Blockchain for Smart Cities: A Systematic Literature Review

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Abstract. We use a systematic literature review methodology to answer the following questions pertaining to smart cities and blockchain: (i) Why was blockchain chosen as the solution? (ii) What blockchains are being considered for use in smart cities and why? and (iii) What blockchain based applications are being researched for smart cities? Our results - based on 45 peer-reviewed academic studies all published in journals that met pre-defined search criteria - show that increased security, privacy, and trust are the reasons most cited in the literature for the use of blockchain for smart cities. Consortium, Hybrid, Private, and Public blockchains are discussed with respect to their suitability for smart cities applications, and finally, we discuss smart cities blockchain applications from the literature using a taxonomy based on the framework defined by Silva et al. [40]. In conclusion, this study highlights the current blockchain challenges and future research opportunities, including the need to change the current mindset of centralized control and trusted third parties to a more participative engagement model across smart cities.

Keywords: Smart cities, blockchain · Blockchain · Distributed ledger technology (DLT) · Internet of Things (IoT) · Sharing economy · Decentralization · Smart contracts · Systematic literature review

1 Introduction

Rapid urbanization and ICT developments have been applied and lead to the origin of the concept of smart city [10]. [14] theorized that a smart city is "when investments in human and social capital and traditional transport and modern ICT communication infrastructure fuel sustainable economic growth and a high quality of life, with wise management of natural resources, through participatory governance". [6] and [16] included areas such as smart governance, smart mobility, smart living, smart use and management of natural resources, smart citizenship and smart economy; these elements are even further expanded upon by [45], who proposed the elements of smart citizenship, smart healthcare, smart grid, smart transportation, supply chain management, smart business, smart home, smart government and smart education.

According to [4] massive efforts are still needed to enable services to connect to one another and to gain real value through such connectivity. [40] expand on the challenges and include integration and interoperability of systems in the application layer, infrastructure and information security concerns, privacy and confidentiality, cyber-

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attacks and the exponential growth of data. [4] confirm that new forms of database design will be required that can be distributed at a city-wide scale and that data collection will rely on crowdsourcing to elicit the preferences of citizens and enable the city to engage in social experimentation around what we know and how we address key urban problems. And this is where blockchain becomes relevant. The United Nations, in their 2018 Revision explicitly point out – in “Goal 11” that “blockchain provides an opportunity to collaborate in a transparent secure way across the many components of smart cities, ensuring sustainability and accountability” [43]. Sustainability improvement is one of the goals of smart cities.

[45] point out that although smart cities and blockchain have been studied extensively in previous works, these two important areas have traditionally been thus far researched separately, and they provide a survey of the state-of-the-art blockchain technology that can be applied in smart cities. To the best of our knowledge, [45] that focused on providing a taxonomy of blockchain-based solutions in smart cities is the first and only attempt to look into the field of blockchain applications to smart cities. We extend this work into two important ways: first, we focus on specific additional questions such as why blockchain was used as the solution, and what blockchains have been considered; secondly, our study differs in scope as we employ a systematic literature review methodology that derives data from journals that meet pre-defined search criteria.

Specifically, the aim of this study is to provide a systematic review of the literature on blockchain application for smart cities to answer the following research questions (i) Why was blockchain chosen as the solution? (ii) What blockchains are being considered for use in smart cities and why? and (iii) What blockchain based applications are being researched for smart cities? The results of our study are potentially useful to researchers in the fields of blockchain and smart cities, but also to practitioners such as urban planners and governments.

The remaining of this paper is structured as follows: Sect. 2 outlines the methodology followed for the systematic literature review. Section 3 presents the findings from the three research questions. Section 4 concludes.

2 Methodology

A systematic literature review methodology is used, which is a process for searching existing literature, evaluating and analysing the literature to report on findings and evidence to allow conclusions to be reached about what is known and not known in the area being researched [11]. The systematic literature review follows pre-defined steps. The first step is to formulate the research questions. We have already presented the questions in the Introduction. The second step is to identify appropriate keywords and formulate the search strings. The main keywords used were “blockchain” and “smart city”, representing the main topics in our research. To ensure that all relevant academic articles were included, it was decided to include variations of the two terms, that is, “distributed ledger” or “DLT” for “blockchain”, and “smart district”, “digital city”, and “smart towns” for “smart city”. Step 3 involved identifying the data sources and setting inclusion and exclusion criteria for the search. The following electronic database sources were searched based on their wide acceptance and respectability among the academic community: (a) Scopus, (b) Science direct, and (c) IEEE Explore digital library. The inclusion criteria used are: (a) papers written in the English language, and (b) the search terms had to be present in the title or keywords or abstract to ensure that the results were narrowly focused on the topic. The search was conducted across all years. The exclusion criteria specified that only papers published in peer-reviewed academic journals are to be included in the systematic literature review; therefore, all other publications are to be excluded. Step 4 involved entering the search strings in the chosen databases and apply the inclusion and exclusion criteria defined in the previous step. This process provided 641 results. In Step 5 these 641 papers were then further evaluated and screened. Papers that were duplicated or where the full text was not available or papers that focused on solely on improving the blockchain or Bitcoin technology were then removed. The above process resulted in a list of 60 unique, relevant papers, selected based on a review of the title, keywords, abstract and document type where available. The last screening required reading the full paper to ensure that the paper did provide insight on the research questions. Research papers were explicitly excluded when the focus was on improving the blockchain technology itself, literature reviews, or when the paper did not focus on any particular use case. This left us with 42 studies. Next, the references of these papers were checked to ensure that any relevant articles that satisfy our criteria were not missed. Three papers were introduced based on this cross-referencing process. Data from the resulted 45 papers were populated into a data collection table to facilitate a content analysis focusing on answering the research questions. Figure 1 provides a visual representation of the steps 1–5 described above.

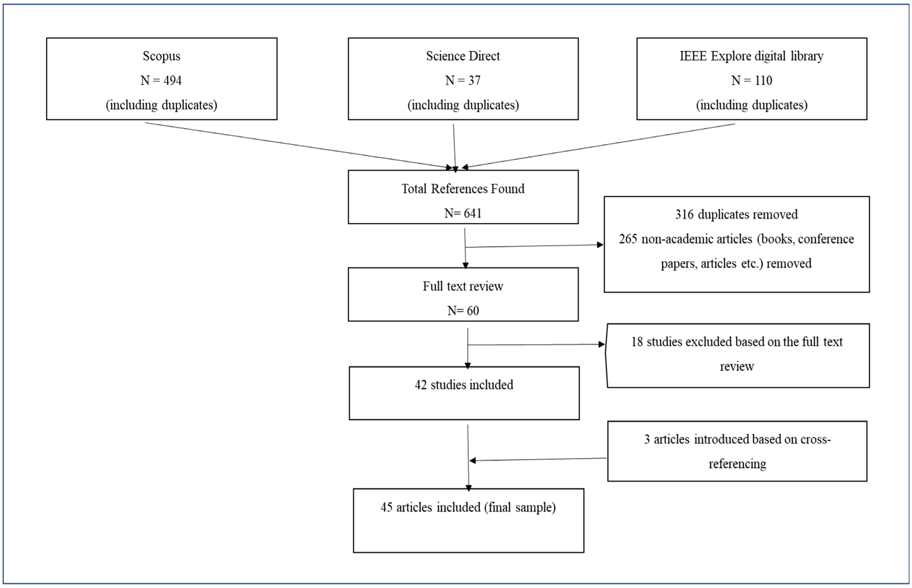

Fig. 1. Data mapping process

3 Results

The final step of the systematic review process is the descriptive review of the literature, followed by the thematic analysis. As the concept of smart cities is new, few papers were published prior to 2018. Through these years, there is gradual evolvement of the focus of research from smart contracts towards a more thorough examination of blockchain applications relevant in use cases of smart cities. Geographically - based on the first author's location - most studies originate from Asia; specifically, most papers originate from China, followed by South Korea and then India. The remaining of this section focuses on the main research questions and the relevant findings based on the systematic literature review.

3.1 Why was Blockchain Chosen as the Solution?

Table 1 highlights the key reasons that blockchain was proposed as a potential solution including increased security, the decentralized nature of the blockchain, and its trustworthiness due to immutability. Privacy was also cited, despite transparency of transactions.

Table 1. Reasons for implementing blockchain applications

Reason for blockchain	No. of papers	Citation
Increased security	32	[1–3, 7, 9, 11–13, 15, 17–20, 22, 25–27, 29, 31–34, 36, 37, 39, 41, 42, 44, 46, 48, 50]
Privacy	16	[9, 11–13, 19, 23, 25, 26, 28, 29, 32, 39, 41, 49–51]
Trust	14	[5, 8, 12, 17, 19, 23, 24, 27, 28, 31, 35, 42, 47, 51]

Blockchain for Increased Security. Security was the top reason cited for the use of blockchain. Due to the massive volume of data, the stakeholders involved and necessary controls, smart cities require high levels of security. Blockchain would improve security across Internet of Things (IoT) in a smart city and sharing economy. This view was reinforced by [2, 3, 11, 13, 19, 22, 29, 32, 34, 39, 41]; and [27].

[33] provide a framework to be used across the IoT ecosystem to detect potential attacks by monitoring and analyzing all the traffic data based on blockchain, while [28] argues that using blockchain to secure IoT is not a suitable solution due to the significant computer power and cost that this entails. [18] propose a 'bubble of trust' where secure virtual zones are created to enable communication of IoT devices. [15] focused on secure IoT device management to ensure integrity, data availability and confidentiality.

In the transport industry, using blockchain to enable secure sharing of Internet of Vehicles (IoV) data was researched by [46] and [8]. [48] focus on solving the security issues of vehicular ad hoc networks (VANETs) through the Block-SDV project, whereas [37] point out that blockchain can be used to build a secure, autonomous transport system for autonomous vehicles. [44] discuss the use of blockchain to implement secure energy delivery services for electric vehicles and energy nodes involving both the transport and energy industry.

In the energy industry, [1] and [31] discuss a secure blockchain-based electrical energy trading system. [7] and [50] discuss secure energy trading for electric vehicles.

In the medical industry, [9] research using blockchain to enable secure sharing of patient medical records with patients, providers, and third parties, whereas [20] focused on securing patient and provider identities.

[25] also suggest that blockchain can provide improved security for user identities. Other studies focus on blockchain for securing information in the casino and entertainment industry [26], blockchain for smart campus cybersecurity [13], and manufacturing supply chain security [36].

Blockchain for Improved Privacy. Identity and access management could be controlled through blockchain [23]. [25] presented a privacy preservation technique to protect user identity, while [13] focused on the social contract enforcement of identity privacy. [51] presented "Reportcoin" blockchain-based incentive anonymous reporting system to combat privacy issues in reporting law violations. [9] define a privacy-preserving framework for access control and interoperability. [11] propose a privacy-preserving blockchain for the analysis of big data in healthcare. Scalability problems and data leakage was a concern in [13].

[28] discusses the "questionable" privacy formats used by central authorities, while [39] in a more technical paper explores the Privacy-Preserving Support Vector Machine training over blockchain-based encrypted IoT data in smart cities. Machine learning based privacy-preserving fair data trading was explored by [49].

The use of blockchain to tackle IoT-related privacy issues is proposed by [19, 29, 32, 38, 41] proposed using a Proof-of-Work scheme to ensure privacy in IoT. [50] discussed the privacy challenges Internet of Vehicles (IoV).

Increased Trust. User trust in the entire system is critical [5]. Trust can be seen from two different perspectives: One perspective is as a result of the inherent blockchain attributes of transparency, immutability and auditability which ensure data integrity [8, 23, 27, 31, 51]. The other perspective emerges from the need to obtain network consensus before a transaction can be committed and the decentralised nature of blockchain technology which results in removing the need to trust centralized third parties [12, 17, 19, 23, 24, 28, 35, 42, 47]. As explained by [51] "blockchain converts trust in people or institutions into trust in the system".

Other Reasons. The concept of blockchain applications for Loyalty and Reward programmes was covered by eight papers. [5] created UniMeCoin for incentive mechanism services. [30] proposed loyalty programmes for local and international travel, and [8] introduced blockchain as a traceable and irreversible mechanism for incentives. Loyalty programmes also received some attention in relation to motivating citizens to participate in the collection and sharing of data [8]; [46], the reporting of issues [51], and validation of data [20].

Six studies cited Peer to Peer (P2P) as a reason for selecting a blockchain solution. Disintermediation [30], better interaction with customers [30] and Decentralized Apps (DApps) based on Peer-to-Peer (P2P) transactions [12] were amongst the more generic applications of blockchain for P2P. Furthermore, [42] presented an approach where no one can unilaterally take actions on behalf of the community. [20] researched the use of blockchain for distributed P2P ASP for IoT, and [31] presented a P2P prosumer-chain energy exchange methodology.

Another important reason cited for using blockchain as a solution was efficiency (see [20, 23, 36]).

The remaining studies focus on currency/token management (see [13, 26, 30, 44, 46] and [27] focus on incentives. Provenance was conceptually discussed by [26]. Lastly, [30] focus on records and rights management; [20] on clinical research and data monetisation, while with [26] look at Notarisation.

3.2 What Blockchains are Being Considered for Use in Smart Cities?

Of the 45 papers analysed, only 16 mentioned a particular type of blockchain, four referred to a public blockchain, seven referred to a private blockchain, one referred to a hybrid and four to a consortium. A summary is shown in Table 2.

Ethereum is the predominant platform, proposed by 12 of the 17 papers that referenced a particular blockchain as a solution, this is possibly due to most of the papers incorporating smart contracts, 31 of 45 papers, as an integral component of the blockchain for smart cities. There were three Non-specified Consortium papers, and one Consortium solution using BigChainDB; One Non-Specified Hybrid solution, one custom public/private blockchain, and one non-specified Ethereum solution. The public blockchains were split amongst Ethereum (two, one Tangle, and one unspecified). Ethereum had seven papers with Private blockchain as the solution.

Table 2. Blockchain types used in Research

Type of blockchain	Blockchain referenced	% of total	Citation
Consortium	Not specified	16%	[7, 8, 50]
Consortium	BigChainDB	5%	[24]
Hybrid	Not specified	5%	[23]
Private	Ethereum	37%	[5, 9, 15, 29, 33, 36, 38]
Private	Ethereum and hyperledger blockchain	5%	[32]
Public	Ethereum	11%	[18, 25]
Public	Tangle (DAG)	5%	[13]
Public	Not specified	5%	[51]
Private and public	Custom based on ethereum	5%	[26]
Not specified	Ethereum	5%	[28]

Public Blockchain. Ethereum Public Blockchain was selected by two studies. [25] attempted to solve the issue of public blockchains being computationally expensive, demanding high bandwidth and extra computational power, and not generally considered completely suitable for most resource constrained IoT devices meant for smart cities. They propose a framework of modified blockchain models allowing for additional privacy and security properties making IoT application data and transactions more secure and anonymous over a blockchain-based network. [18] looked at creating a decentralised blockchain-based authentication system for IoT – both human to device, and device to device. This approach relies on the security advantages provided by blockchain, and will alleviate malicious users, and bring about the following blockchain advantages: decentralised, robust against falsification and alteration, autonomous, smart contracts, scalable. Private blockchain was considered, but disregarded due to the limitations it presented to the above advantages. Ethereum was selected as it has the second greatest ledger in the world, secure, uses smart contracts, accommodates the creation of decentralized applications, (dApps), and it is followed by a big community [18].

[13] suggest Tangle that takes into account constant delays and a random selection algorithm to enforce social contracts and to implement control systems focusing on dynamic deposit pricing; the desired level of compliance is enforced by a pricing signal following a predetermined set of rules.

[51] combine smart contracts with zero knowledge proof to propose a novel Blockchain-based incentive mechanism in ReportCoin, a novel efficient and practical blockchain-based incentive anonymous reporting system that guarantees user identity privacy and reporting message reliability. A public blockchain was suggested because of the openness and transparency, tamper-resistance and decentralization.

Custom Blockchain (Private/Public). [26] specifically focused on how blockchain technology can be applied to logistics management in integrated casinos and entertainment (ICE). “TransICE”, an open, automated, and transparent platform, consisting of two parts, the Shipment Pricing and Scheduling process, and the Pickup, Shipping and Delivery process. They have selected a hybrid model to keep financial transactions are stored on the public blockchain.

Non-specified Ethereum. [28] developed a universal blockchain framework for urban governance that can be used globally and that is Ethereum-based. Off-blockchain preparatory process will be app-based and will inform the on-blockchain smart contract. This on-and-off-blockchain combination is called Group2Group (G2G) system of peers and alleviates pressure on the public blockchain.

Private Ethereum. Ethereum Private Blockchain was selected by eight authors. [29] wanted to leverage off the advantages of confidentiality, integrity, authentication, authorization, trust, verification, information storage, and management, availability challenges need to be addressed. They used Ethereum virtual machine to implement the blockchain distributed network and healthcare insurance claims is taken as an example to test the proposed solution, and the results indicated trust management and security and privacy challenges were addressed [29]. The [29] framework is based on the principle that all the participants are connected in a distributed way to pre-registered entities.

[5] propose a fully centralized version of the blockchain implementing the proof of authority consensus mechanism, creating public auditability through UniMeCoin,

where one single miner is involved in the blockchain under the control of the University of Messina. After the pilot, the decision was taken to migrate to a consortium-chain network in which more partners are involved in the management of UniMeCoin by hosting additional miners [5].

[9] designed Ancile, a permission-based framework that utilises smart contracts access control and obfuscation of data, to be implemented over existing systems; it utilises specific Ethereum tools to create a system that is both cost and storage effective, in an attempt to prevent data breaches of the private information of patients.

[32] present a blockchain and IoT-based Cognitive Edge Framework to support security-and privacy-oriented smart contract services for the sustainable IoT-enabled sharing economy in mega smart cities. The framework offers a sustainable incentive mechanism for a Multi-access edge computing (MEC)-based sharing economy system, which leverages the blockchain and off-chain framework to store immutable ledgers [32].

[33] looked at the security architecture based on the Mininet emulator for an IoT network to prevent cyber-attacks by implementing a decentralized security architecture based on Software Defined Networking (SDN) coupled with a blockchain technology for IoT network in the smart city that relies on the three core technologies of SDN, blockchain, and Fog and mobile edge computing in order to detect attacks in the IoT network more effectively.

[38] proposes a novel hybrid network architecture for the smart city simulated on top of a private Ethereum blockchain network, by leveraging Software Defined Networking and blockchain technologies through a two-part architecture: core network and edge network.

[36] investigated a private Ethereum blockchain-based distributed framework for Automotive Industry in a smart city, and propose a blockchain-based distributed framework, which includes a novel miner node selection algorithm for the blockchain-based distributed network architecture. Simulations using real time data of mined blocks from litecoinpool.org, to test feasibility demonstrated that the proof-of-concept model can be used for wide range of future smart applications [36].

[15] propose a private blockchain-based device management framework that consistently inspects the integrity of the device timely, providing secure and guaranteed device updates and storing the results to keep improper management and updating to cause losses to a smart city.

Consortium/Hybrid. [7] propose a blockchain-based secure energy trading scheme for electric vehicles (EVs), where a blockchain is used to validate EVs' requests. The miner nodes in the blockchain consortium validate the requests on the basis of energy requirements, time of stay, dynamic pricing, and connectivity record, providing transaction security and privacy protection without relying on a trusted third-party to carry out verification.

[50] propose a consortium blockchain-enabled secure energy trading framework for EVs to develop a distributed, privacy-preserved, and incentive-compatible demand response mechanism for IoEV. Challenges, such as a lack of and incentive mechanism, privacy leakage, and security threats are addressed.

[23] introduce a novel scalable architecture that is based on a distributed hybrid ledger model allowing for refined and secure management of data generated and

processed in different geographical and administrative units of a city. A proof of concept mechanism is used, which highlights the need to keep and process citizen data at the local level. The proposed architecture provides secure and privacy protected environment for citizen participatory applications.

[24] conducted an experiment named#SmartME on BigchainDB and designed and implemented a trust-less smart city data acquisition, storage and visualization system layer on top of the #SmartME stack, which was tested in a real-world smart city scenario, by running it on the #SmartME deployment available in the city of Messina.

[8] introduce a trustless, privacy preserving consortium blockchain that includes a smart contract for automatic data sharing and computing cost. Simulations show that the proposed algorithm is scalable, truthful, individually rational, and can maximize the social welfare with low social cost and low computational complexity.

3.3 What Blockchain Based Applications are Being Researched for Smart Cities?

Every eligible paper was reviewed so as to be categorized based on the high-level components defined by the research of [40] (Fig. 2). The classification into components was based on best fit and the stated use case(s). Sometimes they would fall in more than one category; for example, [26] discuss applications for integrated resorts which may be considered as a small city that includes healthcare, transport, logistics, supply chains, hospitality etc.

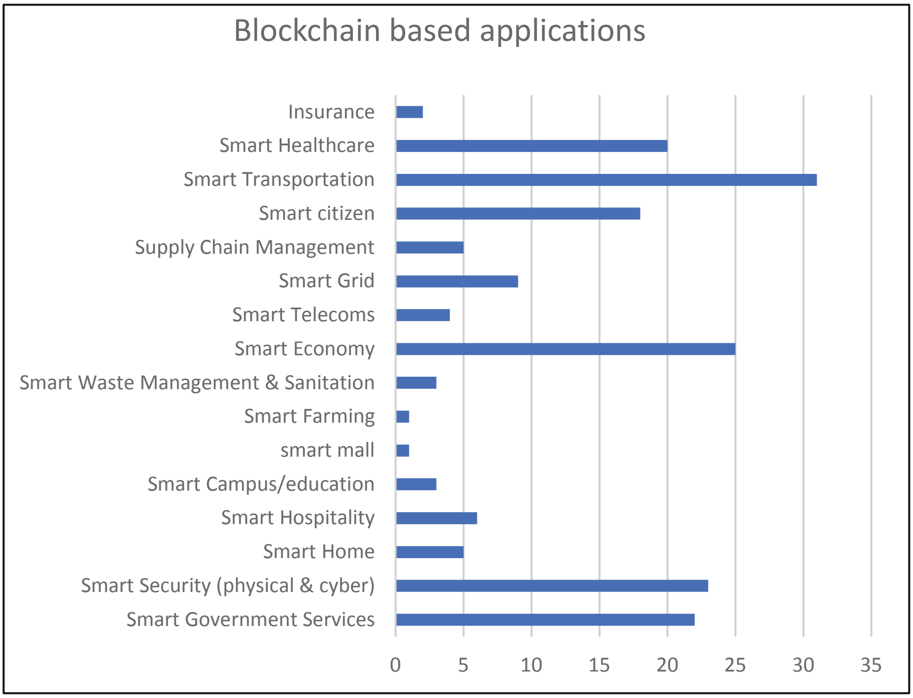

Fig. 2. Blockchain based applications

Below is a detailed breakdown of the top six major themes, comprising 80% of the use cases identified in the research.

Smart Transportation/Mobility. Smart Transportation/Mobility has the highest amount of use cases researched for smart cities, Table 3 lists the use cases and the papers referring to them.

Table 3. Transportation/mobility applications

Application	Citation
Smart transportation/mobility	[17, 24, 26, 32, 36–38, 12]
Electric vehicles	[7, 44]
Automotive loyalty/incentives programs	[36, 44, 8]
Parking	[5, 38]
Car pooling	[5]
Logistics	[21, 26]
Ride sharing/bike sharing	[35, 37]
Data sharing	[41]
Drones	[20]
Environment data using taxi infrastructure	[5]
Traffic data	[5]
Automotive automated payments	[36]
Mobile crowdsensing	[46]
Vehicle registration and maintenance services	[36]
Vehicle and smart phone communications	[48]
Vehicular network	[37]
Smart roads	[18]

The concept of Traffic and traffic control was a theme for [5], which covered "traffic lights" and "car-pooling", "Infrastructure and an ecosystem of potholes" was discussed by [5]

In a research paper focusing on a vehicular network architecture in smart city [38] looked into vehicle resource discovery and sharing, intelligent transport systems which communicate with the home, and incorporating ride sharing and scheduling into the home and vehicular network, as part of a smart home. [44] also looked into integrating electric vehicles into smart homes. [44] also focused on the data management application of the vehicular energy network (VEN), and renewable energy (RE) transportation.

[5] researched the possibilities of environmental data collection using taxi data (speed, GPS, etc). [48] noted the use case for data gathering on the communication between smartphones and vehicles. [17] investigated data forensics in IoT and [18] focus on IoT authentication.

"Smart transportation", supported by logistics and technology is another potential use case under the Logistics and Supply Chain classification. Both [26] and [46] investigated mobile crowdsensing recognising that incentives will be implemented to encourage the automotive crowdsensing. [21] and [26] researched mobility logistics in the pharmaceutical and gaming industries respectively.

Smart Economy. Applications for the smart economy was the second most researched topic, with 25 use cases by different authors. Those are shown in Table 4.

Table 4. Smart economy applications

Application	Citation
Virtual currencies	[5, 26, 30, 50, 51]
Payments	[5, 30, 36, 37]
Loyalty and rewards	[21, 44, 8]
Marketplace	[7, 35, 49]
Investing	[25, 28]
Financial transactions and trades	[17]
Sharing economy	[42]
Econometric Models	[28]
Clinical research and data monetisation	[20]
Smart economy	[12]

Many papers were on the introduction of new virtual currencies as a trading token [50], incentives and rewards token [5, 30, 51] or as e-money across an entire ecosystem [26].

[36] researched the automated payment process in the automotive industry in a smart city and as part of their research into an IoT service ecosystem for smart cities, [5] looked at payments (parking, university services, voting). In the casinos and entertainment industry, their entire research on using blockchain as a platform for the integrated casino and entertainment industry which can be seen as a mini smart city, and also explored financial transactions as a generic concept.

Investing use cases focused to real estate investing [25] and smart malls [38]. Loyalty and rewards incentives is a critical element of influencing participation and engagement with stakeholders in a smart economy and was discussed by [21]. A financial framework for energy delivery for vehicular networks was discussed by [44]. [8] looked into a quality-driven auction based incentive mechanism.

Finance was one of the topics tackled by [17] whilst looking into blockchain technology and its integration with IoT. [49] explored data trading in the big data market, with a specific focus on machine learning and preserving financial privacy. Where [1] researched a smart energy grid based on blockchain technology, whereby energy providers and private citizens can freely exchange energy both as consumers and prosumers.

Smart Security (Physical and Cyber). Smart security is a critical element of a smart city - the entire premise of a smart city is that it is enabled by technology and technology is at high risk of cyber-attacks (Table 5). The most prominent use cases for smart security is around securing information and data. Eight papers focused on secured information management and exchange with [37] describing a model allowing vehicles within a network of vehicles to discover and share their resources and data securely.

[44] examine secure energy delivery services for electric vehicles and energy nodes. [34, 39, 46, 49], and [27] all focused on securing IoT data, whereas [22] were interested in ensuring the security of the collection and trading of data on the network. [28] explored blockchain as the next enabling network, illustrating how blockchain technology can used to connect data processing technologies securely for IoT.

Identity management was the second highest subtopic in security with 5 papers exploring the topic in more detail. In the research into a decentralized blockchain-based authentication system for IoT, [18] noted a use case for Identity and Access Management related to the IoT. Authentication of the integration between a decentralized identity management and distributed credential storage was researched by [17] and by [30] in their smart tourism research where they explicitly noted an integrated identity management network. Tornado was identified as a potential enabler and integrator for blockchain in IoT.

Another sub-topic within secure identity management is the sharing economy. [32] present a blockchain and IoT-based cognitive edge framework for sharing economy services in a smart city. [3] with a focus on healthcare, looked at the data management of firmware detection and self-healing though IoT. This has a huge impact on the Identity management aspect of smart security.

Identity management is also highlighted as a potential use case within logistics and supply chain management by [17], where they looked at blockchain technology and its integration with IoT and found that decentralized identity management, as well as distributed credential storage created good use cases.

Table 5. Smart security (physical and cyber) applications

Application	Citation
Secured information/data management and exchange	[22, 27, 34, 37, 39, 44, 46, 49]
Identity management	[15, 18, 30, 32, 41, 20]
Detect and mitigate security attacks in IoT	[24, 33, 29]
Firmware detection, updates and self-healing IoT	[3, 15]
Data forensics	[17]
Big data auditing	[47]
Secure communication in a distributed environment	[19]
Anonymous reporting	[51]

The remaining use cases included research into a blockchain-based secure device management framework for an IoT network in a smart city, focusing on device management and firmware updates [15]. This research aligned to the paper by [24] around the design of a trustless smart city system where they looked at the acquisition, storage and consumption of sensor data. Additionally [19] researched emerging technologies for sustainable smart city network security, looking at secure communication in a distributed environment, whereas [44] researched a blockchain-based secure incentive scheme for energy delivery in a vehicular energy network, to be integrated into the IoT through the management of devices at home, vehicle, and city.

Smart Government. Governmental services and administration can be trusted, secured, be more transparent and encouraging citizen participation on a blockchain (see Table 6). [21] examines loyalty and rewards platforms, birth and death registries, court case files, property registration, local business registration and voting platforms. [5] also included voting platforms among other applications.

Both [5, 28] made cases for the need of policies, rules, laws, regulations and standards to govern smart cities, and the availability of these on the blockchain. Citizen engagement and participation within smart cites and government was the main point of [28] that discussed use cases for citizens to submit their urban needs onto the blockchain encouraging involvement in policy decisions. [28] also focused on geographical information systems, econometric models, mayors' dashboards and statistical projections. Finally, [22], who discussed an immutable log of events and management of access control to government data.

Table 6. Smart government applications

Application	Citation
Administration including court case files and building information	[21, 28]
Policies, rules, laws, regulations, standards	[28, 5]
Crowdsensing and crowdsourcing	[20, 5]
Voting platforms	[21, 5]
Infrastructure and an ecosystem of services	[5]
Incentive mechanisms	[5]
Registrations (Birth and death, property, local business)	[21]
Citizen data (sharing)	[23]
District area monitoring and safety	[24]
Urban budgeting	[24]
Social compliance	[13]
Log of events and management	[22]
Geographic information system	[28]
Mayors dashboards	[28]
Statistical projections	[28]
Crisis mapping and recovery	[20]

Smart Healthcare. Smart healthcare has also garnered a lot of interest (Table 7). [2] and [9] refer to opportunities in healthcare at a high level. [17] delves deeper into the topic in combination with IoT and describes financial, transactional and trade within intelligent healthcare networks. [18] researches the concept of secure virtual zones (bubbles) where things can identify and trust each other. This creates opportunities for hospitals, healthcare and medical use cases.

[32] are more focused on a sharing economy including smart health services and [26] include smart health in their study of use cases for integrated casino and entertainment. [20] researched various applications in healthcare including medical fraud detection, mechanisms for validating, crediting and rewarding crowdsourced geo-tagged data, public health surveillance and wearables.

Table 7. Smart healthcare applications

Application	Citation
Smart healthcare	[2, 9, 17], [26, 32, 18]
Collection, processing and storage of healthcare data	[20]
Transparent pharmaceutical and medical device supply chains	[21, 20]
Secure sharing of data	[41, 20]
Remote patient monitoring	[11]
Single electronic health record for the citizens	[21]
Smart hospital	[38]
Clinical research and data monetization, medical fraud detection, public health surveillance, wearables	[20]
Healthcare insurance claims	[29]

Smart Citizenship. This pertains to the social element of smart cities where citizen participation and engagement play a major role (Table 8). [35] focusing on this social element to smart cities, explored citizen co-creation, both at the neighbourhood-scale, as well as bi-directional, and city-wide. [35] also brought in the social aspects of using a smart city platform for societal value exchange and co-creation, named WeValue. [28] additionally targeted the “people’s layer” for urban technologies, and Geographical Information Systems.

[5] and [23], specifically looked at “citizen participation” in terms of listing issues, sharing data, and participation in governmental decision-making. Only one paper focused on education falling into the “smart people” subcategory [13].

Table 8. Smart citizenship applications

Application	Citation
Citizen participation and engagement	[23, 24, 28, 35]
Energy trading & marketplace	[1, 2, 7, 50]
Crowdsensing (problem reporting)	[5, 51]
Incentives and rewards	[5, 21]
Sharing economy	[35, 42]
Remote patient monitoring	[11]
Smart living	[17]
Smart people (education)	[12]

Other Classifications. Energy grid applications for "energy exchange" is a popular use case for blockchains. [1] and [31] explore citizens as prosumers, trading energy between providers, prosumers and consumers of smart homes. [35] noted that a smart city platform for societal value exchange may be utilised for energy-savings. [12] researched smart governance, smart living and smart economy of energy management and [1] looked at the data associated with energy trading and a sustainable electrical energy transaction ecosystem between prosumers and consumers of smart homes. [44] proposed a blockchain-based incentive scheme for energy delivery in vehicular energy network creates a case for integrated wireless power transfer technology into the smart home and building in incentive schemes through intelligent reporting. Both [21] and [5] found notable use cases for the use of blockchain in "Renewable energy" within their research.

Another topic of interest was waste management. [18] as well as [24] focused on waste management and sanitation, whilst [5] explored blockchain as an option for payments for waste management in smart cities. [24] focused on the mobility of waste management services.

Smart homes was another interesting topic investigated. [17] in their study on the authentication of blockchain technology and its integration with IoT, explore IoT for smart lives and smart homes. [36] had an architectural approach to smart homes within the smart city.

Supply chain management is mentioned in association with applications of blockchain technology to logistics management in integrated casinos and entertainment [26] automotive industry in a smart city [36], and with the applications of blockchain technology in smart city development in [21] where they looked specifically at pharmaceutical supply chains.

4 Discussion and Conclusions

The intersection of blockchain and Smart Cities has the potential of creating sustainable smart cities aligned to the United Nations sustainable cities and communities' goal. This is also a worth exploring complex topic which spans across multiple disciplines. In this study we employ the methodology of systematic literature review to analyse 45 academic papers published in 33 different journals mostly within the Computer Science field, to answer three research questions.

The first question is why blockchain was chosen as the solution. The main reasons cited were security, privacy, and trust. Security was the top reason cited for the use of blockchain. Due to the vast volume of data, the stakeholders involved, and the necessary controls, smart cities require a very high level of security. Privacy issues involve identity privacy, healthcare privacy, privacy when reporting crimes, privacy issues in Internet of Vehicles. Trust, another reason cited, is enhanced by transparency, immutability and auditability, and the ability to have trustless systems.

The second question concerned the type of blockchain suggested. The most popular type was private blockchain. Public blockchains have been also suggested, as well as Non-specified Ethereum, Private Ethereum, and Consortium/Hybrid.

The third question focuses on the blockchain applications that are being researched for smart cities and to answer that the [40] framework for the thematic taxonomy of applications is applied. Our findings show that smart cities blockchain applications focus on smart transportation, smart economy, smart security, smart government, smart healthcare and smart citizenship applications, creating important links between the social, economic and industry elements of smart cities. Moreover, in reviewing the literature, it became clear that often studies tended to focus on smaller subsets of a smart city; so, a "Smart City" is a conglomeration word for "Smart Places". These include smart campuses, smart suburbs, smart hospitals, integrated casinos, smart malls, etc. but the concept can also expand to include a whole country. The 'place' becomes the centrepiece of the model, and there are six smart themes, facilitated through different blockchains (Fig. 3). The six themes of this taxonomy each have applications associated to it. The breakdown of each as follows: Economy, which has the applications Sharing, Investing and Market-place associated; Environment, associated with Mobility, Energy, and Telecoms; Governance, with its associated Laws & Regulations, and Record Keeping; Services, associated with Education, Healthcare, Insurance, and Waste Management; Security, and its associated Identity Management, and Data Security; and, Citizen, associated with Rewards and Incentives, Participation & Engagement, and Reporting.

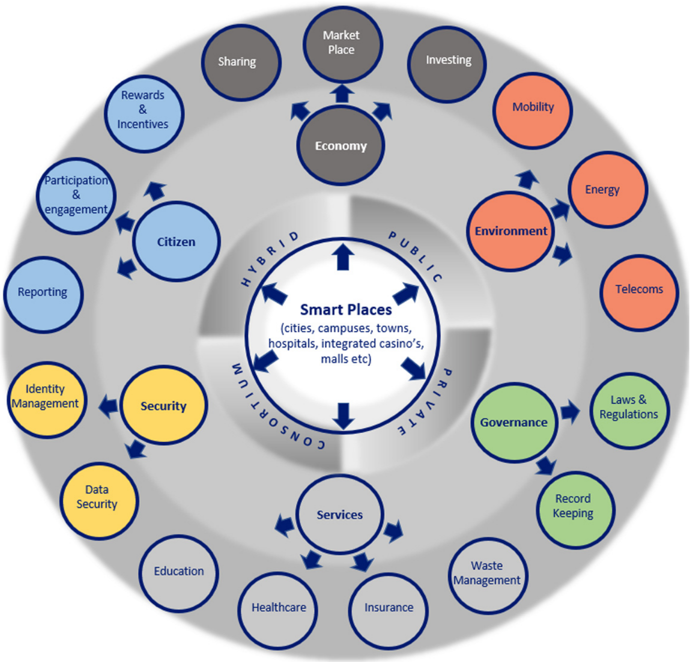

Fig. 3. Graphical view of blockchain based applications

Some of the challenges that emerged are that blockchain solutions need to be carefully thought through and implemented as the very attributes that make blockchain desirable for smart cities could also create challenges that need to be overcome, including the need for notaries, quality data input, regulatory privacy and the ability to be forgotten, additionally future research is needed around blockchain scalability, standards and interoperability across multiple blockchains to enable a holistic ecosystem that brings together all the elements of a smart city.

Enabling the smart citizen as a contributor, prosumer and decision maker within smart cities is particularly inspiring and encouraging. Blockchain based applications within the smart city context are steadily gaining more momentum; however, it has to be noted that they are still in an evolution state. Significant developments and change management will be required to position blockchain based applications for smart cities as an opportunity for transparency, trust and participative citizenry.

In conclusion, opportunities that blockchain based applications can bring to smart cities are discussed, across all sectors and industries. Current blockchain challenges and future research opportunities have been highlighted, including the need to change the current mindset of centralized control and trusted third parties to a more participative engagement model across smart cities.

The smart city is a relatively new concept, and certainly an evolving one and there is a high likelihood that many research papers have been omitted due to researchers classifying their research using alternative terms and not the terms specifically targeted with this study. The selected keywords and databases used for the research may have resulted in missing relevant literature, however the results covered a broad range of use cases and the references of the selected papers were also checked to minimize the inadvertent omission of any papers.

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