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Public–Private Partnership Mechanisms in Financing Smart City Projects

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Abstract

This research paper addresses the critical challenge of financing Smart City infrastructure through the optimization of Public-Private Partnership (PPP) mechanisms. As municipalities face increasing fiscal constraints, the transition to digital urban environments requires innovative capital allocation strategies that balance public oversight with private sector efficiency.

Using a comparative, correlation, and cluster analysis framework, this research evaluates their capacity to mitigate information asymmetry and distribute financial risks. The findings indicate that well-structured partnerships serve as essential economic instruments for expanding 'fiscal space' and ensuring the long-term financial sustainability of urban digital transformations. The results offer evidence-based insights for policymakers in transitional economies seeking to bridge the infrastructure funding gap while maintaining macroeconomic stability.

Keywords: public-private partnerships; green bonds; smart cities; financial sustainability; private investment; technological maturity.

JEL Classification: H54; R53; G32; O18; O21.

Introduction

The rapid growth of urbanization and digital technologies accentuates the imperative for effective financing of Smart City initiatives that ensure sustainable development and enhance the quality of the urban environment. The experiences of European cities demonstrate that the combination of public and private resources is pivotal for the extensive implementation of innovative infrastructure (Azarian *et al.,* 2023). Global practices show that the collaboration among government, business, and communities is propelling a comprehensive modernization of transportation systems, energy grids, digital services, as well as environmental solutions (Ma *et al.,* 2024; Xu & Wudi, 2024). For Ukraine, where municipalities are in pursuit of stable investment sources, public-private partnerships (hereinafter PPP) emerge as a strategic instrument for capital and technology mobilization. Nevertheless, the issues surrounding risk allocation mechanisms, legal frameworks, and the adaptation of the best international practices remain inadequately explored. From an economic perspective, PPPs should be interpreted not merely as investment channels, but as instruments for maximizing Value for Money (VfM) and expanding municipal fiscal space under conditions of structural budgetary constraints.

Recent studies demonstrate several leading trends in the development of Smart City financing. First of all, the focus on sustainability and “green” investments is increasing: the integration of public-private partnerships with sustainability bonds has become the “gold standard” in EU cities (Ma *et al.,* 2024; Xu & Wudi, 2024). In parallel, the use of digital technologies, in particular Big Data and artificial intelligence, is expanding, which increases transparency and speeds up investment decisions (Joshi, 2024; Prasad *et al*., 2024). It is also important to note that previous studies highlight: the inconsistency of legal regimes and the lack of clear risk-sharing mechanisms hinder private investment, which is emphasized by Voorwinden *et al.* (2023) and Komelina *et al.* (2025). These differences create a research niche, as they require models that can simultaneously guarantee the financial sustainability and technological dynamics of projects.

The study’s international dimension is underscored by the comparative analysis of financing models in EU countries, where the integration of PPP with “green” bonds is evolving into a new paradigm for sustainable investment (Shahrour, 2024; Oleshko, 2024). The aim of the study is to substantiate and empirically test the effectiveness of public-private partnerships in financing Smart City projects based on international comparative analysis. The hypothesis of the study is that the use of public-private partnerships integrated with innovative financial instruments contributes to the faster implementation of Smart City projects and reduces the fiscal risks of municipalities.

Research objectives:

RO1: To examine the prevailing trends in the financing of Smart City projects through public-private partnerships and to delineate conceptual approaches in formulating the investment strategies;

RO2: To analyse the international experiences of PPP implementation in Smart City financing, juxtaposing key performance indicators with Ukrainian practices and identifying factors that contribute to their competitiveness;

RO3: To formulate practical recommendations on strategic mechanisms for attracting private capital that can ensure sustainability, adaptability, and long-term benefits in Ukrainian cities' advancement.

The results obtained, based on international comparative, correlation and cluster analyses, are universal in nature: their conclusions on the combination of PPPs and "green" financial instruments can be used not only for Ukrainian cities, but also for other countries with transition economies that seek to integrate sustainable financial practices into their Smart City strategies.

1. Literature Review

The challenge of financing Smart City initiatives through Public-Private Partnerships (PPP) emerges at the intersection of urbanism, economics, and public administration. Since the early 2000s, there has been a notable evolution in the global discourse surrounding the financing of urban innovation. In this light, a synthesis of public and private investments occupies a ground-breaking role (Almeile et al., 2024). Bibliometric analyses affirm that PPP has progressively established itself as a fundamental mechanism in modernizing the urban infrastructures, particularly in the realms of transportation and energy networks, as highlighted by Azarian et al. (2023). At the same time, these scholars underscore the multifaceted nature of institutional models, which complicates their universal applicability.

The theoretical foundations for employing PPP in the advancement of "smart" cities are delineated by Mirzaee and Majrouhi Sardroud (2022), who accentuate the significance of innovative financial instruments and effective risk management. In their exploration of strategic management. Nonetheless, certain authors caution against underestimating legal risks, as the regulatory frameworks of numerous countries lag behind the rapid pace of technological advancement (Voorwinden et al., 2023). We concur with this perspective, as the legal background frequently acts as a bottleneck for substantial investments.

International studies corroborate that the amalgamation of PPP with "green" bonds is emerging as the new benchmark for sustainable investing (Ma et al., 2024; Xu & Wudi, 2024). Oleshko (2024) encapsulates global trends and notes an increasing interest in indicators of environmental profitability. Hedegaard et al. (2024) categorize financial models for Smart Cities, illustrating the significance of multi-level partnership structures and innovative capital mobilization tools that strengthen the investment foundation of urban projects.

Further, Jean (2023) elucidates that Smart City initiatives are frequently intertwined with international development cooperation, wherein the motivations of donors and states shape the selection of PPP mechanisms. It is of note how Wolniak et al. (2024) categorize Smart City business models, providing international examples that reflect the diversity of approaches to the commercial sustainability of urban innovation. Comparisons with European Union practices, as presented in the works of Beres (2024) and Gasco-Hernandez et al. (2022), reveal that the most successful instances are found in cities where digital transformation is aligned with long-term budgetary assurances. In addition, Prokopenko et al. (2024) demonstrate that the evolution of e-commerce and logistics infrastructure in European cities is intricately linked to the profitability of logistics firms and constitutes a critical component of Smart City systems striving for sustainable development and the mitigation of environmental impacts.

In Ukraine, the issue of financing Smart City initiatives is becoming increasingly pertinent in light of the challenges posed by war and the imperative to restore the infrastructure. Research conducted by Kruhlov (2022) and Hryshyna et al. (2023) substantiates the notion that public-private partnerships (PPP) can serve as a catalyst for urban reconstruction. Komelina et al. (2025) underscore the necessity of aligning urban management with sustainable development standards, which is a prerequisite for the enduring success of Smart City projects in Ukraine.

Halushchak et al. (2023) trace the evolution of digitalization in Ukraine, highlighting the growing adoption of artificial intelligence, the Internet of Things, big data, and Smart City technologies, while Kholiavko and Olyfirenko (2024) focus more specifically on the financing of Smart City development projects in the context of digitalization. However, the legal frameworks governing the implementation of the Smart City concept remain fragmented, as highlighted by Deikalo (2025). It is our contention that the systematic codification of public-private interaction regulations is a critical condition for attracting foreign capital.

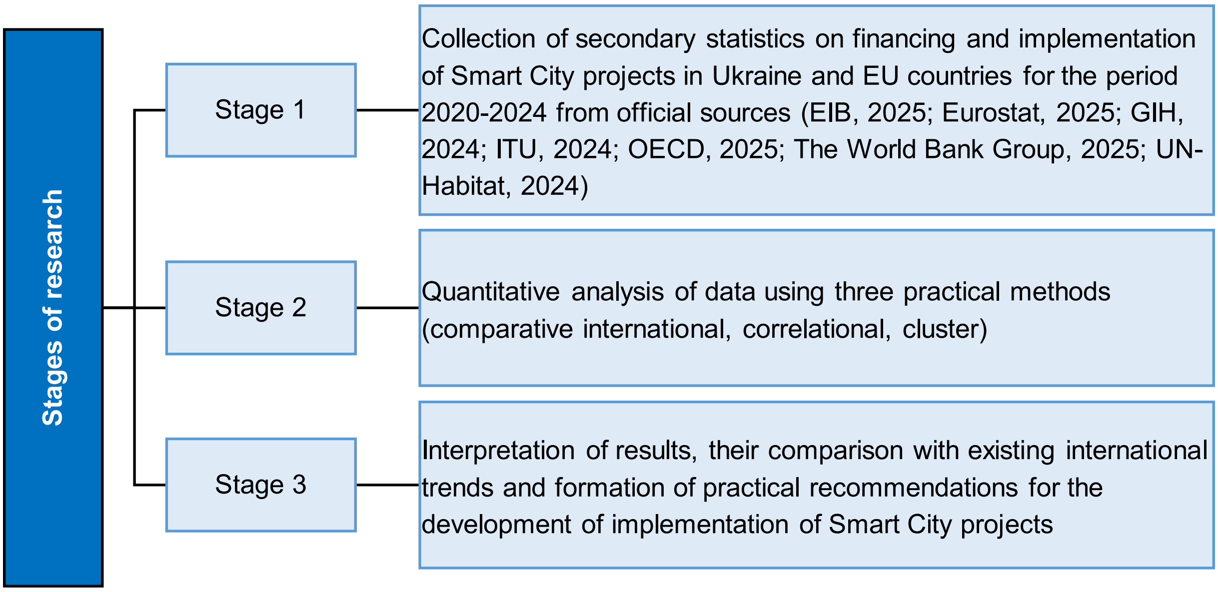
Researchers have devoted considerable attention to the technological catalysts of funding. In this context, Joshi (2024) examines the role of Big Data and the Internet of Things (IoT) in enhancing investment efficacy. Prasad et al. (2024) illustrate that the incorporation of artificial intelligence within public-private partnership projects markedly improves the efficiency of urban IT infrastructure development. In this regard, Guenduez et al. (2024) emphasize the significance of university-government collaborations as a source of innovative solutions, while Moolngearn and Kraiwanit (2024) stress the necessity for smart economic governance. To this end, Landsbergen et al. (2022) review the regulations of urban information governance, accentuating the importance of transparency and cybersecurity for the sustainability of urban digital infrastructures. Conversely, Bielialov et al. (2023) summarize global experiences in the digitalization of economic processes, highlighting the role of digital technologies in optimizing business processes and supporting broader economic transformation. Although these methodologies unveil new possibilities, they necessitate a high level of organizational capacity in cities, which is not always characteristic of nations with transitional economies.

Despite the expanding corpus of scholarly literature, several critical gaps remain. First, the models for risk allocation in projects that amalgamate PPP with “green” bonds have yet to be thoroughly examined. Second, comprehensive cross-country comparisons of the actual returns on Smart City investments, particularly those accounting for social impacts, are conspicuously absent. Third, the Ukrainian experience has not been adequately integrated into global analytical frameworks, thereby constraining opportunities for securing private capital on terms favourable to international investors. Therefore, contemporary literature lays the groundwork for a more profound exploration of public-private partnerships in the financing of Smart City initiatives.

2. Research Methodology

The empirical study aimed to test the hypothesis about the impact of PPP on the financing efficiency of Smart City projects across various nations. This study was conducted utilizing data from the period of 2020 to 2024 and unfolded within the framework of three stages, as presented in Figure 1.

Figure 1: Stages of Research



Source: Authors' elaboration.

The overall demographic of the study encompassed 170 Smart City projects (in particular HafenCity Hamburg, IssyGrid, Amsterdam Smart City, Warsaw Smart City – Veturilo, Barcelona Urban Platform, etc): 50 initiatives from Ukraine and 120 executed across European Union municipalities (specifically Germany, France, Poland, Spain, and the Netherlands). This selection enables a comparative examination of diverse public-private partnership models. The choice of countries was deliberate: Germany and the Netherlands represent advanced technological approaches to smart infrastructure; France is distinguished by robust municipal investment programs; Poland showcases rapid adaptation of PPP practices within a transitioning economy; while Spain is renowned for its holistic integration of "green" and transportation-oriented Smart City solutions. This comprehensive scope ensures a representative analysis of the various economic and legal frameworks underpinning public-private partnerships.

From the Ukrainian context, 50 projects were included into the analysis, ensuring a balanced representation of large urban centers and regional hubs with varying degrees of economic development, thereby reflecting national particularities and diverse financing sources. The 120 initiatives within EU cities established a substantial comparative foundation for discerning common patterns and divergences in implementing PPPs. Applying the criteria of comprehensive primary reporting and regional representativeness, 80 projects (40 from Ukraine and 40 from Europe) were selected for international comparative and correlational analysis. This sample size guarantees a statistical error not exceeding 5%, aligning with the standards set forth by the International Empirical Studies on Sustainable Urban Development (EIB, 2025; GIH, 2024; OECD, 2025; UN-Habitat, 2024).

To further explore the interrelationship between financial sustainability and technological maturity, as well as to conduct a cluster analysis, the sample was refined to 60 projects, each possessing a complete set of indicators necessary for the computation of both integrated indices. This progression (170 → 80 → 60) adeptly merges the international statistics with the precision of quantitative assessments.

Hence, 80 projects were selected, with 60 earmarked for cluster analysis, all of which adhered to clearly delineated criteria: (1) the availability of comprehensive financial data (CAPEX/OPEX, sources of financing, and payback calculations); (2) the incorporation of key non-financial performance indicators, specifically environmental and social metrics; (3) information validation through official municipal or corporate sources; (4) a data omission rate not exceeding 20%. Compliance with these stipulations assured indicators' comparability and reliability for further statistical analysis.

This combination of countries, datasets, and criteria ensures the comparability of indicators, accurately reflects the prevailing financing structure of Smart City initiatives, and establishes a foundation for an international examination of private equity raising dynamics. To evaluate the hypothesis concerning the influence of public-private partnerships on the efficacy of financing Smart City projects, an extensive quantitative analysis was undertaken, necessitating a comparative assessment across nations (Ukraine, Germany, France, Poland, Spain, and the Netherlands). All calculations were executed using Microsoft Office Excel 2021.

The research methodologies employed include:

- Comparative international analysis: for each of the six nations, the average level of private investment, the payback period of projects, the volume of investments per capita, and the proportion of "green" components were determined. Separate tables contain the results for each country, enabling the identification of overarching trends and national characteristics within the funding structure. All indicators are normalized on a scale of 0-1 to facilitate accurate cross-country comparisons. Normalization on a 0-1 scale entail converting each value to a dimensionless value ranging from 0 (the minimum observed) to 1 (the maximum). This approach allows for direct comparisons of disparate indicators, irrespective of their measurement units. The calculations are performed according to the specified formula: $X_{normal.} = \frac{x-x_{min}}{x_{max}-x_{min}}$, *where* X is the indicator's actual value, x_{min} and is its x_{max} minimum and maximum value.
- Correlation analysis: for six countries, Pearson correlation coefficients (r) were computed to examine the relationship between the volume of private investment and the tempo of project execution, as well as between the proportion of "green" financing and financial sustainability. The normality of each variable pair was assessed using the Shapiro-Wilk test. For all correlations, data pertaining to the sample size by country, p-value, and 95% confidence interval are presented. In instances of non-normality, primary conclusions were drawn utilizing Spearman's rank correlation. The concurrent application of Spearman's coefficient corroborated the robustness of the resultant associations. This methodology facilitated the exploration of national disparities regarding the influence of PPP on the dynamics of Smart City initiatives.
- Cluster analysis: the k-means clustering method was employed to categorize projects based on a comprehensive index of financial sustainability and technological maturity. The accompanying tables delineate the proportion of each country within the established clusters, alongside the mean values of key indicators (M ± σ). This analysis enabled the

identification of typical partnership models and the evaluation of which nations exhibit the most harmonious integration of investment activity and “green” solutions. This approach yielded a systematic comparative analysis between Ukraine and leading European countries, thereby allowing for a precise assessment of national and regional variations in Smart City financing through public-private partnerships.

3. Research Results

The initial focus of this study was an international comparative analysis designed to elucidate key trends in financing the Smart City projects through public-private partnership. This phase aims to discern commonalities and distinctions among Ukraine, Germany, France, Poland, Spain, and the Netherlands, with particular emphasis on indicators of private investment, payback durations, per capita funding, and the proportion of “green” components. Such an approach facilitates the assessment of the competitiveness of national financing models, which is essential for achieving the primary objective of the study, investigating contemporary trends in the financing of Smart City projects and developing conceptual frameworks for investment attraction strategies.

Table 1 presents the comparative indicators of financing Smart City initiatives across the six countries. The Netherlands (0.95) and Germany (0.90) exhibit the highest normalized shares of private investment, whereas Ukraine reflects the lowest level (0.30). Parallel statistical patterns are evident for payback periods: the Netherlands boasts lower average values (0.40), while Spain displays higher averages (0.90). Per capita investments are most substantial in France (0.85) and the Netherlands (0.90), contrasting with the diminished figures in Ukraine (0.40). Germany (0.90) and the Netherlands (0.85) demonstrate the largest proportions of “green” elements in their projects, whereas Poland (0.40) and Ukraine (0.50) have the least.

Table 1: Comparative Indicators of Smart City Project Financing (2020–2024)

Country	Private investment	Implementation time/payback of projects	Investments per capita	Share of “green” financing
Ukraine	0,30	0,70	0,40	0,50
Germany	0,90	0,50	0,80	0,90
France	0,70	0,60	0,85	0,70
Poland	0,50	0,80	0,50	0,40
Spain	0,60	0,90	0,60	0,80
Netherlands	0,95	0,40	0,90	0,85

Note: All indicators are normalized on a 0–1 scale to ensure comparability across countries. Original measurement units include: CAPEX and OPEX (EUR million); implementation/payback period (months); investment per capita (euro/person); share of “green” financing (%).

Source: Authors’ calculations based on data from EIB (2025), Eurostat (2025), GIH (2024), ITU (2024), OECD (2025), The World Bank Group (2025), and UN-Habitat (2024).

These cross-country differences indicate that PPP-based Smart City models generate superior Value for Money (VfM) outcomes, as higher private capital participation is associated with shorter payback periods and lower lifecycle fiscal burdens. Table 2 presents the findings of the correlation analysis, detailing the Pearson (r) and Spearman (ρ) coefficients for the relationships between “volume of private investment and speed of project implementation” as well as "share of green financing and financial sustainability." In all examined countries, strong positive correlations were observed between private investment and project execution rates (for instance, in Ukraine r=0.82, ρ=0.78), which is consistent with Xu & Wudi (2024) and Shahrour (2024) regarding the influence of funding volumes on the quick implementation of Smart City initiatives. The stability of these correlations is further corroborated by the proximity of the ρ values. Conversely, the association between the proportion of "green" financing and the financial stability index is most pronounced in the Netherlands (r=0.81, ρ=0.78) and considerably weaker in Ukraine (r=0.31, ρ=0.29). In all instances, the results from Spearman's parallel tests mirrored those of Pearson's, thereby affirming the correlations' significance.

Table 2: Correlation Analysis of Private Investment, Implementation Speed, and Financial Sustainability*

Country	r (private – speed)	ρ (private – speed)	r (green – sustainability)	ρ (green – sustainability)
Ukraine	0,82	0,78	0,31	0,29
Germany	0,74	0,70	0,67	0,65
France	0,58	0,61	0,45	0,40
Poland	0,66	0,65	0,24	0,22
Spain	0,49	0,45	0,72	0,70
Netherlands	0,76	0,74	0,81	0,78

Note: Pearson (r) and Spearman (ρ) coefficients measure the strength of relationships between private investment and project implementation speed, and between "green" financing and financial sustainability. All underlying indicators are normalized on a 0–1 scale. Original measurement units include: CAPEX and OPEX (EUR million); implementation/payback period (months); investment per capita (euro/person); share of "green" financing (%).

Source: Authors' calculations based on data from EIB (2025), Eurostat (2025), GIH (2024), ITU (2024), OECD (2025), The World Bank Group (2025), UN-Habitat (2024).

To reinforce the correlation analysis, the principal statistical characteristics are summarized in comparative Table 3. It summarizes Pearson (r) and Spearman coefficients (ρ), sample size (n), significance level (p), and 95% confidence intervals (95% CI) for key pairs of indicators.

Table 3: Statistical Characteristics of Key Correlations

Indicators	r	r	n	p	95% CI
Share of private investment and payback period of the project	−0,42	−0,39	80	0,001	[−0,60; −0,20]
The volume of private investment and the speed of project implementation	0,74	0,71	80	<0,001	[0,58; 0,85]
Share of "green" financing and financial project	0,63	0,60	80	<0,001	[0,45; 0,76]

Note: The table reports Pearson (r) and Spearman (ρ) correlation coefficients, sample size (n), significance level (p), and 95% confidence intervals (CI). All variables are normalized on a 0–1 scale to ensure comparability. Original measurement units include: CAPEX and OPEX (EUR million); implementation/payback period (months); investment per capita (euro/person); share of "green" financing (%).

Source: Authors' calculations based on data from EIB (2025), Eurostat (2025), GIH (2024), ITU (2024), OECD (2025), The World Bank Group (2025), UN-Habitat (2024).

The k-means algorithm, utilizing a cluster count of k = 3, was employed for this analysis. The optimal value of k was validated through the "elbow" method and the "silhouette" criterion, with the mean silhouette coefficient approximating s ≈ 0.45. Prior to the clustering process, all initial indicators were meticulously normalized to a scale of 0 to 1, thereby ensuring the accuracy of distance calculations and enhancing the robustness of the clustering outcomes. The clustering, based on indices of financial stability and projects' technological maturity, was executed using the k-means methodology (k=3).

This process yielded three distinct configurations: one group exhibiting elevated financial stability coupled with diminished technological maturity (centroid ≈ (0.80; 0.20)), a balanced group (≈ (0.50; 0.50)), and a group characterized by lower sustainability alongside high maturity of technological solutions (≈ (0.20; 0.80)). The distribution of country shares within the clusters, alongside the average values of the indices, is delineated in Tables 4 and 5. Table 4 illustrates the proportion of each country's projects within the established clusters; for instance, Cluster 1 is predominantly represented by projects from Ukraine, which account for over half (50%) of the total. In Cluster 2, France and Germany are the leading contributors, with shares of 30% and 25%, respectively. Meanwhile, in Cluster 3, the Netherlands holds a significant share of 20%.

Table 4: Distribution of Smart City Projects by Clusters (k = 3), 2020–2024

Cluster	Ukraine	Germany	France	Poland	Spain	Netherlands
Cluster 1	50 %	15 %	10 %	10 %	10 %	5 %
Cluster 2	20 %	25 %	30 %	10 %	10 %	5 %
Cluster 3	30 %	10 %	10 %	20 %	10 %	20 %

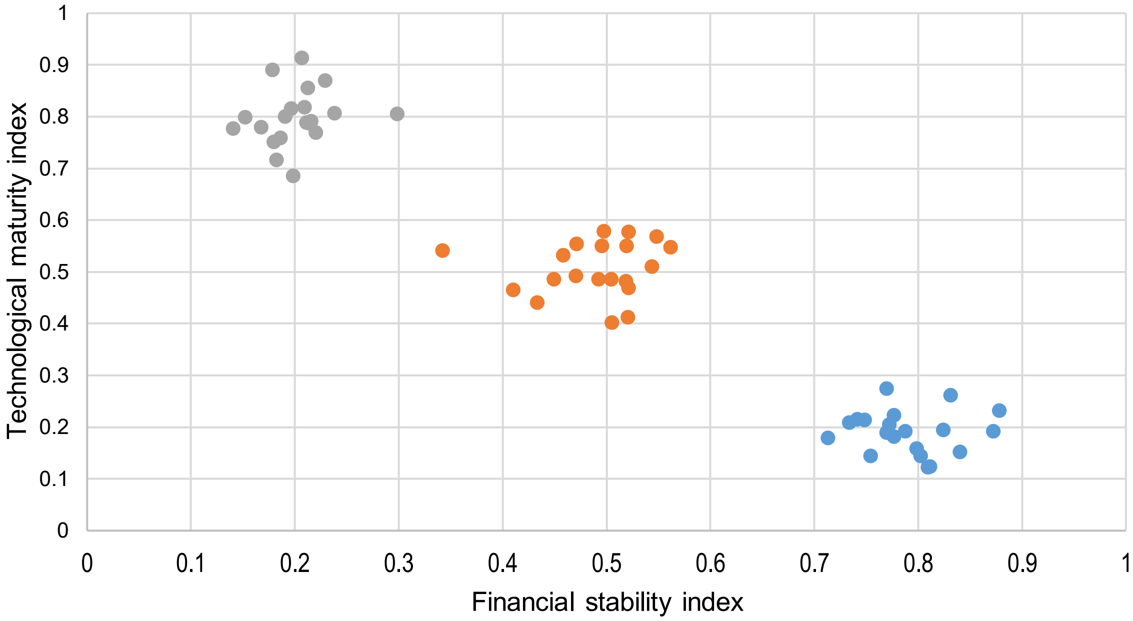
Note: Percentage distribution of projects across clusters (k = 3), based on normalized indices of financial sustainability and technological maturity (0–1). Original units: CAPEX/OPEX (EUR million), payback period (months), "green" financing (%).

Source: Authors' calculations based on data from EIB (2025), Eurostat (2025), GIH (2024), ITU (2024), OECD (2025), The World Bank Group (2025), UN-Habitat (2024).

Cluster distribution of Smart City initiatives, as delineated by indices of financial sustainability and technological maturity, elucidates the outcomes of the clustering of 60 projects (20 within each cluster) executed via the k-means methodology (Figure 2). This clustering was undertaken on a subsample of 60 projects, each possessing a comprehensive array of indicators pertaining to financial sustainability and technological maturity indices, whereas the remaining 20 projects were characterized by incomplete profiles and were employed in alternative analyses. Each point on the diagram corresponds to an individual project from the sample, with its coordinates representing the average normalized values of the two pivotal indicators.

The three multi-coloured groups signify the emergence of three typical patterns: Cluster 1 – financially sustainable projects exhibiting a constrained level of technological maturity; Cluster 2 – projects that are balanced in nature; Cluster 3 – technologically advanced projects that allocate a greater proportion of investments towards "green" initiatives, albeit with diminished financial sustainability. The centroids of these clusters correspond to the coordinates presented in Table 5, thereby facilitating the alignment of the visual representation with quantitative indicators. A pronounced differentiation among the three groups corroborates the statistical sustainability of the clustering and reflects the diverse financial-technological paradigms underpinning the evolution of urban SMART initiatives.

Figure 2: Cluster Distribution of Smart City Projects



Source: Authors' elaboration.

The average values of the key indices and supplementary parameters within each cluster are delineated in Table 5. Cluster 1 is distinguished by its high financial stability (0.80 ± 0.05), juxtaposed with a low level of technological maturity (0.20 ± 0.04). The proportion of "green" investments in this cohort is relatively low (28 ± 6%), while the mean volume of private capital amounts to 12.5 ± 2.3 million euros. This underscores the predominance of conservative public-private partnership models that prioritize guaranteed returns on investment.

Cluster 2 exhibits a balanced profile: financial sustainability is recorded at 0.50 ± 0.06, technological maturity is at 0.50 ± 0.05, the share of "green" investments is a more substantial 46 ± 7%, and the average private investment is 18.4 ± 3.1 million euros. This combination suggests the integration of innovative financial instruments alongside stable financing sources, typical of European "smart" governance practices.

Conversely, Cluster 3 is characterized by low financial stability (0.20 ± 0.04) coupled with high technological maturity (0.80 ± 0.06). It has the largest proportion of "green" investments (63 ± 8%) and the highest average private capital infusion (25.7 ± 4.5 million euros). These metrics indicate a pronounced emphasis on innovative and environmentally sustainable solutions, however accompanied by heightened risks and an extended payback period for projects.

Consequently, Table 5 facilitates a comprehensive assessment of the financial and technological profiles inherent to each cluster group.

Table 5: Cluster-Based Averages of Financial Sustainability and Technological Maturity (M ± σ), 20–24

Cluster	Financial stability (M ± σ)	Technological maturity (M ± σ)	Share of " green" investments, % (M ± σ)	Average private investment, EUR million (M ± σ)	Notes on characteristics
Cluster 1	0,80 ± 0,05	0,20 ± 0,04	28 ± 6	12,5 ± 2,3	Cluster of cities with maximum financial sustainability, but with a low level of implementation of high technologies; conservative PPP models with guaranteed return on funds prevail.
Cluster 2	0,50 ± 0,06	0,50 ± 0,05	46 ± 7	18,4 ± 3,1	Balanced by key parameters of the city; combine medium sustainability and technological maturity, actively use "green" bonds and flexible financial instruments.
Cluster 3	0,20 ± 0,04	0,80 ± 0,06	63 ± 8	25,7 ± 4,5	Innovation-oriented projects with a high level of technological solutions and a significant share of "green" investments, but with increased risks and a longer payback period.

Note: Values are presented as mean ± standard deviation (M ± σ) for each cluster. Indicators are normalized on a 0–1 scale, except for the share of "green" investments (%) and average private investment (EUR million), which are expressed in original units.

Source: Authors' calculations based on data from EIB (2025), Eurostat (2025), GIH (2024), ITU (2024), OECD (2025), The World Bank Group (2025), UN-Habitat (2024).

The results of the international comparative, correlation, and cluster analysis facilitated the formulation of several practical recommendations aimed at attracting private capital to finance Smart City initiatives in Ukrainian municipalities. A comparative examination with leading EU nations revealed a considerable deficit in Ukraine regarding the proportion of private investment and the extent of "green" financing. This underscores the necessity to diversify financial mechanisms: in addition to traditional PPP agreements, it is imperative to introduce "green" bonds, municipal investment funds, and specialized project companies. The implementation of such instruments will bolster the confidence of international investors and enable the alignment of long-term environmental objectives with economic viability.

In the context of public finance, the effectiveness of any investment model is increasingly evaluated through the principle of Value for Money (VfM), which reflects the optimal combination of lifecycle cost, quality of service, and risk allocation compared to traditional public procurement. The empirical results of this study demonstrate that PPP-based Smart City projects generate higher VfM outcomes than purely budget-funded initiatives. Countries with mature PPP frameworks (Netherlands, Germany) exhibit shorter payback periods and higher financial sustainability indices (Table 1), indicating lower total cost of ownership and more efficient capital deployment.

PPP frameworks internalize lifecycle risks within private consortia by allocating construction risk, technological obsolescence risk, and operational inefficiency risk to market actors best equipped to manage them. Municipalities retain strategic oversight while stabilizing their fiscal trajectories through predictable payment schedules, thereby safeguarding long-term budget sustainability. In Smart City projects, construction and technological obsolescence risks are typically borne by the private consortium, while demand and revenue risks are shared through availability payments or minimum-revenue guarantees.

This structure reduces the volatility of municipal cash flows, transforms unpredictable capital expenditures into fixed long-term obligations, and prevents sudden budget shocks. As a result, PPP-based models enhance long-term fiscal sustainability by smoothing expenditure profiles and preserving municipal borrowing capacity. Correlation results (Table 2) confirm that higher private capital participation accelerates project delivery, reducing opportunity costs associated with delayed urban digitalization. Furthermore, the cluster analysis reveals that balanced PPP models (Cluster 2) achieve superior combinations of financial resilience and technological maturity, a configuration rarely attainable through traditional procurement. Consequently, PPP-based financing enhances VfM by minimizing lifecycle expenditures, internalizing technological risks, and expanding fiscal space without increasing public debt. For Ukrainian municipalities operating under post-war budget constraints, this VfM advantage transforms PPP from an alternative tool into a fiscally rational necessity. By shifting upfront capital costs and operational risks off municipal balance sheets, PPP-based Smart City financing expands fiscal space, enabling cities to reallocate scarce public resources toward social and recovery priorities without increasing sovereign or subnational debt.

The correlational analysis demonstrated that in countries with a substantial share of “green” investments, the financial sustainability of projects is significantly higher. Consequently, prioritizing environmental investments and instituting tax incentives for “green” initiatives should form the cornerstone of urban policy. Furthermore, it is advisable to develop risk-sharing agreements and implement municipal income guarantees for private collaborators. The experiences of the Netherlands and Germany (EIB, 2025; OECD, 2025) indicate that commercial risk insurance and data transparency via digital platforms markedly increase investment attractiveness.

Clustering revealed diverse models of project development. Cluster 2, characterized by a harmonious balance of financial sustainability and technological sophistication, can serve as a paradigm for strategic planning in Ukraine. It is recommended to cultivate mixed-type portfolios: some projects should be designed for rapid returns, while others should be high-tech endeavours with prolonged investment cycles. Profits generated from the former category can be allocated to finance more risky innovative solutions while preserving the overall portfolio’s sustainability. Achieving long-term benefits necessitates the institutional and legal consolidation of new mechanisms. A dedicated law on Smart City PPP should be enacted, delineating risk distribution, the procedure for issuing “green” municipal bonds, and guarantees for the fulfilment of long-term contracts. Integrating such legal reforms with digital transparency tools (Big Data, IoT monitoring) will establish the conditions for sustainable, adaptive, and competitive development of Ukrainian cities.

The results of the empirical study substantiated the principal hypothesis of this research, demonstrating that PPP, when amalgamated with innovative financial instruments, significantly increases the efficacy of financing Smart City initiatives. A comparative analysis with the studies conducted by Ma et al. (2024) and Xu and Wudi (2024) reveals a convergence of conclusions regarding the criticality of integrating PPP with “green” bonds to mitigate the fiscal risks faced by municipalities and accelerate the implementation of urban innovations. Shahrour (2024) corroborates these findings, evidencing the beneficial impact of multi-channel financing on the pace of Smart City project implementation. Our data (Tables 1-2) confirm that nations exhibiting a substantial proportion of private investment and “green” financial flows, such as the Netherlands and Germany, possess a statistically lower average payback period for projects, aligning with the trends outlined in the study by Hedegaard et al. (2024).

Notably, cluster analysis unveiled novel patterns that have previously remained unexplored. The identification of three sustainable project clusters, based on a synthesis of financial sustainability and technological maturity, transcends the conventional typologies articulated by Wolniak et al. (2024). In particular, the designation of a balanced Cluster 2, characterized by mean values in both indices, aligns with the “smart governance” models discussed by Kaiser (2024) and Moolngearn and Kraiwanit (2024). Conversely, the existence of Clusters 1 and 3 illuminated structural asymmetries: certain projects exhibit high financial sustainability coupled with low technological maturity, while others display the inverse combination. This structural polarization is only partially addressed in the works of Gasco-Hernandez et al. (2022) and Guenduez et al. (2024), underscoring the novelty of the obtained results.

The findings also align with the studies pertaining to the Ukrainian context. As highlighted by Kruhlov (2022) and Hryshyna et al. (2023), PPP serves as a catalyst for reconstructing infrastructure and attracting foreign investment. However, our study identified markedly lower indices of private investment and “green” financing within Ukrainian projects, corroborating the assertions of Deikalo (2025) regarding the imperative to enhance the legal framework. Correlation analysis data (Table 2) indicated a diminished correlation between “green” financing and financial stability in Ukraine compared to the majority of EU countries, signifying the necessity for a systemic evolution of environmental investment mechanisms. This trend is further reinforced by the findings of Mia et al. (2022), which established that green entrepreneurship fosters profound social transformation and bolsters the sustainability of urban investment paradigms.

A comparison with European practices elucidated in the works of Beres (2024) and Kalenyuk et al. (2024) demonstrates that Ukraine is deficient in financial innovations such as municipal “green” bonds and project companies that facilitate the combination of stability and technological dynamism. Similar conclusions are drawn by Komelina et al. (2025), emphasizing the necessity to align management practices with sustainable development standards. Our findings affirm that it is the balanced financial and technological projects (Cluster 2) that hold the greatest promise for Ukraine.

At the same time, the limitations of the study must be duly acknowledged. First, the sample encompasses 80 projects, which may not accurately represent the entire spectrum of Smart City initiatives throughout Europe and Ukraine. Second, the observation period spanning 2020 to 2024 constrains the capacity to analyse long-term payback cycles. Third, certain indicators (for instance, the proportion of “green” investments) are derived from aggregated data and necessitate an in-depth validation in subsequent research.

Notwithstanding these constraints, the study significantly enhances the scientific comprehension of PPP mechanisms in Smart City financing, underscoring the critical importance of an integrated combination of investment instruments, legal assurances, and technological maturity. Furthermore, the findings corroborate the hypothesis that the confluence of PPP with "green" financial mechanisms constitutes an essential prerequisite for the rapid and sustainable execution of urban innovation projects. This lays the groundwork for further international comparisons and the formulation of practical models for attracting private capital, which can yield enduring benefits in Ukrainian cities' advancement.

According to the study's findings, the principal recommendations for urban and public policy are as follows:

- Risk-sharing in PPP: implement availability payment mechanisms, ensure minimum guaranteed income, and introduce tariff indexation to mitigate the investors' commercial risks;
- "Green" municipal funds: mandate the use of proceeds, procure a Second Party Opinion (SPO), and establish regular post-issuance reporting protocols;
- Standardized covenants for private investors: harmonize the requirements for both financial and non-financial guarantees to bolster creditors' and insurance entities' confidence;
- Transparent KPI methodology for the city: delineate explicit metrics for energy efficiency, digital accessibility, and social impact, accompanied by the open results publication;
- A portfolio of smaller projects instead of a singular large initiative: amalgamate quick-return and technology-intensive ventures, reallocating profits to underpin more daring innovations;
- A concise 12-month roadmap: systematically implement the pilot scheme → documentation → instrument release → execution monitoring to facilitate the rapid scaling of PPP initiatives.

These findings confirm that the integration of PPP mechanisms with innovative financial instruments, particularly green financing, significantly enhances both financial sustainability and implementation efficiency of Smart City projects, thereby validating the study's core hypothesis.

Conclusion

The acceleration of urbanization and digitalization necessitates innovative approaches to financing Smart City initiatives. An empirical investigation encompassing Ukraine, Germany, France, Poland, Spain, and the Netherlands demonstrates that the combination of public-private partnerships with innovative financial instruments, notably green bonds, is statistically correlated with elevated average indices of financial sustainability and faster implementation of urban innovations.

Current trends in the financing landscape of Smart City projects involving public-private partnerships are examined. The comparative analysis reveals that the Netherlands and Germany exhibit superior average shares of private investment alongside reduced average payback periods, whereas Ukraine consistently ranks lower across all critical metrics. An examination of international practices uncovered significant positive correlations between the private investments volume and the implementation speed as well as between "green" financing and the financial sustainability of projects, thereby underscoring the pivotal role of environmental investments. Practical recommendations regarding strategic mechanisms for mobilizing private equity have been formulated based on cluster analysis, which delineates three typical partnership models, ranging from conservative to innovation-balanced.

The conclusions drawn possess significant applied relevance for the formulation of state and municipal policies. It is advisable to leverage the findings for the development of legislative frameworks pertaining to Smart City-PPP, the establishment of hybrid investment portfolios, the introduction of “green” bonds, and the implementation of digital monitoring platforms, all of which will facilitate the mobilization of private capital and ensure the financial sustainability of urban innovations. The practical significance is underscored by the potential for direct application of these proposals within the strategy for reconstructing and modernizing Ukrainian cities, as well as the adapting such methodologies for nations with transition economies.

Future research paths should encompass an extension of the analytical timeframe to monitor the long-term benefits of investment payback, a more profound evaluation of the socio-environmental advantages of projects, and the development of optimal risk allocation models for an integrated approach to PPP and “green” instruments. It is prudent to integrate the findings with other domains, notably the exploration of the digital economy and artificial intelligence, to facilitate adaptive management of urban development. The scientific originality of this work lies in the integration of international comparative, correlational, and cluster analyses to substantiate the financial and technological frameworks of Smart City initiatives, thereby enhancing the comprehension of the mechanisms for effectively attracting private capital in urban development.

Ultimately, the integration of PPP frameworks with sustainable financial instruments represents not only an economic necessity but a strategic pathway for resilient urban transformation in transitional economies.

Credit Authorship Contribution Statement

The authors contributed collaboratively to the development of this research. Prokopenko, O. was responsible for conceptualization, supervision, and overall project administration. Komarnytska, H. contributed to methodology design, investigation, and critical revision of the manuscript. Iankovets, T. was involved in drafting the original manuscript and software-based data processing. Marukhlenko, O. conducted formal analysis and data curation. Protsiuk, N. contributed to visualization and validation of results. All authors reviewed and approved the final version of the manuscript.

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Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethical Approval Statement

This study does not involve human participants, personal data, or experimental procedures. All data used in the analysis are derived from publicly available secondary sources (e.g., EIB, OECD, Eurostat, World Bank, UN-Habitat) and aggregated project-level information. Therefore, ethical approval was not required for this research.

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