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Review

The Smart City from the Energy Perspective

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Abstract

The accelerated development of Smart Cities on a global scale, driven by rapid urbanization and urgent climate challenges, underscores the critical role of advanced energy infrastructures integrated with emerging digital technologies. This article explores the smart city evolution from an energy-centric viewpoint, emphasizing the interdependence between energy systems, digitalization and cutting-edge communication technologies. Adopting a system-of-systems perspective, we examine how different urban subsystems, including energy grids, transportation networks and data management systems, interact to improve overall the urban functionality and long-term viability. Through a structured analysis of recent literature, we highlight the transformative potential of renewable energy integration, intelligent energy management systems and the crucial transition from 5G to 6G communication infrastructures, which collectively promise significant enhancements in urban sustainability, efficiency and resilience. Additionally, we address key challenges such as cybersecurity, vulnerabilities, fragmented standardization frameworks and the need for comprehensive data governance. Viewing smart cities as a complex system-of-systems, this article argues for a holistic and interdisciplinary approach, emphasizing an enhanced interoperability, robust cybersecurity protocols and inclusive participatory governance frameworks.

Keywords: smart city; renewable energy; digitalization; 6G; cybersecurity; interoperability; artificial intelligence; system-of-systems; data governance

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1. Introduction

The global trend toward urbanization has intensified the need for smarter and more sustainable urban development. In 2023, more than half of the world population lived in cities and used up to two thirds of the global resources [1]. This imbalance underscores the necessity for cities to adopt intelligent strategies that optimize urban space and promote long-term resilience through sustainable planning. Smart Cities, as defined by ISO/IEC 30145-1:2021, are IT driven system-of-systems that integrate business processes through advanced technological infrastructure, including the energy sector that plays a foundational role by enabling the transition toward low-carbon, resilient urban environments [2]. Standardization ensures a scalable development, allowing interoperability across smart energy systems, communication networks and big data platforms [3]. New generations of wireless communication, such as 6G, further support this ecosystem with higher data throughput, lower energy consumption and enhanced data protection. Ultimately, the integration of IoT devices across sectors facilitates data-driven urban management, promoting sustainability, energy autonomy and resilience in the evolving smart city landscape [4]. Authors of [5] emphasize the importance of AI in enhancing governance when mediated by IoT and transparent frameworks, while deep reinforcement learning integration with evolutionary algorithms is proposed in [6] for optimizing the energy sector operation to cope with the urban uncertainties and dynamic environment. Similarly, deep learning and blockchain techniques are implemented in [7] to secure authentication mechanisms for device-to-device communication. For a better understanding of IoT challenges and opportunities in smart cities transitions, authors of [8] present a comprehensive overview on IoT successful implementation in energy, transportation, community and healthcare sectors. On the other hand, telecommunication infrastructure remains a backbone of smart cities, as efficient AI deployment relies on a large volume of data. The survey performed in [9] highlights the role of beyond 5G networks in emergency response, healthcare, and autonomous transport, while authors of [10] further stress the importance of telecommunications for integrating IoT and enabling large-scale data flows. These contributions point to B5G/6G as essential enablers for ultra-low latency, reliability, and connectivity among billions of devices. However, security and trust are equally critical. Works as [11] and [12] explore blockchain methods for protecting IoT and smart grids, while authors of [13] expand the review on energy infrastructure security to classical approaches and next-generation technologies, from firewalls and cryptography to edge computing. Together, these works propose decentralized trust frameworks as alternatives to vulnerable centralized models. In [14], an activity-network-things (ANTs)-centric architecture is proposed by authors to increase flexibility in security insurance across key smart-city domains. Finally, sustainability and inclusiveness remain core challenges. In [15], a cognitive city platform is introduced to integrate resilience and anomaly analytics, while authors of [16] and [17] highlight risks of exclusion under top-down governance models. Regional studies from Indonesia [18] and Korea [19], [20] address the living lab methodology and eco-district planning to improve quality of life in terms of economy, mobility, and environment, whereas authors of [21] and [22] examine the intelligent vehicles and digital twin approach to improve the mobility infrastructure for a sustainable transportation sector. These findings confirm that future smart cities must balance technological innovation with social justice, inclusiveness, and sustainability.

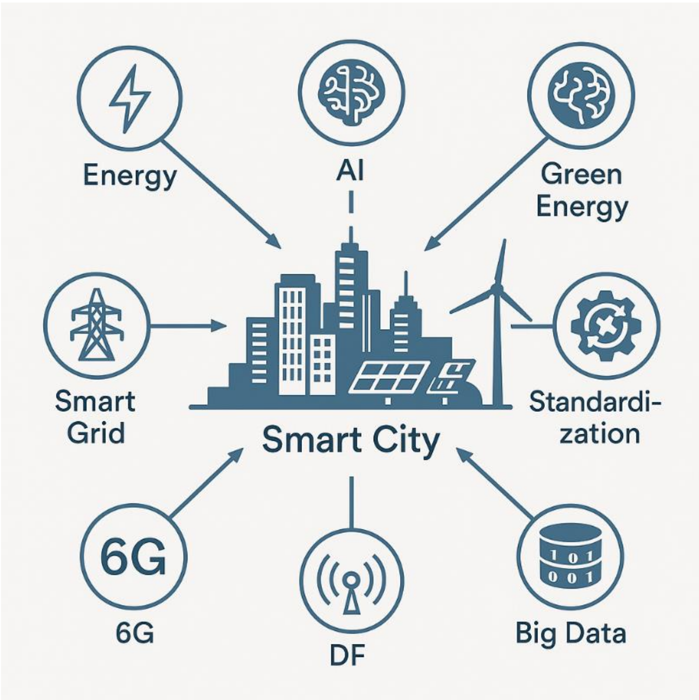

Figure 1. Conceptual representation of a Smart City from the energy perspective.

2. Materials and Methods

The evaluation of energy systems in the context of Smart City development requires a multidisciplinary approach based on integrating emerging technologies, digital infrastructure and smart efficient energy grids. In this scope, to analyze the optimal transition to a sustainable and digital energy sector, as well as to standardization of the development processes, this article employs a methodology based on a comprehensive literature review. The findings are synthesized and

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presented by employing a graphical representation of existing results, ensuring a structured and accessible overview.

Our research related to the *Smart City* concept was conducted with emphasis on *Renewable Energy, Smart Grid, Energy Efficiency, Digitalization, IoT, 6G* and *Big Data*.

The results were synthesized and represented in a graphical way to facilitate coordination between different perspectives. This approach aims to effectively present and highlight the key trends in the field, providing a clear and comprehensive overview of the findings.

An essential component of the analysis involved the examination of technical standards applicable to smart city development. For this purpose, international standard libraries were utilized [23], [24]. The identified standards were categorized into relevant sections including: smart grid infrastructure, smart cities, IoT, cyber security, communications, and new generation technologies such as 6G. The implementation level of these standards was assessed by comparing them with different case studies of smart cities that have integrated such technologies, with the scope of providing valuable insights into their adoption effectiveness.

Although the article selection was based on multiple criteria, this methodology has certain limitations. For example, some analyzed articles may reflect geographical and economic factors that are specific to certain regions, making the authors findings challenging to replicate in different geopolitical contexts.

Technical standards are constantly evolving, and their adoption can significantly depend on the local policies and the technical know-how available in each city. These differences can impact the effective implementation of energy solutions in smart city and, making standardization and interoperability of the different systems challenging keys in the transition to a smarter urban infrastructure.

The proposed methodology conducts a semantic analysis of the relationship between the digitalization of urban spaces, energy efficiency and standardization within the framework of smart urban development, presenting a comprehensive perspective of the various development trajectories while identifying potential challenges that may arise through the implementation and development process.

Table 1. Overview of the selected articles on Smart City Energy perspective.

Ref.	Year	Study Area	Keywords	Proposal	Results
[25]	2023	Southeast Asia	Challenges; efficient energy management; energy modeling; overview; renewable energy; smart city.	Review and analyze the smart city concepts, implementation challenges, sustainable energy management and modeling strategies.	Significant potential for AI-based models in energy management but many challenges due to regulatory and economical barriers
[26]	2024	EU	Energy efficiency; 5G; radio access network; metrics, modeling; data; traffic; user device; base station; wireless; KPI.	Understand the increasing number of connected devices impact on energy usage and data transmission efficiency.	The study highlights the need to balance coverage and efficiency, providing strategic directions for future 5G deployments.
[4]	2023	Global	Smart city; Smart Mobility; 5G; 6G.	Survey aggregating literature on emerging 6G technologies and their applicability in Smart Cities, focusing on connectivity, energy efficiency, and urban	6G transition will be a cornerstone in the design and governance of smart cities, providing a faster, more secure, and energy-efficient alternative to current technologies.

				infrastructure integration.	
[27]	2023	South Korea	Internet of Things; complex problem solving; critical IoT systems; nanogrid; optimization; task modeling; task orchestration	A new mechanism that optimizes decision making based on energy costs and the orchestrating of IoT sensors for peer-to-peer transactions.	The used model, based on the current day energy transactions optimization, reduces the transaction costs of the energy and improves overall energy efficiency and power management.
[28]	2024	Global	Smart Grid; Cyber Threats; PV; Overcurrent relay; Intelligent inverter.	Enhancing energy grid resilience by implementing cybersecurity measures for solar inverters and integrating overcurrent protective relays (OCR) for grid restauration.	Cyberattacks on inverters and OCR protection systems can cause major network disruptions, including overcurrent, voltage fluctuations and uncontrolled disconnections.
[29]	2024	EU	Positive Energy Districts; Smart Storage Systems; Fuzzy Logic Management Systems; Distributed Generation; Hybrid Renewable systems; Energy Resiliency	Proposal of a fuzzy logic-based energy management system used in residential Positive Energy Districts (PED) with the purpose of optimizing self-sufficiency and self-consumption by dynamically managing a centralized energy storage system for green energy solutions.	The proposed energy management system enables the residential Positive Energy Districts to achieve a higher self-sufficiency and self-consumption, with a feasible economic rating, reaching a 6 to 12 years return on investment.
[30]	2022	Taiwan	Low-Carbon Communities; Public-Private Partnerships; Collective actions; Participatory Action Research; Responsible Research Innovation; Environmental Planning; Social Science.	Introducing a holistic approach to the planning model for integrated community empowerment with the scope of transitioning toward a zero-net carbon community, with a focus on collective action, localized resource identification, flexible energy system planning and digital performance monitoring.	Successful zero-net carbon community transitions depend on early community involvement with the purpose of trust-building through public-private partnership, flexible and site-specific planning with transparent monitoring, reducing institutional fragmentation and community reluctance towards new policies and technologies.
[31]	2023	South Korea	Smart City; Sustainable City; Smart Urban Plan; Urban Regeneration Project; Smart Green City.	Development of a diagnostic framework and evaluation of indicators for smart cities assessment and	The current urban plans exhibit moderate sustainability, but present a lack of sufficient smart technology integration,

				transition toward sustainability, policy direction and strategies to enhance urban planning through the integration of smart technologies and sustainable development guidelines.	with significant deficiencies in goal setting, governance and comprehensive implementation strategies, highlighting the need for more adaptive, technology-driven and sustainability focused planning frameworks.
[32]	2023	EU	Smart Governance; Regulatory Requirements; Best Practices; Energy Communities; Citizen Empowerment.	Proposal of a governance and implementation framework for renewable energy communities (RECs) with Positive Energy Districts (PEDs), aligning with Italian regulation with the purpose of enhancing citizen participation, optimize energy management and support energy transition through a multi stakeholder approach.	A well-structured governance model for renewable energy communities (RECs) that is supported by regulatory and technological inceptives can enhance energy efficiency, promote social inclusion and accelerate the transition toward a sustainable Positive Energy District (PED).
[33]	2024	EU	Smart City; Data Sharing; Urban Data Platform; Interoperability; Security	The development of a Municipal Data Utility (KDW) in Mainz, Germany, as a legally secure and interoperable platform for intermunicipal data sharing, designed to facilitate efficient urban governance data-driven decision making, addressing legal and technical challenges.	Successful implementation of a KDW requires a robust legal framework, stakeholder engagement, standardized data governance and scalable technical infrastructure, showing thus the potential to enhance municipal interoperability efficiency and evidence-based decision making in urban management.
[34]	2023	Ukraine	Street and Road Network; Route; Public Transport; Urban Transport Industry; Metric-Tabular Method.	Optimization of the public transport network in Odesa, Ukraine, by restructuring routes, improving scheduling efficiency and prioritizing public transport infrastructure to enhance service reliability, with the	The optimization of public transport in Odesa, through better route planning, dedicated lanes and improved schedule, increases passenger satisfaction and promotes sustainable urban mobility.

				purpose of improving the sustainable urban mobility.	
[35]	2023	EU	Digitalization; Disruptive Mobility; eMobility Adaptation; Electrical Vehicle Sharing Adaptation; Diffusion of Innovation; Smart Communities	Proposal of a model based on the Diffusion of Innovation (DoI) Theory with the purpose of highlighting the factors that influence eMobility sharing services in smart communities, using a mixed method approach that combines quantitative survey analysis and qualitative interviews to provide insights for better integration, infrastructure and policy-making support.	The adoption of eMobility sharing services within smart communities is primarily influenced by perceived advantages, compatibility with user needs and ease of access, therefore improving infrastructure policy support and digital integration for user acceptance; enhancing long term sustainability.
[36]	2023	Global	5G Network; Federated Deep Learning; Internet of Things; Reinforcement Learning; Smart Contract; Systematic Review.	A bibliometric analysis of the convergence between artificial intelligence and blockchain in smart cities, with the purpose of identifying key research trends and emerging applications to enhance urban security and data management.	The integration of artificial intelligence and blockchain in smart cities will lead to enhanced security, efficiency and data management, but faces challenges related to scalability and interoperability.
[37]	2023	EU	Smart Cities; Shared Mobility; Machine Learning; Artificial Intelligence; Mobility Modeling.	Machine Learning based model, utilizing the Ensemble (Tree) method, to assess the accuracy and compliance of user routes in shared mobility systems, with the purpose of enhancing operational management, safety and sustainability of the transportation system in Smart Cities.	The proposed machine learning model achieved over 95% accuracy in predicting the correctness of user trips in shared mobility systems and identified key factors such as speed, travel time and energy consumption, enabling real-time assessment through an integrated application.
[38]	2023	EU	MCDM Methods; Integrated Approach; Sustainable Energy and Climate Development;	Proposal of a multi criteria decision making (MCDM) methodology integrating five	Significant disparities in energy and climate sustainability aiming EU-27 countries, emphasizing that while nations like Sweden

			European Union Member States.	ranking methods (CODAS, EDAS, TOPSIS, VIKOR and WASPAS) to assess the energy and climate sustainability of EU-27 countries.	and Denmark lead in sustainable development, other countries lag due to economic and policy differences.
[39]	2023	Global	Smart City; Smart City Readiness; Smart City Assessment; Developing Economies; PRISMA; Assessment Tools.	A scoping review of Smart City Assessment (SCA) frameworks in developing economies, highlighting the predominant methodologies, gaps in standardization and the need for more integrated, adaptable and stakeholder-inclusive evaluation models to enhance urban sustainability and technological advancement.	The study concludes the need for standardized and integrated Smart City Assessment frameworks in developing economies, highlighting the lack of methodological consistency and the necessity for stakeholder engagement to ensure sustainable and effective smart city implementation.
[40]	2023	EU	Smart Energy; Smart Solutions; Digital Twin; Digitalization; Sensors; Security; Military.	Comparative framework for analyzing city digitalization through digital twin platforms, emphasizing the integration of real-time urban data, security challenges and military applications.	City digitalization is inevitable, but it must be tailored for local realities, incorporate robust cybersecurity measures and leverage data driven decision making with a focus on AI integration and military applications in the smart urban infrastructure.
[41]	2023	EU	Public Administration Reform; e-government; Computer and Society.	Proposal for smart cities to integrate robust privacy by design mechanisms, transparent data governance policies and citizen implication frameworks to mitigate the risk of excessive surveillance and data exploitation, ensuring a balance between digital innovation and individual freedom.	The success of smart cities depends on implementing transparent data protection policies, enforcing legal safeguards against surveillance abuses and fostering public engagement to ensure that technological advancements enhance urban life without compromising privacy and individual freedoms.
[42]	2024	EU	Data Communication; Digital Twins; ICS; Models; Network Control.	A hybrid physical emulated digital twin model for managing electrical power systems, integrating real-time data from	Digital twins are a promising solution for optimizing electrical power systems, but their effective implementation requires standardization, enhanced

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				physical devices with simulated environments, while addressing key challenges.	interoperability, cybersecurity measures and AI usage, combining real and simulated data to improve accuracy and scalability.
[43]	2023	Global	Industry 4.0; Critical Infrastructure; Water Management; IoT Network.	Usage of NB-IoT (narrowband Internet of Things) technology to enhance the renewal saucerization of critical water supply and wastewater treatment infrastructures in smart cities, ensuring high availability and automated management, compliant with industry 4.0 standards.	NB-IoT technologies provide an effective and scalable solution for modernizing and safeguarding critical water supply and wastewater treatment infrastructure in smart cities, while emphasizing the need for future advancements in AI, hyper automation and 6G connectivity for further optimization.

3. Results

3.1. Growing Cities: A Catalyst for Smart Infrastructure

In 2023, the World Bank reported that more than four billion people lived in cities, which represents 57% of the global population [1]. Over the last 15 years, the urban density has increased from an average of 3,500 to 4,261 inhabitants per square kilometer and despite the fact that cities occupied 5% of the global land area, they require more than 75% of global natural resources [44]. This highlights the urgent need for cities to approach a smarter development with an emphasis on sustainability and a better optimization of urban space among the various systems of the city by implementing smarter solutions that support a viable growth with a long-term resilience plan.

An effective transformation process requires a collaborative approach that ensures durable commitment from all actors. As stated in [30], the success of community engagement in the zero-emission transition for different communities depends on the public-private partnerships, trust-building among stakeholders and early resident involvement in the decision-making process. Here, a Participatory Action Research (PAR) framework was applied in a zero-carbon community project in Pinglin, Taiwan, with the focus on the following stages: the process began with the identification of key factors influencing the community engagement, drawing on a collective action theory and a co-evolution theory; the participatory planning model was then implemented, ensuring direct involvement in all the stages of the project, including community selection, local resource assessment, carbon footprint inventory and the integration of energy efficiency and green energy strategies. The implementation of the project was assessed through qualitative and quantitative data collection, using participant observation, interviews with representatives of the community, policymakers, workshops and the analysis of the government documentation.

In [31], a series of indicators were applied to urban planning strategies in Incheon Metropolitan City and Goyang-si, South Korea, with the purpose of evaluating their current level of sustainability and smart city integration. The methodology used to diagnose smart city plans was focused on identifying the optimal transition pathway toward more sustainable and intelligent urban development. To assess and diagnose the urban landscape from a sustainability perspective, the authors propose a set of evaluation indicators based on five components: factual analysis (current situation and forecasting), objectives and targets (goal setting and progress measurement), policies and strategies (sustainable urban development strategies), cooperation and governance (stakeholder participation) and the implementation feasibility (efficiency of policies).

The average sustainability score of the analyzed urban plans was 45.58/100, highlighting the need for significant improvement. The urban intelligence score was even lower at 24.14/100, indicating the limited integration of smart urban technologies in the planning process. General urban development master plans tend to be uniform and fail to account for specific characteristics of each different urban landscape, while urban regeneration plans that score higher in cooperation and governance lack effective integration of smart emerging technologies. These findings highlight the need for tailored planning approaches, based on emerging technology adaptation and stronger local engagement in the strategy development phase.

A primary concern in widespread technology implementation in the urban landscape is represented by the information security in the planning and managing phase, where data exposure can lead to physical and economic impact. Therefore, ensuring cyber resilience through blockchain is crucial for protecting individuals, as well as institutions on the urban scale.

Based on the results, authors of [31] concluded that rather than technology being implemented solely for technological competitiveness, the application of smart technologies should align with the urban development goals, regional conditions and the social acceptance of the people.

3.2. Renewable Energy Systems and Their Urban Applications

The integration of renewable energy sources is a fundamental pillar in the energy transition across the world. However this implementation has its challenges such as grid instability and lack of supportive policies for green initiatives [45]. To accelerate this transition, among the most widely adopted technologies, AI, IoT and big data platforms enable the energy usage optimization and emission reduction, as the adoption of these novel solutions facilitates energy production in a decentralized way and helps the seamless integration into urban energy flows, enhancing the stability of both traditional and smart grids alike [25].

With the ongoing integration of green energy solutions in the power distribution network and communication systems, there has been a growing focus on controlling and protecting these newly interconnected systems; a key priority has been protecting energy infrastructure against cybernetic threats, emphasizing the need for a robust protection strategy. The increased usage of solar systems, inverters and Intelligent Electronic Devices (IED) at a fast pace, has highlighted the vulnerability of energy infrastructures to cyber threats posing concerns about the sustainability and resilience of the power grid. The intelligent inverters used in photovoltaic plants and the protection relays are vulnerable to malicious attacks due to their reliance on wireless communications and advanced Supervisory Control and Data Acquisition (SCADA) systems, while the absence of actualized firmware can result in malfunction with the control protocols, exposing significant vulnerabilities that can compromise the reliability of the power grid [28].

In [25], Smart City initiatives in Southeast Asia were analyzed, with a focus on optimization strategies and the improvement of energy storage and distribution management, by examining key existing infrastructures and applied development trajectories. Thus, the authors identified a realistic progress along with the major challenges that influenced the adoption of smart energy solutions, these challenges being assessed from economical, technological and legislative perspective with the purpose of highlighting the factors that impact the implementation and scalability of novel solutions.

A critical aspect of implementing smart energy infrastructure is represented by the results of the feasibility studies, which assess the actual environmental impact of renewable energy systems and the large scale adaptation of micro-grids based on the climatic conditions of each urban landscape. Also, selecting the appropriate energy management models is essential for ensuring the implementation of a functional and efficient energy system within the urban environment.

A multi-criteria decision making (MCDM) methodology used to assess the energy and climate sustainability of the EU-27 member states is presented in [38] which integrates a set of 17 indicators that were selected to align with the Europe 2020 Strategy and the UN Sustainable Development Goals

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(SDGs) 7 and 13. The evaluation covered years 2010, 2015 and 2020 using five different methods (CODAS; EDAS; TOPSIS; VIKOR and WAPAS) to generate a final assessment score, ranking the 27 countries based on their respective performances in sustainability. Using this analysis methodology, the authors revealed a significant discrepancy among EU countries in terms of energy and climate sustainability. Top performing nations, throughout the analyzed period including Sweden and Denmark, followed by Austria and Finland, maintained consistently high performances. Bulgaria and Cyprus were ranked the lowest due to low energy efficiency and limited use of renewables, while Poland and Czech Republic showed slower progress in reducing greenhouse gas emissions.

The study in [38] emphasizes a growing share of renewable energy in final energy consumption, transmission and electricity production, alongside an overall reduction in greenhouse gas emissions across the EU. However, variations in sustainability levels have been observed which indicates that environmental and energy policies are implemented differently, shaped by economic and social factors.

3.3. From 5G to 6G: Advancing Communication Infrastructure for Smart Cities

The 6G infrastructure represents the successor of the 5G technology and both of these new infrastructures operate at a much higher radio frequency, thus enabling the transfer of larger quantities of data, which favors the widespread use of Internet of Things (IoT). According to [4], the sensors usage is expected to reach billions of units in the near future. One of the biggest advantages of 6G is its significant lower energy consumption compared to the previous generations and its improved security due to the possibility of detecting cyber threats, as well as the power to encrypt data within secure decentralized systems. These aspects make the use of such communication infrastructure highly appealing for smart applications on the urban scale [46].

Smart Cities and 6G will transform the urban environments, but their integration presents challenges including spectrum allocation, infrastructure investment, security risks and regulatory complexities. Achieving global coverage requires massive deployment of base stations, with higher frequency bands demanding additional infrastructure to mitigate signal disruptions. According to [4], despite these challenges, 6G will be a driven motor of the Smart Cities innovation perspective by enabling ultra-fast, low-latency connectivity for autonomous transport, smart grids and public safety, as well as enhanced real-time data communication, optimized energy management and strengthen emergency response systems.

By simulating four different scenarios regarding the implementation and operation in Netherlands and Croatia, authors of [26] assess the impact of the increasing number of user devices (UDs) on energy consumption and 5G network data sharing efficiency, analysis which can provide valuable insights into the long-term effects of device growth on the energy and communication networks performances. In this study, the scenarios varied based on the installation and operation of base stations (BSs): for the first scenario, a gradual deployment is used, in which BSs are installed progressively in response to the increasing number of user devices, the second scenario uses an energy optimization strategy, where the BSs utilize pause mode during inactive periods to reduce energy consumption, the third scenario utilizes a full preinstallation of all the BSs, without optimization and the fourth scenario presents a hybrid approach that combines pause mode with scalable transmission power for improved efficiency.

This analysis identified two key effects over a ten-year period between 2020 and 2030 in the Netherlands and Croatia. Firstly, the energy and data transmission efficiency will improve due to more advanced infrastructures, and secondly, the network coverage may decrease in areas with fewer users due to an increased size of the data packets. For the two countries, the Netherlands experiences a significant increase in user density in urban areas, leading to higher energy efficiency in data transmission per unit, while in contrast, Croatia, which is a more geographically dispersed user base, will require a greater number of base stations in rural areas, resulting in an overall increase in total energy consumption.

Therefore, it can be concluded that 5G networks will improve their energy efficiency per unit of data transfer in the coming years, but overall energy usage will increase, while the implementation of optimization techniques, such as intelligent BSs power management and pause mode utilization, can enhance overall energy efficiency. Given this, energy and communication infrastructure operators should prioritize a balanced approach in their respective development strategies, that optimize both data transfer and energy usage, considering population density and the distinct needs of urban and rural areas [26].

6G technologies play a crucial role in the transformation of smart cities, requiring a reevaluation of the communications sector and wireless technologies in urban environments, transition which must be built on emerging IoT infrastructure and economic factors that support the development and reliable operation of smart cities [46].

According to [4], one of the most important features of the reevaluation of the communication sector is played by the interoperability, data privacy and the security of the digital devices, alongside the different implementation difficulties. 6G makes for an ideal solution for IoT technologies, which are expected to scale to billions of devices in the coming years, due to their ability to operate at higher radio frequency with a greater capacity and lower latency.

This novel technology presents significant improvements over 5G, by utilizing THz frequency bands with the purpose of improving data transfer rates while reducing energy consumption. It can introduce decentralized intelligent networks as well, that present enhanced security and distributed data processing, integrating AI for a dynamic network and resource management system [47].

Smart cities leverage digital technologies to optimize resource management, including intelligent urban transport networks, improved water supply monitoring, optimized waste management, and more efficient lighting and heating solutions for buildings. With the increasing use of IoT and other digital technologies specific to urban environments, the volume of data that is being generated reached massive volumes, with a continuous daily growth, thus data analytics, management systems, storage and infrastructure became a critical component for the development of smart cities. Data analytics enable cities to interpret this information and make data-driven decisions to enhance efficiency and sustainability. A ubiquitous connectivity system can support large-scale IoT infrastructure for enhanced transport and urban management, alongside improving energy efficiency with low-power communication and energy distributed networks resulting in an overall reduced power consumption. Another fundamental component in smart cities is represented by a robust data infrastructure which will serve as the foundation for all data-related activities, including networks, hardware, and software required for data storage, processing, and analysis. With a well-developed data infrastructure, cities can fully leverage the benefits of big data and analytics, fostering a smarter and more sustainable future.

Therefore, 6G can enhance smart energy management systems, enabling cities to coordinate energy production and consumption by integrating renewable sources and storage solutions, while also reducing energy losses in telecom networks through edge and mobile edge computing by minimizing long-distance data transmission. Additionally, smart grids will benefit from IoT sensors and AI, improving anomaly detection and optimizing energy distribution based on real-time demand [4] , [47], [48].

3.4. Advancing Urban Energy Management with Smart Grids and IoT

The Internet of Things (IoT) sensors implementation across different sectors within the communication sector presents significant potential for developing new smart energy systems with highly enhanced performances. Recently, as presented in [49], microgrids and nanogrids solutions have increasingly replaced traditional systems in peer-to-peer energy trading due to their abilities to facilitate horizontal energy transaction by their decentralized structure, thus enabling the possibility of transferring energy in an insular mode and reducing reliance on the main grid and enhancing energy autonomy.

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In this context, the integration of IoT-based systems in key sectors, such as communication and navigation, represents a significant opportunity for the development of the traditional energy system. The adoption of smart grids that are controlled via IoT technologies, can lead to enhanced performances, reduced transaction costs and optimized energy storages capacities [50].

According to [27], in order to optimize the traditional energy transaction solutions, one of the primary challenges is the ensuring of scalability and real-time adaptability, issue that can be effectively addressed through IoT-driven task orchestration and management - a concept introduced by Ashton Kevin, who proposed the digital transformation of the physical world for facile energy transactions. While IoT-based task management is widely applied in healthcare and manufacturing, its adaptation in the energy sector remains relatively limited. Previous research has focused primarily on energy management within smart grids, but there is significant potential to extend IoT applications to key subsectors such as energy trading. Reevaluating these solutions requires alignment with emerging renewable energy technologies, both in large scale and individual levels, as well as the integration of new energy storage solutions and the facilitation of peer-to-peer energy transactions.

The authors of [27] proposed an objective function based on the Particle Swarm Optimization (PSO) algorithm with the purpose of minimizing the costs associated with energy transaction at a nanogrid level. By comparing the two scenarios, optimized and non-optimized costs across 12 nanogrids over 24-hour time intervals, the authors have demonstrated a significant cost reduction in most cases, these results confirming the effectiveness of the proposed method and its potential to enhance sustainability and both financial and energy efficiency of the energy transactions. The optimization of Energy Storage System (ESS) utilization was assessed under three different scenarios: a regular day, a high solar generation day and a solar energy deficit day. In each of the three cases, the proposed IoT-orchestrated system efficiently managed the charging and discharging processes, ensuring an optimal energy allocation. This approach allowed nanogrids to adapt quickly to energy demand fluctuations either by storing surplus energy or utilizing stored energy to compensate for production deficits.

The growing adoption of decentralized photovoltaic installations has highlighted the vulnerability of smart grids, particularly exposing adaptive overcurrent relays (OCRs) to potential cyberattacks, which can compromise grid stability and security.

Simulated attacks, including false data injection (FDI), denial of service (DoS) and Man-in-the-Middle (MITM), targeting smart inverters and OCR protection systems, reveal in [28] the OCRs struggle to correctly identify and manage faults leading to grid instability and power losses. During normal operating conditions, the grid remained stable, maintaining constant voltage and power outputs, however, during cyberattacks, significant current spikes, voltage fluctuations and reduction in active and reactive power were observed, impacting the grid stability. Detailed simulations showed that pulsed signal attacks caused harmonic distortions and power losses, which the OCRs failed to detect due to the short duration of signals, sinusoidal and scaling attacks led to voltage and current fluctuations, resulting in grid faults and PV disconnections, while ramp signal attacks triggered a faster OCR response, that still caused instability.

In [28], the authors leveraged EMTP (Electromagnetic Transient Program) to analyze the transient behavior of electrical grids under both physical faults and cyberattacks, the findings emphasizing the need for advanced protective measures to enhance grid resilience against cybersecurity threats.

The results highlight the urgent need to enhance smart grid protection against cyberattacks by strengthening communication security between protection and control equipment, such as securing the IEC 61850 protocol. It also emphasizes the development of adaptive protection algorithms that consider not only current levels but also harmonic and voltage variations, alongside early attack detection strategies based on network anomaly analysis for improving grid resilience and mitigating cybersecurity threats.

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IoT integration plays a crucial role in multiple critical sectors of smart cities. According to [43], defining key requirements for urban water infrastructure and developing an IoT-based architecture can lead to enhanced management and security of wastewater treatment and critical water supply. A NB-IoT (Narrowband Internet of Things) network was assessed by the authors due to its low energy consumption, wide coverage and enhanced security. The system employs distributed sensors that regulate water levels and monitor chemical treatment in wastewater facilities, while defining performance indicators to evaluate the overall system efficiency. The architecture of the NB-IoT system proposed in [43] consists of two main components: the computing core, comprising the central IoT platform, data storage system and servers for analysis and monitoring and secondly, the action and measurement group that consists of the NB-IoT sensors and actuators integrated into the water supply and wastewater treatment systems.

By utilizing this system, the smart monitoring and control architecture effectively regulated water levels and chemical dosing, improving the overall system efficiency, while the NB-IoT implementation optimized energy consumption, reducing operational costs and providing low latency wide range coverage. Therefore, the system enhanced both energy efficiency and water losses, the evaluated KPIs including: environmental protection, pollution reduction, energy efficiency, water consumption reduction and reduced service interruptions. The obtained results highlight the significant contribution of the NB-IoT networks in securing and optimizing water management in smart cities, facilitation of automation and digitalization, while minimizing human errors for an increased system resilience.

3.5. The Role of Energy in Smart City Transformation

Energy is a fundamental pillar in the development of smart cities, driving the transition toward a more sustainable urban environment through the integration of advanced digital infrastructures [51], [52].

The rapid growth of urbanization has led to significant challenges, including increased air pollution and growing energy demand. Smart cities offer an integrated solution to mitigate the environmental impact by utilizing sustainable technologies such as smart grids and efficient resource management with the purpose of enhancing urban resilience and reducing emissions. Implementing smart city policies requires a gradual transition to clean energy, reducing the reliance on fossil fuels, and therefore, this development trajectory must prioritize the creation of a more sustainable and resilient urban environment through innovative and green technologies and policies [53].

Positive Energy Districts (PEDs) are a key aspect for the European Strategy for a full transition from fossil fuel-based economy to a renewable energy-drive system, according to [29]. This concept represents urban areas that generate at least as much energy as they use annually. To achieve this goal, an integrated and distributed renewable energy generation system is required within these districts. In this study, focused on development and optimization of PEDs with the purpose to support urban decarbonization and energy sustainability, the PEDs were defined as interconnected urban areas that produce surplus renewable energy, rely on smart storage solutions and an efficient energy management system. The methodology introduced in the study implies a fuzzy logic-based energy management system that has the purpose to enhance self-sufficiency and self-consumption within residential PEDs. The authors of [29] highlighted a research gap in the integration of multiple energy demands, including electromobility, household energy usage, thermal energy needs and urban infrastructure. In addition, a holistic approach in the optimization of battery charging states and energy costs remain underexplored. The proposed restorative fuzzy logic-based system applied to small-scale PEDs focuses on efficient local resource utilization and minimalization of renewable energy waste. This model ensures full use of the available renewable energy, considering the electrical grid as a backup supply, reducing thus the energy costs for residents through optimized consumption patterns, with a proven system stability under significant climate changes. The system had a successful implementation in urban landscapes such as Sønderborg, Denmark, where residential energy storage was integrated with photovoltaic systems, enhancing the grid feasibility.

A similar study achieved significant results by implementing and testing the proposed fuzzy logic-based energy management system in a PED in Bilbao, Spain, as well. The district achieved a 75.6% self-sufficiency and 76.8% self-consumption in simulated scenarios, with climate change potentially enhancing these values due to an increase in the solar radiation and photovoltaic energy production, while the energy storage system was optimized to maintain a safe charge level for 87.5% of the time [13]. From an economic point of view, initial investments were recovered within 6 to 12 years, depending on the chosen scenario. However, extreme climatic and geopolitical events can significantly impact PED performances, where the energy bills have a potential to increase by 76.7%, or some climate crises may reduce average energy costs due to higher renewable energy generation.

A study regarding the proposal for a governance and implementation model for Renewable Energy Communities (RECs) integrated into Positive Energy Districts (PEDs), using Italian and European regulations as a reference framework, examined the technical, administrative and social challenges associated with the formation and management of RECs in [32]. Utilizing a comparative analysis of European and Italian regulations, along with a case study on the transposition of EU directives in Italy, the model defined a tree-tired governance structure, comprising advisory, strategic and tactical levels, ensuring a structured decision-making process and identification of critical success factor of REC development through PEST analysis that assess political, economic and technological influences.

The integration of REC into the Italian regulations has demonstrated that a decentralized participation model, based on cooperation among locals, businesses and public administration can significantly accelerate the energy transition, ensuring active participation through a democratic decision-making process while maximizing efficiency. Several challenges were found to persist, such as legislative and bureaucratic barriers for the establishment of RECs, the need for effective benefit redistribution mechanisms and the importance of public awareness and social acceptance of renewable energy [32].

3.6. Leveraging AI for Urban Sustainability and Efficiency

Artificial Intelligence (AI) holds great potential to lead the transition toward a smart urban infrastructure with enhancing the energy efficiency and overall sustainability with the purpose to improve citizen day to day life by reshaping an urban space to better accommodate the needs of local communities [36], [48]. To achieve this goal, AI can be used in various ways to help local authorities with this task, including recreating digital twins of the systems (such as the energy infrastructure), analyzing complex interactions between the different urban components and by managing large data, essential for smart sensors and automations within the interconnected system-of-systems.

In addition to the benefits that AI can present to the local authorities, it can also help residents and tourists in the form of chatbots acting as virtual assistants in various public services as well as real-time directions and instructions. These appliances can also analyze to identify real issues that residents have within the city and find potential issues in the transport infrastructure of the city, thus providing valuable insight for improvement [4].

By using a bibliometric analysis based on scient metric methods to explore the social, conceptual and intellectual structure of the research landscape, the study revealed a sharp increase in publications on AI and blockchain convergence in smart cities since 2019, reflecting growing academic interest [36]. Key research themes focus on smart grids, cybersecurity, IoT, big data and digital twins, emphasizing thus AI and blockchain applications for urban infrastructure optimization and data protection. The initial research was centered on authentication and security concerns. However recent trends emphasize decentralized networks, peer-to-peer energy trading and AI-driven optimization.

The proposed machine learning model in [37] aimed to evaluate the accuracy of user routes in shared mobility systems. The model was developed in four stages: firstly, vehicle identification was performed by modeling the technical data of each vehicle; secondly, travel data was collected, structuring key parameters such as maximum speed, energy consumption and GPS positioning; in the third step, trip classification was conducted using machine learning algorithms, including decision trees, Naïve Bayes, SVM, KNN, neural networks and ensemble models; lastly the model was optimized by focusing on the algorithm with the lowest classification error rate, which results indicating that the Ensemble (tree) model provided the highest accuracy (94.13% for training data and 93.7% for testing data). The model demonstrated its high accuracy, making it suitable for practical implementation, with the most critical parameters influencing trip classification being energy consumption, average speed and travel time. To facilitate real-time monitoring, a dedicated application was developed, with the purpose of integrating the model for real-time analysis of user routes in the shared mobility system. This solution can automate trip evaluation, reducing the need for manual intervention while improving fleet management and lowering maintenance costs. The model can enhance urban transportation safety and sustainability, allowing operators to monitor and optimize the shared mobility system in real time.

Focusing on architecture integration, functionality and implementation challenges, a comparative analysis of digital twin models used in electrical energy systems, is proposed in [42] by evaluating existent solutions in terms of interoperability, data security, continuous model updates and the use of AI to enhance performance. The authors offer a model based on physical emulated (P+E) approach, that combines real physical devices with virtual components with the purpose of simulating operation scenarios in energy systems. The findings indicated that simulation-based models offer greater flexibility and scalability than those relying solely on physical data. However, major challenges include cybersecurity risks, high implementation costs and a lack of global standardization. While physical emulated models allow scenario testing, they have limitations in data accuracy compared to real energy networks. Therefore, AI integration can be recognized as a key factor in process optimization and prediction accuracy, yet it remains underutilized in existing models.

Digital twins offer a promising solution for optimizing energy networks, but their effective implementation requires standardization and interoperability, the usage of hybrid platforms that combine physical and simulated models [22]. This technology enables both controlled scenario testing and real-time data integration, highlighting the need for a clear regulatory framework and industry-academia partnerships to accelerate the adoption of digital twin usage in energy systems [42] .

3.7. Big Data as a Strategic Asset in Smart City Governance

With the expanding adoption of Internet of Things (IoT) technologies in smart cities, the volume of data that is being generated has grown significantly. These new data streams provide a close-up perspective in various inner workings of the city with a strong emphasis on energy transactions, energy usage patterns, public safety and the security of energy supply, along with other critical infrastructures of the city [4].

Data analysis enables smart cities to interpret the information and supports decision making based on realistic trends, this approach favoring the improvement of energy efficiency and the overall sustainability of the urban environment. The management and storage of data is essential in a smart city, and they must ensure a secure yet easy way of access to the various institutions that regulate and shape the urban landscape. This approach should avoid imposing the Silo phenomenon, which creates barriers between governing entities of the city, hindering information sharing.

The development of a municipal data utility (KDW – Kommunales Datenwer) that was designed to facilitate data sharing among municipal actors in Mainz, Germany, was applied to a real-world case in [33], focusing on urban mobility and public transportation infrastructure. The model was used to prioritize functional and non-functional requirements with the purpose of ensuring an efficient and user-oriented platform. First, a requirement analysis was conducted with the use of qualitative research, including experts, local administration, municipal companies, IT departments and public utility services, in the form of interviews aimed at using the Mayring method to identify expectations and concerns regarding data sharing. A legal framework was then established, ensuring compliance with the European regulations, alongside German specific regulations, defining a data governance model that guaranteed controlled access and legal use of the municipal data. The architecture of KDW was developed as a modular platform structured into three layers. The first one is responsible for data collection from multiple sectors, ensuing historical records and real-time sensor data. The second one, representing the data management layer, ensures seamless data handling and identity access management systems based on Keycloak, providing secure and controlled access to the database. The final output layer incorporates the data catalog and analytics tool, with the purpose of creating a visual representation, such as maps and interactive dashboards, facilitating data interpretation and advanced decision making.

The study in [33] highlighted several key aspects regarding the development and adoption of the KDW platform. Firstly, the need for interoperability and standardization emerged as a priority within the interviews, emphasizing the importance of a standardized data-sharing framework aligned with European standards. Secondly, the legal framework was identified as a critical factor to ensure data protection and clear legal responsibilities for the platform adoption. User acceptance was another essential point, with key functionalities valued by users such as open data portal, integrated data analytics, visualization and data-sharing agreements. The scalability of the model enabled the integration of data across various domains such as environment, transportation and economy, as well as possible future expansion at a national and international level. The complexity of such a system remains a challenge, requiring a robust legal framework and technology based on a scalable infrastructure.

In [40], by employing a comparative methodology with the purpose of analyzing the digitalization process in Rotterdam and Brno, focusing on urban digital platforms, the framework included defining digital platform architecture and established data processing methods, identifying cybersecurity risks and evaluating potential military applications in both cities. Rotterdam developed a complex 3D digital twin model that integrates multiple data sources such as infrastructure, mobility and energy usage. In contrast, Brno's approach was based on 2D mapping, focusing on data transparency and accessibility through an API based model. The comparison between the two approaches highlighted key differences in the digitalization strategies: Rotterdam focused on a multi-layered urban infrastructure visualization, while Brno emphasized open data accessibility for its citizens and developers. Several cybersecurity threats were identified, such as data confidentiality, interception attacks and vulnerabilities in the cloud infrastructure, in addition to military applications of smart cities, such as strategic collection of mobility and critical infrastructure data. However, highly digitalized cities also face increased risks of cyberattacks, which could disrupt essential urban functions.

Urban digitalization is inevitable, but it must be implemented with a concrete cybersecurity and data protection plan, each city tailoring its smart city strategy based on its unique social and physical landscape [41]. However, international collaboration and knowledge sharing could accelerate smart technology adoption. Urban digital platforms remain in their early stages, presenting significant opportunities for integrating AI into municipal decision-making processes [40].

Evaluating technological trends, legal frameworks and public acceptance in Italy and Switzerland are investigated in [41], by utilizing a methodology based on documentary analysis of regulations, case studies and comparative interpretation of smart city initiatives, which highlighted how data collection and usage can impact individual freedoms, raising privacy and security concerns. The research takes a critical approach to data driven urbanism, assessing various levels of urban monitoring, including big data, geolocation surveillance and AI driven behavioral analysis, by combining case studies from Italian and Swiss cities, and analyzing the European data protection laws, with the purpose to highlight gaps in the policies and security risks. Findings showed that the smartest city initiatives lacked adequate data protection measures, leading to increased risks of surveillance and profiling, key issues including legal and transparency gaps, the "datafication" of human activities and the use of facial recognition and geolocation without a clear legal framework.

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To prevent excessive digital control in smart cities, some proposed solutions including data protection policies "by design", integrating technical and legislative safeguards to minimize misuse, independent oversight mechanisms and auditors for monitoring data practices and public participation in decision making, with the purpose to ensure a balance between security and individual freedoms [40], [41].

3.8. Public Transport Systems and the Future of Urban Mobility

Based on studies, the most significant drivers in transportation sector improvement turned out to be the perceived relative advantage and compatibility with user needs, while service complexity and trialability had a lesser overall impact. Additionally, observability and visibility of benefits resulting from an eMobility approach can positively influence adoption decisions, according to [35]. Younger individuals with a higher education level and income were more likely to embrace these services. However, several challenges were identified, such as high operational cost, limited charging infrastructure and user skepticism regarding emerging technologies, alongside integration difficulties with the local authorities, which posed a barrier for widespread adoption. Efforts for eMobility sharing adoption should be focused on improving vehicle accessibility and availability by offering trial opportunities and expanding the charging infrastructure, through public policy support and incentives. Digital integration such as blockchain-based payment systems can streamline the user experience, a factor that emerged as a key point in widespread user adoption. Moreover, collaboration between municipalities and private companies is crucial for a successful implementation within smart communities and end-user usage [22], [35].

A study from Odesa, Ukraine, identified three key factors influencing passenger satisfaction in the public transportation system: punctuality, environmental benefits and fuel efficiency. Punctuality proved to be the most critical aspect, with 95% of respondents considering it the top priority, followed by environmental benefits 87% and fuel savings 72% [34]. There is a major inefficiency in Odesa's public transport network, such as route overlap, lack of centralized coordination and high congestion in central areas. According to [34], these challenges contribute to the overall shortcomes and negatively impact on public reception for the transport system, underlying thus the need for network optimization and improved management strategies. Significant variations in passenger flow were also observed throughout the day and across different routes, emphasizing the need for an optimized schedule policy by a proper correlation between route length and passenger volume, as longer routes posed a higher risk of delays and traffic safety issues. Adjusting route schedules based on passenger flow analysis would allow for better frequency adaptation and improved user satisfaction. Additionally, smart traffic management technologies can be leveraged to monitor real-time data and optimize resource allocation, leading to a more advanced and efficient transport operation, focused on the user needs and patterns. An approach of this type can offer valuable insights for policymakers and transportation system operators, serving as a foundation for urban mobility master plans. The findings in [34] underscored that a well-managed public transport system can significantly reduce traffic congestion and enhance urban sustainability and resident quality of life.

A mixed approach has been proposed in [35] for investigating the key factors that influence the adaptation of eMobility sharing services in smart communities, by using quantitative analysis involving a 40 participants survey from 18 organizations in Norway and Ireland. Here, a statistical evaluation using SPSS (Statistical Package for Social Science) was utilized to identify five key factors affecting the adoption: perceived relative advantage, compatibility, complexity, trialability and observability.

3.9. Standardization as a Framework for Urban Resilience and Innovation

Standardization plays an essential role in the development and implementation of smart city technologies, ensuring interoperability, security and scalability across the digital and energy systems. Smart Cities can be viewed as a complex ecosystem of interconnected infrastructures, that consist of smart grids, transportation systems, advanced communications networks like 6G and large-scale big data platforms. Standardization can be utilized to facilitate seamless communication between interconnected infrastructures, preventing fragmented technology adaptation and facilitating integrated data exchange across different systems such as power grids, energy transaction software and energy systems based on IoT. By establishing common protocols, standardization optimizes resource use and enhances the efficiency and reliability of urban energy networks [3].

There is a limited information spectrum regarding 6G wireless technologies standards, but the rapid advancement in wireless systems makes the transition to 6G technologies inevitable. Compared to the previous generation (5G), 6G technologies require less energy and offer enhanced security with improved threat detection and decentralized encryption for data protection [4].

As presented in previous chapters, AI and blockchain technology integration can enhance security and energy efficiency by improving data management capabilities in smart cities. However, challenges still persist in terms of scalability, interoperability and data privacy, according to [36]. These findings, along with the lack of global standardization for these emerging technologies remain a key barrier, with future research focused on federated AI models and hybrid blockchain networks to boost overall security and sustainability of the smart urban ecosystems.

Analyzing existing literature on Smart City Assessment (SCA) in developing economies, with a methodology that follows a structured approach, including data collection from Google Scholar, literature findings, data coding and method classification, such as Conceptual Models, Cognitive Maps, Hierarchical Methods, Best-Worst Method (BWM) and Multi Criterial Decision Making, identified that the key frameworks used were ISO 37122:2019, Smart City Index India, Smart Cities Ranking of European Medium Sized Cities and IoT Enabled Smart City Framework [39].

Smart City assessments in developing economies showed the prioritization of industrial development, IoT integration, sustainability, energy research and political engagement, whilst ISO 37122:2019 emerged as the most widely adopted framework due to its structured methodology and cross-city compatibility. As stated in [39], a lack of standardization among evaluation models limits the results comparability, with many existing models being complex and difficult to implement, posing challenges for local administrations in the most analyzed areas (Malaysia, Romania, India and Turkey). The involvement of key stakeholders, including policymakers, investors, researchers and citizens were identified as critical points for the success of smart city initiatives, as there is a need for an integrated methodology that aligns smart city evacuations with urban planning strategies for sustainable and equitable development.

3.9.1. General Landscape of Smart City and Sustainability Standards

By analyzing the Landscape of Smart Cities Standards, it is possible to map the standardization organizations according to the countries or geographic regions where their frameworks and guidelines are applied. The geographical mapping helps illustrate the regional focus and influence of each standardization body, offering insights into policy alignment, technological priorities and urban development strategies adopted in different parts of the world.

Table 2. Landscape of the Standardization organizations according to the countries or geographic regions, data extracted from: [54].

Region	Standardization body
EU	CEN CITYkeys EC EIP-SCC ESPRESSO ETSI HLEG-AI MonileData
Global	BSI DATEX2 Eden Strategy Institute EIP-SCC ICLEI

	IEC IEEE IMD ISO ISO/IEC ITU-T OCED oneM2M UN UNECE UNESDOC WEF WTO
Spain	IESE
Sweden	EasyPark
USA	NIST

By analyzing the current standards, it is possible to categorize them according to their specific domain of application. This classification provides a clearer understanding of the scope, objectives and technical focus of each standard, supporting more effective implementation and interoperability across smart city initiatives.

Table 3. Categorization of current standards in accordance with their specific domain of application: [54].

Domain	Displayed Title	Number of titles
Citizen	Education, Training and Learning	12
	Health	18
	Safety and Emergencies	4
	Social community and well-being	17
Infrastructure	Buildings	10
	Connectivity	28
	Energy	21
	Mobility	19
	Water	5
Policy	Case Studies and Rankings	7
	Ethics	3
	Strategies, Policies and Planning	17
Sustainability	Sustainability and Resilience	31
Technology Platforms	Data and Architecture	27
	Information Processing	8
	Manufacturing	17
	Smart City	3
	Terms and Definitions	3
	Food and Agriculture	1

3.9.2. ISO Standard Family for Urban Sustainable Development

The ISO 37101:2016 standard, titled "Sustainable development in communities – Management for sustainable development", establishes a structured framework to support communities in

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achieving sustainability, resilience and improved quality of life through a systematic management approach. The standard is designed to help local authorities and other stakeholders define, implement and monitor strategies aligned it sustainable development objectives.

ISO 37101 belongs to a broader family of standards, including ISO 37120 (Indicators for city services and quality of life), ISO 37122 (smart city indicators) and ISO 37123 (resilient cities indicators), which collectively provide guidance on performance measurement, governance and integration of smart and sustainable principles in urban development. Together, these standards enable a holistic, indicator-based approach to urban planning and policy making, fostering transparency, comparability and continuous improvement in community performance at local regional and national levels.

Figure 2. Visual representation of the ISO 37101 family of standards for sustainable urban development.

Figure 3. The current stage of the ISO 37120:2025 adoption.

The foundational standard supporting the development of smart cities is ISO 37120, originally published in 2014, under the title "Sustainable cities and communities – Indicators for city services and quality of life". The standard provides a comprehensive framework of standardized indicators that enable cities to measure and compare the performances of public services and the overall quality of life in a consistent and objective manner. It was first revised in 2018 to incorporate emerging trends in urban governance, technology and sustainability, a new update is scheduled for release in 2025, and as of the time of this article the draft reached 90.93% completion and was officially confirmed as in International Standard [55]. The forthcoming version aims to align more closely with the United Nations Sustainable Development Goals (SDGs), deepen the integration of smart and resilient city concepts and adapt the indicator framework to address current urban challenges such as digital transformation, climate change and social inclusion.

3.9.3. International Organization for Standardization`s technical Committee for Sustainable Development

ISO/TC 268, titled "Sustainable cities and communities," is a technical committee established by the International Organization for Standardization (ISO) in 2012. Its primary objective is to develop international standards that facilitate sustainable development in urban and rural communities, emphasizing aspects such as smartness and resilience. These standards provide requirements, frameworks, guidance, and supporting techniques to assist communities and their stakeholders in achieving sustainability goals [56].

Figure 4. Visual representation of the Sustainable Development Goals (SDGs) [56].

As of the latest update, ISO/TC 268 has published 56 ISO standards, with 19 under its direct responsibility and has 22 standards currently under development, 8 of which are directly managed by the committee [56].

The structure of the committee is split into two different working groups focusing on various aspects of sustainable development:

- ISO/TC 268/SC 1: Smart community infrastructures
- ISO/TC 268/SC 2: Sustainable mobility and transportation

3.9.4. IEEE Standards Association

IEEE SA is dedicated to advancing the standardization of smart cities by offering a comprehensive portfolio of standards and programs that address critical components of smart cities framework [57].

Figure 5. Overview of key IEEE standards for smart city development.

3.9.5. Analysis of Smart and Urban System Standards Categorization

To further understand the standardization landscape in the context of smart cities, a detailed analysis was conducted on various categories of standards and the themes addressed, extracted from a comprehensive inventory of smart city standards [58], encompasses standards published or under development up to the year 2024. The list indicates over 300 standards and specifications relevant for smart city development, the essential standardization organizations who are included in the inventory and were analyzed including: CEN (European Committee of Standardization), ETSI (European Telecommunications Standards Institute), IEC (International Electrotechnical Commission), IEEE (Institute of Electrical and Electronics Engineers), ISO (International Organization for Standardization), ISO/IEC JTC 1 (ISO and IEC Joint Technical Committee JTC 1 for information technology), ITU-T (ITU's Telecommunication Standardization Sector) and OGC (Open Geospatial Consortium) [58]. Figure 6 consolidates all relevant standards identified in the referenced list. Subsequent graphical representations will then focus on each of the four primary sectors, offering a more comprehensive and detailed examination.

Figure 6. Categorization of Standards for Specific Smart Systems within a city [58].

A second representation illustrates in Figure 7 the distribution of standards according to different aspects of the urban system as a whole. A predominance of standards related to "Operation" and "Security, safety, privacy" is observed, suggesting a major importance of the daily functioning of the city. Other significant categories include "Planning and design of infrastructure" and "Management". This distribution highlights the smart city approach as a "system of systems" where robust government and security are essential for ensuring long-term urban functionality and resilience. The importance of "Terminology & architecture" is also highlighted, with "Terms, vocabulary" and "Framework, architecture" high number of appearances indicating their crucial role in standardization.

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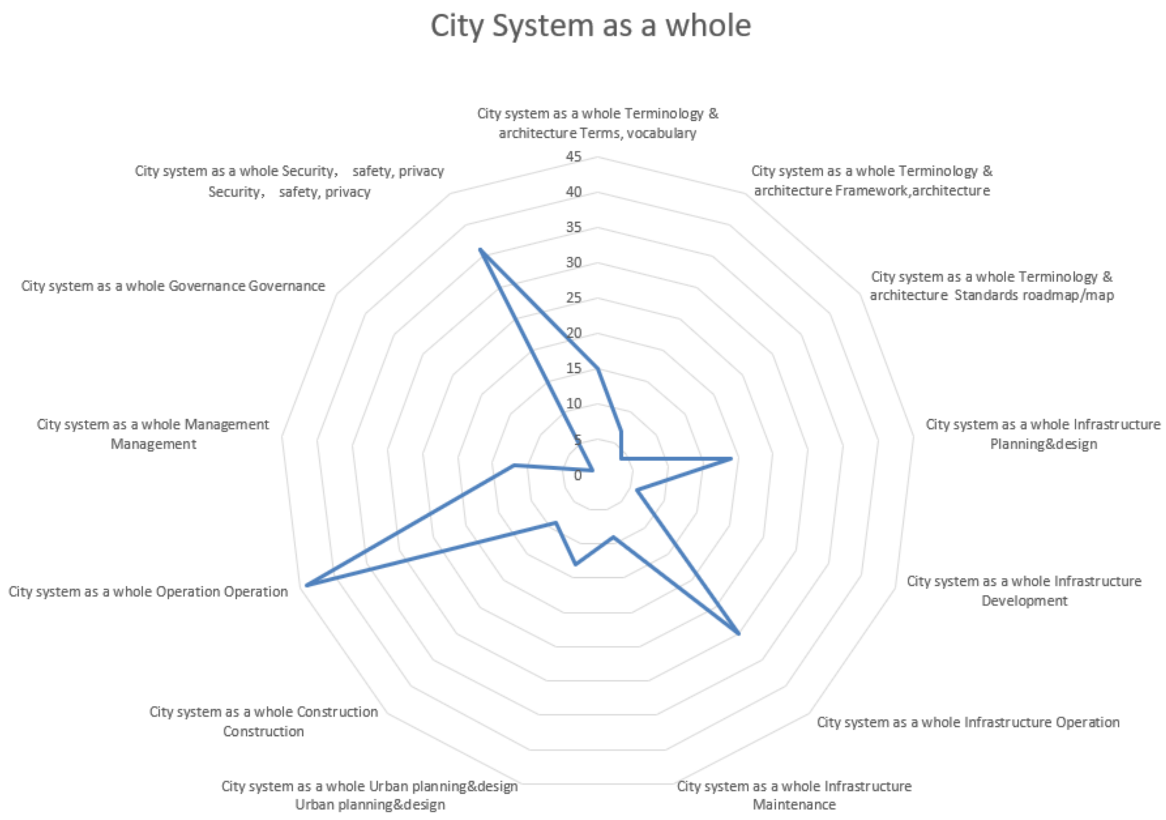

Figure 7. Urban System as a Whole: Distribution of Standards by Aspect [58].

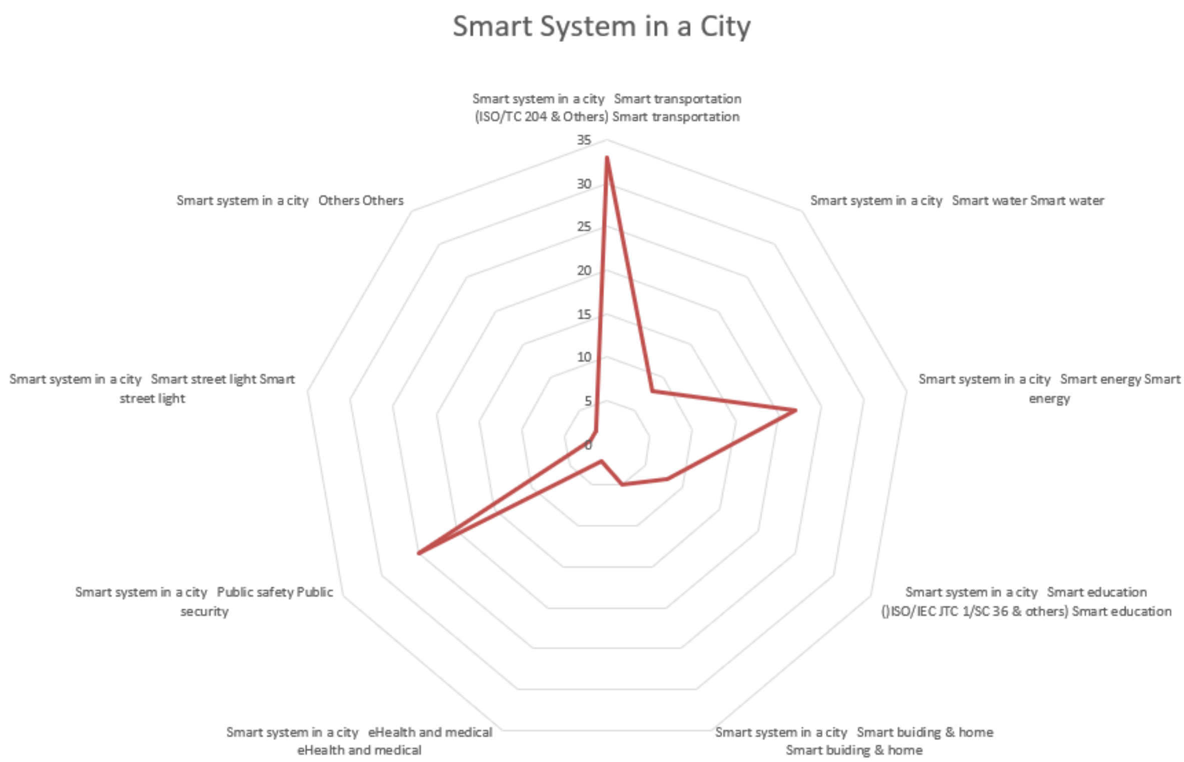

Figure 8. Categorization of Standards for Specific Smart Systems within a City [58].

The visualization in Figure 8 details the categories of standards focused on specific smart system withing a city. Among the most prominent areas are "Smart transportation"; "Public Safety" and "Smart Energy"; the importance of the energy sector is reaffirmed, confirming its fundamental role in the transition to a sustainable urban environment and the integration of advanced technologies. Furthermore, the emphasis on transport and safety reflects key priorities in optimizing urban functions and improving citizens' quality of life.

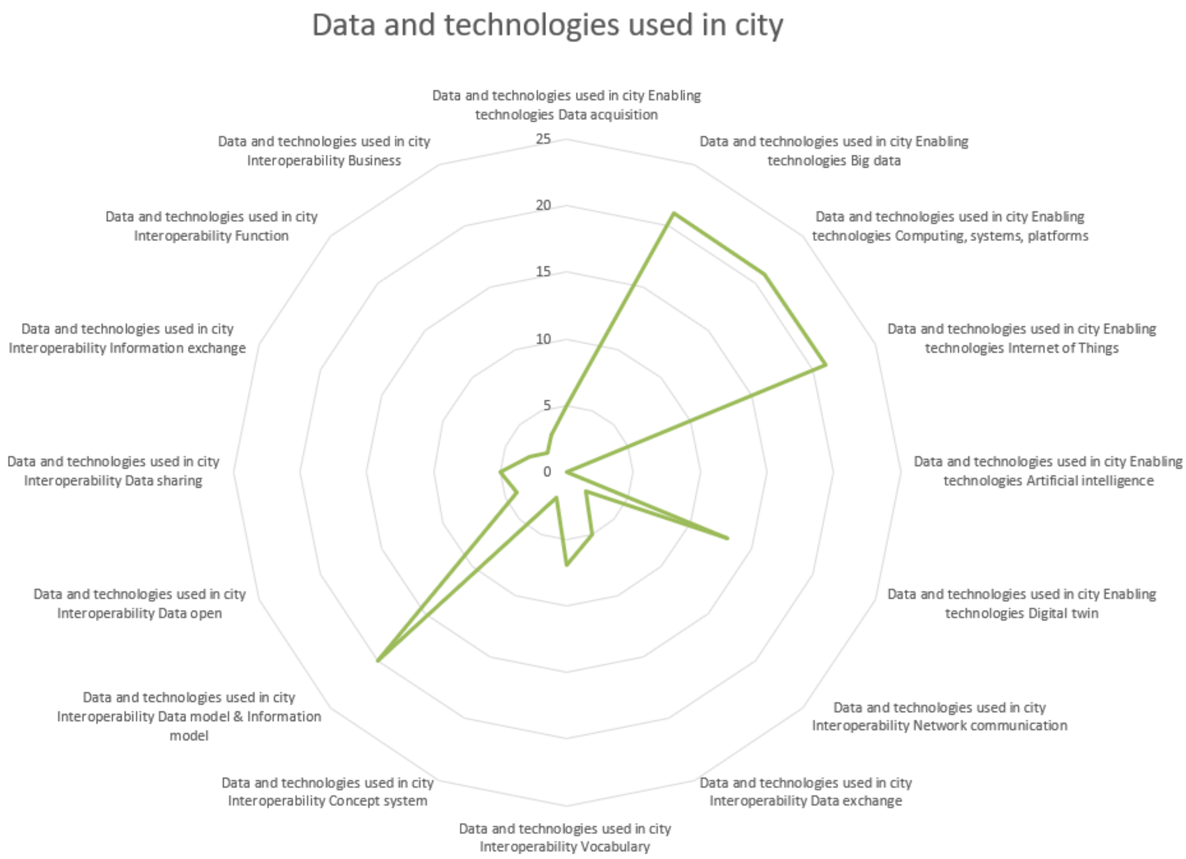

Figure 9. Enabling Technologies and Data Focus in Smart City Standards [58].

This radar chart illustrates the prevalence and application of various data and technology aspects within a city context, categorized into "Enabling Technologies" and "Interoperability". Notably, "Enabling technologies Internet of Things" and "Enabling technologies Computing, systems, platforms" demonstrate the highest levels of adoption, indicating a strong reliance on these foundational technologies. A particular absence of "Artificial Intelligence" as a distinct category can be observed, suggesting its potential transversal integration within other thematic standards.

This radar chart visualizes the results of a "Performance assessment" across various domains, including "Performance," "Sustainability," "Resilience," and "Smartness", with scores ranging from 0 to 10. These metrics are crucial for monitoring the progress and success of smart city initiatives toward their sustainability, efficiency, and resilience objectives. The assessment highlights particularly strong performance in "Assessment Measure" and "Assessment Performance," reaching scores close to the maximum. In contrast, areas such as "Assessment Impact of ICT" and "Assessment Privacy" show considerably lower scores, suggesting either less emphasis or areas requiring significant improvement.

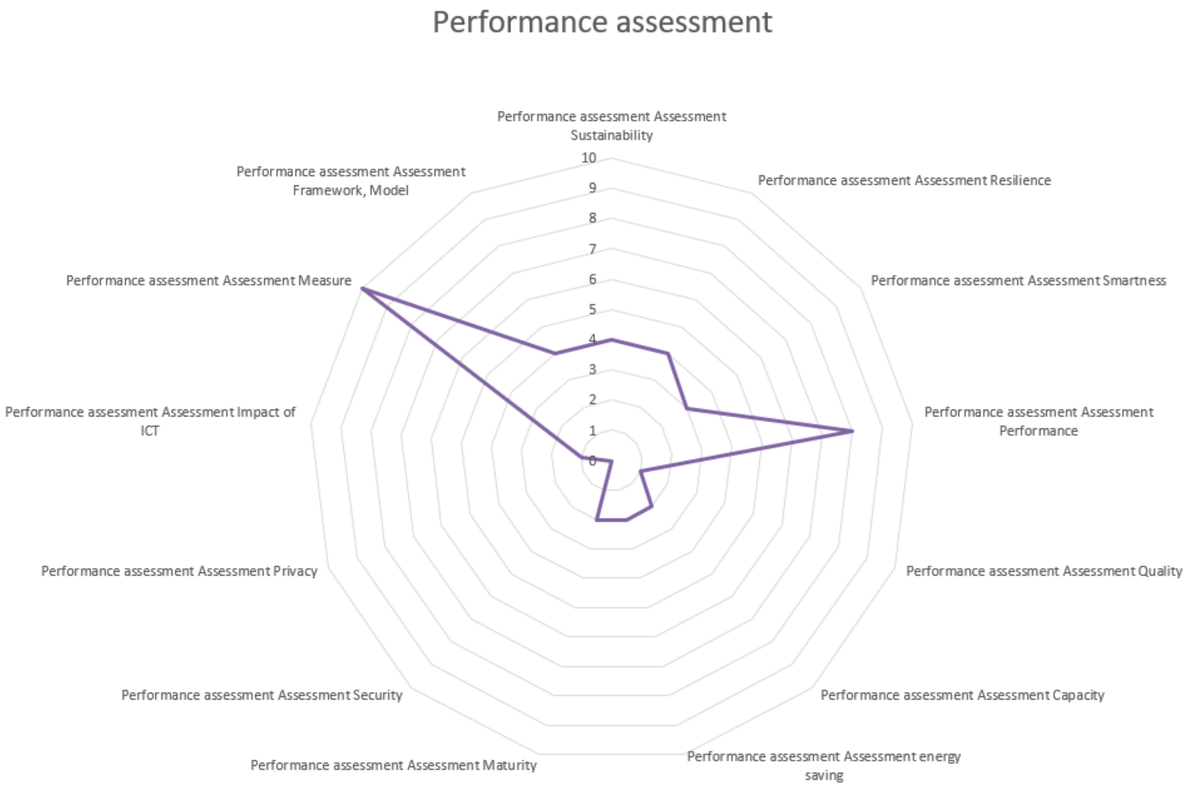

Figure 10. Performance Assessment Metrics in Smart City Standardization [58].

4. Discussions

The evolution of smart cities relies on the strategic convergence of advanced energy systems, digital technologies and robust governance frameworks. As urban population expands and resources demand intensifies [1], our findings underline that transitioning to decentralized renewable energy sources is critical not only from an environmental perspective but also as a driver of economic resilience [29]. The integration of next-generation 6G communications with IoT-enabled smart grids and AI-driven analytics holds considerable potential for optimizing energy consumption and enhancing operational efficiency [26]. Nonetheless, these technological advances must be accompanied by comprehensive cybersecurity measures and adherence to standardized protocols to ensure interoperability across diverse urban infrastructures. Moreover, effective public-private partnerships and active community engagement are indispensable for addressing policy fragmentation and regulatory challenges, thereby ensuring that innovations in renewable energy and digital connectivity translate into sustainable, citizen-driven urban development [34], [35]. In conclusion, this study advocates for a holistic, interdisciplinary approach to smart city transformation that balances technological innovation with strategic regulatory oversight and stakeholder inclusivity, with the scope of paving the way for resilient and adaptive urban environments.

Our analysis indicates that the transition from 5G to 6G is poised to significantly transform the energy landscape by advancing digitalization and integrating IoT-enabled smart grids. Enhanced spectral efficiency and decentralized security protocols embedded to 6G technologies, promise significant reductions in energy consumption and improved data transmission which are vital for managing the increasingly complex urban network [24]. However, these benefits are tempered by substantial challenges such as the capital investments required for upgrading or deploying new 6G base stations, coupled with the need for seamless interoperability with established legacy systems, which present notable financial and technical barriers [29], [32]. Additionally, a surge in the connected devices and the expensive coverage demanded by 6G cybersecurity vulnerabilities, poses a risk that could undermine the stability and integrity of energy infrastructures. Simulation studies

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further reveal geographic discrepancies, in regions such as the Netherlands versus Croatia, that complicate the optimization of network performance and energy efficiency across different urban landscapes [29]. Collectively, these findings underscore the necessity for coordinated policy measures, rigorous standardization and proactive cybersecurity strategies to fully harness the potential of 6G while ensuring sustainable digital integration in the energy sector.

The energy sector plays a foundational role in smart city evolution, acting as an enabler of sustainability and a catalyst for integrating advanced technologies into the urban landscape. A smart city's transition toward green development is fundamentally tied to modernizing its energy infrastructure. Clean energy smart grids are not only technical upgrades, as they are strategic instruments to mitigate urban challenges like pollution and resource strain. Implementing smart city policies in China has been shown to require a gradual shift to renewable energy and reduced fossil fuel reliance, demonstrating how energy initiatives underpin broader urban innovation efforts [2]. In practice, this means deploying distributed renewable generation, enhancing energy efficiency in buildings and the transport infrastructure, as well as using digital controls to balance supply and demand in real time. Such measures directly improve urban resilience and reduce emissions, yielding cleaner air and more reliable energy services for citizens [4].

To enable a structured analysis and visual representation, a total of 111 individual keywords extracted from the reviewed articles were normalized and grouped into thematic categories. The initial keywords varied in phrasing and specificity, including technical terms (e.g. "5G Network", "Digital Twin"), methodological references (e.g., "PRISMA", "Systematic Review") and broader thematic concepts (e.g. "Smart Mobility", "Citizen Empowerment").

A manual content analysis was performed to cluster semantically related terms under broader, representative categories. For instance, "5G", "6G" and "Wireless Communication" were grouped under Wireless Communication (5G/6G), while terms such as "AI", "Machine Learning" and "Deep Learning" were assigned to Artificial Intelligence & ML. This normalization process reduced redundancy, improved clarity and enabled cross – comparison between articles and regions. In total, 11 primary categories were defined, along with an additional "Uncategorized" label for terms that did not clearly fit withing the main themes.

One prominent example of energy-centric urban innovation is the development of Positive Energy Districts (PEDs) in Europe. PEDs are urban areas that produce at least as much energy as they consume annually, embodying the EU's vision for a renewable-powered city district. A recent study introduced a fuzzy-logic energy management system in a residential PED, achieving over 75% self-sufficiency and self-consumption by dynamically optimizing battery storage and solar PV usage [33]. These results underscore that integrated local generation and storage, coupled with intelligent control, can turn neighborhoods into net energy producers while still meeting residents' needs. However, they also highlight emerging challenges – for example, effectively coordinating various energy demands (household electricity, electric vehicle charging, heating/cooling) remains complex. Moreover, extreme events (climatic or geopolitical) can impact PED performance and payback periods, reminding planners that energy strategies must account for uncertainty.

Beyond technical performance, energy initiatives in smart cities are closely linked to governance and community engagement. The rise of Renewable Energy Communities (RECs) exemplifies how energy projects can spur social innovation. In Italy, a multi-level governance model for RECs within PEDs was proposed to enhance citizen participation and multi-stakeholder coordination [36]. This model recognized that decentralized energy systems thrive on local cooperation, and that clear frameworks are needed to distribute benefits, navigate bureaucracy, and earn public trust. Such findings suggest that the energy sector's role extends beyond engineering, as it is an anchor for interdisciplinary collaboration in smart cities, binding together policy, society, and technology. In summary, prioritizing the energy sector in smart city transformation yields concrete sustainability gains (like emission reductions and energy autonomy) and sets the stage for holistic urban innovation. Yet, it requires aligning new technologies with supportive policies and active public involvement to ensure that cleaner energy translates into long-term sustainable urban development.

Modern smart cities are often characterized as "system-of-systems", meaning they consist of multiple interdependent subsystems—energy grids, transportation networks, communication systems, water and waste utilities, public services, and more—that must operate in harmony. This integrated perspective underscores that the value of a smart city emerges not from isolated smart components, but from the synergies among them [3]. Interoperability is therefore paramount: each subsystem should seamlessly exchange data and work together toward common urban objectives. Standardization is a key enabler in this context, as it provides common protocols and interfaces that allow heterogeneous systems to communicate. As noted in recent works, adopting shared standards (for example, in data formats or IoT communication protocols) helps prevent fragmented technology adoption and ensures that a smart grid can "talk to" a smart building or an electric vehicle charging network without custom integration efforts [23]. Indeed, international standards bodies (ISO, IEC, IEEE, etc.) and initiatives are actively shaping frameworks for urban data sharing, IoT interoperability, and performance metrics. The ISO 37122:2019 standard for smart city indicators, for instance, has gained traction as a baseline for consistent assessment in different cities [43]. Cities that embrace these standards are better positioned to integrate new solutions without starting from scratch each time, accelerating innovation.

Interoperability is closely tied to resilience. A system-of-systems approach means that a shock in one domain (e.g., a cyberattack on the power grid or a natural disaster flooding transport tunnels) can cascade across other systems. Conversely, well-integrated city systems can support each other during crises. For example, intelligent energy grids can prioritize power to hospitals and emergency services during outages, and open data from telecom networks can assist traffic management in rerouting around problematic areas. The resilience of a smart city thus hinges on both robust individual systems and their coordinated response capabilities. One critical area of focus is improving the resilience of energy infrastructure in facing new digital threats. The introduction of IoT sensors and ICT in energy (smart meters, automated substations, etc.) has improved efficiency but also created cyber vulnerabilities that can threaten physical grid stability [32]. Simulation studies of coordinated cyberattacks on power distribution components (like photovoltaic inverters and protection relays) show that traditional grid protection schemes may fail to detect or isolate incidents in time, leading to widespread outages and equipment damage. These findings have important implications: they urge the adoption of advanced, cross-cutting security mechanisms and adaptive control algorithms that maintain stability even when data inputs are untrustworthy. More generally, building urban resilience means ensuring that each city subsystem has not only its own backup and recovery plans, but that there are city-level contingency strategies when interdependencies come into play.

Data governance stands out as another pillar in the system-of-systems paradigm. With a great number of devices and organizations generating urban data, clear governance is needed to manage data sharing, privacy, and ownership. The Mainz data utility example again serves as an instructive case: by establishing a legal framework and a multi-layer architecture for data exchange, the city created a neutral space for different departments and external partners to contribute and use data safely. A sound governance model should define who can access what data, under what conditions, and how data quality and security are maintained. Such governance prevents the formation of data silos—where information is trapped in one agency—and instead promotes a "connective tissue" of information that all city systems can draw from. However, achieving this is easier said than done. Interviews with stakeholders in various cities highlight concerns about liability, compliance, and trust when sharing data [37]. Establishing trust requires not only technical solutions (like encryption and access controls) but also institutional arrangements (policies, agreements, and perhaps third-party audits) to reassure participants that their data will not be misused. In the absence of good governance, cities risk either constrained innovation due to overly restrictive data practices or, conversely, exposing themselves to security breaches and public backlash if data flows freely without safeguards. Therefore, treating the smart city as a system-of-systems leads naturally to a call for integrated governance frameworks – ones that align technology deployment with regulatory policy

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and stakeholder engagement. Such frameworks enhance interoperability and resilience by ensuring that all parts of the urban system move in the same direction, guided by shared principles of security, openness, and sustainability.

Figure 11 compares the prevenance of key Smart City research themes across different regions, a horizontal bar chart shows how often each normalized keyword category appears in studies from the EU, South Korea, Southeast Asia, Taiwan, Ukraine and on a global landscape. Categories such as Artificial Intelligence & Machine Learning, Smart Mobility, Smart Energy & Grids, Governance & Public Policy and other are plotted, revealing clear regional discrepancies in focus. For instance, European studies exhibit a string emphasis on governance frameworks and energy systems, reflecting the region's push for integrated policy and sustainability (for example, the widespread adoption of standards like ISO 37122). In contrast, East Asian contexts feature higher frequencies of technology-centric keywords such as AI, IoT and 5G/6G connectivity indicative of a drive toward cutting-edge ICT solutions for urban infrastructure. Regions like Southeast Asia prioritize topics such as IoT-enabled development and energy sustainability, aligning with local development, whereas Ukraine's contributions are case-specific, spotlighting smart mobility and urban transport optimization. Overall, this figure underscores that no single template fits all regional research prioritizing differ markedly, shaped by distinct urban challenges and policy environments.

The global distribution of keywords categories appears relatively balanced across themes, whereas European studies distinctly emphasize digitalization. This reflects Europe's ongoing strategic priority of comprehensive digital transformation. Figure 13 illustrates that heightened standardization correlates closely with increased interest in technological advancements and global urban development strategies. This observation effectively connects the insights depicted in Figures 11 and 12, highlighting how standardization efforts directly support and stimulate broader technological progress and research trends.

Figure 12 turns to the standardization landscape, mapping out Smart City standardization bodies by region. The horizontal bar chart reflects the frequency of keyword appearances grouped by region (Europe, Global, South Korea, Southeast Asia, Taiwan, and Ukraine). Each keyword category, such as Artificial Intelligence & ML, Smart Mobility, Smart Energy & Grids, Governance & Public Policy, and others, is plotted along the vertical axis, while the horizontal axis shows the number of times the category appears in the reviewed literature.–This organizational diagram illustrates a fragmented but layered governance of standards: global entities such as ISO, IEC, ITU-T and oneM2M sit at the international tier, providing broad frameworks for interoperability, while regional alliances and initiatives (for example, CEN and CITYkeys in Europe) develop area specific guidelines. At the national level, individual countries promote their own standards, for instance NIST in the United States or EasyPark in Sweden, targeting local urban priorities.

The visualization reveals that standardization efforts are widespread and decentralized, as virtually every major region has its mix of standard bodies and projects. While the diversity allows tailoring to local contexts, it also highlights fragmentation such as multiple frameworks often address similar Smart City aspects, risking overlap and incompatibilities. A recent "Landscape of Smart Cities Standards" review [54] confirms a proliferation of initiatives, noting that a lack of harmonization among various evaluation models has limited the comparability of smart city outcomes across countries. In practice, city officials and planners face a complex mosaic of guidelines, from high-level sustainability indices to domain specific technical protocols.

Figure 12's regional mapping of these organizations underscores both the opportunities and technological priorities that are being shaped in different parts of the world, yet the absence of a unified framework can hinder global interoperability and knowledge sharing. This infographic presents both the geographic distribution and layered influence of international, regional and national stakeholders in shaping smart and sustainable urban development. This fragmentation has been observed to pose challenges for local administrations, who may struggle with implementing complexes or numerous standards without clear cohesion.

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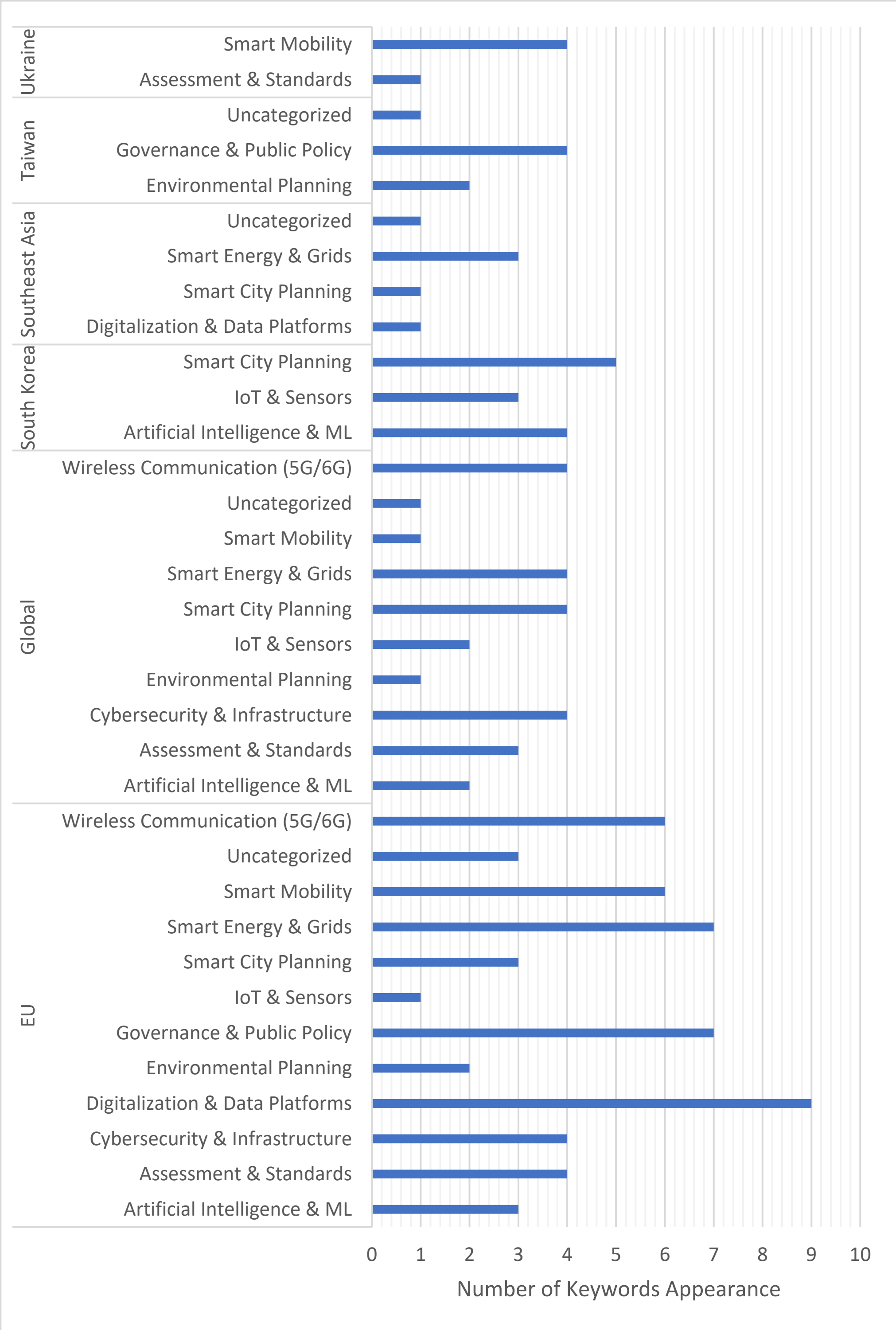

Figure 11. Distribution of normalized keyword categories by study region across the selected smart city articles.

Figure 13 complements this by offering a macroscopic view of thematic categories in Smart City literature through a treemap visualization. Each colored block represents a broad topic area, with its size proportional to the number of publications addressing that theme. Dominant blocks correspond to infrastructure and policy-related themes. Notably, categories tied to technological infrastructure such as digital connectivity and architecture, energy grids and urban mobility occupy a large share of the map, alongside a sustainable block for sustainability and resilience initiatives. Governance and planning themes also feature prominently, underlining the importance of policy direction and standardized strategies in Smart City disclosure. By contrast, comparatively smaller blocks in the treemap (for example, those related to ethics, social inclusion or sector specific applications like food systems) suggest these areas are underrepresented. This imbalance points to a research gap: while cities worldwide have heavily explored digital infrastructure and energy/climate initiatives, fewer studies delve into community-centric and ethical dimensions. Even though some pioneering work integrates citizen empowerment and participatory planning (for example a zero-carbon community project in Taiwan used a participatory approach to engage local stakeholders), such human centered topics remain a minority in the overall Smart City literature.

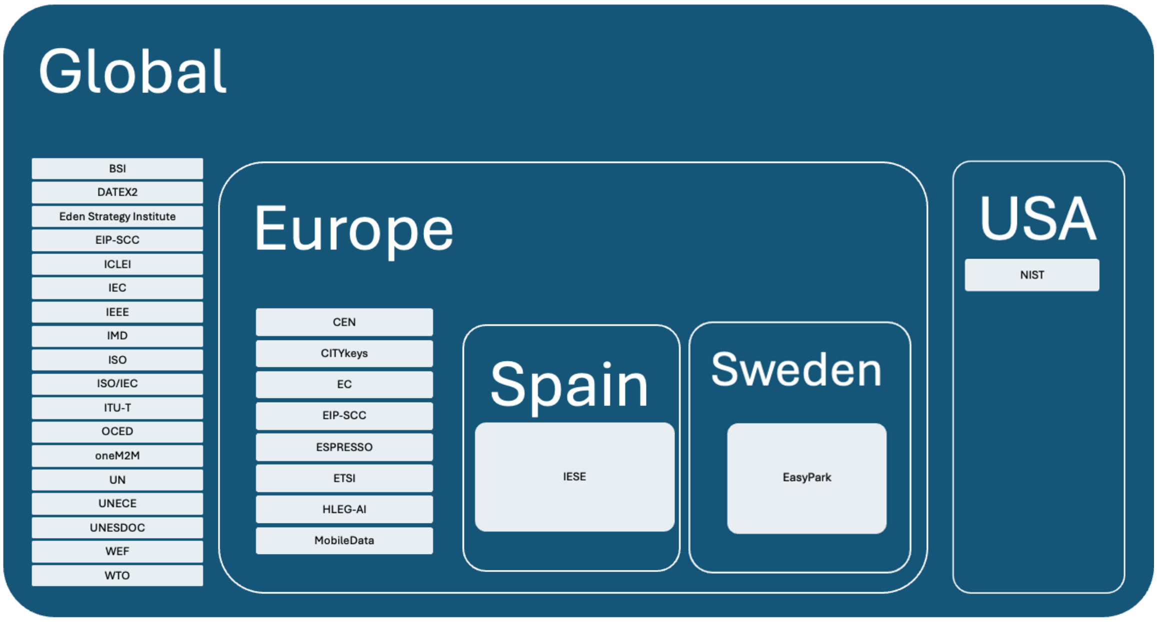

Figure 12. Organizational map of Smart City standardization bodies by regions [54].

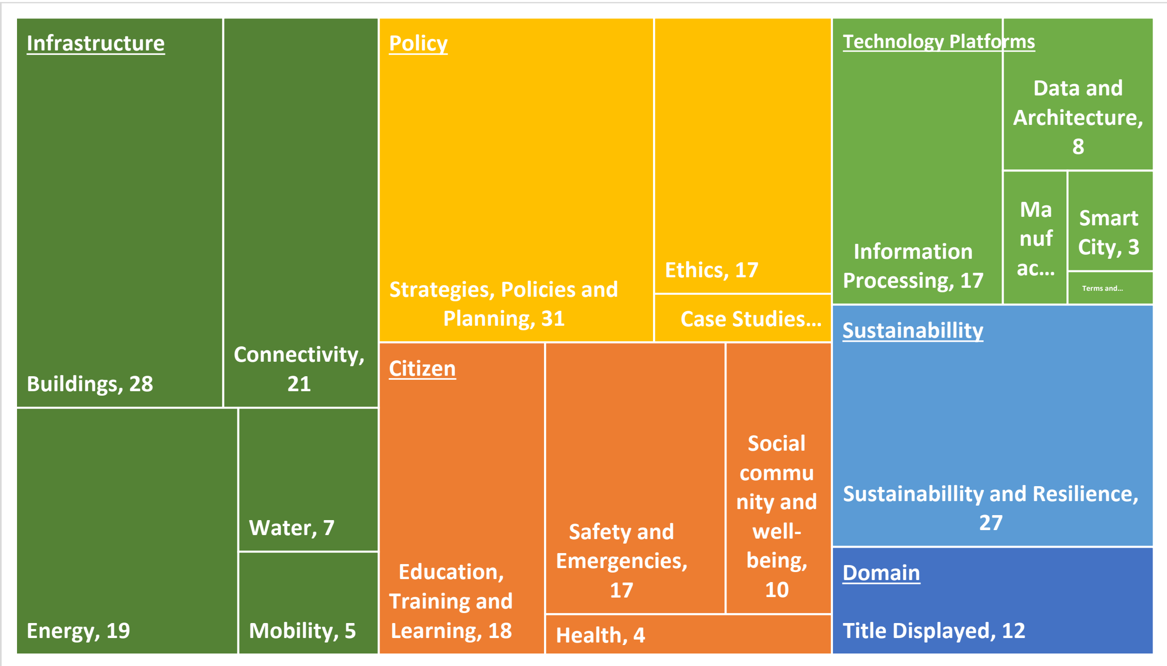

Figure 13. Visualization of thematic categories related to smart city literature [54].

Critical interpretation of these visual insights points to several implications for future research and policy planning. Firstly, the dominance of infrastructure-driven and policy/planning themes

(Figures 11 and 13) suggests that academia and industry have made significant progress on the technical and governance foundations of Smart Cities, for example, in integrating energy grids with ICT or developing sustainability metrics. This focus is in accordance with the needs of rapid digitalization and urbanization, where energy efficient communication networks and robust urban policies must go hand-in-hand. However, the relatively smaller emphasis on social, ethical and human-centric issues implies that these aspects need more attention in the future. Future research should broaden to address citizen engagement, data ethics and equity in Smart Cities, ensuring that technological innovation translates into tangible improvements in quality of life and inclusivity. As noted, empowering local communities in the planning process, through participatory methods, can greatly enhance project outcomes. Secondly, the regional discrepancies in research sector call for greater cross-integration of ideas.

European experiences in policy integration could improve projects in Asia and vice versa, while lessons from pioneering smart mobility trials in Ukraine or sustainability efforts in Southeast Asia could benefit other regions if disseminated. Policymakers and scholars might consider more comparative studies and international pilot projects to bridge these gaps, adapting successful strategies to local conditions.

Finally, the fragmented standardization landscape (Figure 12) highlights an urgent need for coordination and convergence in Smart City standards. Without jeopardizing local adaptability, stakeholders should strive toward interoperable frameworks, for instance, by aligning city indicators with well-established international standards to enable benchmarking and shared learning. Current literature emphasizes immature integrated methodologies that align smart city evaluations with urban planning strategies and stress multi-stakeholder collaboration to overcome policy silos. In other words, this means urban planners, technology providers and standard bodies must work collectively in coordinating policy measures and rigorous standardization efforts, in order to fully harness emerging technologies (like 6G and IoT) for sustainable city development.

Our initial analysis on distributed keyword categories across regional studies (Figure 11) mapped standardization bodies by region (Figure 12) and visualized thematic categories (Figure 8). These insights are reinforced by another detailed analysis of the IEC standards inventory, which allows for a further dissection of standardization priorities.

The figures describing the ”City system as a whole” and ”Smart systems in a city” from the standards inventory (Figures 7 and 8, as discussed in section 3.9.5) highlight the emphasis on daily operations, security, and key areas such as transportation and energy. This reinforces the observation that a large part of the existing literature and standardization efforts focus on building the technical and sustainable backbone of smart cities, as well as on the efficient governance of these interdependent systems. The prevalence of operation-related standards underscores the importance of ensuring continuous functionality and efficient resource management in a city considered a “system-of-systems”.

Furthermore, the analysis of ”Data and technologies used in the city” (Figures 9 and 10) provides crucial insight into the role of digitalization. Significant investments in Big Data, IoT, and Digital Twins are confirmed, reflecting efforts to optimize data-driven urban management. What is particularly relevant to the theme of interoperability is the high weight of standards dedicated to “Data and information models” and “Vocabulary” within the interoperability section. This observation strengthens the argument that standardizing communication protocols and data formats is fundamental to enabling subsystems to collaborate efficiently and to prevent technological fragmentation, a key point of smart city resilience. The discrepancy regarding the number of standards exclusively dedicated to AI (0 mentions in this specific classification) compared to the widespread recognition of its role (mentioned in other sources) suggests that AI is either transversally integrated into other areas of standardization (e.g. smart grids, smart transport), or that specific AI standards are still in an early stage of development.

The consistent presence of “Smart energy” and “Sustainability” in this standards analyses underscores the coherence with the study’s previous conclusions, which emphasize the fundamental

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role of the energy sector in the evolution of smart cities and in achieving sustainability and emission reduction goals.

The evolution of smart cities is conditioned by the strategic convergence of advanced energy systems, digital technologies, and robust governance frameworks. As urban populations grow and resource demand intensifies, our findings underscore that the transition to decentralized, renewable energy sources is critical not only from an environmental perspective but also as a driver of economic resilience. Integrating next-generation 6G communications with IoT-based smart grids and AI-driven analytics holds considerable potential for optimizing energy consumption and improving operational efficiency. However, these technological advancements must be accompanied by comprehensive cybersecurity measures and adherence to standardized protocols to ensure interoperability across various urban infrastructures. Furthermore, effective public-private partnerships and active community involvement are indispensable for addressing policy fragmentation and regulatory challenges, thereby ensuring that innovations in renewable energy and digital connectivity translate into sustainable, citizen-centric urban development. In conclusion, this study suggests a holistic and interdisciplinary approach to smart city transformation, balancing technological innovation with strategic regulatory oversight and stakeholder inclusivity, with the aim of paving the way for resilient and adaptive urban environments.

5. Conclusions

This review has highlighted that the transformation toward smart cities is a multifaced process, justified by the central role of the energy sector and strengthened by advances in digital technology and governance. Key findings emphasize that transitioning urban energy systems to cleaner, smarter models is both a pressing necessity and an opportunity: smart grids, renewable energy integration and initiatives like Positive Energy Districts can substantially reduce emissions and improve resilience, but they require supportive policies and active community participation to succeed. The rapid evolution from 5G to 6G networks, along with the proliferation of IoT devices, is set to provide the ultra-connectivity needed for advanced smart city applications. This enhanced connectivity will enable real-time management of infrastructure and new services, such as autonomous mobility and interactive public services, yet it also demands careful attention to energy usage and cybersecurity. Our synthesis underlines that smart cities must be treated as a complex system-of-systems, where interoperability and data governance are fundamental design principles.

The review also brings forward the inherent challenges and limitations faced in current smart city implementations. Issues of privacy, data security, and equitable access to technology are recurrent concerns that can limit public acceptance of smart city projects if left unaddressed. Likewise, disparities in resources and technical capacity between cities and especially between developed and developing contexts, mean that one-size-fits-all solutions are impractical – local adaptation and capacity building are necessary components of any smart city strategy. Despite these challenges, the overall trajectory of research and practice is encouraging. There is a clear trend toward adopting interdisciplinary approaches: city planners, engineers, IT specialists, policymakers, and social scientists are increasingly collaborating to align technological innovation with societal needs and sustainability goals. This integrated approach is evident in emerging governance models for energy communities, the inclusion of stakeholders in data platform design, and the push for AI and data analytics that serve public interest in addition to efficiency.

Standardization across technologies and domains emerges as a critical enabler for this integration, facilitating communication between subsystems and ensuring that innovations can be scaled and replicated across different urban contexts. In summary, the analysis of contemporary Smart City research and standardization reveals a field maturing in its technical and policy dimensions, yet still evolving toward holistic integration. Addressing the identified gaps, by expanding research horizons and unifying standardization efforts, will be crucial for developing energy efficient, digitally integrated and resilient Smart Cities in the years ahead.

In conclusion, achieving the vision of sustainable smart cities will require sustained effort on multiple fronts. Technological innovation in energy, communications and computing, must go hand-in-hand with robust frameworks for cybersecurity and standardization. Equally important is the human and institutional dimension, as governance mechanisms, regulatory policies and community engagement models that ensure technology deployment must be responsible and inclusive. The findings of this review reinforce that future smart city development cannot be the domain of isolated sectors. Instead, it demands an integrated and interdisciplinary approach. By learning from current experiences and continuing to research open questions, cities worldwide can navigate the digital transformation in a way that enhances urban sustainability and improves quality of life. Ultimately, the smart city from an energy perspective is more than just a high-tech ideal, but a pathway to harmonizing urban growth with environmental management and social well-being, a goal that will guide the next generation of urban development.

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