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# WHAT FACTORS WILL SHAPE THE FUTURE OF SUSTAINABLE AND SMART CITIES IN EUROPE? EVIDENCE FROM THE DELPHI STUDY

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ABSTRACT: The article aims to identify and assess the factors shaping the development of sustainable and smart cities in Europe and their interrelationships. With respect to the objective, three research questions were formulated: (I) What are the factors supporting the development of sustainable and smart cities in Europe?, (II) What are the limiting factors (barriers) to the development of sustainable and smart cities in Europe?, (III) What are the main factors influencing the development of sustainable and smart cities in Europe? As part of the research process, the following methods were applied: horizon scanning, STEEPVL analysis, the Delphi method and structural analysis. The study involved 131 experts from 28 countries, whose articles on sustainable and smart cities development are indexed in the Web of Science database. The directions analysed include: smart governance and citizen participation; renewable energy microgrids with decentralised energy trading; delegating decisions to AI-based systems; and urban digital twins. The Delphi results unambiguously indicate three main enabling factors: access to external sources of finance; advanced digital infrastructure together with data integration; and a high level of cybersecurity and data protection. The principal barriers were identified as: a low level of integration across urban systems and a lack of data interoperability; limited fiscal capacity of local authorities; and institutional resistance to change and to the digital climate transition. The results of the structural analysis indicate that institutional governance, the maturity of data infrastructure and interoperability set the trajectory of change. The findings entail practical implications: institutional governance and regulatory transparency should be strengthened; diversified, multi-source funding should be ensured; interoperability should be prioritised; and AI and digital twins should then be scaled in step with capability development and a security-by-design approach.

KEYWORDS: sustainable city, smart city, participation, energy, digital twins, artificial intelligence, structural analysis, Delphi method, STEEPVL analysis

## Introduction

In an era of intensive urbanisation, digitisation and the climate crisis, the prospect of sustainable and smart cities is becoming crucial to Europe's future. The cities of the future will not merely be places of residence. They will become hybrids of technological, ecological and social ecosystems, the development of which requires a thorough, interdisciplinary approach (Correia et al., 2022; Almulhim & Yigitcanlar, 2025). In Europe, the strategic framework for cities is set by the European Green Deal and the legally binding target of climate neutrality by 2050, as well as the EU mission "100 Climate-Neutral and Smart Cities by 2030", whose role is to accelerate the deployment and scaling of solutions across the Union (European Commission, 2025c; Directive, 2024; Szpilko & Ejdys, 2022). Achieving these objectives calls for consideration of a range of factors that will shape the development trajectory of European cities over the coming decades.

Awareness of supporting factors and barriers is a key element in the process of developing sustainable and smart cities in Europe. The main objective of the research was therefore to find answers to three research questions:

- What are the factors supporting the development of sustainable and smart cities in Europe?
- What are the limiting factors (barriers) to the development of sustainable and smart cities in Europe?
- What are the main factors influencing the development of sustainable and smart cities in Europe?

In the context of the future development of sustainable and smart cities, four theses were analysed:

Thesis 1. The management of smart and sustainable cities will increasingly be delegated to decision-making systems based on artificial intelligence, which will optimise in real time the allocation of resources, energy consumption, and urban logistics;

Thesis 2. Smart cities will implement comprehensive digital twins that will become real-time urban laboratories, enabling the simulation of sustainable development scenarios, risk management, and the support of participatory governance models;

Thesis 3. The transition towards climate-neutral cities is likely to be accelerated by the progressive integration of renewable energy microgrids, supported by blockchain systems enabling decentralised energy trading.

Thesis 4. The management of sustainable and smart cities will increasingly rely on citizen participation and digital tools (smart governance), which will allow residents to co-create urban policies and monitor their implementation.

The remaining part (Section 2) of the article consists of a literature review intended to justify the adopted research theses. Section 3 sets out the methodology, with particular emphasis on the Delphi technique and structural analysis. The findings are presented in Section 4 and discussed in Section 5. Finally, conclusions are drawn, the study's limitations are acknowledged, and avenues for future research are indicated.

## An overview of the literature

### Background of the study

Early formulations of the 'smart city' and the 'sustainable city' have now converged into a coherent 'smart sustainable city' concept, in which digital technologies are a means rather than an end. The institutional U4SSC (UNECE/ITU) definition describes such a city as "an innovative city that uses ICT and other means to improve quality of life and the efficiency of urban services and operations, ensuring that the needs of present and future generations are met across the social, economic, environmental and cultural dimensions" (UNECE, 2021). Measurement standards for this agenda are mature: ISO 37122 develops indicators for smart cities, while the ITU-T Y.4903 recommendation sets KPIs for smart sustainable cities aligned with the SDGs (ISO, 2019; ITU-T, 2016). Systematic reviews highlight the convergence of the 'smart' and 'sustainable' paradigms and the need to link digital investment to tangible environmental and social outcomes (Sharifi et al., 2024; Almeida et al., 2024; Szum, 2021; Winkowska et al., 2019). Europe's deployment lever is the EU Mission 'Climate-Neutral and Smart

Cities', which mobilises cities towards climate neutrality and the digitisation of public services (NetZeroCities, 2025a).

The importance of this agenda is growing, as climatic and demographic pressures concentrate in cities. Urban areas consume around 75% of energy and account for nearly 70% of global greenhouse gas emissions (IEA, 2024; UN-Habitat, 2024). The *World Cities Report 2024* points to escalating heat and flood risks and the need for a data-driven and just transition (UN-Habitat, 2024). Digital technologies support adaptation: digital twins and AI assist in managing flooding, urban heat and mobility, but they require transparent data governance and accountability (Nguyen, 2024; Weil et al., 2023; Mazzetto, 2024).

At the same time, social and institutional risks are intensifying. Research on 'data justice' and AI urbanism warns of profiling, algorithmic bias and asymmetries of power over data (Tedeschi, 2024; Cugurullo et al., 2024). The OECD emphasises that the success of smart cities depends on mature models of data governance, cybersecurity and participation (OECD, 2024). City networks promote digital-rights frameworks to protect privacy and involve residents in shaping urban digital ecosystems (Cities Coalition for Digital Rights, 2021; Cities Coalition for Digital Rights, 2024). An increasing body of work also stresses that deploying AI in planning and management requires public-accountability criteria and mechanisms for participation and social oversight (Wang & Yorke-Smith, 2025; Lartey & Law, 2025; Fontes et al., 2024).

These premises underpinned the formulation of the following four theses, which were subsequently assessed by experts in a Delphi study.

### Thesis 1. The management of smart and sustainable cities will increasingly be delegated to decision-making systems based on artificial intelligence, which will optimise in real time the allocation of resources, energy consumption, and urban logistics

Cities are entering an era of data-driven management, where the complexity of systems (energy, mobility, water, waste) necessitates the automation of decisions. Planning literature indicates that AI is shifting from a role of analytical support to co-decision-making and co-management of urban services, particularly where rapid response and scalability are required (Wang & Yorke-Smith, 2025; Szpilko et al., 2023). Systematic reviews of AI deployment in urban governance show rapid growth in applications across spatial policy and public services, alongside the development of data-governance models (Lartey & Law, 2025). Operationalisation is facilitated by urban digital twins, which combine real-time data streams with simulation and prediction – providing a platform for closed-loop control (Weil et al., 2023). In the energy sector, the maturity of digital twin architectures and edge–cloud integration enables autonomous control of resources in multi-carrier systems (Aghazadeh Ardebili et al., 2024). This trend is supported by policy and practice. The IEA documents that cities integrating data from the power grid and municipal services, through digitalisation and algorithmic methods, achieve efficiency and demand-flexibility targets more quickly (IEA, 2024).

The empirical basis for this thesis is expanding across three critical domains. First, in buildings and energy infrastructure: reviews demonstrate that interpretable machine learning improves forecasting, HVAC (heating, ventilation, and air conditioning) control and flexibility management, translating into energy savings and better operator decision-making in near real time (Chen et al., 2023). Second, in transport: meta-analyses from 2025 show that multi-agent RL is becoming the standard for adaptive signal control, minimising delays and emissions under traffic variability (Michailidis et al., 2025; Xiao et al., 2025). These models are accompanied by scalable implementations – for example, federated RL tested on real road networks (Monaco, Cologne) – which reduce waiting times and improve throughput, without centralising sensitive data (Bao et al., 2023). Taken together, these streams of evidence indicate that optimised, near-real-time control of urban resources and logistics is already technically achievable and will become more widespread as data governance matures.

For the delegation of decisions to AI systems to accord with the 'smart & sustainable' idea, frameworks for accountability and participation are essential. Recent work in urban governance proposes people-centred criteria and resident involvement across the lifecycle of AI systems (goal definition, metric design, appeal mechanisms), which mitigates risks of bias and strengthens the legitimacy of algorithmic decisions (Fontes et al., 2024). In parallel, the review by Lartey & Law (2025) shows that institutionalising data governance, cybersecurity and model transparency is a precondition for scale. Taken together, the combination of mature data platforms (DT), real-time optimisation algorithms,

DOI: 10.34659/eis.2025.94.3.1272

and responsible governance means that an ever larger share of operational decisions in cities will be delegated to AI systems – with benefits for energy efficiency, logistics and the quality of public services (Wang & Yorke-Smith, 2025).

### Thesis 2. Smart cities will implement comprehensive digital twins that will become real-time urban laboratories, enabling the simulation of sustainable development scenarios, risk management, and the support of participatory governance models

Urban digital twins combine a 3D model, real-time data streams, and analytical and simulation modules. The literature highlights their growing role as 'urban laboratories' for testing climate, mobility and spatial-planning policies before implementation in the physical world (Weil et al., 2023; Mazzetto, 2024). European public policy envisages the widespread uptake of Local Digital Twins and provides a toolkit with a reference architecture to enable cities to deploy twins and simulate scenarios powered by data from multiple sectors (European Commission, 2025a; European Commission, 2025b). This shifts the focus of governance from ex post monitoring to proactive, iterative experimentation in (near) real time.

The strongest empirical base concerns risk management and resilience. Stormwater and urban-catchment twins, powered by online sensors, improve forecasting and enable live control of drainage infrastructure, reducing the risk of flooding (Kim et al., 2025). Comprehensive 'urban flooding digital twin' frameworks have also been outlined for the design and operation of such systems, taking account of user needs and data integration (Ge & Qin, 2025). Case studies (including reviews and accounts relating to Virtual Singapore) show that DT platforms integrate environmental and urban layers, enable analyses of solar exposure and temperature, and simulate development scenarios aligned with sustainable-development goals (Caprari et al., 2022; World Economic Forum, 2022). As a result, twins are becoming a 'test-before-invest' tool for energy, mobility and climate-adaptation policies.

To fulfil the 'smart & sustainable' promise, digital twins must also support co-governance and participation. Recent work proposes 'perception-powered' and 'citizen-centric' twins that combine city models with perceptual data and resident-facing interfaces, facilitating co-creation and deliberation (Luo et al., 2025a; Luo et al., 2025b). This thread is rounded out by studies on 'participatory cities' and digital governance frameworks, indicating that the democratisation of data and interactive DT visualisations increases acceptance of social trade-offs and the transparency of decisions (Helbing, 2024; Frantzeskaki et al., 2025). In combination with the European agenda on Local Digital Twins, this creates a practical pathway towards real-time urban laboratories that simultaneously optimise and engage.

### Thesis 3. The transition towards climate-neutral cities is likely to be accelerated by the progressive integration of renewable energy microgrids, supported by blockchain systems enabling decentralised energy trading

The thesis rests on two increasingly convergent trends: the rapid proliferation of renewable energy sources (RES) in cities and the digitisation of energy markets. Microgrids enable local balancing of demand, supply and flexibility, reduce network losses, and increase resilience to failures. A review of real-world 'zero-carbon microgrid' deployments shows that such systems accelerate decarbonisation when they combine photovoltaics, storage and demand-side control, with control executed in (near) real time (Chen et al., 2024). From a broader urban–energy perspective, the IEA indicates that cities – through distributed renewables and digital management tools – can accelerate progress towards climate neutrality (International Energy Agency, 2024).

The second pillar is EU regulation, which effectively mandates deep integration of renewables into the urban fabric and prepares the ground for local markets. The recast EPBD, in Article 10, requires all new buildings to be 'solar-ready' and, for public and large-floor-area buildings, introduces phased obligations to install solar technologies from 2026, with the scope expanding through to 2030 (Directive, 2024a; European Commission, 2025a). RED III raises the binding RES target and streamlines procedures, while strengthening the framework for energy communities and energy sharing at the distribution level (Directive, 2023). The EU electricity-market reform of 21 May 2024 promotes long-term contracts, flexibility and an active role for consumers, reducing barriers to local

DOI: 10.34659/eis.2025.94.3.1272

markets and microgrids (Directive, 2024b). In practice, this means cities will need to link buildings and neighbourhood blocks into systems capable of self-balancing and informed energy trading, renewables-based microgrids.

The technological glue of this transformation is transactionality based on AI and blockchain (Szpilko et al., 2024). In microgrids, peer-to-peer (P2P) mechanisms enable secure, decentralised energy trading among prosumers, storage units and charging nodes, while respecting the constraints of low- and medium-voltage (LV/MV) networks (Tarashandeh & Karimi, 2024). Research shows that combining P2P trading with robust microgrid control improves system efficiency and resilience (Veerasamy et al., 2024). Recent literature reviews confirm the maturity of auction models, cooperative/non-cooperative games and smart contracts, while also pointing to the need for scaling and integration with network operators (Islam et al., 2024). Complementarily, projects are emerging to optimise P2P trading using blockchain in urban-microgrid contexts (Sun et al., 2024). As 'solar-ready/solar-install' obligations, energy communities and market reforms are implemented, and decision algorithms gain access to real-time data, delegating urban energy management to AI systems will accelerate the transition towards climate-neutral cities.

### Thesis 4. The management of sustainable and smart cities will increasingly rely on citizen participation and digital tools (smart governance), which will allow residents to co-create urban policies and monitor their implementation

In the literature, smart governance is defined as technologically supported collaboration between public authorities, residents and stakeholders, oriented towards better outcomes and more open processes (Meijer & Rodríguez-Bolívar, 2016; Tomor et al., 2019; Szpilko et al., 2020b). International policy is moving in this direction. The OECD shows that citizen deliberation improves decision quality and trust (OECD, 2020), while UN-Habitat publishes the *International Guidelines on People-Centred Smart Cities*, emphasising inclusivity, digital rights and co-governance (UN-Habitat, 2025). In Europe, Climate City Contracts (CCC) require co-creation with local stakeholders and citizens, embedding participation in the formal urban policy cycle (European Commission, 2025c).

The literature points to the rapid development of an ecosystem of participatory platforms (consultations, participatory budgeting, voting), but also to gaps in feedback and accountability mechanisms (Shin et al., 2024; Ruijer et al., 2023). Case studies of Decidim in Barcelona and Madrid document a shift from consultation to co-creation and civic oversight of implementation (Smith & Prieto Martín, 2021), and systematic reviews of digital participatory-budgeting configurations show how platform design affects the quality of deliberation and decisions (Palacin et al., 2024). Within the EU Cities Mission programme, these tools are embedded in CCC processes and citizen-engagement guides, facilitating the standardisation of practice (NetZeroCities, 2023a; NetZeroCities, 2023b).

A review of research on citizen dissatisfaction with the smart city underscores that legitimacy requires real agency, transparent data rules and clear mechanisms for monitoring implementation (van Twist et al., 2023). Mission Cities documents and the implementation plan provide common MRV (monitoring–reporting–verification) frameworks and periodic progress reporting for Climate City Contracts (European Commission, 2021; NetZeroCities, 2025b). Combined with UN-Habitat guidelines, this signals a gradual shift from occasional consultations to continuous, data-driven co-governance.

## Research methods

### Research process

The study was conducted using a 4-phase methodology. Four main methods were used: horizon scanning, STEEPVL analysis, Delphi study, and structural analysis (Figure 1).

The study opened with a horizon-scanning exercise, in which experts explored how future developments might shape sustainable and smart cities across the STEEPED dimensions (Van Woensel & Vrščaj, 2015). Given the complexity of the topic, which typically demands specialist insight, this initial step was pivotal. At this point, we established a guiding framework based on STEEPED (Social, Technological, Economic, Environmental, Political/Legal, Ethical and Demographic) to ensure that pro-

DOI: 10.34659/eis.2025.94.3.1272

spective impacts were examined through an interdisciplinary lens (Ejdys et al., 2023; Ejdys & Szpilko, 2023). Drawing on the existing literature on the drivers of sustainable and smart city development, the scan assessed emerging trends and their likely implications. Using the STEEPED lens, the member research team compiled a broad inventory of factors shaping sustainable and smart cities.

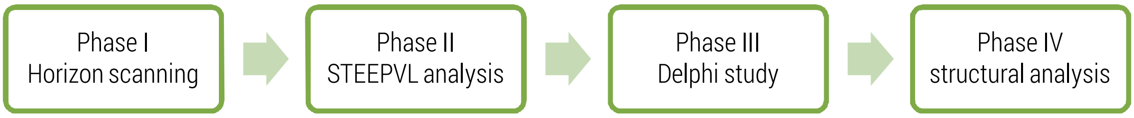



Figure 1. Research process

In the second stage, these factors were organised and consolidated according to the STEEPVL scheme (an extension of PEST/STEEP/TEEPSE/STEEPL), (Popper, 2018; Loveridge, 2002; Ejdys et al., 2019). They were grouped into seven categories: social (S), technological (T), economic (E), ecological/environmental (E), political (P), value (V) and legal (L). This framework was selected because these categories are especially salient in the smart and sustainable city domain, where social, technological, political and economic dimensions are paramount. Each expert (see the "research experts" section) then evaluated the selected factors in terms of their role, classifying them as either enablers (supports) or constraints (barriers). Up to five factors in each category (enablers and barriers) could be indicated by each expert as the most significant.

The next step involved a Delphi study. The Delphi technique treats informed expert assessment as a legitimate input to constructing a forward-looking view of the subject matter and is widely used to anticipate long-term developments under uncertainty. It is particularly suitable where conventional forecasting tools are ill-matched to the phenomena, where reliable data are scarce, or where external forces largely shape outcomes. The method entails surveying a defined expert panel at least twice: respondents complete a questionnaire offering long-term projections about a given issue, and in the subsequent round, they answer the same instrument after seeing aggregated results from the previous round. Qualitative and quantitative analyses are then performed, and the information fed back to panellists can be refined to improve coherence (Bowles, 1999; Cape, 2004; Szpilko, 2014). Experts may revise or reaffirm their positions in light of the interim findings, which tend to produce clearer judgments. Finally, the collected material is analysed and a research report is prepared (Loo, 2002; Skulmowski et al., 2007). In this study, two Delphi rounds were run to enhance consensus among respondents. The overall process is illustrated in Figure 2.

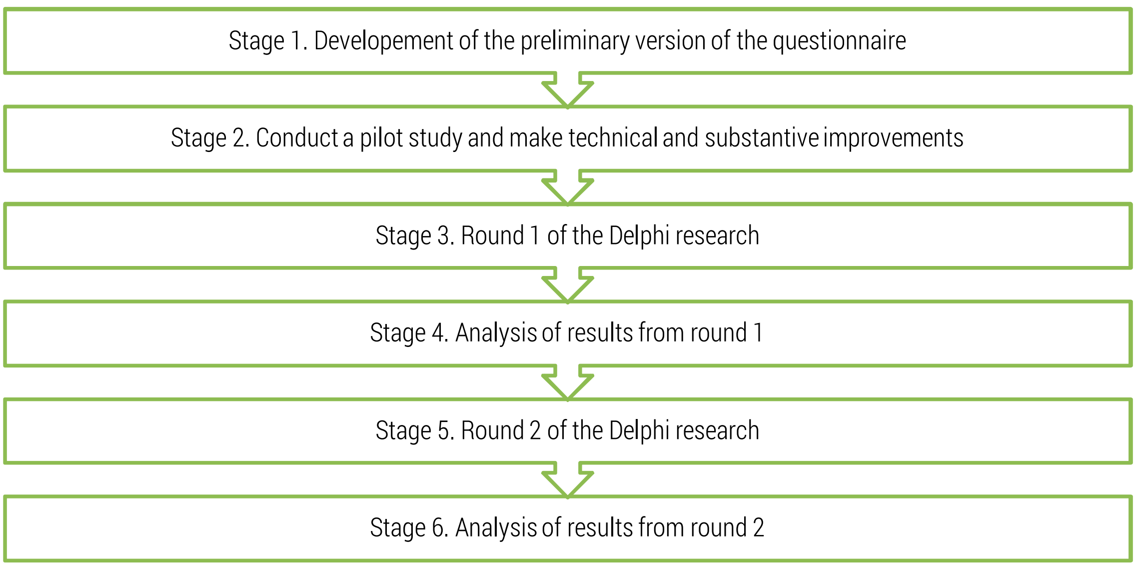



Figure 2. The main stages of the Delphi research methodology

DOI: 10.34659/eis.2025.94.3.1272

In the fourth and final phase of the research process, structural analysis was conducted. Structural analysis provides a means of organising and examining sets that contain numerous mutually interacting factors. One method for identifying such factors is STEEPVL, which is applied in the second stage of the study. It enables the nature and strength of mutual interactions to be determined, making it possible to isolate key variables on the basis of established relationships (Nazarko et al., 2013).

Within the structural analysis, for each pair of factors A and B, two questions are posed: does factor A exert a direct influence on factor B? if so, what is the level of that influence – low, medium, or high? Interactions are coded on a four-point scale: 0 – no influence; 1 – weak influence; 2 – medium influence (material but not decisive); 3 – strong influence (decisive) (Arcade et al., 1994; Nazarko et al., 2011).

The matrix obtained from the structural analysis may then be processed with tools such as MICMAC. Using MICMAC allows analysis and comparison of the hierarchy of variables, taking into account both direct and indirect dependencies, and thus provides deeper insight into the system under study (Arcade et al., 1994).

Application of MICMAC in structural analysis enables classification of the factors affecting the area under investigation according to their role and type of influence. The following categories are distinguished: crucial, goal, result, supplementary, determinant, external, regulatory, and autonomic (Szpilko et al., 2020a).

Crucial factors are characterised by both a high level of influence on other system elements and a substantial degree of dependence on remaining variables. Goal factors are more subject to the influence of other factors than they themselves influence the system; they reflect potential development pathways or desired end-states. Dependent (result) factors have limited capacity to exert influence while showing high dependence; they are particularly susceptible to the effects of key and determinant factors. Determinant factors exert a very strong influence on system functioning (acting as drivers or barriers) and are often difficult to control. Supplementary and regulatory factors have only a modest impact on the system as a whole, yet can support the achievement of strategic objectives. Autonomic factors display minimal influence on and low dependence within the system, so their importance is limited. External regulatory factors exert a moderate influence on the system – greater than autonomous factors but less than determinants – while the system itself has only a slight effect on them (Szpilko et al., 2020a).

## Research experts

Experts were identified based on articles by searching for the keywords 'smart and sustainable city' in the Web of Science database. Inclusion criteria were applied when selecting experts from the WoS database. Each expert was required to have a record of at least three articles on the analysed topic and to be affiliated with a European institution. By the end of March 2025, the database compiled for the study comprised 1,630 experts from European countries conducting research in sustainable development and smart cities. Care was taken to remove duplicate entries for experts' names from the database. Each expert could complete the research questionnaire only once per round of the study. Invitations were distributed via the online platform, which embedded a direct link to the questionnaire so that, upon opening the email, experts could access it immediately.

The research process was carried out from April to June 2025. The study engaged 147 experts in round one and 131 in round two. For further analyses, only responses from 131 experts who rated their knowledge as very high (32.52%), high (52.03%), or medium (15.45%) were retained. Sixteen respondents who reported low or very low knowledge were thanked and did not proceed to the remaining questions. The response rate after Round II was 8.04%. In the subsequent stage of the study – the structural analysis – 47 experts participated (response rate: 2.88%). The characteristics of the expert are presented in Table 1.

The expert cohort in the sustainable and smart cities field was diverse across gender, age, education, sectors and countries. Men accounted for 55.49%, women for 42.75%, and 0.76% preferred not to disclose. The largest age groups were 45–54 (40.46%) and 35–44 (32.82%). Smaller shares were 55–64 (16.79%), 25–34 (5.34%) and 65+ (4.58%). All respondents held higher education: 33.59% were professors, 64.89% held a PhD, and 1.53% held other higher degrees. Most identified as scientists/researchers (89.31%). Experts represented 28 countries. The largest shares were from Poland

DOI: 10.34659/eis.2025.94.3.1272

and Spain (7.63% each), Italy and Portugal (6.87% each), and Germany, Greece and the Netherlands (5.34% each), with further representation from France and Romania (4.58% each), Croatia, Lithuania and Slovakia (3.82% each), Czechia, Hungary, Latvia and Bulgaria (3.05% each), Austria, Belgium, Finland, the United Kingdom, Ireland and Sweden (2.29% each), Cyprus, Denmark, Estonia, Norway and Slovenia (1.53% each), and Switzerland (0.76%).

Table 1. Characteristics of the experts participating in the study

| Variable | Characteristics |
|---|---|
| Gender | man – 55.49%; woman – 42.75%; prefer not to disclose – 0.76% |
| Age | 25-34 years – 5.34%; 35-44 years – 32.82%; 45-54 years – 40.46%; 55-64 years – 16.79%; 65 years or older – 4.58% |
| Education | higher – Professor – 33.59%; higher – PhD – 64.89%; higher – BA, BEng, BSc, MA, MSc, etc. – 1.53% |
| Represented sector* | scientists, researchers – 89.31%; teachers – 30.53%; companies/industry – 3.82%; national, regional and local government / policy-makers – 0.76%; NGOs – 2.29%; special interest groups e.g. volunteer contributors and citizen scientists – 1.53% |
| Country | Poland – 7.63%; Spain – 7.63%; Italy – 6.87%; Portugal – 6.87%; Germany – 5.34%; Greece – 5.34%; Netherlands – 5.34%; France – 4.58%; Romania – 4.58%; Croatia – 3.82%; Lithuania – 3.82%; Slovakia – 3.82%; Czechia – 3.05%; Hungary – 3.05%; Latvia – 3.05%; Bulgaria – 3.05%; Austria – 2.29%; Belgium – 2.29%; Finland – 2.29%; United Kingdom – 2.29%; Ireland – 2.29%; Sweden – 2.29%; Cyprus – 1.53%; Denmark – 1.53%; Estonia – 1.53%; Norway – 1.53%; Slovenia – 1.53%; Switzerland – 0.76% |

* Percentages for sectors may exceed 100% as respondents could indicate multiple affiliations.
Source: authors' own elaboration.

## Results of the research

### STEEPVL analysis

Based on a literature review and taking the STEEPED aspects into account, an initial list of factors was compiled. After sorting and aggregation, the factors were assigned to the corresponding STEEPVL categories. Subsequently, 131 experts identified 14 main factors, which were grouped into seven categories: social, technological, economic, ecological, political, values, and legal. A summary of all analysed factors is presented in Table 2.

Table 2. Factors of the STEEPVL analysis

| Acronym | Name of factor | Factor type | Factor character | Percentage of responses |
|---|---|---|---|---|
| NAI | Involvement of national authorities | Political | support | 92.37% |
| DIDI | Level of digital infrastructure development and data integration | Technological | support | 81.68% |
| AEF | Availability of external funding sources (EU funds, climate funds) | Economic | support | 80.15% |
| CSDP | State of cybersecurity and data protection | Technological | support | 67.94% |
| DCR | Level of digital competences among residents | Social | support | 64.12% |
| SRS | Engagement of the science and research sector | Social/Economic | support | 72.52% |
| PEB | Level of pro-environmental behaviours among residents | Ecological/Values | support | 59.54% |
| USDI | Degree of integration of urban systems and data interoperability | Technological | barrier | 89.31% |

DOI: 10.34659/eis.2025.94.3.1272

| Acronym | Name of factor | Factor type | Factor character | Percentage of responses |
|---|---|---|---|---|
| SDCA | Level of specialised digital competences in public administration | Social/Technological | barrier | 71.76% |
| FCM | Financial capacity of local governments | Economic | barrier | 94.66% |
| IACT | Institutional approach to change and digital–climate transformation | Political/Values | barrier | 85.50% |
| LTS | Existence of stable and long-term strategies for smart city development | Political | barrier | 70.99% |
| LRF | Clarity and coherence of legal and regulatory frameworks concerning new technologies | Legal | barrier | 62.60% |
| SP | Level of social participation | Social | barrier | 75.57% |

Source: authors' own elaboration.

Based on the experts' assessments, key factors STEEPVL were identified (the table includes only the factors with the highest number of responses). Among the enablers, the highest shares were for the involvement of national authorities (92.37%), the development of digital infrastructure and data integration (81.68%), and access to external funding (80.15%). The strongest barriers, in the experts' view, are the financial capacity of local authorities (94.66%), interoperability and the integration of urban systems (89.31%), and the institutional approach to digital–climate transformation (85.50%). On average, barriers (78.63%) outweigh enablers (74.05%). This indicates that, despite technological and political readiness, closing the funding gap of local authorities, ensuring interoperability, and strengthening strategic and regulatory governance are very important.

## Delphi research

Drawing on the literature review, the research team developed four theses for a Delphi study on the future development of sustainable and smart cities. The selection process began with an analysis of reports, review articles, statistical data, and input from European experts across research, industry, and policy.

Within the sustainable and smart cities area, four theses were developed:

Thesis 1. The management of smart and sustainable cities will increasingly be delegated to decision-making systems based on artificial intelligence, which will optimise in real time the allocation of resources, energy consumption, and urban logistics;

Thesis 2. Smart cities will implement comprehensive digital twins that will become real-time urban laboratories, enabling the simulation of sustainable development scenarios, risk management, and the support of participatory governance models;

Thesis 3. The transition towards climate-neutral cities is likely to be accelerated by the progressive integration of renewable energy microgrids, supported by blockchain systems enabling decentralised energy trading;

Thesis 4. The management of sustainable and smart cities will increasingly rely on citizen participation and digital tools (smart governance), which will allow residents to co-create urban policies and monitor their implementation.

Respondents generally rated the significance of the theses for the development of sustainable and smart cities in Europe highly, as evidenced by the predominance of 'high' and 'very high' responses in both rounds and their increase in Round II of the Delphi study. The highest ratings were given to thesis T4 – the combined share of 'high' and 'very high' rose from 77.86% in Round I to 86.26% in Round II, with 'very high' alone increasing from 44.27% to 49.62%. Thesis T3 also maintained a strong position – 54.96% → 63.35% in total ('high' 37.40% → 44.27%, 'very high' 17.56% → 19.08%). Theses T1 and T2 likewise gained in importance: T1 from 45.04% to 56.49%, and T2 from 38.17% to 46.57% for the combined 'high' and 'very high' indications. In parallel, the share of 'medium' ratings decreased across all theses, indicating a shift towards more decisive assessments, and the proportion of 'low' and 'very low' responses fell for T1, T3 and T4 (remaining unchanged for T2 – 20.61%). The detailed distribution of responses in Rounds I and II is presented in Table 3.

DOI: 10.34659/eis.2025.94.3.1272

Table 3. Significance of theses for development of sustainable and smart cities in Europe – results of the first and second rounds of the Delphi study

| Thesis | Very low significance | | Low significance | | Medium significance | | High significance | | Very high significance | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Round I | Round II | Round I | Round II | Round I | Round II | Round I | Round II | Round I | Round II |
| T1 | 3.82% | 2.29% | 19.08% | 17.56% | 32.06% | 23.66% | 32.06% | 41.22% | 12.98% | 15.27% |
| T2 | 9.16% | 7.63% | 11.45% | 12.98% | 41.22% | 32.82% | 25.19% | 31.30% | 12.98% | 15.27% |
| T3 | 3.82% | 2.29% | 7.63% | 8.40% | 33.59% | 25.95% | 37.40% | 44.27% | 17.56% | 19.08% |
| T4 | 1.53% | 0.76% | 3.05% | 3.05% | 17.56% | 9.92% | 33.59% | 36.64% | 44.27% | 49.62% |

Source: authors' own elaboration.

To assess the importance of each thesis for the development of sustainable and smart cities in Europe, a significance index ($I_{SI}$) was computed (Ejdys, 2013):

$$I_{SI} = \frac{\mathrm{n_{VHS}} \cdot 100 + \mathrm{HS} \cdot 75 + \mathrm{MS} \cdot 50 + \mathrm{n_{LS}} \cdot 25 + \mathrm{n_{VLS}} \cdot 0}{\mathrm{n}}, \tag{1}$$

where:
nVHS – number of responses 'very high significance',
nHS – number of responses 'high significance',
nMS – number of responses 'medium significance',
nLS – number of responses 'very low significance',
nVLS – number of responses 'low significance',
n – number of total responses.

The $I_{SI}$ indicator ranges from 0 to 100. Scores above 50 denote a high level of thesis significance, whereas scores below 50 denote a low level. The nearer the score is to zero, the lower the significance.

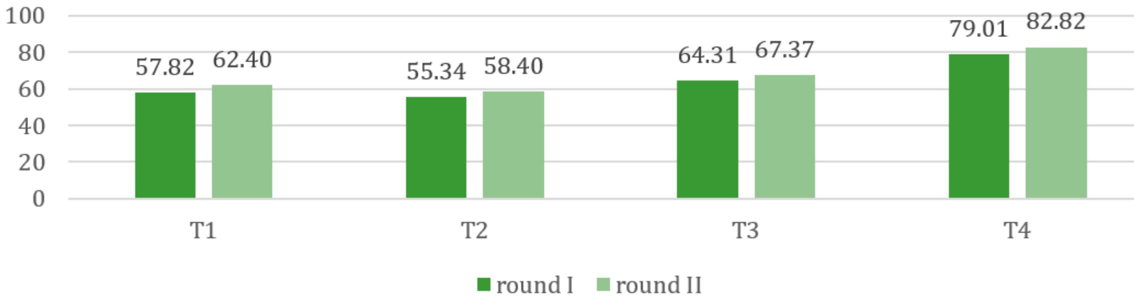



Figure 3. Values of significance indicators for the theses in the sustainable and smart cities area

The analyses were conducted in a comparative perspective. All four theses reached high significance levels, as shown by the indicators in Figure 3. The highest significance index was recorded for T4, increasing from 79.01 in Round I to 82.82 in Round II, which confirms its clear primacy. T3 also scored strongly, rising from 64.31 to 67.37. Moderate yet notable gains were observed for T1 (57.82 → 62.40) and T2 (55.34 → 58.40). The ordering of theses remained stable across rounds (T4 > T3 > T1 > T2), and the consistent upward shifts (from +3.1 to +4.6 points) indicate growing consensus around their importance.

In the Delphi survey, participants assessed when each thesis is likely to be realised, choosing among five options: by the end of 2028, in 2029–2035, in 2036–2045, after 2045, or never. The distribution of responses follows a similar pattern across theses, with expectations clustering in the 2029–2035 and 2036–2045 periods (Figure 4).

DOI: 10.34659/eis.2025.94.3.1272

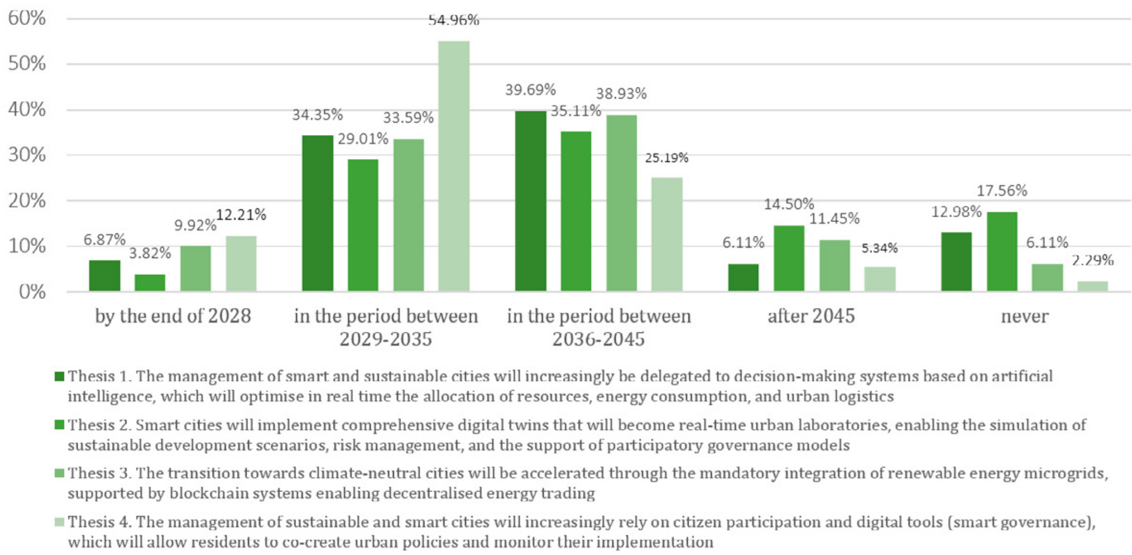



Figure 4. Timescale for implementation of the theses

Thesis 4 is viewed as the most near-term: 54.96% expect implementation in 2029–2035 and 12.21% by 2028 (67.17% by 2035 in total), while only 2.29% think it will never be realised. This is the lowest 'never' share among all theses. Theses 1 and 3 are placed mainly in the medium term. For T1, 34.35% indicate 2029–2035 and 39.69% 2036–2045 (80.91% by 2045), with 12.98% 'never'. For T3, 33.59% and 38.93% fall in these periods respectively (82.44% by 2045), and 6.11% 'never'. Thesis 2 is judged slower and more uncertain: a plurality (35.11%) place it in 2036–2045. It has the highest shares 'after 2045' (14.50%), 'never' (17.56%) and only 32.83% expect realisation by 2035. Overall, experts anticipate earlier realisation for T4, mid-term horizons for T1 and T3, and the latest timeframe with the greatest scepticism for T2.

Experts participating in the study were asked to indicate the extent to which the factors identified in the STEEPVL analysis both favour and hinder the implementation of each thesis. Ratings were given on a five-point scale: to a very high degree, high, medium, low, and very low. To assess how far each factor supports or constrains the realisation of a given thesis, a support index (IS) and a barrier index (IB) were calculated for each factor using the following formula (Ejdys, 2013):

$$I_{S\ or\ B} = \frac{\mathrm{n_{VH}}\cdot 100 + \mathrm{H}\cdot 75 + \mathrm{M}\cdot 50 + \mathrm{n_L}\cdot 25 + \mathrm{n_{VL}}\cdot 0}{\mathrm{n}}, \tag{2}$$

where:
nVH – number of responses 'very high degree',
nH – number of responses 'high degree',
nM – number of responses 'medium degree',
nL – number of responses 'low degree',
nVL – number of responses 'very low degree',
n – number of total responses.

The indicator ranges from 0 to 100. A value above 50 means the factor strongly supports or constrains the thesis. The closer the value is to 100, the stronger the support or barrier. A value below 50 indicates a low degree to which the factor supports or constrains the thesis. The closer the value is to 0, the weaker the influence.

In both Delphi rounds, the analysed factors were rated as clearly conducive to implementing the four theses – for every factor, the round-wise mean (averaged across theses) exceeded 60.00 points, and the second round showed a consistent increase averaging 2.32 points (Table 4). The highest overall favourability was attained by access to external sources of funding (EU funds, climate funds), with a round II mean of 80.06 across theses, peaking at 83.21 for Thesis 1. Very strong support is also provided by the development of digital infrastructure and data integration (mean 78.35) and grow-

DOI: 10.34659/eis.2025.94.3.1272

ing concern for cybersecurity and data protection (mean 77.58). The remaining determinants remain unequivocally positive: growing digital competences of residents and public administration (70.66), support from national authorities (70.13), engagement of the science and research sector (68.38), and an increase in pro-environmental behaviours among residents (64.84).

Table 4. Values of factors supporting to the implementation of these (drivers for the development of sustainable and smart cities in Europe) – results of the first and second rounds of the Delphi survey

| Factor | Thesis 1. The management of smart and sustainable cities will increasingly be delegated to decision-making systems based on artificial intelligence, which will optimise in real time the allocation of resources, energy consumption, and urban logistics | | Thesis 2. Smart cities will implement comprehensive digital twins that will become real-time urban laboratories, enabling the simulation of sustainable development scenarios, risk management, and the support of participatory governance models | | Thesis 3. The transition towards climate-neutral cities is likely to be accelerated by the progressive integration of renewable energy microgrids, supported by blockchain systems enabling decentralised energy trading | | Thesis 4. The management of sustainable and smart cities will increasingly rely on citizen participation and digital tools (smart governance), which will allow residents to co-create urban policies and monitor their implementation | |
|---|---|---|---|---|---|---|---|---|
| | Round I | Round II | Round I | Round II | Round I | Round II | Round I | Round II |
| Support from national authorities | 63.85 | 66.15 | 70.96 | 73.46 | 70.61 | 72.33 | 66.09 | 68.60 |
| Development of digital infrastructure and data integration | 76.15 | 78.63 | 76.91 | 79.58 | 76.15 | 78.24 | 74.61 | 76.94 |
| Access to external sources of funding (EU funds, climate funds) | 80.53 | 83.21 | 73.66 | 75.95 | 77.29 | 79.58 | 79.01 | 81.49 |
| Increasing concern for cybersecurity and data protection | 73.09 | 75.38 | 71.95 | 74.43 | 77.29 | 79.20 | 78.63 | 81.30 |
| Growing digital competences of residents and administration | 70.35 | 72.29 | 66.02 | 68.36 | 67.18 | 69.47 | 69.66 | 72.52 |
| Engagement of the science and research sector | 70.99 | 73.09 | 66.54 | 68.46 | 66.60 | 68.51 | 60.96 | 63.46 |
| Increasing level of pro-environmental behaviours among residents | 61.72 | 64.45 | 59.88 | 62.21 | 65.38 | 67.31 | 63.08 | 65.38 |

The balance of influence is similar across theses, with specific emphases in round II: for Thesis 1, external funding (83.21) followed by infrastructure and data integration (78.63) and cybersecurity (75.38); for Thesis 2, infrastructure and data integration (79.58) with external funding (75.95) and cybersecurity (74.43); for Thesis 3, external funding (79.58), cybersecurity (79.20) and infrastructure and data integration (78.24); for Thesis 4, external funding (81.49) and cybersecurity (81.30), complemented by infrastructure and data integration (76.94) and rising digital competences (72.52). Taken together, the results indicate a triad of key implementation conditions: funding, digital infrastructure with data integration, and high standards of cybersecurity; factors related to science and to pro-environmental attitudes, although lower, remain positive and may play a stabilising role. The uniform improvement in round II reflects growing expert confidence that the environment for implementing the analysed theses is gradually strengthening. Beyond identifying supporting factors, the Delphi study also examined barriers, indicating which ones constrain each thesis and to what degree.

All seven key barriers, in the experts' view, recorded index values above 50.00 for every thesis in both Delphi rounds, indicating that they are highly limiting to implementation. In both Delphi rounds, the assessed barriers were substantial, and round II showed a consistent increase averaging 2.18 points (Table 5).

DOI: 10.34659/eis.2025.94.3.1272

Table 5. Values of factor of barriers to the implementation of the theses (limiting factors for building sustainable and smart cities in Europe) – results of the first and second rounds of the Delphi survey

| Factor | Thesis 1. The management of smart and sustainable cities will increasingly be delegated to decision-making systems based on artificial intelligence, which will optimise in real time the allocation of resources, energy consumption, and urban logistics | | Thesis 2. Smart cities will implement comprehensive digital twins that will become real-time urban laboratories, enabling the simulation of sustainable development scenarios, risk management, and the support of participatory governance models | | Thesis 3. The transition towards climate-neutral cities is likely to be accelerated by the progressive integration of renewable energy microgrids, supported by blockchain systems enabling decentralised energy trading | | Thesis 4. The management of sustainable and smart cities will increasingly rely on citizen participation and digital tools (smart governance), which will allow residents to co-create urban policies and monitor their implementation | |
|---|---|---|---|---|---|---|---|---|
| | Round I | Round II | Round I | Round II | Round I | Round II | Round I | Round II |
| Low level of integration of urban systems and lack of data interoperability | 82.25 | 84.73 | 84.16 | 87.02 | 74.43 | 76.34 | 68.13 | 70.61 |
| Shortage of specialised digital competences in public administration | 65.46 | 67.56 | 77.10 | 79.58 | 64.69 | 66.41 | 62.02 | 64.31 |
| Limited financial capacity of municipal governments | 74.05 | 77.10 | 80.53 | 83.40 | 73.66 | 75.76 | 64.89 | 66.60 |
| Institutional resistance to change and to digital–climate transformation | 78.63 | 81.11 | 76.34 | 78.63 | 67.75 | 69.66 | 59.73 | 61.64 |
| Lack of stable and long-term strategies for the development of smart cities | 70.42 | 72.71 | 67.94 | 70.61 | 62.12 | 64.62 | 62.02 | 63.74 |
| Fragmentation of legal provisions and unclear regulatory frameworks concerning new technologies | 58.65 | 60.58 | 61.15 | 62.69 | 64.50 | 66.22 | 52.10 | 54.58 |
| Insufficient social participation | 58.07 | 59.84 | 59.04 | 61.54 | 59.11 | 61.24 | 71.18 | 72.33 |

The greatest overall severity was recorded for the low level of integration of urban systems and lack of data interoperability, with a round II mean of 79.68 across all these, peaking at 87.02 for Thesis 2. High barrier levels were also observed for the limited financial capacity of municipal governments (75.72) and for institutional resistance to change and to digital–climate transformation (72.76). The remaining constraints were material: the shortage of specialised digital competences in public administration (69.47), lack of stable and long-term strategies (67.92), insufficient social participation (63.74), and fragmentation of legal provisions with unclear regulatory frameworks (61.02).

The balance of constraint is similar across theses, with specific emphases: for Thesis 1, interoperability (84.73) followed by institutional resistance (81.11) and municipal finances (77.10); for Thesis 2, interoperability (87.02) with municipal finances (83.40) and specialised competences (79.58); for Thesis 3, interoperability (76.34), municipal finances (75.76) and institutional resistance (69.66); for Thesis 4, insufficient social participation (72.33) and interoperability (70.61), complemented by municipal finances (66.60). Taken together, the results highlight a triad of critical limiting conditions – interoperability, municipal finance, and institutional resistance. Legal fragmentation is weaker on average but remains non-negligible. The uniform increase in round II signals mounting perceived constraints and calls for priority action.

## Structural analysis

Within the structural analysis, experts assessed the pairwise strength of influence among the 14 factors identified in the STEEPVL analysis. The entries in the final matrix reflect the modal strength of direct influence between each pair of factors (0–3). The degree of mutual influence among the factors determining the development of sustainable and smart cities is presented in Table 7. Table 6 summarises the core properties of the direct-influence matrix.

Table 6. Characteristics of the direct influence matrix

| Dimension of the matrix | Value |
|---|---|
| Number of zeros (no influence) | 37 |
| Number of 1s (weak influence) | 62 |
| Number of 2s (medium influence) | 81 |
| Number of 3s (strong influence) | 16 |
| Degree of completion | 81.12% |

The matrix was 14×14, which meant experts were asked to determine 196 pairwise relationships between variables. In 16 cases, the dominant value was three, indicating strong links; medium links were identified in 81 cases, and weak links in 62. In 37 cases, no link was observed. Non-zero entries accounted for 81.12% of all cells, indicating a high degree of interconnection among the variables analysed.

Table 7. Degree of mutual influence among the 14 factors determining the development of sustainable and smart cities in Europe

| Acronym | NAI | DIDI | AEF | CSDP | DCR | SRS | PEB | USDI | SDCA | FCM | IACT | LTS | LRF | SP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NAI | 0 | 2 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 3 | 3 | 2 | 3 | 2 |
| DIDI | 1 | 0 | 1 | 2 | 1 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 1 | 2 |
| AEF | 2 | 3 | 0 | 1 | 1 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 1 | 2 |
| CSDP | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 2 | 1 | 0 | 1 | 0 | 0 | 1 |
| DCR | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 |
| SRS | 2 | 2 | 1 | 2 | 2 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| PEB | 2 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 2 | 2 | 1 | 3 |
| USDI | 1 | 2 | 0 | 2 | 1 | 2 | 2 | 0 | 2 | 2 | 2 | 2 | 1 | 2 |
| SDCA | 0 | 2 | 0 | 2 | 1 | 1 | 1 | 2 | 0 | 0 | 2 | 0 | 1 | 1 |
| FCM | 1 | 3 | 2 | 2 | 1 | 2 | 2 | 3 | 2 | 0 | 2 | 1 | 0 | 2 |
| IACT | 3 | 3 | 1 | 2 | 2 | 3 | 2 | 3 | 2 | 1 | 0 | 2 | 2 | 2 |
| LTS | 1 | 2 | 1 | 0 | 1 | 1 | 2 | 2 | 1 | 1 | 3 | 0 | 1 | 2 |
| LRF | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 2 | 3 | 1 | 0 | 1 |
| SP | 2 | 2 | 0 | 0 | 0 | 1 | 2 | 1 | 1 | 1 | 2 | 3 | 2 | 0 |

Table 8 summarises the total direct influences among fourteen factors shaping the development of sustainable and smart cities. The results show that the greatest direct leverage is exerted by involvement of national authorities (NAI, 29), institutional approach to change and digital climate transformation (IACT, 28) and engagement of the science and research sector (SRS, 25). Substantial,

DOI: 10.34659/eis.2025.94.3.1272

system-shaping effects are also associated with the availability of external funding sources (AEF, 23), financial capacity of local governments (FCM, 23) and level of digital infrastructure development and data integration (DIDI, 23).

Among the most dependent variables, IACT (27), DIDI (26) and degree of integration of urban systems and data interoperability (USDI, 26) stand out, indicating strong sensitivity to the wider configuration of factors. A pronounced dependence is also observed for the level of social participation (SP, 23) and the level of pro-environmental behaviours among residents (PEB, 22), suggesting that participatory and behavioural outcomes are more often shaped by the system than they are primary drivers of it.

Two factors combine high influence and high dependence and thus act as central "relay" variables: IACT (28/27) and DIDI (23/26). By contrast, NAI (29/17) and AEF (23/11) behave as strong drivers with relatively low dependence, whereas USDI (21/26), SP (17/23) and PEB (15/22) are highly dependent outcomes with more limited driving power.

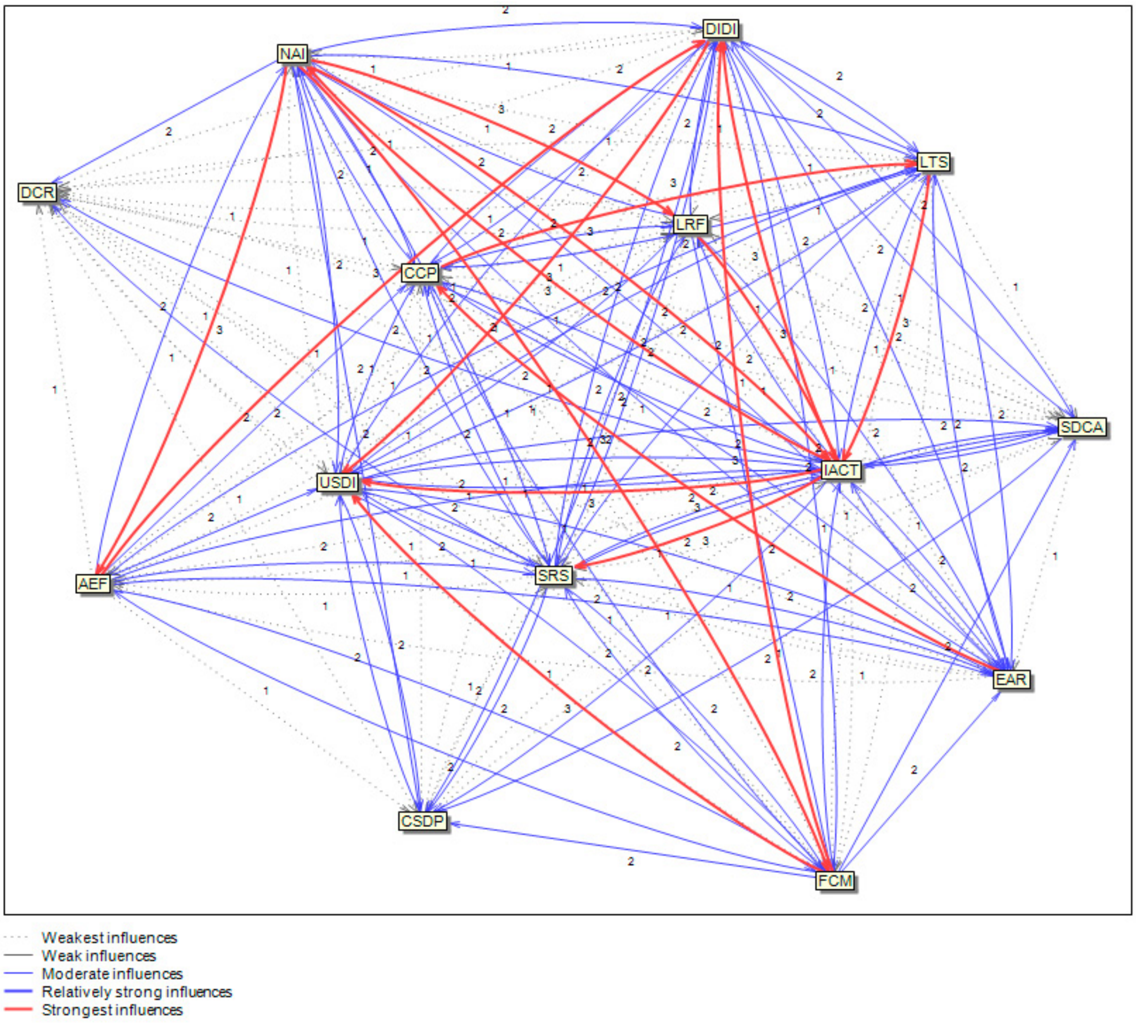
Table 8. Total direct influence between factors

| Acronym | Factor | Total influence | Total strength of dependence |
|---|---|---|---|
| NAI | Involvement of national authorities | 29 | 17 |
| DIDI | Level of digital infrastructure development and data integration | 23 | 26 |
| AEF | Availability of external funding sources (EU funds, climate funds) | 23 | 11 |
| CSDP | State of cybersecurity and data protection | 7 | 17 |
| DCR | Level of digital competences among residents | 10 | 14 |
| SRS | Engagement of the science and research sector | 25 | 20 |
| PEB | Level of pro-environmental behaviours among residents | 15 | 22 |
| USDI | Degree of integration of urban systems and data interoperability | 21 | 26 |
| SDCA | Level of specialised digital competences in public administration | 13 | 16 |
| FCM | Financial capacity of local governments | 23 | 17 |
| IACT | Institutional approach to change and digital–climate transformation | 28 | 27 |
| LTS | Existence of stable and long-term strategies for smart city development | 18 | 20 |
| LRF | Clarity and coherence of legal and regulatory frameworks concerning new technologies | 20 | 16 |
| SP | Level of social participation | 17 | 23 |
| | | 272 | 272 |

Source: authors' own elaboration with the use of MIC-MAC software.

Within the MICMAC-based structural analysis, a graph of direct influences was constructed (Figure 5). The analysis shows that nine factors exert very strong effects on eleven other factors, underscoring the tightly coupled nature of the system. The institutional approach to change and digital climate transformation (IACT) exerts the strongest influence on the engagement of the science and research sector (SRS), the involvement of national authorities (NAI), the degree of integration of urban systems and data interoperability (USDI), and the level of digital infrastructure development and data integration (DIDI). The involvement of national authorities (NAI), in turn, most strongly shapes the availability of external funding sources (AEF), the financial capacity of local governments (FCM), the institutional approach to change and digital–climate transformation (IACT), and the clarity and coherence of legal and regulatory frameworks concerning new technologies (LRF). The financial capacity of local governments (FCM) has its strongest effects on the degree of integration of urban systems and data interoperability (USDI) and the level of digital infrastructure development and data integration (DIDI), while the availability of external funding sources (AEF) most strongly drives the level of digital infrastructure development and data integration (DIDI). The level of digital infrastructure development and data integration (DIDI) most strongly influences the degree of integration of urban systems and data interoperability (USDI). The existence of stable and long-term strategies for smart city development (LTS) exerts its strongest influence on the institutional approach to change and digital–climate transformation (IACT); the state of cybersecurity and data protection (CSDP) most strongly affects the existence of stable and long-term strategies for smart city development (LTS); the clarity and coherence of legal and regulatory frameworks concerning new technologies (LRF) most strongly affects the institutional approach to change and digital–climate transformation (IACT); and the engagement of the science and research sector (SRS) most strongly affects the state of cybersecurity and data protection (CSDP). A strong influence is thus visible for thirteen of the fourteen factors. The only factor that does not exert either a strong or very strong influence is the level of digital competences among residents (DCR), which is chiefly dependent on the involvement of national authorities (NAI), the engagement of the science and research sector (SRS), and the institutional approach to change and digital–climate transformation (IACT).

Figure 5. Graph of direct influences




Source: authors' own elaboration with the use of MIC-MAC software.

The placement of factors on the influence–dependence plane (Figure 6) yields eight groups.

In the crucial factors group sits the institutional approach to change and digital–climate transformation (IACT), reflecting its central steering role. The goal group comprises the level of digital infrastructure development and data integration (DIDI) and the degree of integration of urban systems and data interoperability (USDI), i.e., targets that the system seeks to achieve. The results group consists of the level of social participation (SP) and the level of pro-environmental behaviours among residents (PEB), which represent system outcomes.

DOI: 10.34659/eis.2025.94.3.1272

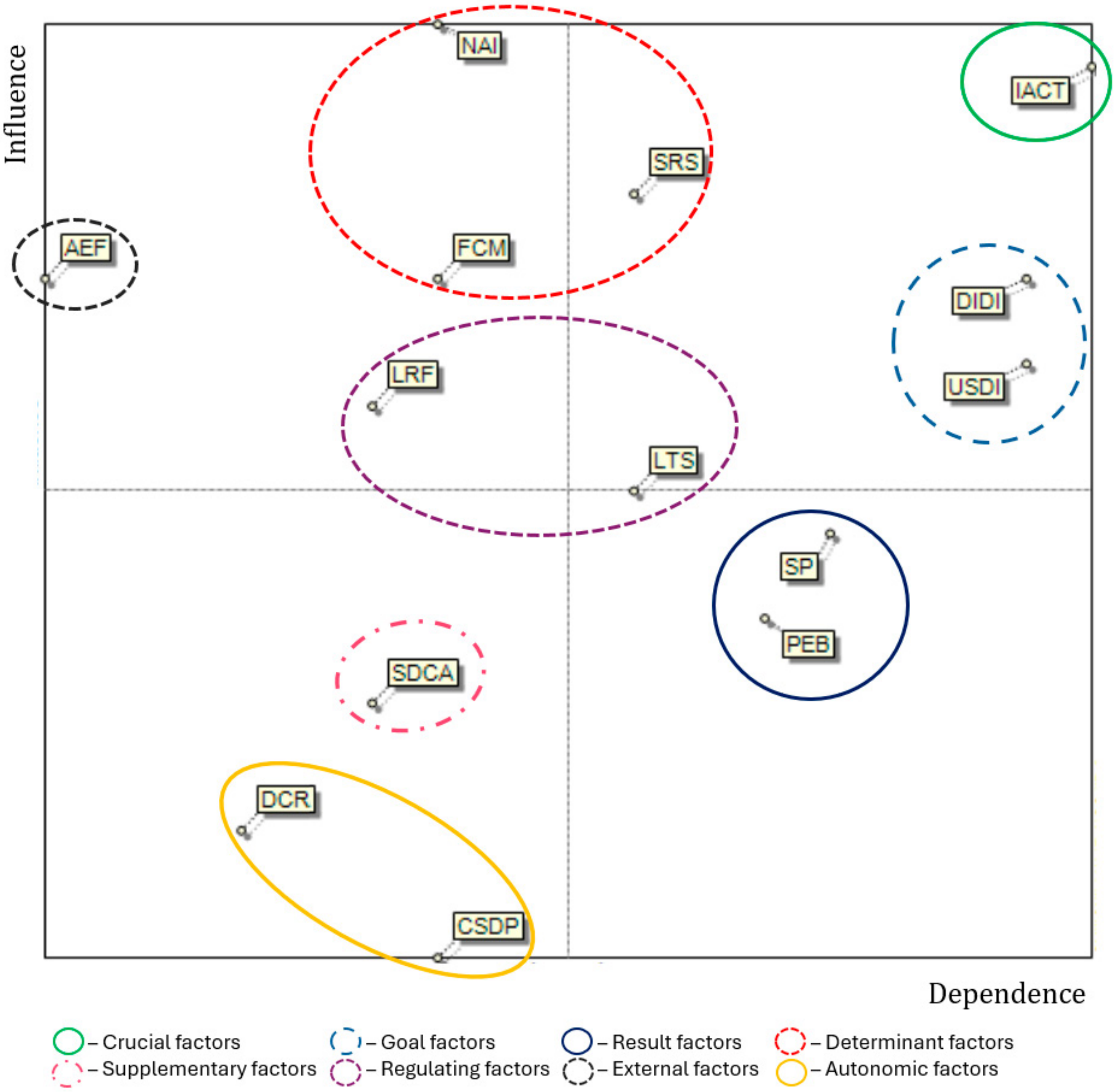



Figure 6. Classification of factors in the structural analysis based on direct influences
Source: authors' own elaboration with the use of MIC-MAC software.

The autonomic group contains two factors with limited connectivity – the level of digital competences among residents (DCR) and the state of cybersecurity and data protection (CSDP). The external factor is the availability of external funding sources (AEF). Its impact on the system is greater than that of the autonomic factors, while the system's feedback on it remains limited. The supplementary group includes a single factor, the level of specialised digital competences in public administration (SDCA). The regulatory group gathers the clarity and coherence of legal and regulatory frameworks (LRF) and the existence of stable and long-term strategies (LTS). Finally, the determinants of the system are formed by the involvement of national authorities (NAI), the financial capacity of local governments (FCM), and the engagement of the science and research sector (SRS) – the principal political, economic and social drivers shaping the entire configuration.

## Discussion of the results

The thesis indicating that the management of sustainable and smart cities will increasingly rely on citizen participation and digital tools that enable residents to co-create public policies and monitor their implementation (Thesis 4) was judged by the study's respondents to be the most important. In their view, implementation of this thesis can be supported by external sources of funding, a developed digital infrastructure with data integration, and high cybersecurity standards. Additional support may come from growing digital competencies within public administration and among residents. At the same time, the key constraints were assessed as an insufficient level of social participation, gaps in interoperability, and the limited fiscal capacity of local authorities. This profile accords with international findings. Enduring participation develops where cities have clear rules for data governance, accountable platforms, and visible feedback loops between consultation and decision-making (OECD, 2023; van Twist et al., 2023). In Europe, the strengthening of public-sector interoperability through the Interoperable Europe Act supports the stability of digital processes, while ENISA reviews underline the need for security-by-design in public services, confirming the importance of the conditions identified by respondents (Regulation, 2024; ENISA, 2024).

The thesis concerning the acceleration of the transition towards climate-neutral cities through the mandatory integration of renewable energy microgrids, supported by solutions enabling decentralised energy trading (Thesis 3), also received high ratings. In the respondents' opinion, implementation is supported by external funding, secure data practices, and a mature digital infrastructure. The most important barriers are interoperability gaps, the limited fiscal capacity of local authorities, and institutional resistance. Recent reviews confirm that urban microgrids deliver benefits when photovoltaics, storage, and demand response are coordinated in near real time and when integration is well designed (Chen et al., 2024). In parallel, the literature on peer-to-peer energy markets indicates that auction mechanisms, co-operative game models, and smart contracts support local balancing, provided they are accompanied by standards and alignment with network regulation – conditions that remain essential for scaling (Islam et al., 2024). This is consistent with respondents' views on the need for external finance, coherent data flows, and predictable market-regulatory rules.

The thesis concerning the wider delegation of operational decisions to decision-making systems based on artificial intelligence that optimise resource allocation, energy consumption, and urban logistics in real time (Thesis 1) was assessed positively. In the respondents' view, it is supported by access to funding, a robust data infrastructure, and cybersecurity. Constraints centre on interoperability bottlenecks, institutional resistance, the costs of modernising legacy systems, and shortfalls in specialised competences. Convergent conclusions emerge from recent reviews of AI in urban planning and management. Scaling requires change management, transparent models, and secure data pipelines, even where operational gains are clear (Lartey & Law, 2025). Critical work on AI urbanism also stresses legitimacy and accountability, especially where algorithms mediate rights or allocate public goods (Cugurullo et al., 2024). In Europe, the Interoperable Europe Act sets the basis for cross-departmental and cross-sector data exchange, and ENISA assessments reinforce the case for security-by-design in OT and IoT environments typical of urban services. This helps to explain why respondents highlight institutions, interoperability, and security as conditions for success (Regulation, 2024; ENISA, 2024).

The thesis concerning the implementation of comprehensive urban digital twins as real-time urban laboratories that enable the simulation of sustainable development scenarios, risk management, and support for participatory models (Thesis 2) was considered by respondents to be less important than the other theses. In their assessments, implementation can be supported by developed digital infrastructure and data integration, funding, and cybersecurity. Constraints include a lack of interoperability, financial limitations, and shortages of specialised digital competences in public administration. These conclusions are consistent with reviews that identify standards, data governance, and organisational maturity as the main requirements for moving from pilots to city-scale (Mazzetto, 2024). At the same time, case studies in public-safety domains – such as stormwater and flood twins – show tangible value when data quality and integration are assured (Kim et al., 2025). EU tools, including the Local Digital Twin Toolbox, are designed to reduce entry costs and harmonise interfaces, which corresponds to the barriers cited by respondents (European Commission, 2025b).

DOI: 10.34659/eis.2025.94.3.1272

The implications drawn from the structural analysis complement this picture. The greatest leverage lies with upstream steering factors: the involvement of national authorities, the institutional approach to change, and the engagement of the science and research sector. These shape funding channels, regulatory clarity, and programme architecture – elements that the literature shows are decisive for scaling digital participation, AI solutions, and digital twins (OECD, 2023; Lartey & Law, 2025; Mazzetto, 2024). Digital infrastructure and data integration function as a relay factor with high influence and high dependence. Integration and interoperability of urban systems act as a goal factor that advances only when upstream drivers are activated. Social participation and pro-environmental behaviours emerge as results of a well-steered, secure data system supported by stable funding.

From this configuration follows a practical sequence of actions that directly supports the implementation of the four theses. First, national steering and multi-source financing should be strengthened. This entails co-ordination of programmes, predictable co-funding, and transparent rules that allow cities to build project portfolios. Second, interoperability should be put in order. This means adopting common standards, open interfaces, and data schemas, which – consistent with European frameworks – facilitate exchange between departments and operators. Third, deployment should be coupled with skills development and with security from the procurement stage onwards. This applies both to specialised capabilities within public administration and to security-by-design practices for OT and IoT environments. Such sequencing reduces system risks first, then enables the scaling of AI and digital twins in everyday services. As a result, the cross-cutting barriers become manageable, while the enabling core consists of external finance and a coherent data layer (integration & interoperability), underpinned by cybersecurity as a baseline operating condition, which can move theses from concept to practice.

## Conclusions

The findings from the study indicate the conditions that determine the success of the transformation towards sustainable and smart cities. The overarching conclusion is the role of a triad: external finance, digital infrastructure with data integration, and cybersecurity. It is not stand-alone technologies that matter. Stable sources of funding, a coherent data layer, and safe operating standards form the starting point for implementation across all four thesis areas analysed in the study.

Against this backdrop, the key barriers are clear. Lack of interoperability between systems, limited fiscal capacity of local authorities, and institutional resistance are cross-cutting in nature. They are not merely technical problems. They touch on organisational, financial and regulatory arrangements. The weaker the connections between systems and units, the greater the risk that investments will remain fragmented and the potential of data will be left unused.

An important complement comes from the structural analysis. The highest-leverage factors – namely the involvement of national authorities, the institutional approach to change and to the digital climate transition, and the engagement of the science and research sector – shape the environment in which cities can act at all. Digital infrastructure with data integration functions acts as a relay factor. It is both the result of good steering and a precondition for subsequent stages. Integration and interoperability of urban systems then become a system goal that moves the whole configuration forward when upstream drivers are activated. Social participation and pro-environmental behaviours appear mainly as outcomes of improved data governance, stable funding and clear lines of accountability.

A practical sequence of actions follows from this picture. National steering and the transparency of rules should be strengthened so that cities can operate in a coherent institutional environment. This means clear legislation, strategies and guidance. Multi-source financing should then be secured to cover both build-out and ongoing operation. The next step is to prioritise interoperability in public procurement and system architecture by adopting standards, open interfaces and sound metadata management, which reduces the risk of isolated island deployments. Only on such a foundation does it make sense to scale AI and digital twins widely, coupling them with capacity-building in public administration and security-by-design in OT/IoT environments. This sequence helps convert scattered innovations into a coherent portfolio of public services.

The study has several limitations. The conclusions are based on expert assessments (the Delphi method), which means they reflect agreed perceptions rather than direct measurements of implementation. The panel had a European profile, which limits straightforward transfer of the results to other institutional contexts. Two rounds encouraged convergence of opinions, but did not fully eliminate the influence of respondent selection or potential biases. In the structural analysis (MICMAC), a direct-influence matrix on a 0–3 scale was used. This approach simplifies the continuity of relationships and does not model indirect effects or dynamics over time. In addition, the STEEPVL component focuses on the most frequently indicated factors, which may marginalise less frequently mentioned yet locally important conditions.

In future research, it will be valuable to combine a perception-based perspective with empirical data on implementations and outcomes. City panels are needed with measures of interoperability maturity, cybersecurity quality, the use of digital twins and AI, and actual service outcomes. Comparative case studies covering different types of cities and institutional regimes are recommended, together with quasi-experimental analyses of the adoption of standards and interoperability clauses in public procurement to estimate cost and quality effects. Further work is also needed on organisational change in public administration, with a focus on competences, roles and accountability practices that shorten the path from pilot to stable operation and reduce the risk of implementation failure.

## Acknowledgements

The research leading to these results has received funding from the commissioned task entitled “VIA CARPATIA Universities of Technology Network named after the President of the Republic of Poland, Lech Kaczyński”, under the special purpose grant from the Minister of Science, contract no. MEiN/2022/DPI/2577 action entitled “In the neighbourhood – inter-university research internships and study visits.”

## The contribution of the authors

Conceptualisation, D.S., A.R., E.N., G.L. and T.G.; literature review, D.S., A.R., E.N., G.L. and T.G.; methodology, D.S.; formal analysis, D.S.; data collection, D.S.; writing, D.S., A.R., E.N., G.L. and T.G.; conclusions and discussion D.S., A.R., E.N., G.L. and T.G. All authors have read and agreed to the published version of the manuscript.



## References

Aghazadeh Ardebili, A., Zappatore, M., Ramadan, A. I. H. A., Longo, A., & Ficarella, A. (2024). Digital Twins of smart energy systems: a systematic literature review on enablers, design, management and computational challenges. Energy Informatics, 7, 94. https://doi.org/10.1186/s42162-024-00385-5

Almeida, F., Guimarães, C. M., & Amorim, V. (2024). Exploring the Differences and Similarities between Smart Cities and Sustainable Cities through an Integrative Review. Sustainability, 16(20), 8890. https://doi.org/10.3390/su16208890

Almulhim, A. I., & Yigitcanlar, T. (2025). Understanding Smart Governance of Sustainable Cities: A Review and Multidimensional Framework. Smart Cities, 8(4), 113. https://doi.org/10.3390/smartcities8040113

Arcade, J., Godet, M., Meunier, F., & Roubelat, F. (1994). *Structural analysis with the MICMAC method and actors' strategy with Mactor method*. Paris: AC/UNU Millennium Project Futures Research Methodology.

Bao, J., Wu, C., Lin, Y., Zhong, L., Chen, X., & Yin, R. (2023). A scalable approach to optimize traffic signal control with federated reinforcement learning. Scientific Reports, 13, 19184. https://doi.org/10.1038/s41598-023-46074-3

Bowles, N. (1999). The Delphi technique. Nurs Stand, 13(45), 32–36. https://doi.org/10.7748/ns1999.07.13.45.32.c2650

Cape, B., (2004). Gathering opinion and initiating debate: the success of the Delphi Method in purely qualitative research. Library and Information Research, 28(89), 35–44. https://doi.org/10.29173/lirg164

Caprari, G., Bellagente, P., Girelli, V. A., Pagliari, D., & Vitti, A. (2022). Digital Twin for Urban Planning in the Green Deal Era: A State of the Art and Future Perspectives. Sustainability, 14(10), 6263. https://doi.org/10.3390/su14106263

Chen, L., Gao, L., Xing, S., Chen, Z., & Wang, W. (2024). Zero-carbon microgrid: Real-world cases, trends and challenges. Renewable and Sustainable Energy Reviews, 203, 114720. https://doi.org/10.1016/j.rser.2024.114720

Chen, Z., Xiao, F., Guo, F., & Yan, J. (2023). Interpretable machine learning for building energy management: A state-of-the-art review. Advances in Applied Energy, 9, 100123. https://doi.org/10.1016/j.adapen.2023.100123

Cities Coalition for Digital Rights. (2021). *Digital Rights Governance Framework* (concept draft open for feedback). https://citiesfordigitalrights.org/sites/default/files/DIGITAL%20RIGHTS%20FRAMEWORK_CONCEPT%20FOR%20FEEDBACK.pdf

Cities Coalition for Digital Rights. (2024). *A milestone for digital rights in cities*. https://citiesfordigitalrights.org/milestone-digital-rights-cities?

Correia, D., Marques, J. L., & Teixeira, L. (2022). The State-of-the-Art of Smart Cities in the European Union. Smart Cities, 5(4), 1776–1810. https://doi.org/10.3390/smartcities5040089

Cugurullo, F., Caprotti, F., Cook, M., Karvonen, A., McGuirk, P., & Marvin, S. (2024). The rise of AI urbanism in post-smart cities: A critical commentary on urban artificial intelligence. Urban Studies, 61(6), 1168–1182. https://doi.org/10.1177/00420980231203386

Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652, Pub. L. No. 32023L2413, 2413 OJ L (2023). https://eur-lex.europa.eu/eli/dir/2023/2413/oj/eng

Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast) (Text with EEA relevance), Pub. L. No. 1275 OJ L (2024a). https://eur-lex.europa.eu/eli/dir/2024/1275/oj/eng

Directive (EU) 2024/1711 of the European Parliament and of the Council of 13 June 2024 amending Directives (EU) 2018/2001 and (EU) 2019/944 as regards improving the Union's electricity market design, Pub. L. No. 32024L1711, 1711 OJ L (2024b) https://energy.ec.europa.eu/topics/markets-and-consumers/electricity-market-design_en?

Ejdys, J. (2013). *Regional economic foresight. Scenarios of local development of the Mazowieckie Voivodeship* [*Regionalny foresight gospodarczy. Scenariusze rozwoju lokalnego województwa mazowieckiego*]. Warszawa: Związek Pracodawców Warszawy i Mazowsza, https://depot.ceon.pl/handle/123456789/7637 (in Polish).

Ejdys, J., & Szpilko, D. (2023). How to ensure the resilience of semiconductor supply chains in the European Union? Polish Journal of Management Studies, 28, 101–122. https://doi.org/10.17512/pjms.2023.28.1.06

Ejdys, J., Czerewacz-Filipowicz, K., Halicka, K., Kononiuk, A., Magruk, A., Siderska, J., & Szpilko, D. (2023). *A preparedness plan for Europe: Addressing food, energy and technological security*. Brussels: European Parliamentary Research Service.

Ejdys, J., Gudanowska, A., Halicka, K., Kononiuk, A., Magruk, A., Nazarko, J., Nazarko, Ł., Szpilko, D., & Widelska, U. (2019). Foresight in Higher Education Institutions: Evidence from Poland. Foresight and STI Governance, 13, 77-89. https://doi.org/10.17323/2500-2597.2019.1.77.89

ENISA. (2024). *Report on the state of cybersecurity in the Union* (condensed version). https://www.enisa.europa.eu/publications/2024-report-on-the-state-of-the-cybersecurity-in-the-union

European Commission. (2021). *100 Climate-Neutral and Smart Cities by 2030 – Implementation Plan.* https://research-and-innovation.ec.europa.eu/system/files/2021-09/cities_mission_implementation_plan.pdf

European Commission. (2025a). *EU Mission: Climate-Neutral and Smart Cities.* https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/climate-neutral-and-smart-cities_en

European Commission. (2025b). *The EU LDT Toolbox empowers European cities with digital twin tools for smarter, data-driven urban planning.* https://interoperable-europe.ec.europa.eu/collection/ldttoolbox

European Commission. (2025c). Annex 8 to Communication to the Commission Approval of the content of the draft Commission Notice providing guidance on new or substantially modified provisions of the recast Energy Performance of Buildings Directive (EU) 2024/1275, Solar energy in buildings (Article 10). https://energy.ec.europa.eu/document/download/fd6f89fe-711b-4025-bc37-76b99baaa3fe_en

Fontes, C., Al Haddad, C., Antoniou, C., & Lütge, C. (2024). Assessing the collective challenges of AI: An applied framework focused on people centeredness and public participation. Urban Governance, 4(4), 245–254. https://doi.org/10.1016/j.ugj.2024.12.003

Frantzeskaki, N., Collier, M., Hölscher, K., Gaziulusoy, I., Ossola, A., Albulescu, P., Bonneau, M., Borgström, S., Connop, S., Dumitru, A., Geneletti, D., Gorissen, L., Levin-Keitel, M., MacIntyre, T., Mascinga, I., McQuaid, S., Tabory, S., von Wirth, T., Vandergert, P., Vos, P., Penha-Lopes, G., Säumel, I., Wachtel, T., & Wittmayer, J. (2025). Premises, practices and politics of co-creation for urban sustainability transitions. Urban Transform 7, 7. https://doi.org/10.1186/s42854-025-00075-9

Ge, C., & Qin, S. (2025). Urban Flooding Digital Twin System Framework. Systems Science & Control Engineering, 13(1), 2460432. https://doi.org/10.1080/21642583.2025.2460432

Helbing, D., Mahajan, S., Carpentras, D., Menendez, M., Pournaras, E., Thurner, S., Verma, T., Arcaute, E., Batty, M. & Bettencourt, L. M. A. (2024). Co-creating the future: participatory cities and digital governance. Philosophical Transactions A, 382(2285), 20240113. https://doi.org/10.1098/rsta.2024.0113

International Energy Agency. (2024). *Empowering Urban Energy Transitions – Executive summary. Paris: IEA.* https://www.iea.org/reports/empowering-urban-energy-transitions/executive-summary

International Organization for Standardization. (2019). Sustainable cities and communities – Indicators for smart cities (ISO Standard No. 37122:2019). https://www.iso.org/standard/69050.html

International Telecommunication Union (ITU-T). (2016). *Recommendation ITU-T Y.4903/L.1603 – Key performance indicators for smart sustainable cities to assess the achievement of sustainable development goals.* https://www.itu.int/rec/dologin_pub.asp?id=T-REC-Y.4903-202203-I%21%21PDF-E&lang=e&type=items

Islam, S. N. (2024). A Review of Peer-to-Peer Energy Trading Markets: Enabling Models and Technologies. Energies, 17, 1702. https://doi.org/10.3390/en17071702

Kim, Y., Oh, J., & Bartos, M. (2025). Stormwater digital twin with online quality control detects urban flood hazards under uncertainty. Sustainable Cities and Society, 118, 105982. https://doi.org/10.1016/j.scs.2024.105982

Lartey, D., & Law, K. M. Y. (2025). Artificial intelligence adoption in urban planning governance: A systematic review of advancements in decision-making and policy-making. Landscape and Urban Planning, 258, 105337. https://doi.org/10.1016/j.landurbplan.2025.105337

Loo, R., (2002). The Delphi method: a powerful tool for strategic management. Policing. An International Journal of Police Strategies & Management, 25(4), 762-769. https://doi.org/10.1108/13639510210450677

Loveridge, D. (2002). The STEEPV acronym and process – a clarification. Ideas in Progress. PREST Policy Research in Engineering, Science and Technology, 29. https://www.yumpu.com/en/document/read/12087765/the-steepv-acronym-and-process-a-clarification

Luo, J., Liu, P., Kong, X., Shen, J., Wu, Q., & Xu, D. (2025b). Urban digital twins for citizen-centric planning: A systematic review of built environment perception and public participation. International Journal of Applied Earth Observation and Geoinformation, 143, 104746. https://doi.org/10.1016/j.jag.2025.104746

Luo, J., Liu, P., Xu, W., Zhao, T., & Biljecki, F. (2025a). A perception-powered urban digital twin to support human-centred urban planning and sustainable city development. Cities, 156, 105473. https://www.sciencedirect.com/science/article/abs/pii/S0264275124006875

Mazzetto, S. (2024). A Review of Urban Digital Twins Integration, Challenges, and Future Directions in Smart City Development. Sustainability, 16(19), 8337. https://doi.org/10.3390/su16198337

Meijer, A. J., & Rodríguez-Bolívar, M. P. (2016). Governing the smart city: A review of the literature on smart urban governance. International Review of Administrative Sciences, 82(2), 392–408. https://doi.org/10.1177/0020852314564308

Michailidis, P., Michailidis, I., Lazaridis, C. R., & Kosmatopoulos, E. (2025). Traffic Signal Control via Reinforcement Learning: A Review on Applications and Innovations. Infrastructures, 10(5), 114. https://doi.org/10.3390/infrastructures10050114

Nazarko, J., Ejdys, J., Kononiuk, A., & Olszewska, A.M. (2013). Structural analysis as a method of data classification in foresight studies [Analiza strukturalna jako metoda klasyfikacji danych w badaniach foresight]. Prace Naukowe Uniwersytetu Ekonomicznego we Wrocławiu, 78, 44-53. https://www.dbc.wroc.pl/dlibra/publication/27220/edition/24612#description

Nazarko, J., Wnorowski, H., Ejdys, J., Kononiuk, A., Olszewska, A., & Gudanowska, A. (2011). *Structural analysis of factors influencing the development of nanotechnology in the Podlaskie Province* [*Analiza strukturalna czynników rozwoju nanotechnologii w województwie podlaskim*]. Białystok: Oficyna Wydawnicza Politechniki Białostockiej.

NetZeroCities. (2023a). *Climate-neutral City Contract – Concept (D1.3).* https://netzerocities.eu/wp-content/uploads/2023/01/D1.3-Climate-neutral-city-contract-concept.pdf

NetZeroCities. (2023b). *Citizen Engagement Model and Template Action Plan (D8.3).* https://netzerocities.eu/wp-content/uploads/2023/11/D8.3_Citizen-Engagement-Model-and-Template-Action-Plan.pdf

NetZeroCities. (2025a). *112 Mission Cities striving for climate neutrality by 2030. Brussels: NZC Mission Platform*. https://netzerocities.eu/mission-cities/

NetZeroCities. (2025b). *Climate City Contracts: A Roadmap to Climate Neutrality*. https://netzerocities.eu/climate-city-contract/

Nguyen, A. (2024, May 23). *How AI is arming cities in the battle for climate resilience*. https://www.reuters.com/sustainability/climate-energy/how-ai-is-arming-cities-battle-climate-resilience-2024-05-23

OECD Centre for Entrepreneurship, SMEs, Regions and Cities. (2024). *Activity Report 2024. Paris: OECD*. https://www.oecd.org/content/dam/oecd/en/about/directorates/cfe/CFE-2024-Annual-Activity-Report.pdf/_jcr_content/renditions/original./CFE-2024-Annual-Activity-Report.pdf

OECD. (2020). *Innovative Citizen Participation and New Democratic Institutions.* https://www.oecd.org/content/dam/oecd/en/publications/reports/2020/06/innovative-citizen-participation-and-new-democratic-institutions_11aa2baf/339306da-en.pdf

OECD. (2023). *Smart City Data Governance: Challenges and the Way Forward.* https://doi.org/10.1787/e57ce301-en

Palacin, V., McDonald, S., Aragón, P., & Nelimarkka, M. (2024). Configurations of Digital Participatory Budgeting. ACM Transactions on Computer-Human Interaction, 31(2), 28. https://doi.org/10.1145/3635144

Popper, R. (2018). *Foresight Process and Fundamentals.* https://prospectivaalc.org/wp-content/uploads/2018/05/p3_4_t3_foresight-process.pdf

Regulation (EU) 2024/903 laying down measures for a high level of public sector interoperability across the Union (Interoperable Europe Act), Pub. L. No. 32024R0903, 903 Oj L (2024). https://eur-lex.europa.eu/eli/reg/2024/903/oj

Ruijer, E., Van Twist, A., Haaker, T., Tartarin, T., Schuurman, N., Melenhorst, M., & Meijer, A. (2023). Smart Governance Toolbox: A Systematic Literature Review. Smart Cities, 6(2), 878–896. https://doi.org/10.3390/smartcities6020042

Sharifi, A., Allam, Z., Bibri, S. E., & Khavarian-Garmsir, A. R. (2024). Smart cities and Sustainable Development Goals (SDGs): A systematic literature review of co-benefits and trade-offs. Cities, 146, 104659. https://doi.org/10.1016/j.cities.2023.104659

Shin, B., Floch, J., Rask, M., Bæck, P., Edgar, C., Berditchevskaia, A., Mesure, P., & Branlat, M. (2024). A systematic analysis of digital tools for citizen participation. Government Information Quarterly, 41(3), 101954. https://doi.org/10.1016/j.giq.2024.101954

Skulmoski, G.J., Hartman, F.T., & Krahn, J., (2007). The Delphi Method for Graduate Research. Journal of Information Technology Education, 6, 1-21. https://doi.org/10.28945/199

Smith, A., & Prieto Martín, P. (2021). Going Beyond the Smart City? Implementing Technopolitical Platforms for Urban Democracy in Madrid and Barcelona. Journal of Urban Technology, 28(1–2), 311–330. https://doi.org/10.1080/10630732.2020.1786337

Sun, C., Wu, Z., & Zhu, Z. (2024). Microgrid optimisation: blockchain-enabled peer-to-peer energy trading. Cyber-Physical Systems. https://doi.org/10.1080/23335777.2024.2394786

Szpilko, D. (2014). The use of Delphi method in the process of building a tourism development strategy in the region. Ekonomia i Zarządzanie, 6, 329–346. https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-4a8da916-296f-434e-b086-247589dbfffe

Szpilko, D., & Ejdys, J. (2022). European Green Deal – research directions. a systematic literature review. Ekonomia i Środowisko – Economics and Environment, 81(2), 8–38. https://doi.org/10.34659/eis.2022.81.2.455

Szpilko, D., Fernando, X., Nica, E., Budna, K., Rzepka, A., & Lăzăroiu, G. (2024). Energy in Smart Cities: Technological Trends and Prospects. Energies, 17(24), 6439. https://doi.org/10.3390/en17246439

Szpilko, D., Glinska, E., & Szydło, J. (2020a). STEEPVL and structural analysis as a tools supporting identification of the driving forces of city development. European Research Studies Journal, 23(3), 340–363. https://doi.org/1 0.35808/ersj/1642

Szpilko, D., Jimenez Naharro, F., Lăzăroiu, G., Nica, E., & de la Torre Gallegos, A. (2023). Artificial intelligence in the smart city – a literature review, Engineering Management in Production and Services, 15(4), 53–75. https://doi.org/10.2478/emj-2023-0028

Szpilko, D., Szydło, J., & Winkowska, J. (2020b). Social Participation of City Inhabitants Versus Their Future Orientation. Evidence From Poland. WSEAS Transactions on Business and Economics, 17, 692–702. https://doi.org/10.37394/23207.2020.17.67

Szum, K. (2021). IoT-based smart cities: A bibliometric analysis and literature review. Engineering Management in Production and Services, 13(2), 115–136. https://doi.org/10.2478/emj-2021-0017

Tarashandeh, N., & Karimi, A. (2024). Peer-to-peer energy trading under distribution network constraints with preserving independent nature of agents. Applied Energy, 355, 122240. https://doi.org/10.1016/j.apenergy.2023.122240

Tedeschi, M. (2024). Datafication and urban (in)justice: Towards a digital spatial justice. Geography Compass, 18(6), e12763. https://doi.org/10.1111/gec3.12763

Tomor, Z., Meijer, A., Michels, A., & Geertman, S. (2019). Smart Governance For Sustainable Cities: Findings from a Systematic Literature Review. Journal of Urban Technology, 26(4), 3–27. https://doi.org/10.1080/10630732.2019.1651178

UNECE. (2021). *People-Smart Sustainable Cities.* https://unece.org/sites/default/files/2021-01/SSC%20nexus_web_opt_ENG_0.pdf

UN-Habitat. (2024). *World Cities Report 2024: Cities and Climate Action.* https://unhabitat.org/sites/default/files/2024/11/wcr2024_-_full_report.pdf

UN-Habitat. (2025). *International Guidelines on People-Centred Smart Cities. "Smart Cities for People: empowering lives, protecting the planet, advancing prosperity.* https://unhabitat.org/sites/default/files/2025/02/international_guidelines_on_people_centred_smart_cities_10.02.25_shared.pdf

van Twist, A., Ruijer, E., & Meijer, A. (2023). Smart cities & citizen discontent: A systematic review of the literature. Government Information Quarterly, 40(2), 101799. https://doi.org/10.1016/j.giq.2022.101799

Van Woensel, L.D., & Vrščaj, D. (2015). *Towards Scientific Foresight in the European Parliament In-depth Analysis.* https://www.europarl.europa.eu/RegData/etudes/IDAN/2015/527415/EPRS_IDA%282015%29527415_REV1_EN.pdf

Veerasamy, V., Hu, Z., Qiu, H., Murshid, S., Gooi, H. B., & Nguyen, H. D. (2024). Blockchain-enabled peer-to-peer energy trading and resilient control of microgrids. Applied Energy, 353(A), 122107. https://doi.org/10.1016/j.apenergy.2023.122107

Wang, T., & Yorke-Smith, N. (2025). Introduction: AI for and in Urban Planning. Urban Planning, 10, 9417. https://doi.org/10.17645/up.9417

Weil, C., Bibri, S. E., Longchamp, R., Golay, F., & Alahi, A. (2023). Urban Digital Twin Challenges: A Systematic Review and Perspectives for Sustainable Smart Cities. Sustainable Cities and Society, 99, 104862. https://doi.org/10.1016/j.scs.2023.104862

Winkowska, J., Szpilko, D., & Pejić, S. (2019). Smart city concept in the light of the literature review. Engineering Management in Production and Services, 11(2), 70–86. https://doi.org/10.2478/emj-2019-0012

World Economic Forum. (2022). *Digital Twin Cities: Framework and Global Practices.* https://www.weforum.org/publications/digital-twin-cities-framework-and-global-practices/

Xiao, F., Lu, J., Li, L., Tu, W., & Li, C. (2025). Advances in reinforcement learning for traffic signal control: a review of recent progress. Intelligent Transportation Infrastructure, 4, liaf009. https://doi.org/10.1093/iti/liaf009

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## JAKIE CZYNNIKI BĘDĄ KSZTAŁTOWAĆ PRZYSZŁOŚĆ ZRÓWNOWAŻONYCH I INTELIGENTNYCH MIAST W EUROPIE? WYNIKI BADANIA DELPHI

STRESZCZENIE: Artykuł ma na celu identyfikację i ocenę czynników kształtujących rozwój zrównoważonych i inteligentnych miast w Europie oraz ich wzajemnych oddziaływań. W odniesieniu do celu sformułowano trzy pytania badawcze: (I) Jakie czynniki sprzyjają rozwojowi zrównoważonych i inteligentnych miast w Europie? (II) Jakie czynniki ograniczają (utrudniają) rozwój zrównoważonych i inteligentnych miast w Europie? (III) Jakie są główne czynniki wpływające na rozwój zrównoważonych i inteligentnych miast w Europie? W ramach procesu badawczego zastosowano: horizon scanning, analizę STEEPVL, metodę Delphi i analizę strukturalną. W badaniu wzięło udział 131 ekspertów z 28 krajów, publikujących artykuły z zakresu zrównoważonego i inteligentnego rozwoju miast, indeksowane w bazie Web of Science. Analizowane kierunki obejmują: smart governance i partycypację mieszkańców, odnawialne mikrosieci energetyczne ze zdecentralizowanym obrotem energią, delegowanie decyzji na systemy oparte na AI oraz miejskie cyfrowe bliźniaki. Wyniki Delphi jednoznacznie wskazują trzy główne czynniki sprzyjające: dostęp do zewnętrznych źródeł finansowania, rozwiniętą infrastrukturę cyfrową oraz integrację danych, a także wysoki poziom cyberbezpieczeństwa i ochrony danych. Za najważniejsze bariery uznano: niski poziom integracji systemów miejskich i brak interoperacyjności danych, ograniczony potencjał finansowy samorządów oraz opór instytucjonalny wobec zmiany i transformacji cyfrowo-klimatycznej. Wyniki analizy strukturalnej wskazują zaś, że sterowanie instytucjonalne, dojrzałość infrastruktury danych i interoperacyjność wyznaczają trajektorię zmian. Z uzyskanych wyników wynikają implikacje praktyczne: należy wzmocnić sterowanie instytucjonalne i przejrzystość prawa, zapewnić wieloźródłowe finansowanie, nadać priorytet interoperacyjności, a następnie skalować AI i cyfrowe bliźniaki wraz z rozwojem kompetencji i podejściem security-by-design.

SŁOWA KLUCZOWE: zrównoważone miasto, inteligentne miasto, partycypacja, energia, cyfrowe bliźniaki, sztuczna inteligencja, analiza strukturalna, metoda Delphi, analiza STEEPVL