

Article

# Blockchain as a Driver for Smart City Development: Application Fields and a Comprehensive Research Agenda

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**Abstract:** The term “Smart City” denotes a comprehensive concept to alleviate pending problems of modern urban areas which have developed into an important work field for practitioners and scholars alike. However, the question remains as to how cities can become “smart”. The application of information technology is generally considered a key driver in the “smartization” of cities. Detailed frameworks and procedures are therefore needed to guide, operationalize, and measure the implementation process as well as the impact of the respective technologies. In this paper, we discuss blockchain technology, a novel driver of technological transformation that comprises a multitude of underlying technologies and protocols, and its potential impact on smart cities. We specifically address the question of how blockchain technology may benefit the development of urban areas. Based on a comprehensive literature review, we present a framework and research propositions. We identify nine application fields of blockchain technology in the smartization of cities: (1) healthcare, (2) logistics and supply chains, (3) mobility, (4) energy, (5) administration and services, (6) e-voting, (7) factory, (8) home and (9) education. We discuss current developments in these fields, illustrate how they are affected by blockchain technology and derive propositions to guide future research endeavors.

**Keywords:** Smart Cities; blockchain; distributed ledger technology; literature review; research agenda; research propositions; technology driver

## 1. Introduction

According to the United Nations (UN), in 2018 a total of 55% of the world’s population lived in urban agglomerations, compared to roughly 30% in 1950. The UN predicts this percentage will steadily grow toward 68% by 2050 [1]. Other researchers claim that, due to inconsistent definitions, even these numbers underestimate the true extent of urbanization. As of 2018, an estimated 84% of the world’s population already lives in urban areas, based on geospatial technology using high-resolution satellite images [2]. Regardless of the current discussions on what constitutes an urban area, the ongoing trend toward more centralized metropolitan areas with high population density leads to numerous challenges for city developers, planners, and municipal governments. “Smart Cities” are proposed as a solution to many of the current challenges associated with the rapid growth of cities. Smart Cities represent a comprehensive concept that focuses on the deployment of information and communication technologies that encompass many aspects of living in a high-density urban area [3].

Academia has always played an important role in this discussion by conducting research that defines core concepts [3], reports case studies [4], and offers frameworks [5], thereby informing

coordinated research endeavors. Additionally, several research streams specifically investigate the role of technology and how it can serve as a driver or enabler for the creation of smart cities [6–8]. As one of the more recent technological innovations, blockchain technology, a distributed ledger to create append-only immutable databases, has attracted much interest in smart-city researchers and builders [9,10]. However, to date, there is no comprehensive framework available to identify research clusters and to also derive relevant research questions. This paper, therefore, addresses the following two research questions:

- (1) In which fields can blockchain technology foster the development of smart cities?
- (2) What research propositions arise from the application of blockchain technology in smart cities?

In order to answer these questions, we searched and analyzed the literature to identify the main topics at the intersection of blockchain technology and smart cities. We created a framework of nine emerging application fields of Blockchain technology in smart cities and then derived several propositions to help coordinate future research.

This paper is organized as follows. In Section 2, we elaborate on the two main concepts of this paper, namely smart cities and blockchain technology. We provide definitions and a brief description of their main components. In Section 3, we describe our methodological approach, followed by the core of this paper in Section 4, which provides a framework that breaks down the impact of blockchain on smart cities in nine distinct fields of application, each of which has already attracted considerable attention in the academic literature. We discuss each field, show how blockchain technology can play an important part in building smart cities, and conclude each section with one or more research propositions. In Section 5, we summarize our findings and consider various limitations of our approach.

## 2. Smart Cities and Blockchain Technology

### 2.1. The Concept of Smart Cities

The proliferation of big data and the rapid growth of the Internet of Things (IoT) have significantly contributed to the emergence and feasibility of numerous smart-city initiatives [11–13]. The concept of “smart cities” represents an umbrella term for a utopian urban development that integrates information and communication technologies to help citizens, governments as well as for-profit and not-for-profit organizations generate and exchange real-time data [14] and increase the efficiency of cities’ operations in areas such as energy consumption, logistics, transportation, and public services. While there is no definition of “smart city” universally agreed upon at this time [15], there is a broad consensus that a smart city constitutes an urban innovation ecosystem that is intended to mitigate the challenges associated with the rapid growth of urban populations through the integration of information and communication technologies and the application of next-generation innovations to all walks of life. Allam et al. [3] list various definitions, most of which include technology as the main constituent of a smart city. For the purpose of this paper, we build upon the main characteristics as mentioned in the literature and propose the following definition:

*“A smart city is a geographical area with a high population density that uses information and communication technologies (ICT) to connect and monitor critical infrastructural components and services with the goal of improving the efficiency and the environmental, economic and social sustainability of its operations as well as the quality of life for its citizens”.*

To fully capitalize on the benefits of a smart city, significant investments in human and social capital, traditional infrastructure (e.g., transportation) and modern ICT infrastructure must be made in order to attain sustainable economic growth, improve the quality of life for citizens, and maintain wise management of natural resources. According to Caragliu et al. [16], a smart city is characterized by a participatory governance structure that emphasizes the role of business-led urban development to establish networked infrastructures, the critical position of high-tech and creative industries to

empower social inclusion, the importance of social and relational capital in urban development, and the need for social and environmental sustainability. Addressing the problems of urbanization, a growing number of cities around the world are considering a “smart city” approach to enhance the quality of life of their citizens and to foster sustainability [17–19]. According to Manville et al. ([20], p. 9), smart cities seek “to address public issues via ICT-based solutions on the basis of a multi-stakeholder, municipally based partnership”. Moreover, the concept of smart cities builds on a rapidly evolving paradigm. The seamless interactions between ubiquitous digital technologies and urbanization hold the promise of optimizing various city functions and of revamping the citizens’ socio-economic status [21]. This implies that smart cities are enabled by several drivers, including technology. The vision to mitigate the challenges caused by the rapid growth of the urban population cannot be realized without effective, real-time, and reliable data access and processing [22]. Similarly, the concept of smart cities aims to create an environment where technology is fully embedded within the city, synergizing various social dimensions to efficiently allocate resources, adding high-value services, and improving the quality of life for citizens.

Technology supports a fast transition to smart cities that is enabled by a high level of interconnectivity between different stakeholders. In this respect, the degree of smartness depends on a variety of factors [23–25]. For example, the structural components of smart cities, such as their underlying infrastructure and services, need to be compatible with the smartness of the design of its urban environment [26–28]. Chourabi et al. [18] posit that the essence of smart cities does not lie in higher levels of infrastructural and technological complexity, but rather, in the identification of a citizen’s needs and finding ways to fulfill them [29]. Designers of smart cities should look for innovative ways to build a new technological architecture that is able to accommodate economic, social, and environmental needs. In this regard, Li et al. [30] argue that the development of smart cities poses unprecedented challenges for businesses, as they need to adopt new tools and techniques in order to capture reliable business insights. Such tools and techniques are crucial to increase the transparency and the convenience of the smart-city infrastructure, including transport networks, power grids, healthcare, telecommunication, education, and government services. Previous studies further highlight those smart-city designers, infrastructure stakeholders, coordinators, and policymakers have to develop more secure networked relationships, interoperable data exchange models, and efficient sharing economy platforms in banking, healthcare, and transportation, for example [9,31–33]. This requires the introduction of foundational technologies capable of supporting superior infrastructure that spans several technological components and services. Smart-city initiatives also need to increase the level of automation and intelligence of modern residential areas, improve the quality of services, and efficiently manage diverse urban activities for the benefit of smart citizens. As it is generally considered a potential driving force for innovation, blockchain technology is the natural choice for enabling numerous use cases in this respect. It can empower smart cities to overcome numerous problems pertaining to infrastructural elements in a broad sense, such as the technological, social, and financial environment, and the lack of integration between these elements [27].

## 2.2. *The Concept of Blockchain Technology*

Blockchain technology was originally developed to ensure the integrity of documents [34] and was introduced on the Internet when an anonymous person or team operating under the pseudonym of Satoshi Nakamoto released a white paper entitled “Bitcoin: A peer-to-peer electronic cash system”, as a response to the 2008 global financial crisis [35]. The main application proposed by Nakamoto is the use of electronic cash known as Bitcoin. Bitcoin is considered the first successful system that bypasses central authority for issuing currency, transferring ownership, and confirming transactions electronically [36]. Aside from enabling direct transactions among Bitcoin holders, blockchain technology offers a generic solution to the double-spending problem [35,37], which denotes a situation in which the same digital token is spent more than once. The power of blockchain technology lies in the fact that it ensures trust among untrusting members [38] and that it enables numerous use cases by eliminating

intermediaries and streamlining transactions [39]. In the Bitcoin network, trust is established through the demonstration of proof-of-work (PoW) by mining nodes that solve a computationally intensive cryptographic problem [40]. In other blockchains, different mechanisms exist to establish consensus within a network of peers, each having its own advantages and shortcomings [41]. In a blockchain network, a block is a data structure that allows storing information as a list of transactions [42]. The resulting chain of data blocks is decentralized, distributed, permanent, chronologically ordered, and tamper-proof [43]. Blocks are created and incorporated into the blockchain system in a way that allows for the whole chain of valid network activities to be easily traced, from the introduction of the initial block [44]. It is noteworthy to mention that blockchain is frequently used synonymously with the broader term “distributed ledger technology” to subsume various technologies that create shared ledgers among a number of network participants. Based on the level of decentralization and underlying governance mechanisms, blockchains are sometimes differentiated into public, private, and consortium blockchains or permissionless versus permissioned blockchains [45]. This distinction has led to substantial discussion in the literature on what actually constitutes a blockchain and is beyond the scope of this study. In this paper, we use a comprehensive definition of blockchain as a

*“digital, decentralized and distributed ledger in which transactions are logged and added in chronological order with the goal of creating permanent and tamperproof records”* [43] (p. 547).

Beyond the scope of cryptocurrencies, numerous applications of blockchain technology exist which have far-reaching implications across a multitude of industries [46–55] and thus also impact smart-city development [56]. The dynamics of the development is further enhanced by the combination of blockchain together with Artificial Intelligence (AI) [57], the Internet of Things (IoT) [58], 5G and architectures that allow for the remote processing of data, frequently labeled as cloud, fog and edge computing [59,60].

### 3. Methodology

We conducted a systematic literature review to investigate application fields for blockchain technology in smart cities. The articles included in our review were found through a search performed in the Web of Science database, which is considered to be one of the most authoritative and multidisciplinary data repositories in the world, indexing nearly all leading scholarly journals [61]. A key benefit of the Web of Science is its transparency and organization [62]. Web of Science is recognized for its comprehensive coverage of reliable resources of scholarly articles, containing more than 12,000 journals. This search was conducted using the title, abstract, and keywords options by employing the following query and a Boolean operator (Algorithm 1):

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#### Algorithm 1

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- 1: TOPIC: (blockchain AND “smart cit\*”)
  - 2: Refined by: DOCUMENT TYPES: (ARTICLE OR REVIEW)
  - 3: Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, ESCI.
- 

In terms of language, we considered only publications in English. No specific date was set for the year of publication. To refine the initial sample and ensure the scholarly nature of the literature retrieved [63], we included scholarly articles only. After applying our selection criteria, 75 papers were kept for further analysis. Subsequently, each of these papers was carefully read and categorized according to the main area of interest, keeping those that are relevant and provide answers to our first research question, namely the identification of blockchain application fields in smart cities. After this step, we had to exclude two papers which did not fall within the scope of our search. The final body of literature hence comprised 73 papers, all of which were published between 2016 and 2020.

Each article was then categorized according to the main application field of blockchain in the context of smart cities. In this process, several clusters of topics emerged which we used as the

foundation of our framework. In the final step, we developed research propositions in which we capture the essence of the literature in each of the application fields. In doing so, we summarize the research to date and pinpoint possible new areas of investigation. Figure 1 summarizes this process of literature review and the development of research propositions.

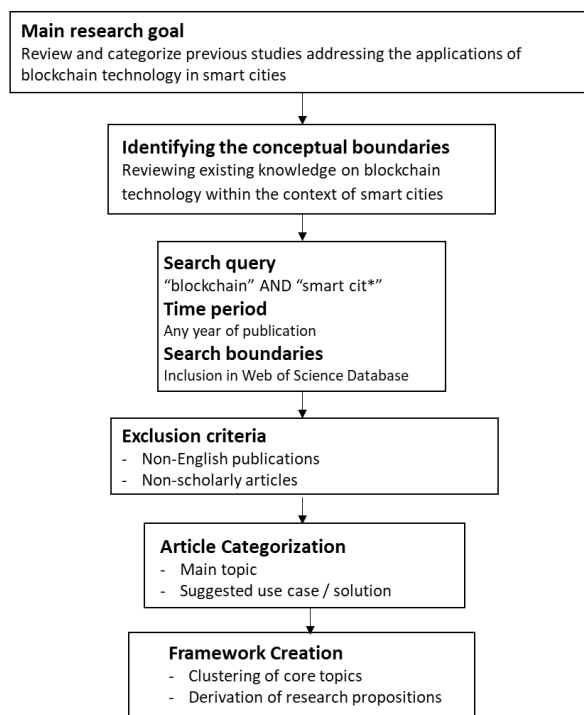


Figure 1. Literature review procedure and filtering criteria.

#### 4. Application Fields of Blockchain in Smart Cities and Research Propositions

Our analyses of the findings and discussions in the literature on blockchain and smart cities yield several clusters of topics where the application of blockchain technology may lead to progress and facilitate the creation of smart cities. In the following, we will focus on nine main application fields of blockchain in smart cities as identified by the literature. These are smart healthcare, supply chains, and logistics, mobility, energy, public administration and services, e-voting, factory, home, and education (see Table 1). All these fields constitute application fields of blockchain in and of themselves, that is, outside of the context of smart cities. However, our literature review reveals that these application fields are central building blocks of a smart city in the above definition.

Table 1. Blockchain application clusters in smart cities.

		Example of Articles
Specific focus	Smart Healthcare	[32,64–70]
	Smart Logistics and Supply Chains	[14,65,69,71–74]
	Smart Mobility	[14,67,72,75]
	Smart Energy	[66,69,76–78]
	Smart Administration and Services	[32,67,79–81]
	Smart E-Voting	[65,67,69]
	Smart Factory	[33,67,68,73,82,83]
	Smart Home	[14,66,67,75,76]
	Smart Education	[60,84]

In the following sections, we will present the literature on each of these fields. Each section will culminate in one or more research propositions.

#### 4.1. Smart Healthcare

The healthcare sector has witnessed a substantial increase in the amount of patient data being transmitted between healthcare providers and insurance companies [85], which has led to the emergence of data-driven healthcare models. As a result, healthcare services are operating with and producing enormous amounts of private information that require a high level of security and access control [86,87]. Blockchain technology can provide several benefits pertaining to smart healthcare. According to Kundu [32], a blockchain-enabled healthcare system ensures the integrity and interoperability of medical health records, improves the quality of adjudication in insurance claims, and offers high-quality patient-centric services. In that respect, blockchain not only helps to overcome challenges related to data security but can also ensure data integrity, transparency, and shared access [64]. The use of blockchain also supports a data-management architecture that facilitates the management, exchange, and sharing of scattered patient health data by offering a shared and immutable data structure [65,66]. It is also argued that blockchain technology can ensure fast access to health data in addition to the general benefits of availability and immutability of a blockchain [66]. A pressing challenge of health records is that their storage is scattered across multiple healthcare organizations (e.g., health information exchanges that provide shared patient records [64]) and hospitals, in siloed record-keeping systems that render available patient data inaccessible to healthcare providers when urgently needed. The application of blockchain supports the development of smart healthcare through the consolidation and securing of health records [32,67], through the monetization of health data for research purposes [32,68], as well as through the ease of access to and transfer of patient health records [65].

In e-health services, blockchain demonstrates a high level of reliability, which can be valuable in the delivery of more customized and effective healthcare assistance. Instead of being controlled by a central authority, blockchain provides secure decentralization of the patient's personal information, making medical reports and documents more accessible to patients and doctors in health emergencies [69]. Fast access to health data can allow doctors to detect warning signs of serious illnesses in the early stages, thereby saving many lives. This is especially important in areas with high population density as the recent tragic events around COVID-19 have demonstrated. According to the World Economic Forum (WEF), COVID-19 "makes a compelling case for the wider integration of blockchain". This is due to its ability to create transparent, inter-operable, and connective networks that can potentially replace today's value networks characterized by a lack of connectivity and seamless data exchange [88]. To fight the COVID-19 pandemic, researchers from Spain have piloted blockchain technology to support health officials in making smarter decisions regarding the pandemic, including social distancing and quarantine measures [89]. By leveraging the technology during this pandemic, it would be possible to protect smart citizens' health data from privacy infringement and nefarious usage. The collaborative capabilities of blockchain can also be beneficial for streamlining healthcare processes, tracking COVID-19 patients, and reducing hospital overload. In this context, existing academic research has already illustrated how blockchain, in combination with artificial intelligence (AI) and a geographic information system (GIS), can enable the rapid diffusion of information about the outbreak of a pandemic and the subsequent tracking of people that are tested positive. In such a system, federated blockchain platforms help to quickly derive triangulated data [90].

Moreover, the heavy reliance on medical big data and IoT-based wearable technologies in diagnosis and treatment processes is well-suited for the adoption of blockchain, as the distributed nature of the technology offers additional security and privacy properties in the healthcare network [70]. Blockchain can be extremely useful in guaranteeing trustworthy and reliable data which enables big-data technologies to unlock their full potential and create new applications based on healthcare data. Overall, Boulos et al. [68] note that blockchain applications are currently being explored for securing healthcare data, managing pharmaceutical supply chains, promoting clinical research and

data monetization, preventing medical fraud, increasing public health surveillance, and providing proper access to truly public and open geo-tagged data. Therefore, blockchain technology presents new opportunities for healthcare stakeholders to reconsider their existing operational models in order to deliver high-quality medical services to citizens. Smart-city policymakers (including governmental ones) have to exercise considerable judgment and account for different factors associated with blockchain adoption in healthcare. In countries where public or publicly funded medical services are delivered to citizens at the level of local governments, blockchain can increase the trust of citizens in their local governments. This can be achieved as smart cities can use the technology to revamp their healthcare systems and create more agile networks for services. Given the manifold potentials of blockchain for designing healthcare systems for smart cities, we suggest the following research propositions:

RP\_Hea1: By enabling shared, immutable and privacy-aware databases, blockchain technology facilitates the design and deployment of smart healthcare systems with better healthcare outcomes at lower costs.

RP\_Hea1: The use of blockchain technology in smart-city healthcare increases patient privacy as well as the satisfaction of patients, healthcare-service and insurance providers, and administrators with the system.

#### 4.2. Smart Logistics and Supply Chains

Due to the ever-increasing volume of traffic and numerous other distribution inefficiencies, city logistics is one of the most prevalent topics of smart-city planners [91]. The deployment of information technology (IT) has given rise to the development of multidisciplinary solutions in logistics and supply-chain activities [92]. Over time, the scope of functions of logistics and supply-chains have evolved, encompassing multiple activities and areas of intricate value chains [71]. It should be noted that smart logistics is also heavily intertwined with smart factories, which emphasizes the manufacturing aspect and will be covered in a later section.

The use of advanced technologies has significantly influenced how logistics and supply-chain processes operate to deliver goods and services to customers. While the move toward data-driven logistics and supply chains has contributed to the improvement of the capabilities, operational efficiencies, and competitive position of many companies, smart logistics is still not fully equipped to cope with dynamic changes in the business environment [93]. Christopher and Holweg [94] argue that most supply chains lack flexibility and the ability to adapt quickly to changing market and environmental conditions. Viau et al. [95] note that the decentralization and fragmentation of supply chains exacerbate poor process visibility, long delivery delays, complex transportation networks, and difficulties in the integration of logistics and supply-chain activities.

Blockchain technology has the potential of raising the performance of logistics and supply-chain operations in smart cities. It can simplify the communication and exchange of information between the different partners involved in logistics processes [71]. Supply-chain stakeholders can use blockchain to efficiently manage the flow of services and goods between various points in the network, increase the security of IoT devices used [69], and support due diligence. Blockchain is considered crucial for the traceability and integration of supply-chain processes [72,73], enabling the tracking of all business transactions in real-time and thus adding value to the final products [72]. In smart cities, a highly visible supply-chain is an auspicious approach to reducing information asymmetry, uncertainties, and operational inefficiencies. Blockchain makes it possible to enhance the performance of supply chains and the consistency and traceability of products through their production and consumption cycle, which aids smart city development. A future smart city is highly dependent on efficient supply chains and a wide variety of micro-industries with increasingly dynamic business interactions. Similarly, blockchain technology allows smart city consumers to track and trace the provenance of their products or services, thereby increasing consumer satisfaction and trust [14]. The technology maximizes the effectiveness of traceback procedures, prevents counterfeiting and fraud [71], and optimizes several logistics and supply-chain management processes such as product delivery, inventory management,

and order fulfillment [14]. In the logistics industry, Aggarwal et al. [69] emphasize that blockchain is an effective solution for the coordination of documents, faster customs clearance, approvals, and the reduction of processing time. As a result, the smart features and functionalities offered by blockchain can be used to increase the competitiveness of supply-chain partners, streamline operations, reduce logistics costs [74] as well as reduce traffic congestion within city boundaries. Hence, we propose:

RP\_Log1: Blockchain technology can enable smart cities to reduce logistics-related congestion and pollution.

RP\_Log2: Blockchain technology can enable companies in smart cities to devise and implement more cost-efficient logistics and supply-chain management systems, to reduce their ecological footprint, and to raise customer satisfaction.

### 4.3. Smart Mobility

One core feature of smart cities is the smart mobility of citizens [96]. Smart mobility improves the availability and accessibility of modern and sustainable transportation systems. As per Chun and Lee [97], smart mobility can lead to a more comprehensive and smarter future public transportation, enabled by smart technology. Smart mobility requires the development of efficient, clean, and safe means of public transport. The management of transportation systems has been a challenging task for any modern city [14]. The use of blockchain technology for smart mobility allows for the development of innovative and sustainable transport modes. In this context, Ferdous et al. [14] point out that the use of blockchain-based and IoT-integrated systems offers continuous tracking of passengers and vehicles. This can be a starting point for multiple applications and services based on machine-learning algorithms, for example in designing transportation timetables, in anticipating commuter demand in different parts of the city, and in assigning driver shifts so that transportation requirements, as well as human needs, are simultaneously taken into consideration. Smart-city designers can apply blockchain to assist them in the creation of an efficient transportation network that enables citizens to search and pay for transportation services directly. Rahman et al. [75] state that the technology can be used to consistently capture and store granular data related to the driver and the car profile, maintaining a full and immutable history of maintenance, accidents, and transfers. Smart mobility solutions based on the blockchain can improve the performance of public transportation. They also enable flexible insurance premiums based on driver behavior data (e.g., speed, braking habits), and facilitate car-sharing services [67]. Furthermore, blockchain applications promote an intelligent and private mobility environment. Smart vehicles themselves can exert control over their data, exchange information with smart homes, and securely perform financial transactions such as the automatic payment of charging time via cryptocurrencies [67]. Blockchain technology can support the move of the automotive industry toward Mobility-as-a-Service (MaaS) solutions and enable several services such as remote software-based vehicle maintenance operations, insurance services, smart charging services, and car-sharing [72]. Therefore, blockchain technology can enhance the mobility of citizens within smart cities by ensuring a more sustainable, efficient, safe, cost-effective, and flexible transportation system that is able to balance the environmental, social, and economic needs of current and future generations. In the same way, the applications of blockchain can greatly benefit smart mobility by allowing local transportation decision-makers to optimize routing strategies and schedules, accommodate the varying needs of citizens, and maximize environmental friendliness. We suggest the following two propositions:

RP\_Mob1: Blockchain technology can enable public transportation systems and private mobility providers to reduce emissions, lower costs, raise revenue, and increase customer satisfaction.

RP\_Mob2: Blockchain technology can provide citizens of smart cities with better access to public transportation, lower commute times, and higher levels of privacy.



#### 4.4. Smart Energy

Smart energy is a conceptual paradigm [98] related to the energy consumption of private users, individuals, and groups of organizations [99]. The main objective of smart energy is to ensure the consumption of clean, low-cost, and efficient energy. As the need for smart energy has increased, there is an opportunity for blockchain technology to create a more resilient environment for the entire energy industry. In this context, Park et al. [76] argue that the implementation of blockchain can facilitate peer-to-peer (P2P) energy production and consumption. Smart energy systems could use blockchain to preserve the privacy of the users [66] and deter malicious actors from selling or buying an unreasonable amount of energy. Similarly, blockchain enables individuals and users to precisely monitor their use of energy as well as the composition of their energy mix. This can contribute to avoiding energy waste, boosting the use of green energy (e.g., by trading certificates), and reducing the use of fossil fuels [100]. By boosting green energy trading and allowing smart citizens to sell their excess green energy in a trustworthy manner, blockchain can also be a driving force toward the fulfillment of renewable energy targets. The shift to green energy enabled by blockchain can accelerate the sustainability of smart cities, reduce the impact arising from fossil fuel energy technologies, particularly in regard to investment costs, environmental harm, and lengthy implementation lead times. The decentralized nature of facilities that generate green energy (e.g., solar energy) corresponds with the ability of blockchain to simplify the process of collecting, validating, and delivering power-capacity data within a power company. Therefore, the use of blockchain produces more reliable and accurate capacity forecasts. These assist governments in the distribution of subsidies and the granting of tax breaks to green energy suppliers. For example, Park et al. [76] propose a design for a blockchain-based P2P energy-transaction platform. The benefits of this system include the development of energy-efficient smart homes, low-cost energy transactions, and the trading of energy surpluses. Blockchain offers households and businesses the opportunity to effectively manage energy trading requests by reducing delays in communication and increasing the security of transactions [77,78].

Smart cities can substantially benefit from blockchain's abilities to maximize energy efficiency and improve the planning and management of energy resources. A recent study by Aggarwal et al. [69] highlights that blockchain is useful in the regulation of energy transformation and distribution in the smart grid, bringing more transparency to energy transactions. Park et al. [76] contend that the use of blockchain-based energy tags in transaction processes can directly connect several energy resources and home appliances, thus providing users with high-quality, low-cost, and efficient energy anywhere and anytime. Blockchain provides a strong communication backbone that can be used in the energy network to streamline and secure P2P energy trading processes [78]. The degree to which blockchain is able to secure energy transactions plays an important role in achieving higher accuracy in the measurements of the operating conditions of smart electricity grids, smart meters, and IoT sensors used in energy production, transmission, and distribution. Data generated from energy management systems can be securely stored on the blockchain and used by decision-makers to measure the optimal level of energy and safety margins they should supply and ensure. This results in the following propositions:

- RP\_Ene1: Blockchain technology can provide public energy management systems for smart cities, with better access to data, and the potential to lower costs and waste in energy production and distribution.
- RP\_Ene2: Blockchain technology can provide private households and businesses in smart cities with secure access to energy at a lower cost, strengthen their privacy, and facilitate transactions on P2P energy markets.
- RP\_Ene3: Blockchain technology can provide detailed information on the actual composition of the energy mix, leading to a partial replacement of fossil fuels by green energy.

#### 4.5. Smart Administration and Services

The rapid development of urban areas and the need for improving the life of smart citizens have led to the evolution of modern public administration [71]. In a smart city, the main responsibility of the public administration is to establish confidence in the achievement of smart city objectives by ensuring open data, long-term commitments, targeted policies, and leadership [101]. While public administration serves as a vehicle for sustainable development, it still needs to be redesigned to operate more successfully [102] and overcome the challenges ensuing from the heavy reliance on centralized systems [103]. To mitigate these issues, the incorporation of blockchain technology carries the potential to widen the scope of public service systems and to create more innovative public service delivery channels. The higher privacy levels that blockchain can bring about is well-suited for e-administration [79]. The technical aspects of the technology can guarantee more privacy and security, increasing the trust of smart citizens and encouraging their inclusion and participation in public affairs. To enable a transition toward a smart government, blockchain has currently been tested in several countries, including the United Arab Emirates, the United States, Sweden, Ukraine, and the United Kingdom [67]. A recent study by Li et al. [67] emphasizes the benefits of blockchain and smart contracts in the automation of public services, such as tax collection, benefits distribution, property and land registries, identity management, regulatory compliance, and management of government records. Moreover, blockchain can significantly support public administration in providing smart citizens with secure access to information, resulting in stronger citizen engagement in public management.

Responding to citizen concerns, public agencies in municipal and regional administration can introduce blockchain to enhance government transparency and service quality [32]. Blockchain can become an effective tool for promoting public goals, improving interoperability, and ensuring efficient delivery of public services. For example, França et al. [80] propose the application of blockchain to improve solid waste management in small municipalities in Brazil. The authors find blockchain capable of ensuring the integrity of public information and of enabling public managers to obtain more transparency. A similar study was conducted by Marsal-Llacuna [81] to explore the potential of blockchain as a means for universal delivery of urban governance in a decentralized and bottom-up manner.

Overall, extant literature provides clear evidence that blockchain fosters the development of democratic public administration models and favors the inclusion of citizens. The introduction of technology in public administration could reduce barriers to the use of its electronic services for smart citizens. In this respect, blockchain can allow public administration to offer more personalized services to citizens and do so more transparently. Summarizing, we propose:

RP\_Adm1: Blockchain technology allows for increased efficiency and transparency in the public administration of smart cities and holds the potential for increasing citizen trust in public administration.

RP\_Adm2: Blockchain technology can provide citizens of smart cities with more privacy in dealing with the government and more personalized, convenient, and inclusive access to high-quality public services.

#### 4.6. Smart E-Voting

The strong need for governments to move online and adopt e-voting in elections has been identified in many countries [104]. A growing body of scholarly research on e-voting is testimony to the importance of the ability of governments to provide convenience, access, and accountability in democratic elections [105]. Recently, COVID-19 has demonstrated that citizen access to secure e-voting procedures may be crucial in maintaining both public health and democratic processes in times of pandemics.

As a critical component of the smart city paradigm, e-voting systems can be significantly supported by blockchain technology. Key-benefits of blockchain in e-voting processes stems from the

high authentication capabilities of the technology and its ability to securely store votes and enhance the transparency of elections. In this regard, Li et al. [67] argue that blockchain-based e-voting systems can increase the efficiency of voting in terms of time and cost of election services. To enhance citizen engagement, blockchain technology makes the electoral process more transparent and prevents attempts to manipulate voting data [69]. Thanks to the security of blockchain and its signature mechanisms, possibilities of electoral fraud in e-voting systems can be minimized, increasing voters' trust in the election process by eliminating risks of corruption and voter fraud. An open-source blockchain voting system called "Follow My Vote" has been developed with the goal of connecting voters and authorities to ensure a transparent and traceable election process [65]. In such systems, voters can use their private keys to check their voting choices at any time. Blockchain allows smart-city administrators to save costs during the development of an election infrastructure because smart citizens would have the chance to exercise their voting right irrespective of their geographical location. With the use of remote blockchain-based e-voting systems, smart citizens will be able to confidentially cast their votes, while keeping at bay all potential human errors or falsifications inherent in manual and centralized computerized systems. By capitalizing on the capacities of blockchain, smart city e-voting can reduce the complexity of voting systems, overcome their security challenges, and increase the overall reliability in the election process. Thus, we propose:

RP\_Vot1: Blockchain technology can enable e-voting in smart cities, which increases efficiency, reduces cost, and helps to ensure a fair and democratic voting process.

RP\_Vot2: For citizens of smart cities, blockchain technology can facilitate participation and trust in processes of democratic decision making.

#### 4.7. Smart Factory

Smart factories constitute a crucial building block for smart cities. The "smart factory" philosophy revolves around the introduction of hyper-efficient manufacturing, suitable for highly dynamic environments and turbulent market conditions [106]. A smart factory is a collection of sensors and autonomous systems that are capable of self-optimizing and making autonomous decisions in order to produce more personalized and intelligent products [107]. The challenges in the implementation of smart factories are numerous. For instance, several factories are still experiencing abrupt breakdowns, process disruptions, and scheduled and unscheduled maintenance [108]. Operating in smart factories can also exacerbate the risks posed by cyberattacks, industrial espionage [109], and unreliable manufacturing data.

According to Wildemann and Hojak [110], the success of smart factories hinges on the ability to manage massive amounts of data. For this, blockchain can provide trustworthy decentralized management, governance, and tracking of every IoT device and equipment used in smart factories [33]. Mistry et al. [73] argue that blockchain can help manufacturing applications operate more efficiently and faster over unreliable networks, and enable faster data distribution and secure industrial automation. In highly turbulent operational environments, blockchain can make smart factories more reactive, flexible, and ready to cope with alternative production planning and scheduling decisions. More specifically, the technology is useful for remote software updates during manufacturing, automatic fault diagnoses, and predictive maintenance [67,82]. In the operation and maintenance of industrial facilities, blockchain can be an effective solution where there is a heavy reliance on advanced electro-mechanic equipment because the technology can yield substantial savings through predictive maintenance and traceability of materials sourced for manufacturing [68]. Blockchain gives factory workers the opportunity of concentrating on monitoring production processes while simplifying autonomous workflows and the sharing of services among industrial IoT devices [33]. The combination of blockchain technology and smart-factory equipment is conducive to increasingly automatic and autonomous production processes. By the same token, the use of blockchain-based decentralized data sharing can not only support security for on-chain smart-factory data [83], but also aid production data analysts in generating reliable forecasting, continuous process controls, and real-time responses.

Therefore, by counting on real-time and reliable data stored on blockchain systems, smart factories can contribute to the economic prosperity of smart cities, creating highly-coordinated, data-driven, and performance-centered manufacturing systems. Blockchain can foster manufacturing excellence in smart factories [108] through the improved architectural imperatives necessary for the construction of next-level factories in smart cities. This leads to the following propositions:

RP\_Fac1: Blockchain technology can form the basis for smart factories within smart cities by creating secure and reliable manufacturing systems.

RP\_Fac2: Smart factories based on blockchain technology will lead to automated workflows that increase the efficiency and effectiveness of operations.

#### 4.8. Smart Home

Related to smart cities, IoT technologies and Internet appliances have significantly contributed to the development of smart homes. Smart homes reflect the growing use and integration of multiple new technologies through home networks for enhancing the quality of life [111]. Exemplifying a technologically-driven living environment, smart homes provide their residents with higher levels of safety, convenience, and comfort. They allow for the alignment of home settings with the residents' preferences [73]. While smart homes are adaptable to environmental conditions (e.g., in their heating and cooling), they still need to tackle a number of issues. Apthorpe et al. [112] indicate that the ubiquity of IoT devices in smart homes heightens privacy risks. Edwards and Grinter [113] note that smart home designers encounter several difficulties in the creation of smart-home systems, such as a lack of user knowledge and system transparency. According to the authors, residents need to thoroughly understand all parts of a smart-home system.

The benefits of integrating blockchain technology into smart homes are evident. Ferdous et al. [14] point out that blockchain can contribute to trust and traceability in smart homes. The technology allows residents the capability of tracking all devices and sensors used for achieving context-aware service provisioning. Data are readily generated by smartphone applications and IoT sensors through ambient sensing, including user activity, energy usage, security measures, and human physiological data. All data can be recorded on the blockchain and also be used in sharing economy services [75]. Digital signatures can be used to detect suspicious activities and to securely assign each smart-home device its own identity [67]. The decentralized, transparent, and secure nature of blockchain provides a unique platform for smart-home sensors, actuators, and devices to communicate seamlessly and to conveniently share information across platforms. Examining the advantages of the technology for several applications including smart homes, Makhdoom et al. [66] developed an innovative blockchain-based privacy-preserving platform called "Privysharing". Beyond the description of their system, the authors advocate blockchain as a tool to protect the confidentiality of smart home user data, secure data processing, and reward users for sharing their data with other stakeholders. Moreover, blockchain has the potential to solve the lack of interoperability between smart-home objects. This is a prerequisite for the integration, communication, and proper functioning of smart homes within smart cities. On this point, Park et al. [76] underscore the key role of blockchain in facilitating the interaction between smart homes, boosting automatic energy trading activities in smart homes, and promoting more sustainable practices between smart homes and within smart cities. Blockchain represents a promising opportunity to address existing issues that slow down the wide-scale implementation of smart homes. Smart-home designers are therefore required to improve the technical feasibility of blockchain and enhance its usability in order to upgrade the intelligence of smart homes and increase the convenience of modern home residents.

RP\_Hom1: Blockchain technology supports the development of smart homes by creating interoperable systems that communicate and exchange data with each other.

RP\_Hom2: Within the concept of smart cities, citizens live in smart homes that use blockchain technology to ensure the privacy and data sovereignty of their residents.

#### 4.9. Smart Education

A key characteristic of a smart city is the smartness of its inhabitants, their desire for learning and for pursuing higher education degrees [114], and their willingness to accept new technologies. The development of smart cities is therefore closely linked to the need for education. More specifically, the quality and viability of smart cities hinge on education and the quality of schools in regards to local development and the integration between educational institutions and smart cities [27]. While ICT has widely permeated education, the digitalization of educational records has increased the pressure to ensure the security and privacy of their online storage [115]. The field of education has witnessed significant challenges in terms of the need for securing personal data that are enriched with significant details such as citizenship, migration, financial, and social information gathered by educational establishments. Concerns over the use of student information have risen [116] as the collection of learning analytics and big data has become more common in higher education [117]. According to Zhou and Hu [118], the security of academic information systems constitutes a critical factor that restricts the quality of information services and also has a great effect on the storage and transfer of resources. Blockchain technology provides a highly secure design for handling huge amounts of educational data [60]. As such, the technology represents a secure ledger for storing educational documents such as student transcripts, certificates, and degrees, allowing each individual to own and share his/her own digital certificates on a peer-to-peer network [65]. Blockchain can help to transform higher education models into sustainable lifelong learning platforms.

While laws and policies for governance and control of educational data have been established in many jurisdictions, they fail to address security concerns regarding the unauthorized collection and use of students' sensitive data [119]. Blockchain offers the opportunity of creating a technological layer that can be used to secure the sharing and verification of learning achievements. For example, Aamir et al. [84] developed a blockchain-based architecture to automate the verification of academic records of individuals and to strengthen the privacy and control of academic credentials when students finish a curriculum or when international employers require the validation of academic records. The major benefit of incorporating blockchain in smart education is the independent and automatic verification of student achievement data without the need for educational institutions to initiate, own, or award degree certificates. Moreover, blockchain strengthens the security of educational records and increases the correctness and reliability of data by limiting the possibilities of tampering the ledger [60]. The security of blockchain also increases students' and teaching staffs' level of trust in online education providers, assessment methods, educational background and credentials, and intellectual properties [120]. The introduction of a decentralized and secure university management system is also considered fundamental to optimizing the use of educational resources. As blockchain prevents malicious attacks and data leakage, the higher levels of data security would benefit students as they would be able to make more informed educational decisions [65].

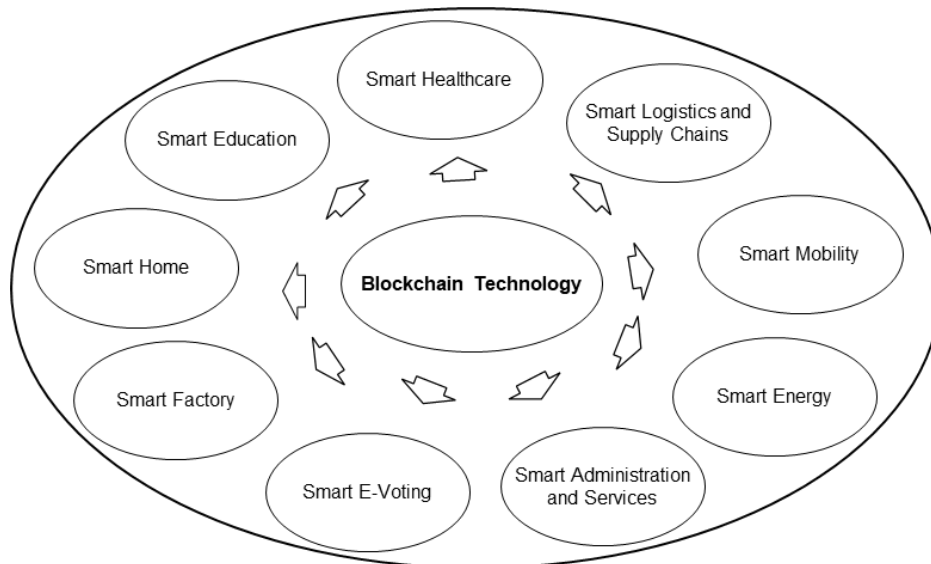
By creating an environment of data security within smart cities, blockchain technology allays the concerns over security issues inherent to the educational system, increases the credibility of students' academic achievement records, and strengthens the sense of belongingness and participation in educational programs. Therefore, blockchain can be used to empower the human dimension of smart cities through the development of smarter campuses and educational institutions, increasing student creativity and problem-solving skills. This leads to our final proposition:

RP\_Edu1: Blockchain technology enables smart education by providing a platform for the trustworthy and immutable recording of personal achievements.

### 5. Discussion, Limitations and Future Research

This paper is guided by two research questions, pertaining to (1) the fields in which blockchain technology can foster the development of smart cities and (2) the identification of important research propositions that arise from the application of blockchain technology in smart cities. We summarize

and organize the findings from previous research as a foundation for novel investigations. Using a comprehensive literature review, we identify fields in which blockchain technology is likely to have a major impact on the overall development of smart cities (Figure 2). Most importantly, each field can serve as a starting point for further in-depth research.



**Figure 2.** Blockchain Technology as a Driver for Smart City Applications.

Our research propositions need to be understood as suggested starting points for future research rather than an all-embracing overview of the field under investigation. While we believe that at present our framework is comprehensive, new research fields may emerge in the future. Furthermore, several of the fields overlap and interact with each other. We do not discuss these overlaps and interactions in the interest of brevity. For the same reason, we also excluded an in-depth discussion of topics that, while being important, are not specific to smart cities, such as the use of blockchain to tackle the outbreak of pandemics. Our framework should therefore not be understood as a model that delimits the boundaries of current research but rather as an inspiration for other researchers to pick up one of the topics and pursue an in-depth and incremental investigation of the subject. In order to achieve such incremental research, it is crucial to build upon a shared repository of definitions and concepts which we have outlined in this paper.

More research is also needed to investigate the value that blockchain can generate in combination with different architectures such as cloud, fog, and edge computing. This applies in particular to the solution of scalability problems that such architectures can provide. Similarly, the combination of blockchain and Artificial Intelligence (AI) offers intriguing new research opportunities in regard to several application fields discussed in our paper. Adding AI capabilities in data analytics could amplify the benefits of blockchain technology for smart cities in areas such as health care services, administration, energy production, and trading, as well as in business logistics and personal mobility [57].

The findings presented in this paper are based on previous research and are thus limited by the repository of papers currently available in academic databases. Long publishing cycles might lead to the exclusion of relevant research that is currently under review. We also acknowledge the possibility of a “positivity bias” in published research regarding the usefulness of blockchain technology in building smart cities. Submission or publication of papers with a positive stance of the contribution of blockchain may be more likely than submission or publication of papers with a negative stance. The literature included in our analysis mainly discusses blockchain as a driver of smart cities and provides little consideration of the potential negative side effects of its deployment. Such negative side effects might include, for example, a loss of perceived privacy on the side of consumers and

an over-reliance on a technology that has not yet been sufficiently tested. Additionally, new attack vectors and security compromises might arise through the application of blockchain technology. Future research is encouraged to discuss possible negative implications of technology in the context of smart cities.

We refrained from recommending specific blockchain platforms for any application since blockchain is undergoing rapid technological development. As we have outlined, numerous application scenarios exist.

Smart cities and blockchain technology share two common properties: First, they are rather broad concepts. Research on smart cities is an applied field with the goal of creating more livable urban environments. Blockchain is a technical platform with the potential for empowering numerous generic applications. Second, both fields are currently in a stage of growth and significant progress can be expected in the near future. In the case of blockchain, numerous novel solutions are being tried out to create more efficient solutions that ensure the scalability of transactions without relying on energy-intensive consensus mechanisms, such as proof of work. Consequently, technological progress triggers new opportunities for smart cities which will require further critical investigation. The framework we develop in this paper is thus intended to assist researchers in finding worthwhile research topics and creating an incremental research agenda beneficial to academia and the industry.

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