporting the development of a democratic and just society by strengthening human leadership and supporting fundamental rights.

Stability and security – creating safe and technically reliable solutions, resistant and preventing potential damage.

Privacy and data protection – providing citizens with access and appropriate control over their own data. The data used should be checked for appropriate quality and integrity.

Transparency – ensuring the traceability of AI systems.

Diversity, non-discrimination and fairness – ensuring diversity and equal and fair treatment.

Social and environmental well-being – enhancing positive social change, supporting sustainable development and ecological responsibility.

Accountability – ensuring accountability mechanisms for artificial intelligence systems and their results.

Artificial intelligence solutions are constantly changing, evolving in a dynamic environment, therefore they require appropriate assessment methods that can be used at every stage of their life cycle. The very process of their assessment should be a continuous process. In order to assess and verify the implementation of ethical AI requirements, methods were proposed and divided into technical and non-technical (*Figure 1*).

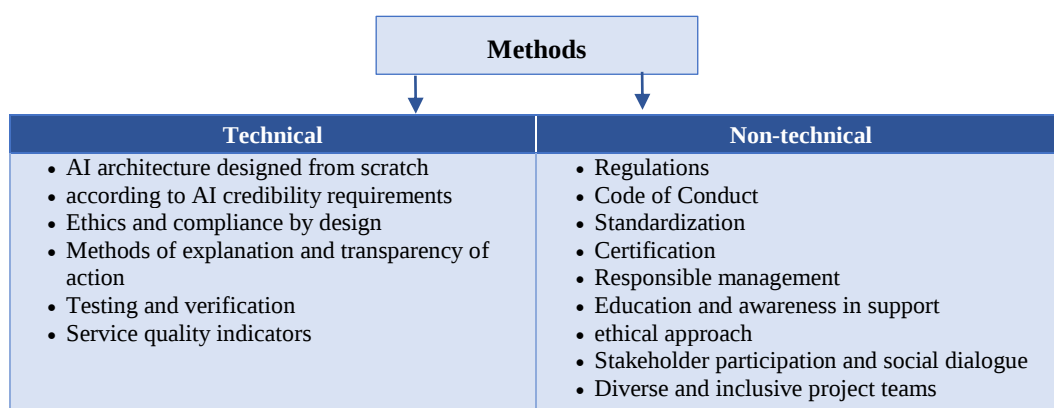


Figure 1. AI evaluation methods

Source: ethics guidelines for trustworthy AI (2019).

The proposed set of methods resembles project methodologies, probably known to many managers.

The third part focuses on verifying each of the key AI credibility requirements using a checklist. This list should be flexible and tailored to specific cases. this summer it is planned to launch a pilot phase aimed at collecting opinions on the prepared checklist³. After taking into account the collected comments, an updated checklist was proposed at the beginning of 2020.

The last part of the report presents examples of beneficial uses and risks associated with artificial intelligence. Many countries are already using practical solutions that support socially important areas, e.g. health or education. Positive examples are presented in *Figure 2*.

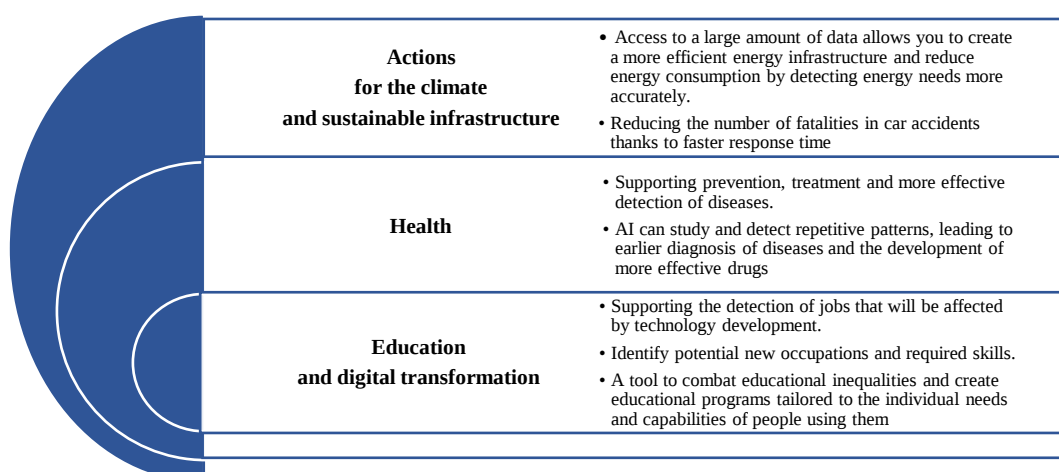


Figure 2. Practical solutions that support socially important areas

Source: ethics guidelines for trustworthy AI (2019).

³ It is also planned to expand the EU's cooperation with other countries, such as Japan, Canada and Singapore, and to participate in international discussions and initiatives, including under the G-7 and G-20. The pilot phase will also cover companies from other countries and international organizations.

The document of the European Commission also indicates many areas that require discussion, and often legal regulations. Trust in artificial intelligence may be synonymous with the need to give up the rights of a citizen. It is very important to decide which values are more important, e.g. whether it is possible to limit a citizen's freedom while increasing his security.

The risks are listed in *Figure 3*, presented below.

Identification and tracking of citizens	Automatic identification of persons (e.g. using face or voice recognition systems) can be used to unlawfully track citizens, thus violating their freedom
Hidden AI systems	There is no information about cooperation with the artificial intelligence system in a given procedure or process
Evaluation of citizens in violation of their fundamental rights	The lack of transparent procedures and methodologies using scoring systems can result in discrimination and unfair evaluation of citizens, customers, etc.
Deadly defense systems	The use of automatic defense systems, in which the factor of human decision is eliminated, raises ethical questions and may lead to an uncontrolled arms race.

Figure 3. Risks and limits for a citizen's freedom

Source: ethics guidelines for trustworthy AI (2019).

In May 2018, the General Data Protection Regulation (GDPR) entered into force, which has a significant impact on the development of artificial intelligence (driven by, among others, data sets). Their processing provides huge amounts of information and can have an impact on AI solutions. It is necessary to apply the provisions of the GDPR already in the design phase, when building and implementing AI elements. Experts are already asking questions about whether the GDPR will not limit the technological revolution and raise doubts related to the interpretation of the current regulations.

Some initial information on the case studies strategies for selected countries are presented in *Table 1*.

Table 1
AI implementing experiences – case studies for selected countries

Country	Key actions connecting the AI implementation
France	The France Intelligence Artificially report was published, and the introduction of both documents was intensively promoted as the #FranceAI initiative
	Report "For a meaningful artificial intelligence. Towards a French and European strategy" analyzes the current situation in France and describes in detail what development directions to take to become a leader in the field of AI
	To achieve the leading position, the French government planned to invest EUR 1.5 billion in the development of artificial intelligence by 2022. Of this amount, 700 million will be allocated to research. Investments in AI are expected to double the number of students working in this area
	France emphasizes the possibilities offered by AI in terms of ecological impact on the environment, e.g. by understanding ecosystem dynamics and optimizing resource management (including energy). Artificial intelligence can help reduce energy consumption. It can be used in environmental protection (e.g. using drones for afforestation or mapping living species using image recognition technology). In a green economy powered by AI, access to data is essential. It is crucial to ensure access to open data sets, e.g. on weather, agriculture, transport, energy consumption, climate
	The report proposes the creation of an AI ethics committee, responsible for the public debate, which will deal with topics related to the ethics of artificial intelligence. Another proposal is to automate administrative procedures so that citizens better understand administrative rules and how they affect them

End of Table 1

Country	Key actions connecting the AI implementation
Great Britain	The UK published its Artificial Intelligence Action Plan in April 2018 (Industrial Strategy. Artificial Intelligence Sector Deal). The advantage of Great Britain is its academic background (including universities in Oxford, Cambridge and Leeds)
	The UK strategy itself is coherent, full of specific assumptions supported by specific numbers. It is based on 5 pillars (see Ideas, People, Infrastructure, Business environment, Places): I. Ideas/concepts
	The main objective of the strategy is to make the UK the most innovative economy in the world. This will be made possible by investments and increased spending in the area of research and development (R&D). Expenses are expected to increase to 2.4% of GDP by 2027
	Education ecosystem is conducive to development in the field of science and technology. Cooperation with universities is to be a base that will provide a highly qualified staff of scientists and employees in the field of AI
	Infrastructure support is provided primarily in the area of data. It is not only about improving the current data infrastructure, but also increasing the amount and availability of high-quality public data
	The UK has ambitions to become the best economic ecosystem to start and develop an AI-based business. The ecosystem also means access to capital, which is why the British Business Bank has created a fund for targeted investments with capital of GBP 2.5 billion (the activities of the fund, together with the private sector, will enable financing projects at the level of GBP 7.5 billion)
	The creation of a national strategy is to mobilize regions to create their own AI strategies (which will use local assets). Particularly important is the issue of transport between regions and cities, which will be incubators for the business of the future. Therefore, it is assumed that the new fund (called the Transforming Cities Fund) will provide GBP 1.7 billion to finance projects to improve transport connections in metropolitan regions
USA	The USA is one of the world leaders in the field of artificial intelligence. It is here that the biggest players – GAFAM (Google, Amazon, Facebook, Apple, Microsoft) have their headquarters. These companies are undoubtedly associated with technological innovations, access to data and extensive infrastructure. They are an inspiration for many startups and create a massive ecosystem, because according to data, 40% of all global AI startups start their operations in the USA
	The USA ecosystem also includes strong research regions (San Francisco Bay Area, New York, Boston) and academic units at the highest level (including MIT, Stanford). Qualified staff is about 850,000 specialists in the field of artificial intelligence. Research and investments in AI are supported by an appropriate funding system
	October 2016, the Executive Office of the President of the United States issued a report, preparing for the Future of Artificial Intelligence, describing actions that the government should take to increase the economic and social benefits of AI
	A separate plan was created, covering only issues related to R&D and the provision of qualified staff (National Artificial Intelligence Research and Development Strategic Plan). The plan was issued by the Networking and Information Technology Research and Development Subcommittee (NITRD)
	The US sees the role of public policy in providing education and training and the appropriate transformation of workers, which is necessary to develop relevant skills and, if necessary, re-industry workers. AI solutions should be governable, transparent and understandable to be able to effectively cooperate with humans. Attention is also drawn to the ethical dimension for practitioners, students, researchers and decision-makers responsible for artificial intelligence
	The US is meticulous about ethics, it has included priorities in its strategy that are considered ethically controversial. For example, the US government aims to develop AI in weapons systems. There is an international discussion about the potential of AI-controlled weapons
China	China's plan assumes that by 2030 it will become the world leader in AI, and the Chinese business based on artificial intelligence will be worth USD 150 billion. International players such as Baidu, Alibaba, Tencent and Xiaomi (BATX for short) are already active in the Asian region – well-known enterprises originating from China. These companies have their own huge research facilities and dynamically implement artificial intelligence in their services
	Artificial intelligence was already one of the 10 strategic sectors/areas of development listed (the others include new information technologies, aviation equipment, modern ships, energy saving, agricultural machinery, new materials, medical devices). China wants to stop copying technological solutions and start creating them based on its own innovations
	The detailed AI strategy was announced on July 20, 2017 in the Next Generation Artificial Intelligence Development Plan published by The State Council of China. So, the goal is to become the world leader in artificial intelligence – is implemented in 3 stages: <i>Stage I:</i> 2017–2020. The goal is to equalize technological levels. By 2020, China wants to catch up with AI pioneers, such as the US. They estimate that their market will then reach USD 23 billion. <i>Stage II:</i> 2020–2025. The second stage is to lead China to specialization and leadership in selected fields of artificial intelligence in 2025. These fields are primarily medicine, agriculture, national defense and smart cities. <i>Stage III:</i> 2025–2030. The goal of the third stage, scheduled for 2030, is for China to become the world leader in AI. It is advanced research and implementation in business and society that will make China number one

Source: authors' elaboration based on (European Judicial Systems – CEPEJ Evaluation Report, 2024).

4. Analysis and evaluation of the artificial intelligence and machine learning in financial services

Artificial intelligence and machine learning are being rapidly adopted for a range of applications in the financial services industry. As such, it is important to begin considering the financial stability implications of such uses. Because uses of this technology in finance are in a nascent and rapidly evolving phase, and data on usage are largely unavailable, any analysis must be necessarily preliminary, and developments in this area should be monitored closely.

Many applications, or "use cases", of AI and machine learning already exist. The adoption of these use cases has been driven by both supply factors, such as technological advances and the availability of financial sector data and infrastructure, and by demand factors, such as profitability needs, competition with other firms, and the demands of financial regulation. Some of the current and potential use cases of AI and machine learning include:

- Financial institutions and vendors are using AI and machine learning methods to assess credit quality, to price and market insurance contracts, and to automate client interaction.
- Institutions are optimizing scarce capital with AI and machine learning techniques, as well as back-testing models and analyzing the market impact of trading large positions.
- Hedge funds, broker-dealers, and other firms are using AI and machine learning to find signals for higher (and uncorrelated) returns and optimize trading execution.
- Both public and private sector institutions may use these technologies for regulatory compliance, surveillance, data quality assessment, and fraud detection.

In order to be able to analyze and evaluate the use of AI and machine learning in financial services, several important hypotheses must be articulated:

- The more efficient processing of information, for example in credit decisions, financial markets, insurance contracts, and customer interaction, may contribute to a more efficient financial system. Applications of AI and machine learning can help improve regulatory compliance and increase supervisory effectiveness.
- At the same time, network effects and scalability of new technologies may in the future give rise to third-party dependencies. This could in turn lead to the emergence of new systemically important players that could fall outside the regulatory perimeter.
- Applications of AI and machine learning could result in new and unexpected forms of interconnectedness between financial markets and institutions, for instance based on the use by various institutions of previously unrelated data sources.
- The lack of interpretability or "auditability" of AI and machine learning methods could become a macro-level risk. Similarly, a widespread use of opaque models may result in unintended consequences.

• As with any new product or service, there are important issues around appropriate risk management and oversight. It will be important to assess uses of AI and machine learning in view of their risks, including adherence to relevant protocols on data privacy, conduct risks, and cybersecurity. Adequate testing and "training" of tools with unbiased data and feedback mechanisms is important to ensure applications do what they are intended to do.

Overall, AI and machine learning applications show substantial promise if their specific risks are properly managed.

This paper defines AI as the theory and development of computer systems able to perform tasks that traditionally have required human intelligence. AI is a broad field, of which "machine learning" is a sub-category⁴. Machine learning may be defined as a method of designing a sequence of actions to solve a problem, known as algorithms, which optimize automatically through experience and with limited or no human intervention⁵. These techniques can be used to find patterns in large amounts of data (big data analytics) from increasingly diverse and innovative sources.

Many machine learning tools build on statistical methods that are familiar to most researchers. These include extending linear regression models to deal with potentially millions of inputs, or using statistical techniques to summarize a large dataset for easy visualization. Yet machine learning frameworks are inherently more flexible; patterns detected by machine learning algorithms are not constrained to the linear relationships that tend to dominate economic and financial analysis. In general, machine learning deals with (automated) optimization, prediction, and categorization, not with causal inference⁶. In other words, classifying whether the debt of a company will be investment grade or high yield one year from now could be done with machine learning. However, determining what factors have driven the level of bond yields would likely not be done using machine learning.

A variety of factors that have spurred adoption of AI and machine learning in financial services. On the supply side, financial market participants have benefitted from the availability of AI and machine learning tools developed for applications in other fields. These include availability of computing power owing to faster processor speeds, lower hardware costs, and better access to computing power via cloud services.

As more firms adopt these tools, the financial incentives to access new or additional data and to develop faster and more accurate AI and machine

⁴ Examples of AI applications that are not machine learning include the computer science fields of ontology management, or the formal naming and defining of terms and relationships by computers, as well as inductive and deductive logic and knowledge representation. In this paper, for completeness, we often refer to "AI and machine learning", with the understanding that many of the important recent advances are in the machine learning space.

⁵ An algorithm may be defined as a set of steps to be performed or rules to be followed to solve a mathematical problem. More recently, the term has been adopted to refer to a process to be followed, often by a computer. See: Samuel (1959), Mitchell (1997), Jordan & Mitchell (2015).

⁶ Here, prediction is understood as identifying something as likely before the event based on experience. Causal inference and forecasting are done from a scientific perspective on the basis of analysis of the past.

learning tools may increase. In turn, such adoption and development of tools may affect incentives for yet other firms.

A variety of technological developments in the financial sector have contributed to the creation of infrastructure and data sets. The proliferation of electronic trading platforms has been accompanied by an increase in the availability of high-quality market data in structured formats. In some countries, such as the United States, market regulators allow publicly traded firms to use social media for public announcements. In addition to making digitized financial data available for machine learning, the computerization of markets has made it possible for AI algorithms to interact directly with markets, putting in real-time complex buy and sell orders based on sophisticated decision-making, in many cases with minimal human intervention. Meanwhile, retail credit scoring systems have become more common since the 1980s, and news has become machine readable since the 1990s. With the growth of data in financial markets as well as datasets – such as online search trends, viewership patterns and social media that contain financial information about markets and consumers – there are even more data sources that can be explored and mined in the financial sector.

On the demand side, financial institutions have incentives to use AI and machine learning for business needs. Opportunities for cost reduction, risk management gains, and productivity improvements have encouraged adoption, as they all can contribute to greater profitability. In a recent study, industry sources described priorities for using AI and machine learning as follows: optimizing processes on behalf of clients; working to create interactions between systems and staff applying AI to enhance decision-making; and developing new products and services to offer to clients. In many cases these factors may also drive "arms races" in which market participants increasingly find it necessary to keep up with their competitors' adoption of AI and machine learning, including for reputational reasons (*Figure 4*).

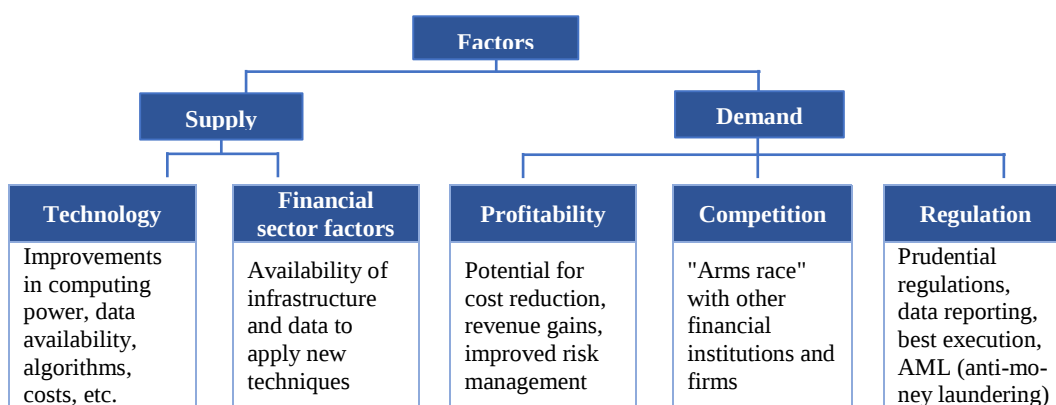


Figure 4. Supply and demand factors of financial adoption of AI and machine learning

Source: authors' study based on: Artificial intelligence and machine learning in financial services (2017).

A number of developments could impact future adoption of a broad range of financial applications of AI and machine learning. These developments include continued growth in the number of data sources and the timeliness of access to data; growth in data repositories, data granularity, variety of data types; and efforts to enhance data quality. Continued improvement in hardware, as well as AI and machine learning software as a service, including open-source libraries, will also impact continued innovation. Development in hardware includes processing chips and quantum computing that enable faster and more powerful AI. These developments could enable cheaper and broader access to AI and machine learning tools that are increasingly powerful. They could make more sophisticated real-time insights possible on larger datasets, such as real-time databases of online user behavior or internet-of-things (IoT) sensors located around the world.

At the same time, sophisticated software services are becoming more widely available. Some of the software services are open source libraries made available in the past few years that provide researchers with off-the-shelf-tools for machine learning. There are also a growing variety of vendors that provide machine learning for financial market participants, including some firms that scrape news and/or metadata and enable users to identify the specific features (webpages viewed, etc.) that correlate with the events they are interested in predicting. As services emerge to provide, clean, organize, and analyze these data for financial insights, the cost to users of incorporating sophisticated insights may fall significantly. Thus, at the same time, risks related to multiple users of the same information and techniques across the financial sector could grow.

The legal framework for relevant data will likely also impact the adoption of AI and machine learning tools. Breaches of personal data or uses of data that are not in the interests of consumers may be expected to lead to added data protection legislation. In addition, the development of new data standards, new data reporting requirements, or other institutional changes in financial services can impact the adoption of AI and machine learning in specific markets.

Financial stability implications depend critically on the uses of AI and machine learning. To assess these implications, questions to be considered would include which AI and machine learning tools are being used to make which types of decisions, on what time scales, to address which financial functions, and where and at what level human involvement is being integrated.

AI and machine learning are being adopted for a number of purposes across the financial system. Examples include:

- **Sentiment indicators:** Social media data analytics companies use AI and machine learning techniques to provide "sentiment indicators" to a number of financial services players. Investor sentiment indicators are being developed and sold to banks, hedge funds, high-frequency trading traders, and social trading and investment platforms.

- **Trading signals:** Machine learning can help firms to increase productivity and to reduce costs by quickly scanning and making decisions based on more sources of information than a human can. Therein also lies a limitation of machine

learning technology: by identifying and relying on patterns that were predictive of outcomes in the past, these tools are susceptible to false information. For example, there were market moves across equities, bonds, foreign exchange, and commodities in April 2013 after trading algorithms reacted to a fraudulent news Tweet announcing two explosions at the White House. These types of issues may be exacerbated with more widespread use of machine learning.

• AML/CFT (anti-money laundering and combating the financing of terrorism) and fraud detection: Seeking to increase productivity and simultaneously reduce costs and risks, while complying with regulations, some firms use AI for AML/CFT and fraud detection at financial institutions (van Liebergen, 2017). Firms can also use machine learning for credit monitoring and risk mitigation purposes.

Micro- and macro-financial perspectives of the application of AI/ML are presented in *Table 2*.

Table 2

Micro- and macro-financial perspectives of the application of AI/ML
in the financial system

Areas of application	Perspectives
<i>Micro-financial</i>	
Financial markets	Since AI and machine learning have the potential to substantially enhance the efficiency of information processing, thereby reducing information asymmetries, applications of AI and machine learning have the potential to strengthen the information function of the financial system (AI and machine learning may enable certain market participants to collect and analyze information on a greater scale; AI and machine learning may lower market participants' trading costs)
Financial institutions	AI and machine learning have the potential to enhance the efficiency and profitability of financial institutions, while reducing their costs and risks, through various channels. Greater profitability could aid the build-up of buffers and ultimately benefit system-wide stability (AI and machine learning may enhance machine-based processing of various operations in financial institutions, thus increasing revenues and reducing costs; AI and machine learning can be used for risk management through earlier and more accurate estimation of risks; the data intensity and open-source character of research in AI and machine learning may encourage collaboration between financial institutions and other industries, such as e-commerce and sharing economy businesses)
Consumers and investors	If AI and machine learning reduce the costs and enhance the efficiency of financial services, consumers could obtain a number of benefits (Consumers and investors could enjoy lower fees and borrowing costs if AI and machine learning reduce the costs for various financial services; Consumers and investors could have wider access to financial services. For example, applications of AI for robo-advice might facilitate people's use of various asset markets for their investments; AI and machine learning could facilitate more "customized" and "personalized" financial services through big data analytics)
<i>Macro-financial</i>	
Enhancing the efficiency of financial services	More efficient risk management of individual banks' loan portfolio and insurers' liabilities may benefit the aggregate system. AI and machine learning could help process information on the fundamental value of assets, thus allocating funds to investors and projects more effectively. Moreover, if AI and machine learning increase the speed and reduce the costs of payment and settlement transactions, for example by executing trades at times when there are available counterparties with corresponding demand, this may stimulate transactions for real activities
Facilitating collaboration and realizing new "economies of scope"	Were AI and machine learning to facilitate collaboration between financial services and various industries, such as e-commerce and "sharing economy" industries, this could realize new economies of scope and foster greater economic growth. For example, customer analysis based on transaction data attached to payment and settlement activities (for example, "who buys what, when, and where?") would encourage cooperation between e-commerce and financial services
Stimulating investments in AI and machine learning related areas	Many firms, including non-financial businesses, appear eager to apply AI and machine learning to their business. The growth in investments in AI and machine learning-related R&D can directly contribute to economy-wide investment and thus stimulate economic growth

Source: authors' elaboration based on (Merton, & Bodie, 2005).

The use of AI and machine learning technology is changing the provision of some financial services. While data on the extent of adoption in various markets is quite limited, dialogue with market participants suggests that some segments of the financial system are actively employing AI and machine learning. These applications are thus currently more widely used than other key innovations, such as distributed ledger technology or smart contracts. In particular, fraud detection, capital optimization, and portfolio management applications appear to be growing rapidly. Most market participants expect that AI and machine learning will be adopted further. Because of this, it is important to start thinking about the financial stability implications now rather than after the potential implications have been realized. The analysis is necessarily partial and will benefit from greater understanding of use cases over time. Moreover, the changes will not result in a material change to financial stability and hence fall outside the scope of this paper.

The use of AI and machine learning in financial services may bring key benefits for financial stability in the form of efficiencies in the provision of financial services and regulatory and systemic risk surveillance. The more efficient processing of information on credit risks and lower-cost customer interaction may contribute to a more efficient financial system. The internal (back-office) applications of AI and machine learning could improve risk management, fraud detection, and compliance with regulatory requirements, potentially at lower cost. In portfolio management, the more efficient processing of information from AI and machine learning applications could help to boost the efficiency and resilience of financial markets – reducing price misalignments earlier and (under benign assumptions) reducing crowded trades. Finally, with use cases by regulators and supervisors, there is potential to increase supervisory effectiveness and perform better risk analysis in financial markets.

Many current providers of AI and machine learning tools in financial services may fall outside the regulatory perimeter or may not be familiar with applicable law and regulation. Where financial institutions rely on third-party providers of AI and machine learning services for critical functions, and rules on outsourcing may not be in place or not be understood, these services and providers may not be subject to supervision and oversight. Similarly, if providers of such tools begin providing financial services to institutional or retail clients, this could entail financial activities taking place outside of the regulatory perimeter.

The uses of AI and machine learning should continue to be monitored. As the underlying technologies develop further, there is potential for more widespread use, beyond the use cases discussed in this paper. It will be important to continue monitoring these innovations and to update this assessment in the future.

Conclusions

The deployment of artificial intelligence and machine learning systems in the financial sector will continue to accelerate. This trend is driven by rapid increases in computational powers, data storage capacity, and big

data, as well as by significant progress in modeling and use-case adaptations. The COVID-19 pandemic is accelerating the shift toward a more contactless environment and increasingly digital financial services, which will further strengthen the appeal of AI/ML systems to providers of financial services. Use of AI/ML will bring important benefits but will also raise significant financial policy challenges. AI/ML systems offer financial institutions the potential for significant cost savings and efficiency gains, new markets, and better risk management; bring customers new experiences, products, and lower costs; and offer powerful tools for regulatory compliance and prudential oversight. However, these systems also bring about ethical questions and new unique risks to the financial system's integrity and safety, of which the full extent is yet to be assessed. The task facing financial sector policymakers is further complicated by the fact that these innovations are still evolving and morphing as new technologies come into play. These developments call for improvements in oversight monitoring frameworks and active engagement with stakeholders to identify possible risks and remedial regulatory actions.

Regulators should broadly welcome the advancements of AI/ML in finance and undertake the preparations to capture its potential benefits and mitigate its risks. This includes the timely strengthening of institutional capacity, recruiting relevant expertise, building up knowledge, improving external communication with stakeholders, and expanding consumer education. Deployment of AI/ML systems in the financial sector has proven to be most effective when there are national AI strategies in place that involve all relevant public and private bodies. Cooperation and knowledge sharing at the regional and international level is becoming increasingly important. This would allow for the coordination of actions to support the safe deployment of AI/ML systems and the sharing of experiences and knowledge. Cooperation will be particularly important to ensure that less-developed economies have access to knowledge related to techniques and methods, use cases, and regulatory and supervisory approaches. Finally, the evolving nature of the AI/ML technology and its applications in finance mean that neither the users, the technology providers and developers, nor the regulators understand, currently, the full extent of the strengths and weaknesses of the technology. Hence, there may be many unexpected pitfalls that are yet to materialize, and countries will need to strengthen their monitoring and prudential oversight.

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