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On the sustainability of smart and smarter cities in the era of big data: an interdisciplinary and transdisciplinary literature review

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Abstract

There has recently been a conscious push for cities across the globe to be smart and even smarter and thus more sustainable by developing and implementing big data technologies and their applications across various urban domains in the hopes of reaching the required level of sustainability and improving the living standard of citizens. Having gained momentum and traction as a promising response to the needed transition towards sustainability and to the challenges of urbanisation, smart and smarter cities as approaches to data-driven urbanism are increasingly adopting the advanced forms of ICT to improve their performance in line with the goals of sustainable development and the requirements of urban growth. One of such forms that has tremendous potential to enhance urban operations, functions, services, designs, strategies, and policies in this direction is big data analytics and its application. This is due to the kind of well-informed decision-making and enhanced insights enabled by big data computing in the form of applied intelligence. However, topical studies on big data technologies and their applications in the context of smart and smarter cities tend to deal largely with economic growth and the quality of life in terms of service efficiency and betterment while overlooking and barely exploring the untapped potential of such applications for advancing sustainability. In fact, smart and smarter cities raise several issues and involve significant challenges when it comes to their development and implementation in the context of sustainability. With that in regard, this paper provides a comprehensive, state-of-the-art review and synthesis of the field of smart and smarter cities in relation to sustainability and related big data analytics and its application in terms of the underlying foundations and assumptions, research issues and debates, opportunities and benefits, technological developments, emerging trends, future practices, and challenges and open issues. This study shows that smart and smarter cities are associated with misunderstanding and deficiencies as regards their incorporation of, and contribution to, sustainability. Nevertheless, as also revealed by this study, tremendous opportunities are available for utilising big data analytics and its application in smart cities of the future to improve their contribution to the goals of sustainable development by optimising and enhancing urban operations, functions, services, designs, strategies, and policies, as well as by finding answers to challenging analytical questions and thereby advancing knowledge forms. However, just as there are immense opportunities ahead to embrace and exploit, there are enormous challenges and open issues ahead to address and overcome in order to achieve a successful implementation of big data technology and its novel applications in such cities.

Keywords: Smart cities, Smarter cities, ICT of pervasive computing, Big data analytics, Big data applications, Urban intelligence functions, Sustainability, Sustainable development, Urban systems and domains

Introduction

Cities have a central and defining role in strategic sustainable development; and therefore, they have increasingly gained a central position in operationalising and applying it. This is clearly reflected in the Sustainable Development Goals (SGDs) of the United Nations' 2030 Agenda for Sustainable Development, which entails, among other things, making cities more sustainable and resilient [127], as well as well documented by European Commission [48]. This is anchored in the recognition that cities as the engines of, and the hubs of innovation that drive, economic development are the world's major consumers of energy resources and significant contributors to GHG emissions. It is estimated that they consume about 67% of the global energy demand and generate up to 70% of the harmful GHG emissions. Accordingly, they represent the key generators of environmental pollutants and the main hotspots of vulnerability to climatic hazards and related upheavals, in addition to social inequality, disparity, vulnerability, and insecurity [20]. In view of that, they are seen as the most important arena for instigating major sustainability transitions, adding to being the key sites of economic, environmental, and social dynamism and innovation and thereby holding great potential for making significant contributions to social transformation and thus sustainable development [22]. As such, they provide ideal testing grounds and operating environments for innovative ICT solutions pertaining to diverse urban systems and domains. In this regard, the UN's 2030 Agenda regards ICT as a means to promote socio-economic development and protect the environment, increase resource efficiency, achieve human progress and knowledge in societies, upgrade legacy infrastructure, and retrofit industries based on sustainable design principles [127, 129]. Hence, the multifaceted potential of the smart city approach as enabled by ICT has been under investigation by the UN [128] through their study on 'Big Data and the 2030 Agenda for Sustainable Development'.

Unprecedented in their magnitude and influence in history, the spread of urbanisation and the rise of ICT are among the most important global shifts at play across the world today, and will undoubtedly change urbanism in a drastic and irreversible way. As widely estimated, the urban world will become largely technologized, computerised, and urbanised within just a few decades, and ICT as an enabling, integrative, and constitutive technology of the twenty-first century will accordingly be instrumental, if not determining, in addressing many of the conundrums posed, the issues raised, and the challenges presented by urbanisation [20]. It is therefore of strategic value to start directing the use of emerging ICT into understanding and proactively mitigating the potential effects of urbanisation, with the primary aim of tackling the many intractable and wicked problems involved in urban operational functioning, management, planning, and development, especially in the context of sustainability which is another macro-shift at play across the world today. Indeed, the rapid and anticipated urbanisation of the world pose significant and unprecedented challenges associated with sustainability (e.g., [39, 46, 53]) due to the issues engendered by urban growth in terms of resource depletion, environmental degradation, intensive energy usage, air and water pollution, toxic waste disposal, endemic traffic congestion, ineffective decision-making processes, inefficient planning systems, mismanagement of urban infrastructures and facilities, poor housing and working conditions, public health and safety decrease, social vulnerability and inequality, and so on [20]. These accordingly affect the quality of life and well-being of citizens as well as the efficiency of urban operations and functions [40]. In short, the multidimensional effects of unsustainability in modern and future cities are most likely to exacerbate with urbanisation [20]. Urban growth will jeopardise the sustainability of cities [102]. Therefore, ICT has come to the fore and become of crucial importance for containing the effects of urbanisation and facing the challenges of sustainability. ICT becoming part of mainstream debate in this regard emanates from the increasing ubiquity presence of, and new discoveries in, computing, coupled with the massive use of its technological applications across various urban systems and domains. In fact, advanced sophisticated technologies and novel complex approaches are now more needed than ever to address and overcome the challenges and issues facing modern and future cities. This pertains to the way these cities should be monitored, understood, analysed, and, hence, operated, managed, organised, and planned to improve and maintain their contribution to the goals of sustainable development. There is an increasing recognition that emerging and future ICT constitutes a promising response to the challenges of urban sustainability due to its tremendous, yet untapped, potential to catalyse and boost sustainable development processes (e.g., [6, 16, 20, 24, 25, 82]. Many urban development approaches reference the role of ICT in achieving the goals of sustainable development (e.g., [4, 6, 20, 122]. As pointed out by Bibri [20], ICT constitutes an effective approach to decoupling the health of the city and the quality of life of citizens from the energy and material consumption and concomitant environmental risks associated with urban operations, functions, services, designs, and policies.

In the wake of the rapid advancement of ICT of various forms of pervasive computing, recent research has started to focus on incorporating sustainability in the smart city concept and approach (e.g., [5, 6, 102]). The underlying assumption is that, as ICT becomes spatially omnipresent across urban environments, i.e., data sensing, data processing, cloud/fog computing, and wireless communication networking become more and more combined with infrastructure, architecture, ecosystem services, human services, and even citizens' bodies, smart cities can become smarter and also so as to solving environmental problems and responding to socio-economic needs (e.g., [16, 20, 106, 113, 124]). Therefore, most of the prospects and opportunities in this regard relate to what is labeled 'smarter cities', a class of cities which is viewed as future visions of smart cities, and is characterised by an ever-growing embeddedness and pervasion of ICT into the very fabric of the city [20]. They include ubiquitous cities, sentient cities, ambient cities, real-time cities, and cities as Internet-of-everything. For these cities, big data analytics is seen as a critical enabler and powerful driver in regard to the transformation of their ecosystem on several scales, including the way sustainability can be understood, applied, and planned.

Undoubtedly, the main strength of the big data technology is the high influence it will have on smart cities of the future or smarter cities and on citizens' lives (e.g., [5, 16, 18, 20, 54, 73, 79, 83, 104, 124]). Thereby, the notion of big data analytics and its application in sustainable urban development has gained traction and foothold among urban scholars, scientists, practitioners, and policymakers over the past few years. Indeed, big data computing as a new paradigm is fundamentally changing the way modern cities can sustainably be operated, managed, planned, and developed, shaping and driving decision-making processes within many urban domains [20], especially with regard to optimising resource utilisation, mitigating environmental risks, responding to socio-economic needs, and enhancing the quality of life and well-being of citizens in an increasingly urbanised world. This paradigm is clearly on a penetrative path across all the systems and domains of smart and smarter cities that rely on advanced ICT in relation to operational functioning, management, planning, and development. This is manifested in the proliferation and increasing utilisation of the core enabling technologies of big data analytics across those cities badging or regenerating themselves as both smart and smarter for storing, managing, processing, analysing, and sharing colossal amounts of urban data for the primary purpose of extracting useful knowledge in the form of applied intelligence functions and simulation models. Big data are regarded as the most scalable and synergic asset and resource for smart and smarter cities to enhance their performance on many scales, as they have become the fundamental ingredient for the next wave of urban analytics [20]. As a result, many governments have started to exploit urban data and their numerous benefits to support the development of smart and smarter cities across the globe with regard to sustainability, efficiency, resilience, equity, and the quality of life. However, to facilitate big data analytics and achieve a successful implementation of the associated applications and services towards reaching this goal, huge investments in the underlying core enabling technologies are needed.

However, according to a recent literature review [25], while smart and smarter cities have played a key role in transforming different areas of human life, they are still associated with misunderstanding and deficiencies with regard to incorporating the goals of sustainable development. Also, there is a weak connection between smart targets and sustainability goals [6, 20, 28], despite the proven role of ICT in supporting modern cities in moving towards sustainability [25]. On this note [6], conclude that the smart city and sustainable city landscapes are extremely fragmented both on the policy and the technical levels, and there is a host of unexplored opportunities toward sustainable smart city development. In all, smart and smarter city approaches raise many issues and present significant challenges in the context of sustainability (e.g., [2, 20]).

Concerning big data analytics and its application, while research has recently been active in the realm of smart and smarter cities, the bulk of work tends to deal largely with economic growth (management, efficiency, innovation, productivity, etc.) and the quality of life in terms service efficiency and betterment (e.g., [15, 54, 73, 79, 83, 108]), while overlooking and barely exploring the untapped potential of big data applications for advancing the different aspects of sustainability. Indeed, many of the emerging smart solutions are not aligned with sustainability gaols [2]. In view of that, smart and smarter cities need to direct their focus towards utilising big data applications for improving their contribution to the goals of sustainable development across urban domains [20].

This paper provides a comprehensive, state-of-the-art review and synthesis of the field of smart and smarter cities as regards sustainability and related big data analytics and its application in terms of the underlying foundations and assumptions, research issues and debates, opportunities and benefits, technological developments, emerging trends, future practices, and challenges and open issues. This extensive interdisciplinary and transdisciplinary review and synthesis endeavours to present a detailed analysis and synthesis and critical evaluation and discussion of the available qualitative and quantitative research covering the topic of smart and smarter cities, with a particular emphasis on cross- and beyond disciplinary forms of knowledge. It is deemed important to identify and stimulate new research opportunities in the field. The added values of this review involve thoroughness, comprehensiveness, topicality, and original contribution in the form of novel insights as a result of analysing, synthesising, and critically evaluating a large body of recent works. The main motivation for this paper is to capture further and invigorate the application demand for the urban sustainability solutions that big data analytics can offer in the context of smart and smarter cities.

The remainder of this paper is structured as follows. "Methodical-topical literature review methodology" section outlines the literature review and synthesis methodology in terms of approach, search, selection, organisation, and purpose. In "Conceptual, theoretical, and discursive foundations and assumptions" section, the relevant conceptual, theoretical, and discursive foundations and assumptions are presented, described, and discussed. "A detailed survey of relevant work: issues, debates, gaps, benefits, challenges, opportunities, and prospects" section provides a detailed, two-part survey of the relevant work in terms of issues, debates, gaps, benefits, opportunities, and prospects. The first part addresses smart cities in terms of general and particular research strands, deficiencies, and potentials with regard to sustainability, as well as smarter cities in terms of characteristic features, social shaping dimensions, and the current issues of and future potentials for sustainability. The second part covers big data analytics and its application in smart and smarter cities in terms of research status and data growth projection, the urban data deluge in city analytics and its sources and enabling capabilities, research issues and future prospects, core enabling technologies, and big data applications and their sustainability effects and benefits (specifically covering a critical evaluation of topical studies, analytical and practical applications for multiple smart/smarter city domains, and data-driven sustainable smart cities). "The main scientific and intellectual challenges and common open issues" section identifies the key scientific and intellectual challenges and sheds light on the common open issues associated with the use of big data analytics and related applications in (enabling, operating, managing, and planning) smart and smarter cities. The paper ends, in "Discussion, conclusion, and contribution" section, with concluding remarks, findings, reflections, and contributions.

Methodical-topical literature review methodology

This extensive review and synthesis involves the exploration of a vast and diverse array of literature on the topic (including journal articles, conference proceedings, books, reports, and dissertations), and integrates and fuses various disciplinary, scientific, and technological areas at the core of this study, with an emphasis on the qualitative research in the field. In light of this, and given moreover the nature of this topic, adopting a topical approach to this review and synthesis is deemed more relevant than a systematic one. Indeed, this paper determines the usefulness of this substantive category of review and synthesis to this endeavour. In addition, this review and synthesis is methodical in the sense that it is arranged according to, characterised by, or performed with a method or order. Also, it is done based on a loose coupling of technical and social perspectives (e.g., [87, 140]). In view of that, a review and synthesis method is developed as a means to indicate the issues (concepts, theories, academic discourses, themes, and topics) to be addressed, search strategy for retrieving the sought articles and other documents, inclusion and exclusion criteria for identifying and selecting the relevant ones, and abstract review protocols. Prior to delving into such method, it is useful to elucidate what the interdisciplinary and transdisciplinary approach entails in the context of this paper.

Interdisciplinary and transdisciplinary approach

Interdisciplinarity and transdisciplinarity have become a widespread mantra for research within diverse fields, accompanied by a growing body of academic publications. The field of sustainable smart and smarter cities is profoundly interdisciplinary and transdisciplinary in nature, so too is research within, and thus literature on, it. This also applies to any review and synthesis of this literature, which is accordingly multidisciplinary as well in the sense of using insights and methods from several disciplines, or involving several disciplines in an approach to a problem or topic. These disciplines include, but are not limited to: urban planning, urban development, geography, sustainable development, sustainability science, environmental science, data science, computer science, ICT, systems thinking, complexity science, policy, and innovation. However, multidisciplinary efforts remain limited in impact on theory building for coping with the changing human condition [99]. Clearly, sustainable smart and smarter city research naturally lends itself to multidisciplinary, interdisciplinary, and transdisciplinary approaches and strategies (e.g., [20, 138]). For a descriptive account of the interdisciplinary and transdisciplinary approaches to research, the interested reader can be directed to Bibri [20, 22]. However, they all require conceptual precision in order for research outcomes to be valid and usable (e.g., [89]). In all, this interdisciplinary and transdisciplinary literature review and synthesis is a topical, analytical, and organisational unit that is justified and determined by the essence and orientation of the research field of sustainable smart and smarter cities in terms of the underlying scholarly approach. As such, it is an opportunity to situate the researcher in an ecology of ideas, a process which can be approached from the perspective of complexity and intricacy. In this respect, the key dimensions that can be considered, especially in relation to transdisciplinarity, include: integrating rather than eliminating the researcher from the research, meta-paradigmatic rather than intra-paradigmatic, research-grounded rather than discipline-grounded, and applying systems and complexity thinking rather than reductionism.

Hierarchical search strategy and scholarly sources

A literature search is the process of querying quality scholarly literature databases to gather applicable research documents related to the topic under review. A broad search strategy was used, covering several electronic search databases, including Cristin, NTNU Open, Scopus, ScienceDirect, SpringerLink, ACM digital library, and Sage Journals, in addition to Google Scholar. The main contributions came from the leading journal articles in relevance to the topic on focus. The hierarchical search approach to searching for literature involved the following:

- Searching databases of reviewed high quality literature;
- Searching evidence based journals for review articles; and,
- Routine searches and other search engines.

In addition, the collection process is based on [111] four criteria for assessing the quality of the sought material, namely:

1. Authenticity: the evidence gathered is genuine and of unquestionable origin.
2. Credibility: the evidence gathered is free from error and distortion.
3. Representation: the evidence obtained is typical.
4. Meaning: the evidence gathered is clear and comprehensible.

Selection criteria: inclusion and exclusion

To find out what has already been written on the topic of this multifaceted study, the above search approach was adopted, whose objective was to identify the relevant studies addressing the diverse research strands that constitute this interdisciplinary and transdisciplinary review and synthesis. The preliminary selection of available material was done in line with the issues being investigated as pertaining to those strands, using a variety of sources that are up-to-date and authoritative.

The selection was initially bounded with the issues intended to be investigated in relation to the topic of this study. This is underpinned by the recognition that once the research issues are set, it becomes possible to refine and narrow down the scope of reading, although there may seem to be hundreds of sources of information that appear pertinent [25]. With that in mind, for an article or document to be considered of relevance for providing information or evidence on the issues in question, it should cover one of the conceptual/theoretical subjects or thematic/topical categories intended to be examined, as demonstrated by the sections and subsections of this paper. The focus was on the articles and documents that provided definitive primary information or evidence from an interdisciplinary and/or transdisciplinary perspective. While certain methodological guidelines were deemed essential to ensure the validity of the review, it was of equal importance to allow flexibility in the application of the topical literature review and synthesis methodology to capture the essence of research within the interdisciplinary and transdisciplinary field on focus. The whole idea was to 'accumulate a relatively complete census of relevant literature' [140]. In all, scoring the articles and documents was based on the inclusion of issues relating to the topic on focus. Conversely, the articles and documents excluded were those that did not meet specific criteria in terms of their relevance to the issues being addressed. As to abstract review, the abstracts were reviewed to assess their pertinence to the review and to ensure a reliable application of the inclusion and exclusion criteria. Inclusionary discrepancies were resolved by the re-review of abstracts. The process allowed to further refine and narrow down the scope of reading.

The keywords searched included 'smart cities', 'smart cities AND sustainability', 'smart cities AND big data analytics', 'smart cities AND big data applications', 'smart cities AND sustainability AND big data applications', 'smart cities AND sustainable cities', 'smarter cities AND sustainability', 'smarter cities', 'ambient cities', 'sentient cities', 'ubiquitous cities', 'real-time cities', 'data-driven cities', 'smart cities and the IoT', 'smarter cities AND big data applications', and 'smarter cities AND sustainability AND big data applications', and 'urban sustainability AND big data applications', and 'sustainable urban development and smart applications', in addition to the derivatives of these keywords. These were used to search against such categories as the articles' keywords, title, and abstract to produce some initial insights into the topic. To note, due to the potential limitations associated with relying on the keyword approach, backward literature search (backward authors, backward references, and previously used keywords) and forward literature search (forward authors and forward references) were additionally used to enhance the search approach [140].

Combining three organisational approaches

This literature review and synthesis is structured using a combination of three organisational approaches, namely thematic, inverted pyramid, and the benchmark studies. That is to say, it is divided into a number of sections representing the conceptual and theoretical subjects and the thematic and topical categories for the topic of sustainable smart and smarter cities. The examination and discussion of relevant issues is organised accordingly while, when appropriate, starting from a broad perspective and then dealing with a more and more specific one in terms of studies. In doing so, the focus is on the major writings and publications considered as significant in the field.

Purpose

The literature review is typically performed to serve many different purposes, depending on whether or not it is motivated by, or an integral part of, a research study, as well as on its focus, scope, and aim. Within the scope of this paper, however, it was carried out with the following specific objectives in mind:

- To examine and discuss the underlying foundational constructs and their integration and fusion from an interdisciplinary and transdisciplinary perspective, respectively.
- To analyse, evaluate, and synthesise the existing knowledge in line with such constructs as set for this study.
- To highlight the strengths, weaknesses, omissions, and contradictions of the existing knowledge, thereby providing a critique of the research that has been done within the field and related subfields.
- To discuss the identified strengths and weaknesses, with an emphasis on the performance of smart and smarter cities with respect to sustainability and the untapped potential of big data applications for its advancement in the future.
- To identify and discuss the knowledge gaps and opportunities within the field with regard to sustainability and related big data applications.

- To identify the key relationships between the research findings by comparing various studies addressing the different topics of the study, with a particular focus on sustainability and related big data applications.

Conceptual, theoretical, and discursive foundations and assumptions

Smart cities

According to a recent review conducted by Bibri and Krogstie [25], the roots of the smart city concept date back to the 1970s under what is labeled the 'cybernetically planned cities', and then in urban development and planning proposals associated with networked or wired cities since the 1980s. Several views claim that the concept was introduced in 1994 [38], and that it is only until 2010 that the number of publications and scientific writings on the topic increased considerably, after the emergence of smart city projects as supported by the European Union [65]. As echoed by Neirotti et al. [102], the smart city concept's origin can be traced back to the smart growth movement during 1990s. Yet, it is not until recently that this movement led this concept to be adopted within urban planning and development [16]. However, regarding its early conceptualisation and connotation, the concept was mostly associated with the efficiency of technological smart solutions with respect to the operational functioning, management, and planning pertaining to energy, transport, physical infrastructure, distribution and communication networks, economic development, service delivery, and so forth. Smart growth implies the ability of achieving greater efficiencies through coordinating the forces that lead to free growth (do-nothing policy): transportation, land use speculation, resource conservation, and economic development, rather than letting the market dictate the way cities grow [16]. At present, however, many cities across the globe compete to be smart cities in the hopes of reaping the efficiency benefits economically, socially, or, more recently, environmentally by taking advantage from the opportunities made possible by big data analytics and its wider application across urban domains. It is also in this context that it has increasingly become attainable to achieve the required level of sustainability, resilience, and equity, in addition to improving the quality of life and ensuring higher levels of transparency and openness and hence democratic and participatory governance, citizenry participation, and social inclusion. Achieving all these benefits require sophisticated approaches, advanced technologies and their novel applications and services, resources, financial capabilities, regulatory policies, and strategic institutional frameworks, as well as an active involvement of citizens, institutions, and organisations as city constituents. Worth noting is that the growing interest in building smart cities based on big data analytics as an advanced technology is increasingly driven by the needs for addressing the challenges of sustainability and to contain the effects of urbanisation. Besides, the main features of smart cities have become a high degree of information and technology integration and a comprehensive application of computing resources.

In recent years, the smart city as a catchphrase and phenomenon has drawn increased attention and gained traction among universities, research institutes, governments, policymakers, businesses, industries, and consultancies across the globe. Notwithstanding this prevalence worldwide, the smart city concept is still without a universally agreed definition. In other words, a shared definition of smart city is not yet available or offered. It is difficult to identify common trends of smart cities at global level [102]. Moreover, despite the wide use of the concept and its operationalisation today, there is still obscure and inconsistent understanding of its meaning (e.g., [2, 5, 8, 16, 20, 25, 36, 93, 119, 137]). Consequently, multiple meanings have been, and continue to be, adopted by different people within different contexts. The concept having different connotations and being approached from a variety of perspectives is clearly manifested in the various ways in which many governments set initiatives or implement projects to enable their cities to become, badge, or regenerate themselves as, or manifestly plan to be, smart. In all, a large number and variety of definitions (e.g., [3, 5]) have been suggested with different foci and orientations. Table 1 depicts a set of other definitions of smart cities with other foci and orientations.

The smart city continues to be a difficult concept to pin down or strictly delineate. The best way of looking at it is by the context within which it can be applied, as hinted at above. This implies that smart city projects, programs, and initiatives tend to be based on specific objectives, technological capabilities, financial abilities, human and social resources, regulatory policies, institutional frameworks, political mechanisms, governance arrangements, and so on [20]. They can also be determined or driven by the state-of-the-art research, development, and innovation in the area of ICT and related applications, infrastructures, platforms, systems, models, methods, computational analytics, and so forth. However, in relation to the objectives, for example, Batty et al. [16] identify a number of smart city projects, including modelling urban land use; modelling network performance; sensing, networking, and the impact of social media; mobility and travel behaviour; transport and economic interactions; integrated databases across urban domains; participatory governance and planning structures; and decision support as urban intelligence. Concerning the financial abilities, many governments are funnelling huge expenditures (colossal investments) into ICT research, development, and innovation, which is manifested in the high number of jointly funded research endeavours as well as smart initiatives and implementation projects (e.g., [2]).

Table 1 Definitions of smart cities

Different foci and orientations of smart city definitions
'A smart city is…a city which invests in ICT enhanced governance and participatory processes to define appropriate public service and transportation investments that can ensure sustainable socio-economic development, enhanced quality-of-life, and intelligent management of natural resources' [5]
'A smart city is a very broad concept, which includes not only physical infrastructure but also human and social factor' [102]
'Connecting the physical infrastructure, the IT infrastructure, the social infrastructure, and the business infrastructure to leverage the collective intelligence of the city… A city striving to make itself "smarter" (more efficient, sustainable, equitable, and livable' [36]
'Smart cities is a term…that describe cities that, on the one hand, are increasingly composed of and monitored by pervasive and ubiquitous computing and, on the other, whose economy and governance is being driven by innovation, creativity and entrepreneurship, enacted by smart people' [79, p. 1]
A smart city is 'a city in which ICT is merged with traditional infrastructures, coordinated and integrated using new digital technologies' [16]
'As presently understood, a smart city is one that strategically uses networked infrastructure and associated big data and data analytics to produce a: *smart economy*…; *smart government*…; *smart mobility*…; *smart environments*…; *smart living*…; and *smart people*…' [80, p. 8]

Yet, scholars, academics, planners, ICT experts, and policymakers converge on the idea that the use of ICT pertains to all domains of smart cities, and hence on considering it as an inseparable facet thereof [20]. In this line of thinking, a common thread running in most of the definitions of smart city is its characteristic features and technological components, which are usually observed in smart city proposals, projects, and initiatives, irrespective of their scale, scope, national context, and available resources. In the context of this paper, however, a smart city can be described as a city that is increasingly composed of, and monitored and operated by, various forms of pervasive computing, as well as whose planning and governance are being driven by innovation as enacted by various stakeholders that capitalise on and exploit cutting-edge technologies in their endeavours and practices. In this light, being instrumented and pervaded with digital devices, systems, and platforms that generate big data, smart cities can enable real-time analysis of urban life, environment, and dynamics as well as new modes of urban planning and governance, and also provide the conditions that are conducive to envisioning and enacting more sustainable, efficient, resilient, transparent, and open human and urban environments. Accordingly, a smart city can also be taken to mean a technologically and data-analytically advanced city that is able to understand its environment and citizens and explore and analyse various forms of urban data to generate useful knowledge in the form of applied intelligence that can immediately be used to solve different kinds of problems, or to make changes to improve the quality of life and the health of the city in terms of sustainability, efficiency, and resilience. In this line of conceptualisation, Batty et al. [16] describe smart cities as 'constellations of instruments across many scales that are connected through multiple networks which provide continuous data regarding the movements of people and materials in terms of the flow of decisions about the physical and social form of the city'. However, the financial abilities, human/social resources, and regulatory policies required to develop, implement, and sustain smart cities are the most significant challenges governments around the world are concerned about and are dealing with. Positively, the emerging technologies such as big data analytics hold great potential to transform such challenges into opportunities.

Furthermore, based on a recent survey of the field of smart cities [25], there are two main approaches to smart city: (1) the technology-oriented approach, i.e., infrastructures, architectures, platforms, systems, applications, and models and (2) the people-oriented approach, i.e., stakeholders, citizens, knowledge, services, and related data [20]. In other words, there are smart city strategies that focus on the efficiency and advancement of hard infrastructures in terms of transport, energy, communication, and distribution networks, and so on (e.g., [45, 52, 74, 79, 83, 93]) and those that prioritise the soft infrastructures in terms of social and human capital, participation, equity, safety, cultural heritage, and so forth (e.g., [7, 17, 75, 76, 88, 102]). There are also smart city strategies that combine these two perspectives (e.g., [16, 73]). To gain a broad understanding of the concept of smart city, the interested reader can be directed to Song et al. [119] who provide a detailed overview of the foundations, principles, and applications of smart cities. Also, Nam and Pardo [101] conceptualise smart city with the dimensions of technology, people, and institutions.

It is of particular relevance in this paper to highlight the body of the literature focusing on the defining role of ICT (e.g., big data analytics and its application) as well as human and social capital in smart cities in terms of the dimensions of sustainability (e.g., [5, 6, 10, 16, 82, 102]). This strand of research is concerned with smart cities as urban innovations whose focus is on advancing, harnessing, and integrating physical, human, and social infrastructures for environmental protection, economic regeneration, and enhanced public and social services [20]. The most cited definition in this regard is provided by Caragliu et al. [30]: a city is smart city '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 a wise management of natural resources, through participatory governance.' This definition is linked to a model that has been used as a ranking system—developed based on six smart dimensions, namely, economy, environment, mobility, living, people, and governance—against which smart cities can be assessed in terms of their development and implementation. However, this model neither specifies how these dimensions can be prioritised as to the contribution to sustainability, nor how they can, combined, add value to sustainable development. However, as an extension of this definition, Pérez-Martínez et al. (2013, cited in [2]) describe smart cities as 'cities strongly founded on ICT that invest in human and social capital to improve the quality of life of their citizens by fostering economic growth, participatory governance, wise management of resources, sustainability, and efficient mobility, whilst they guarantee the privacy and security of the citizens.' In this line of thinking, Batty et al. [16, pp. 481–482] describe smart cities as cities 'in which ICT is merged with traditional infrastructures, coordinated and integrated using new digital technologies,' and where 'intelligence functions…are able to integrate and synthesise…[urban] data to some purpose, ways of improving the efficiency, equity, sustainability, and quality of life in cities.' In all, this view of smart cities highlights—at the level of discourse though—the potential of ICT in catalysing and improving sustainable development processes. In this context, a sustainable smart city is an innovative city that uses ICT and other means to improve the efficiency of urban operations, functions, and services as well as enhance the quality of life of citizens, 'while ensuring that it meets the needs of present and future generations with respect to economic, social, environmental as well as cultural aspects' [130].

In light of the above analytical account, the available definitions of smart cities have several commonalities as well as distinctions, i.e., converging on some dimensions and diverging on others apart from technological aspects, including economic, environmental, physical, political, social, cultural, institutional, organisational, and futuristic, in addition to the extent of different sustainability dimensions and their integration. Yet, the majority of these definitions tend to focus on integrated solutions for achieving a sustainable utilisation of resources, efficient operation of infrastructures and facilities, high quality of life, and effective urban planning and governance. In more detail, as an attempt to provide a comprehensive definition of smart city from a generic perspective that combines the core features of smart cities as a broad concept [20], describes smart city as a city that badges or regenerates itself as smart, or manifestly plans to be so, in terms of achieving efficiency, sustainability, resilience, equity, and livability by investing in, and hence enhancing and continuously advancing, the ICT infrastructure, physical infrastructure, economic infrastructure, and social infrastructure to leverage collective intelligence for the purpose of integrating urban systems and coordinating urban domains in ways that these components exceed their sum as to the collective behaviour of the whole city. In other words, it is an innovative city that focuses on developing, implementing, and applying advanced ICT to all its systems and domains, and accordingly perform in an innovative, forward-looking, strategic, and participatory way to enhance its key features: environment, economy, people, mobility, living, and governance, on the basis of the intelligent combination of endowments and activities of independent and aware citizens together with other urban stakeholders (organisations, institutions, industries, enterprises, etc.), thereby ensuring and maintaining socio-economic development, the quality of life, the efficiency of service delivery, the intelligent management of natural resources, and the optimised operation of infrastructures and facilities—ideally in line with the fundamental goals of sustainable development.

Smarter cities and other faces of cities

Smart cities come in many faces depending on the way ICT is applied, the extensiveness of its use, the degree and form of its ubiquity, and/or the focus of its orientation, as well as the kind of digital technology by which it is coordinated and integrated [20]. The common faces that emerged before, or in parallel with (only for a few of them), the adoption of the concept of smart city in urban planing and development around the mid 1990s include: networked cities, wired cities, cyber cities, digital cities, virtual cities, intelligent cities, knowledge cities, and cyber cities, among other nomenclatures. For example, digital cities tend to focus on the hard infrastructure whereas intelligent cities on the way such infrastructure is used [12–14], and wired cities embrace ICT as a development strategy, pioneer in embedding digital infrastructure and systems into their urban fabric and utilize them for entrepreneurial and regulatory effect [43]. However, they all share a focus on the effects of ICT on urban forms, processes, and modes of living, and have largely been subsumed within the label 'smart cities' in recent years, although each of those terms is used in a particular way to conceptualize the relationship between ICT and contemporary urbanism [79]. There are also hybrid cities which merge two faces of smart cities or one from smart/smarter cities and one from sustainable cities, such as cyber-physical cities, ubiquitous eco-city, knowledge eco-city, and smart compact city, and so forth. In addition to these faces are the ones that are inspired by the prevalent ICT visions of pervasive computing, including ambient cities, sentient cities, ubiquitous cities, real-time cities, and cities as Internet-of-everything (e.g., [79, 84, 105, 108, 113, 114, 123, 143]). For example, the real-time city is likely to become a reality in many cities over the next decade, as urban administrations seek to capitalise on new data streams and new products are bought to market that help governments and citizens make sense of the city [79]. These cities have materialised as a result of the advance of ICT of pervasive computing, or rather the evolvement of the dominant ICT visions into achievable and deployable computing paradigms. Seen as future forms of smart cities, they are quite different from what has been experienced hitherto in terms of smartness and its effects on human life at several levels. They have come to be identified or labelled as 'smarter cities' due to the magnitude of ICT and the extensiveness of data with regard to their application and use across urban systems and domains. The prospect of smarter cities is increasingly becoming the new reality with the massive proliferation of the core enabling technologies underlying ICT of pervasive computing, namely sensor networks, data processing platforms, wireless communication networks, and cloud and fog computing models across different spatial scales [25]. The initiatives of smarter cities in several countries across Europe, the USA, and Asia are considered as national urban development projects epitomising the increasing significance and role of advanced ICT, especially big data analytics, in enhancing the operations, functions, services, strategies, and policies of smart cities of the future associated with planning, management, development, and governance [20]. The conceptualisation of smarter cities is built upon the core features of the prevalent ICT visions in terms of the pervasion of technology into the very fabric of the city, the omnipresence and always-on interconnection of computing resources, applications, and services across many spatial and temporal scales. The emerging connotations of smart cities of the future or smarter cities are numerous. Townsend [124] defines a smart city as an urban environment where ICT 'is combined with infrastructure, architecture, everyday objects, and even our own bodies to address social, economic and environmental problems'. Piro et al. [106] conceive of it 'as an urban environment which, supported by pervasive ICT systems, is able to offer advanced and innovative services to citizens in order to improve the overall quality of their life'. Su et al. [121] describe it as city which mainly focuses on embedding the next-generation of ICT into every conceivable object or all walks of life, including roads, railways, bridges, tunnels, water systems, buildings, appliances, hospitals, and power grids, in every corner of the world, and constituting the IoT. In addition, the concept of smarter cities has been associated with the orientation of smart cities towards achieving the goals of sustainability in the future. In this line of thinking Chourabi et al. [36], describe a smart city as a city which strives to become smarter as to making itself more sustainable, equitable, efficient, and livable. This is also consistent with what smart cities of the future entail according to Batty et al. [16]. The underlying assumption is that smarter cities or smart cities of the future have tremendous potential compared to current smart cities as to advancing sustainability. Indeed, there has recently been a conscious push for cities in Europe to be smarter and thus more sustainable, leading to the need to benchmark these cities' efforts using advanced assessment frameworks to rank them based on how smarter and more sustainable they are. For a detailed account of smarter cities, the interested reader can be directed to Bibri [20] where there is a whole chapter about the transition of smart cites to smarter cities and the future potential of the underlying ICT of pervasive computing for advancing environmental sustainability. This is projected to happen because of the prospective advancements and innovations pertaining to big data analytics as an advanced form of ICT (e.g., [5, 16, 20]).

In light of the above, a smarter city can be understood as a city where advanced ICT is combined with physical, infrastructural, architectural, operational, functional, and ecological systems across many spatial scales, as well as with urban planning processes and governance models, with the primary aim of improving sustainability, efficiency, equity, and livability. Here, smartness should go beyond the technological advancement and efficiency of solutions to include a focused orientation towards incorporating, considering, and achieving the goals of sustainable development. Of relevance to underscore here is that current smart cities strive for smartness targets instead of sustainability goals (e.g., [2, 93]). In all, common to all smart cities of the future or smarter cities as urban development approaches is the idea that ICT is, and will be for many years yet to come, central to urban operations, functions, services, strategies, and policies.

Irrespective of which ICT vision smart cities of the future or smarter cities tend to instantiate or be built upon, whether be it Sentient Computing, Ambient Intelligence, Ubiquitous Computing, the IoT, or a combination of two or more of these technological visions, such cities are taken to mean urban spaces loaded with clouds of data intended to shape the life and experience of citizens and bring about major transformations to their environments. Here, big data analytics is given a prominent role, as all over the city, the underlying core enabling technologies can monitor urban areas (in terms of activities, citizen behaviours, events, social dynamics, locations, spatiotemporal settings, environmental states, etc.); analyse, interpret, evaluate, model, and simulate the continuously collected steams of data; and then deploy the obtained results in the form of intelligence and planning functions applicable to various urban domains across several spatial scales. While the current notion of smart cities can 'be understood as a collection of plural research traditions, performed and commissioned by divergent actors all with their own motivation and implicit understanding of what a city is or should be' [113], the impetus behind the concept of smarter cities or smart cities of the future [16, 20] based on big data analytics and its application—is to mobilise and align urban stakeholders through research and development endeavours for the purpose of promoting and advancing sustainability by using advanced ICT to continuously evaluating and strategically planning the contribution of such cities to the goals of sustainable development [20]. Indeed, this goal of big data analytics and its application in smarter cities is more in conjunction with the aspiration and intention of the diverse stakeholders that support the integration of big data technology and the associated information sources.

Big data computing

Big data: concept and characteristics

There is no definite definition of big data. Therefore, many definitions have been suggested and are available in the literature, with each tending to offer a particular or different view of the concept based on the context of use and hence serving as, as one way of looking at it, a constituting or complementary aspect of the full picture of the concept. For example, a survey of the emerging literature conducted by Kitchin [79] denotes a number of key characteristic features. Big data are:

- Huge in *volume*, consisting of terabytes or petabytes of data;
- High in velocity, being created in or near real-time;
- Diverse in *variety*, being structured and unstructured in nature, and often temporally and spatially referenced;
- *Exhaustive* in scope, striving to capture entire populations or systems (n = all), or at least much larger sample sizes than would be employed in traditional, small data studies;
- Fine-grained in *resolution*, aiming to be as detailed as possible, and uniquely indexical in identification;

- *Relational* in nature, containing common fields that enable the conjoining of different data sets;
- *Flexible*, holding the traits of extensionality (can add new fields easily) and scaleability (can expand in size rapidly).

A great deal of the existing definitions tend to converge on three main attributes of big data: the huge *volume* of data, the wide *variety* of data types, and the *velocity* at which the data can be collected and analysed. These are identified as the most agreed upon Vs (e.g., [49, 86]). Yet, big data tend to be characterised by a number of other Vs than these three, including inveracity, validity, value, and volatility (e.g., [72]). See Bibri [20] for a descriptive account of these Vs. In the context of this paper, the term 'big data' is essentially used to mean collections of datasets whose volume, velocity, variety, exhaustivity, relationality, and flexibility make it so difficult to manage, process, and analyze the data using the traditional database systems and software techniques. In other words, big data refer to humongous volumes of both structured and unstructured data that cannot be processed and analysed with conventional applications, or that exceed their computational and analytical capabilities. However, as a common thread running through most of the definitions of big data, the associated information assets are, to reiterate, of high-volume, high-variety, and high-velocity, and thus require cost-effective, innovative forms of data processing, analysis, and management. In the context of smart and smarter cities, the term can be used to describe a colossal amount of urban data, typically to the extent that their manipulation, analysis, management, and communication present significant computational, analytical, logistical, integrative, and coordinative challenges. Such data are invariably tagged with spatial and temporal labels, commonly streamed from a large number and variety of sources, and mostly generated automatically and routinely; hence, it is near on impossible to make sense of, or decipher, the big data generated in smart and smarter cities based on computing technology in current use [20]. Therefore, the big data deluge flooding within smart and smarter cities entails rather the use of novel technologies and their integration in terms of algorithms and techniques that are based on supervised and unsupervised learning methods (e.g., classification, clustering, regression, causal modelling, etc.), techniques (e.g., data mining, machine learning, statistical analysis, database querying, etc.), and processing platforms (Hadoop, Spark, HBase, MongoDB, etc.) that could work beyond the limits of the existing analytic systems employed to extract useful knowledge from large masses of data for timely and accurate decision-making and enhanced insights.

Big data analytics: concept and characteristics

The term 'big data analytics' denotes 'any vast amount of data that has the potential to be collected, stored, retrieved, integrated, selected, preprocessed, transformed, analyzed, and interpreted for discovering new or extracting useful knowledge. Prior to this, the analytical outcome (the obtained results) can be evaluated and visualised in an understandable format before their deployment for decision-making purposes (e.g., an enhancement of, or a change in, an operation, function, service, design, strategy, or policy). Other computational mechanisms involved in big data analytics include search, sharing, transfer, querying, updating, modelling, and simulation. In the context of sustainable smart and smarter cities, big data analytics refers to a collection of sophisticated and dedicated software applications and database management systems run by machines with very high processing power, which can turn a large amount of urban data into useful knowledge for enhanced, well-informed decision-making and deep insights in relation to various urban domains, such as transport, mobility, traffic, environment, energy, land use, waste management, education, healthcare, public safety, planning and design, and governance' [21, p. 234].

The common types of big data analytics being used in the context of smart and smarter cities are: descriptive, predictive, diagnostic, and prescriptive [20]. They are to be applied to extract useful knowledge of different forms of intelligence from large datasets, which can in turn be used to serve various purposes depending on the urban application domain. As far as the complexity of big data analytics is concerned, it is commonly characterized by four Is, namely (1) In-situ analytics which directly operates on the data where it sits without requiring an expensive process of Extract, Transform, Load (ETL), (2) interactive analysis where the analysts work interactively with data and the subsequent questions are formulated depending on the results of the previous ones, (3) incremental analysis which requires maintaining models under high data arrival rates and datasets be interactively analyzed based on the previous results, and (4) iterative analysis which iterates over the data several times in order to build and train a model of the data (e.g., predictive data mining) rather than just extract data summaries or make grouping (e.g., descriptive data mining).

Big data processing platforms

There exist many data processing platforms that can be used to perform big data analytics in terms of storage, manipulation, management, analysis, and evaluation of large masses of data to extract useful knowledge deployable in the form of intelligence in relation to various urban domains as to operations, functions, strategies, designs, and policies. The use and implementation of such platforms depend, or vary based, on several factors pertaining to the computational, analytical, logistic, integrative, and coordinative requirements of big data projects as well as their objectives (e.g., environmental sustainability, social sustainability, public services, etc.). Among the existing data processing platforms being used in smart and smarter cities based on cloud computing and fog/edge computing (see [21] for a detailed account and comparison of these two models) include Hadoop MapReduce, Spark, Stratosphere, and NoSQL-database system management (e.g., [5, 20, 49, 69, 73, 115]). These platforms 'perform big data analytics related to a wide variety of large-scale applications intended for different uses associated with the process of sustainable urban development, such as management, control, optimisation, assessment, and improvement, thereby spanning a variety of urban domains and sub-domains… Thus, they are prerequisite for data-centric applications in the context of sustainable smart and smarter cities' [21, p. 203].

Underpinning technologies

As a new paradigm, big data computing amalgamates, as underpinning technologies, large-scale computation as well as new data-intensive techniques and algorithms and advanced mathematical models to build and perform data analytics. It demands a huge storage and computing power for data curation and processing for the purpose of discovering new or extracting useful knowledge typically intended for immediate use in an array of multitudinous decision-making processes to achieve different purposes. It entails the following components, of which [23] provides a descriptive account:

- Advanced techniques based on data science fundamental concepts and computer science methods.
- Data mining models.
- Computational mechanisms involving such sophisticated and dedicated software applications and database management systems.
- Advanced data mining tasks and algorithms.
- Modeling and simulation approaches and prediction and optimization methods.
- Data processing platforms.
- Cloud and fog computing models.

Big data application

Big data analytics has become a key component of the ICT infrastructure of smart and smarter cities due to its role in improving sustainability, resilience, efficiency, and the quality of life (e.g., [5, 6, 16, 20–22, 25, 26, 54, 83]) through effective decision-making processes and thus desired outcomes. In this context, it targets the intelligent decision support and optimisation and simulation associated with the operational functioning, planning, design, and development of urban systems as operating and organizing processes of urban life in terms of control, automation, management, efficiency, enhancement, and prediction as urban intelligence functions. One example of such functions concerns the provision of ecosystem services and the delivery of human services, as well as the effectiveness of strategies and policies based on emerging trends and shifts, in line with the long-term goals of sustainability [20]. The target of big data analytics entails the implementation of decision-taking processes, optimization strategies, and simulation models. All in all, there is a growing consensus that big data analytics and its application will create and enable, in light of the projected advancements and innovations within related platforms, techniques, processes, and methods, immense possibilities and fascinating opportunities in the near future.

A detailed survey of relevant work: issues, debates, gaps, benefits, challenges, opportunities, and prospects

Smart and smarter cities

Research strands from a general perspective

In the field of smart and smarter cities, research in its various forms is inherently interdisciplinary and transdisciplinary and remarkably heterogeneous in terms of programs and endeavours. As such, it involves a plethora of issues, debates, challenges, risks, impacts, benefits, opportunities, prospects, trends, global shifts, and practices, or an amalgamation of these. In this respect, the topic of smart and smarter cities brings together a wide variety and large number of studies, including research directed at conceptual, theoretical, applied theoretical, analytical, empirical, practical, discursive, futuristic, visionary, socio-technical, and so on with such directions as computational, technical, technological, architectural, environmental, spatial, social, political, cultural, institutional, economic, and overarching. Indeed, the recent years have witnessed a great interest in, and a proliferation of publications and scientific writings on, the topic of smart and smarter cities from diverse multi-perspectival approaches, reflecting the magnitude, breadth, depth, and heterogeneity of research within the field [20, 25]. This continues to rapidly and dynamically evolve with varied and new emphases and aims, as well as with more integrated and holistic approaches, manifested in the miscellaneous contributions being, and will continue to be, made or produced by a great deal of researchers, scholars, academics, planners, and experts to the conceptualisation, design, development, and implementation of smart and smarter cities and related future visions. In all, the field of smart and smarter cities merges broad streams of scholarship, which entail many research strands, and as the body of literature on smart and smarter cities has evolved remarkably over the past 10 years or so, new social issues and concerns have been brought to the analysis, and new uses of technology and their ends have been proposed and criticised, respectively. Speaking of such issues and concerns, to note, the challenge is that, as pointed out by Lytras and Visvizi [89], research originating in the social sciences tends to reduce the centrality of ICT in smart city research, and hence, the depth and breadth of implications that emerge at the intersection of ICT in urban spaces and innate social problems remain underexplored.

In a recent extensive interdisciplinary literature review [25], provide a comprehensive review of the field of smart and smarter cities in terms of the underlying foundations and assumptions, state-of-the art research and development, research opportunities and horizons, emerging scientific and technological trends, and future planning practices. There are several research strands addressed in their review, which can be seen from a general perspective in the context of this paper. Theses strands (supported by recent research) are presented below:

Theory and practice The theory and practice of urban computing, urban ICT, and urban science and related sub-areas (e.g., data sensing, big data analytics, context-aware computing, urban informatics, cloud computing, fog/edge computing, middleware infrastructures, intelligence functions, simulation models, database management and integration, wireless communication networks, decision-support systems, etc.) and their relation to the operational functioning, management, planning, development, and implementation of smart and smarter cities with respect to such diverse urban domains as energy, natural environment, built environment, transport, mobility, traffic, water, waste, design, education, healthcare, public safety, governance, economy, and science and innovation. The main focus of this strand of research is on the advancement, use, and application of ICT of ubiquitous computing for optimisation, control, automation, management, and assessment purposes, particularly in relation to economic development, service delivery, and the quality of life. Owing to its origins, smart and smarter city research remains dominated by analytical perspectives and applicable insights from broadly conceived ICT of pervasive computing. Even though smart and smarter city research has, over the past few decades, transformed into a multidisciplinary, interdisciplinary, and transdisciplinary field, housing, integrating, and fusing a variety of domains and disciplines, it is still heavily based on computer science and engineering, with an explicit focus on how advanced technologies and their applications and services may be applied in urban environments [22, 89].

Conceptual and theoretical work The body of the conceptual and theoretical work focuses on developing and examining the existing definitions and theoretical models to provide both a shared conceptualisation and understanding of smart and smarter cities as well as a basis for discussions or debates on what the smart and smarter city approach aspires or claims to deliver with respect to smartness and sustainability and their integration and synergy. The second part of this strand of research focuses further on the theories and academic discourses underpinning the thinking about and the conception of the subject and phenomenon of smart and smarter cities. It is concerned with analysing the discourse of smart urban development and discussing how diverse political mechanisms and policy measures are devised and implemented to institutionalise this discourse, and therefore make it function and culturally and publicly disseminate it, as well as how the ensuing decisions are made in relation to the implementation of ICT and its use for operationalising smart urban development. Among the issues related to this strand of research involve the definition of theoretical terms and models and the creation of discursive notions and constructions along with different understandings, adding to how these underlying issues are germane to the subject of smart and smarter cities. Accordingly, 'this subject has a theoretical base that is open to interpretation, evaluation, and examination, or in it, theoretical debate seems to be rife and a key aspect of the discipline of smart urban planning and development. Having a practical application, the subject of city within this discipline relies on theoretical assumptions and foundations. And it requires environmental, social, cultural, economic, and physical issues to be addressed…, as well as institutional priorities and technological considerations…to be set apart from theoretical matters of urban planning and development as internally consistent models… In all, this strand of research is concerned with comparing and evaluating concepts and approaches, weighing up arguments, rethinking issues, and challenging discursive assumptions' [25, p. 15].

Analytical work The analytical work investigates propositions about what makes a new city badges itself, and an existing city regenerates itself, as smart, or what shows that a city is manifestly planning to become smart, as well as the extent to which a modern city uses advanced ICT to fashion advanced urban intelligence functions and simulation models pertaining to different domains and thus directed for various purposes. This strand of research covers descriptions, elaborations, assessments, and/or classifications of smart and smarter cities based on the use and application of emerging and future ICT in relation to operations, functions, services, designs, strategies, and policies by analysing previous and ongoing projects, initiatives, and programs and their potential effects on the different aspects of urbanity. The recent propositions being investigated tend to put an emphasis on specific technologies (e.g., big data analytics, context-aware computing, cloud and fog computing, etc.) and their novel applications and services, along with the challenges involved in achieving various smart and smarter city statuses accordingly.

Advanced ICT impacts The impacts advanced ICT can have on how we think about and conceive of cities in the sense that the technology propels us to rethink or alter some of the fundamental or established concepts and approaches through which we understand, analyse, operate, organise, assess, and value urban life towards creating and discovering novel ways of living and working in the city and interacting with the environments in terms of, for example, sustainability. Here, the argument is that smart and smarter cities may thrive further or get smarter by leveraging their informational landscape in ways that allow to improve and maintain their contribution to the goals of sustainable development. This is due to the fact that ICT is founded on the application of data science and complexity science, which are well positioned to tackle the complex challenges of urbanisation and sustainability. The focus in this context is on understanding the link between the smart and smarter city technologies and their pertinence for providing innovative solutions for sustainability. In this case, the cities standing on a smartness scale spectrum can well embrace and pursue the goals of sustainable development through related initiatives, programs, and projects, and thereby achieve the required level of sustainability as to operations, functions, services, strategies, designs, and policies within urban domains.

Deficiencies and misunderstandings pertaining to sustainability The emphasis in this strand of research is on the lack or week connection between smart cities and sustainable cities, and whether or the extent to which the concept of smart and smarter city incorporates the goals of sustainable development. In this regard, it has been argued that the existing definitions of smart and smarter city set up no baseline for sustainability, and do not include what sustainable development entails, although defining this concept is of crucial importance for identifying and specifying the purpose for which smart solutions should be used and applied, and also for assessing whether or the degree to which such solutions contribute to sustainability. In fact, the concept of smart and smarter city seems to say little about the manner in which the substance behind the smart solutions is linked to the goals of sustainable development, especially in relation to environmental sustainability.

A recent research wave has started to investigate technological propositions about what makes cities particularly smarter in terms of achieving the goals of environmental sustainability; however, these propositions are too often, if not always, mentioned without consideration of the rather established strategies (design concepts and principles and planning practices) through which environmental urban sustainability can be achieved, namely density, diversity, compactness, and mixed-land use, as well as ecological design, passive solar design, and sustainable transportation, in addition to environmental management and control, environmental policy, renewable energy, and design coding. The underlying premise is that ICT as an integrative and constitutive technology can make a substantial contribution to enhancing the outcome of these strategies if planned strategically and its implementation is directed for the purpose in the context of smart and smarter cities. The way forward is to adopt the cutting-edge solutions being offered by big data analytics and its novel applications and services associated with environmental sustainability. This strand of research is also part of, and hence, related issues are examined and discussed in, the next section given their high relevance to the topic of this study.

Scientific challenges The scientific challenges facing smart cities of the future or smarter cities and pertaining to the use and application of emerging and future technologies such as big data analytics and its novel applications. Such challenges include, but are not limited to, the monitoring of urban infrastructure and its connection with its operational functioning, planning, and development through control, automation, optimisation, management, and simulation; the exploration of the idea of smart and smarter cities as innovation labs in terms of developing and applying intelligence functions across different urban domains; the construction and aggregation of many urban simulation models pertaining to various urban systems and domains in terms of their integration and coordination, respectively, and thereby providing portfolios of such models that inform future designs; the development of effective technologies that ensure equity and fairness and improve the quality of city life; the optimisation of physical mobility and the improvement of virtual mobility for reducing environmental impacts and enhancing spatial and non-spatial accessibility to opportunities, services, and facilities for citizens; the creation of technologies that enhance citizen participation and engagement as well as create shared knowledge for democratic governance.

Potential risks of ICT to sustainability This strand of research looks at the negative implications of the development and implementation of smart and smarter cities in terms of the design, use, application, and disposal of ICT for environmental and social sustainability. Smart and smarter cities pose significant risks to the environment due to the massive use of ICT of pervasive computing. Driving this line of research is a set of questions addressing the way smart and smarter cities should measure and identify risks, uncertainties, and hazards associated with ICT use and set safety standards accordingly, i.e., sustainable design principles and environmental policies. The involved risks of ICT go beyond environmental sustainability to include social sustainability in terms of equity, fairness, participation, inclusion, privacy, security, and so on. In particular, it is important to address the digital divides pertaining to education, age, social status, culture, ethnicity, gender, and disability. Angelidou [9] found that most smart city strategies are poorly adapted to accommodate the local needs of their area, fail to incorporate bottom-up approaches, and fall short in considering issues of privacy and security. In a recent work, Carrasco-Sáez et al. [31] propose a new pyramid of needs for the digital citizens as a way of transitioning towards smart human cities or socially sustainable smart cities. Regardless, socio-economic factors affect the use of smart technologies, and to fully optimise their potential, such factors need to be addressed so that smart and smarter city technologies can play a part in contributing to sustainability. As stated by Batty et al. [16], 'New technologies have a tendency to polarise and divide at many levels and we need to explore how new forms of regulation at the level of urban transport and planning, and economic and community development can be improved using future and emerging technologies'. And one way this can be accomplished is by, according to the authors, balancing efficiency and equity. For a detailed account and discussion on the relevant digital gaps associated with ICT of pervasive computing, the interested reader can be directed to Bibri [19]. Visvizi and Lytras [134] address the role of policy in making smart cities more socially inclusive. Further, however, the most eminent threat of ICT in the context of smart and smarter cities lies in its multidimensional effects on the environment, as ICT as an enabling, Integrative, and constitutive technology is embedded into a much wider socio-technical landscape (economy, institutions, policy, politics, and social values) in which a range of factors and actors other than techno-scientific ones are involved. In addition, the prospect of smarter cities as future visions of smart cities is becoming increasingly the new reality with the massive proliferation of the core enabling technologies of ICT of pervasive computing across urban systems, domains, and environments. Indeed, they typically instantiate the dominating ICT visions in Europe, Asia, and the USA, namely Ubiquitous Computing, Ambient Intelligence, and the Internet of Things. The evolvement of this smart urban development approach is increasingly driven by the growing application of, and the rising demand for, big data analytics and its novel applications and services as a set of novel technologies. Of importance to underscore in this regard, though, is that these technologies need to be well understood when placing high expectations on and marshalling huge resources for developing and deploying smarter cities or smart cities of the future. There exist intricate tradeoffs and relationships between and among the positive impacts, negative effects, and unintended consequences of ICT of pervasive computing in relation to the environment—flowing mostly from the design, development, use, application, and disposal of ICT throughout smart and smarter cities [20]. Nevertheless, there are several potential ways to mitigate the potential risks pertaining to the development of ICT of pervasive computing and thus smart and smarter cities. Especially, most of the related novel applications are still under development, and thus, a lot more can be done in this direction prior to their deployment. It remains to see the extent to which new technological innovation opportunities will be embraced and exploited in this regard, and their effects be realised with regard to environmental sustainability in the context of smarter cities or smart cities of the future, in particular. Bibri [20] provides a detailed overview and discussion of the key technical, social, political, institutional, and organisational remedies to deal with the multiple effects triggered by, and associated with, the design, use, application, and disposal of ICT, including direct and indirect effects, rebound effects, systemic effects, and constitutive effects. See Bibri and Krogstie [24] for a detailed discussion. These remain, however, complex and intricate and thus problematic to tackle. Regardless, it is high time to link ICT research, development, and innovation with the agenda of sustainable development and thus to justify future ICT investments by environmental concerns and socio-economic needs in the context of smarter cities or smart cities of the future.

Frameworks, models, and infrastructures The smart and smarter city frameworks, models, and infrastructures are associated with the assessment, development, and implementation of smart and smarter cities, and are shaped by socio-cultural factors, technological capabilities, available resources, regulatory policies, institutional practices, and so on. The existing frameworks and models are being used to rank or benchmark the existing and emerging smart and smarter cities in relation to smartness and sustainability as well as their synergy and integration. They are based on a variety of dimensions with a set of factors or criteria gauging success, including mobility, environment, energy, transport, life quality, economy, and governance. The existing infrastructures involve the different aspects of ICT in terms of its development and implementation in smart and smarter cities (e.g., sensor technologies, data processing platforms, cloud and fog computing models, wireless communication networks, middleware infrastructures, etc.). The purpose is to provide a smart and smarter city basic backbone for enabling ICT-based control, automation, optimisation, management, and planning, as well as privacy and security in relation to urban operations, functions, services, designs, and policies.

All in all, the state of the scholarly research within the rapidly burgeoning interdisciplinary and transdisciplinary field of smart and smarter cities shows that the large body of the topical studies carried out thus far tend to focus largely on the advancement and potential of emerging and future technologies and their novel applications and services as new opportunities offering numerous benefits and robust solutions. This relates to diverse urban domains in terms of enhancing the efficiency of urban systems and improving the quality of life of citizens. However, the rapid pace of ICT development and innovation seems to happen ad hoc when new technologies and their applications and services become available—rather than grounded in a focused overall approach or directed to solving the most pressing issues and significant challenges associated with sustainability in an increasingly urbanised world. Indeed, more efforts need to be done for developing and implementing the kind of smart solutions that are oriented towards addressing, or for a realistic tackle of, environmental concerns and socio-economic needs, especially in the context of smarter cities or smart cities of the future. Findings from a recent study carried out by Angelidou et al. [6] suggest that the smart city and sustainable city landscapes are extremely fragmented both on the technological and policy levels, and that there is a host of unexplored opportunities and horizons toward new approaches to sustainable smart development, many of which are still unknown. Moreover, the research field of smart and smarter cities is currently fragmented due to its ill-defined character and scattered research programs, thereby fostering discontinuity, and consequently, smart perspectives remain too diverse to resolve [20]. At the practical level, to add, there is a great deal of diversity among smart and smarter cities in terms of the previous and ongoing projects and initiatives. And in this sense, it is of relevance to look at the smart and smarter city endeavour as an ambition which can be driven by a wide range of target objectives as well as available resources, technical capabilities, and policy regulations, and also shaped by diverse disruptive technologies and how these are embedded in the socio-cultural context as part of the socio-technical landscape. Obviously, there will be multiple ways to achieve such objectives, manage available resources, design and execute policy regulations. This should have direct implications for the success of smart and smarter cities, including in relation to their sustainability performance and its continuation.

Research strands of particular relevance to the topic of the study

The topic of this study entails other relevant research strands than the above mentioned ones in terms of review. These strands are also part of the broad streams of scholarship that constitute the field of smart and smarter cities. With that in mind, the focus of this subsection is on reviewing the field of smart and smarter cities in relation to sustainability and related big data applications.

The inadequate contribution of smart cities of today to the goals of sustainable development and thus their poor sustainability performance Since its adoption in urban planning and development in 1994 until recent years, the concept of smart city has been criticised for not explicitly incorporating the goals of sustainable development in its definition, as well as for lacking the connection with that of sustainable city (e.g., [2, 6, 20, 25, 28, 55, 56]). According to a recent study carried out by Ahvenniemi et al. [2] on the difference between smart cities and sustainable cities, in the former economic and social aspects tend to dominate over environmental aspects. Also, Kramers et al. [82] point out that the concept of smart city says little about the environmental sustainability performance of cities. Moreover, in examining the concept of smart city through the lens of strategic sustainable development, Colldahl et al. [37] conclude that this concept is associated with limitations pertaining to sustainability, i.e., 'does not necessarily allow for cities to develop in a sustainable manner'. Therefore, Ahvenniemi et al. [2] suggest a redefinition of the smart city concept towards a more integrated direction, a definition that highlights the dimension of environmental sustainability. Furthermore, Bibri [23] notes that the contribution of smart cities to sustainable development remains vague. In relation to this, while some of the challenges pertaining to urbanisation are already being addressed through the development of smart technologies [29, 40, 133], many of the proposed smart solutions in this regard are not aligned with sustainability targets, thereby the emergence of sustainable smart cities [2, 20]. Overall, as concluded by Bibri and Krgostie [25], the existing smart city approaches raise critical issues, pose special conundrums, and involve significant challenges—when it comes to their development and implementation as to their contribution to the goals of sustainable development. In more detail, Bibri [20] provides a detailed review of the field of smart and smarter cities in terms of its state-of-the art research and development and foundations and assumptions, and presents a tabulated version of his discussion on the shortcomings of smart cities in terms of sustainability performance. Among the points mentioned and that are of more relevance to the topic of this study are presented below:

- There is no general consensus about whether there needs to be any substance behind the claim of smartness for, or how it is linked to, sustainability.
- Smart technologies are less focused on providing solutions for the challenges and pressing issues related to sustainability and more focused on optimising the efficiency of solutions.
- There is a discrepancy between smart solutions and sustainability problems.
- There particularly is a weak connection between smart solutions and environmental problems.
- There is a mismatch between smart targets and sustainability goals.
- There are gaps between theory and practice and visions and their realisation with regard to the sustainability dimension.
- Current ICT investments and technological innovation orientations fall short in considering or embracing the goals of sustainable development.

- The field is unable to proceed in anything like a cumulative fashion and to contribute systematically and constructively to the development of innovative technologies for sustainability.
- Smart technologies mostly provide pre-configured/pre-formatted solutions for yet-to-find urban problems, rather than the needed solutions for tackling the challenge of sustainability.
- ICT research, development, and application are directed mainly towards economic development.
- There are divergences in terms of the current and future use of big data applications, as well as in terms of related innovation.
- The existing assessment performance frameworks lack environmental indicators and tend to overemphasise economic aspects.
- ICT poses great risks to and negative implications for environmental and social sustainability.

Furthermore, concerning the lack of connection, integration, and synergy between smart cities and sustainable cities, Bibri and Krogstie [25] provide a list of the key discrepancies in this regard, which include in relevance to the topic of this paper:

- Smart cities focus mostly on ICT advancement and the efficiency of solutions and fall short in considering, if not ignoring, design concepts and principles and planning practices of urban sustainability and their effects and benefits.
- Smart cities continue to strive for smart targets rather than integrating them with sustainability goals.
- Sustainability goals and smartness targets are misunderstood as to their interconnection.
- The two landscapes of the smart city and sustainable city are extremely fragmented on the technical and policy levels.
- Smart cities need to leverage their informational landscape together with their physical landscape in line with the vision of sustainability.
- Smart technologies are still being developed for building and enabling smart cities without any orientation towards, or any consideration of, improving the contribution to the goals of sustainable development.
- The existing smart city performance assessment frameworks need to be redeveloped in ways that incorporate the design concepts and principles and planning practices of sustainability as well as environmental indicators.

In relation to the latter point, while a recent wave of research work has started to focus on various technological propositions about what makes cities smart and smarter as to contributing to, or achieving, the goals of sustainable development [25], such propositions are too often investigated without consideration of the rather established strategies for achieving urban sustainability, specifically design concepts and principles and planning practices, such as compactness, mixed-land use, density, diversity, passive solar design, sustainable transport, ecological design, and design coding. In line with this, Angelidou et al. [6] conclude that there is a host of unexplored opportunities towards new approaches to sustainable smart development as a way to address and overcome the existing fragmentation between smart cities and sustainable cities pertaining especially to the technical level. Of importance to underscore here is that for many contemporary urban scholars, theorists, and planners, the adoption of the strategies through which sustainable urban forms can be achieved is necessary for achieving the required level of sustainability (e.g., [42, 62–64, 67, 141, 142]). This is irrespective of how intelligently, by using advanced ICT, urban systems (built environment, infrastructure, ecosystem services, human services, and administration) can be managed and integrated and urban domains (transport, energy, mobility, traffic, water and waste, natural environment, health and safety, education, governance, economy, science and innovation, etc.) can be coordinated and coupled, as well as how these systems and domains can be planned and developed [20, 26]. Rather, cities can well become smartly sustainable pr sustainably smart if the ubiquity and massive use of ICT could primarily be directed towards improving sustainability (e.g., [16, 20, 28, 55, 82, 112]). In this regard, smarter cities remain well positioned for providing the kind of computationally augmented urban environments that can provide the favourable conditions and offer the cutting-edge solutions that are conducive to boosting the process of sustainable development [25]. Overall, regardless of the type of the innovative solutions proposed for enhancing sustainability performance in smart and smarter cities, it is of crucial importance to ensure that urban development initiatives and projects resonate with the significant themes in debates on the design concepts and principles and planning practices pertaining to sustainable urban forms. Bibri [20] provides a detailed account of these themes and propose a matrix linking them with big data applications in the context of smart sustainable cities of the future.

Moreover, Ahvenniemi et al. [2] contrast 8 smart city and 8 sustainable city assessment frameworks as performance measurement systems with respect to 12 application domains as a way to examine how the former compares with the latter regarding both commonalities and differences. They observe a much stronger focus on modern ICT in the former in relation to economic and social aspects and a deficiency in environmental indicators, to reiterate. The 12 application domains included in this study comprise transport; energy; water and waste management; natural environment; built environment; health and safety; education; well-being; and citizen engagement; governance; economy; culture, science and innovation; and ICT, based on 3 impact categories: environmental, economic, and social sustainability, involving 958 indicators altogether. They conclude that smart cities need to improve their sustainability performance with support of advanced technologies. They suggest, based on the main identified gap between the two classes of assessment performance frameworks, the improvement of smart city ones in ways that incorporate and use impact indicators that measure the environmental and social targets of sustainable development, in addition to the economic ones, and thus gauge the contribution of smart cities to sustainability. As indeed noted by Marsal-Llacuna [92], in the academic debate, smart cities are criticised for their focus on the economic dimension of sustainability while disregarding environmental and social dimensions.

In light of the above, smart cities need to direct more efforts into embracing the goals of sustainable development and harnessing their informational assets and physical structures together accordingly so as to mitigate their shortcomings associated with sustainability. This can occur through (re)developing urban environments, areas, and spaces in ways that (re)orientate ICT use and innovation towards contributing to, and enhancing design concepts and principles and planning practices of, sustainability. Especially, several topical studies performed in recent years emphasise the need for pursuing this alternative developmental path for advancing sustainability (e.g., [6, 20, 25, 26]). Smart cities can become sustainable and sustainable cities smart when ICT is primarily utilised for and directed towards enhancing sustainability performance with respect to what each of these two urban development strategies lack in terms of any potential inadequacy as to this performance (e.g., [5, 16, 18, 20, 26, 55, 82, 112]). This pertains mainly to environmental sustainability. Indeed, Ahvenniemi et al. [2] and Angelidou et al. [6] report the misalignment between the targets of smart urban growth and sustainable urban development, with the former stating that smart city assessment frameworks downplay the importance of environmental sustainability, and the latter highlighting the unexplored role of smart applications in advancing environmental sustainability.

Realising the tremendous potential of smart cities of the future for advancing sustainability In the early 2010s, Erdmann and Hilty [44] highlighted the crucial role that ICT could play in sustainable urban development by decoupling resource consumption and environmental impact from economic growth, while noting that the topic of ICT for sustainability had not attracted actionable political interest as of yet. In looking at smart cities through the lens of strategic sustainable development, Colldahl et al. [37] note that smart cities hold great potential for advancing sustainability, as it is a powerful approach to enabling cities to become more sustainable due to the role of ICT in providing advanced solutions for addressing the complex challenges and pressing issues of sustainability, in addition to planning cities in a more innovative and forward-thinking manner. In reference to smart cities of the future, Batty et al. [16] point out that cities can only be smart if there are intelligence functions that are able to integrate and synthesise the data to some purpose, ways of improving efficiency, sustainability, equity, and the quality of life. Future ICT in its form of big data analytics and its application is concerned with researching smart cities not simply in terms of their instrumentation: 'constellations of instruments across many scales that are connected through multiple networks which provide continuous data regarding the movements of people and materials in terms of the flow of decisions about the physical and social form of the city' [16], but also in terms of the way this instrumentation is opening up new opportunities for and new forms of advancing sustainability.

It is not until very recently that smart sustainable/sustainable smart urban development as an intellectual discourse did elicit and attract great attention among urban scholars, practitioners, and policymakers, as well as ICT experts and computer scientists working within the area of applied urban science or urban informatics, especially in the subfield of big data and its relation to urban analytics, planning, and development. Evolving subsequently into a more powerful and established techno-urban discourse emanates from the fact that the strategic urban actors are increasingly relating to it in a structured way in different contexts of their practices—socially anchored and culturally institutionalised actions [20]. The accordingly increasing insertion, functioning, and dissemination of such discourse is increasingly shaped and influenced by the emerging smart technologies and their future generation being under vigorous investigation and scrutiny by ICT industry consortia, collaborative research institutes, policy networks, and Quadruple Helix of University-Industry-Government–Citizen relations in terms of research, development, and innovation within ecologically and/or technologically advanced nations [20].

Concurrently, the concept of smart sustainable/sustainable smart cities has gained momentum as both a holistic approach to urban development as well as an academic and societal pursuit, not least in technologically and ecologically advanced nations [24]. That is to say, it has become important not only in urban planning and policymaking, but also in urban research and practice, generating worldwide attention as a powerful framework for strategic sustainable urban development [20]. Further, this concept has emerged as a result of three important global trends at play across the world, namely the rise of ICT, the diffusion of sustainability, and the spread of urbanisation [25]. As echoed by Höjer and Wangel [55], the development of ICT, sustainability awareness, and urban growth as interlinked shifts have recently converged under what is labelled 'smart sustainable cities'. Accordingly, such cities represent a new techno-urban phenomenon that materialised around the mid–2010s (e.g., [2, 4, 6, 25, 55, 60, 82, 130]). The underlying idea revolves around leveraging the prevalence and advance of ICT of pervasive computing in the transition towards the needed sustainable development in an increasingly urbanised world [20]. Worth pointing out is that there are several differences between sustainable smart cities and smart sustainable cities. One obvious distinction to highlight is that the former involves those cities that badge themselves as smart and are striving to become sustainable, and this class of cities often relates to technologically advanced nations. The latter entails those cities that badge themselves as sustainable and are striving to improve and maintain their contribution to sustainability using the advanced forms of ICT, and this class of cities pertains to ecologically advanced nations.

However, the development of sustainable smart cities is increasingly gaining traction and pre-eminence worldwide, surpassing all other urban development approaches, especially in the world's major cities, supported by policymakers, governments, research institutions, universities, and industries. Given the apparent relevance and usefulness of the findings produced in the field of smart cities, the related research and development has been embraced and advocated by the United Nations (UN), the European Union (EU), and the Organisation for Economic Co-operation and Development (OECD) (e.g., [89]). For example, a common understanding shared by the European Commission and reflected in the Smart Cities and Communities European Innovation Partnership (SCCEIP) is that smart technologies in their various forms hold great potential for achieving sustainability in smart cities, particularly in relation to the intersection between energy, transport, and ICT, where the associated industries have been invited to collaborate with cities to address their challenges and needs [47]. This will enable innovative, integrated, and efficient technologies to roll out and enter the market more smoothly, making cities the nexus of innovation [47]. Accordingly, the European Union's policies highlight the synergy between smart technologies and sustainable urban development, as manifested additionally by the EU's current 10-year development strategy through which the objectives of fostering smart, inclusive, and sustainable development in Europe were set, and at the heart of which innovation is seen as a means to tackle the environmental challenges associated with climate change and intensive energy use and its inefficiency. Moreover, recent research and policy reports highlight synergies and benefits at the intersection of smart and sustainable urban development [6]. The most widely cited report of the World Urbanisation Prospects series of the United Nations [126] clearly states that this trend of integrating both urban development paradigms in terms of polices and practices will continue to rise at least up to 2050, highlighting the growing role of ICT in mitigating the rising challenges of sustainability. As stated in the report, the policy implications drawn from this study include the use of ICT in facilitating a sustainable mode of urbanisation, one that enhances and efficiently delivers services to diverse urban stakeholders, as well as the necessity to have accurate, consistent, and timely data to inform city-related policy-making, among others. The United Nations has already begun to explore the role of big data for sustainable development in the form of action-oriented research in that direction [127].

In addition, many governments have recently set ambitious targets to transition their cities to being sustainable smart using a variety of initiatives and programs, or have adopted the concept of smart city and implemented big data applications to reach the required level of sustainability and to improve the living standards. Accordingly, it has become of crucial importance to develop and utilise new methods for measuring the performance of sustainable smartness (e.g., [36, 61, 139]). This is due to the growing realisation of the untapped potential of the emerging smart technologies, especially big data analytics and its application, for addressing the challenges of sustainability and containing the effects of urbanisation.

While there is a growing interest in this flourishing field of research, the academic discourse on sustainable smart urban development within the relevant literature is still scant and also heavily weak on empirical grounding—yet rapidly burgeoning [25]. Indeed, a few studies exploring the subject of sustainable smart cities have been published in the mainstream journals. The case is evidently different from smart cities as an urban development strategy that has been around for more than two decades or so, thereby witnessing a proliferation of academic publications and scientific writings and thus demonstrating a large body of successful practices. However, the extent to which the field of sustainable smart cities is blossoming gives a clear indication of its future developmental path and research direction. In fact, this field of research has materialised in response to the need for overcoming the numerous challenges and issues pertaining to the existing approaches to smart cities with regard to sustainability and urbanisation, as adequately discussed in the previous section.

The research on sustainable smart and smarter cities is garnering increased attention, and its status is consolidating as one of the fanciest and fertile areas of research today. This hot topic and recent wave of research has started to highlight and explore, respectively, the growing significance and role of the advanced forms of ICT in increasing the contribution of smart and smarter cities to the goals of sustainable development. This research wave has become more established about two decades or so after the adoption of the concept of smart city in the domain of urban planning and development in 1994, and in parallel with the emergence and success of the aforementioned discourse of sustainable smart urban development. Explicitly, when this concept has become widespread and mature, and concurrently, most of the core enabling technologies (sensor technology, cloud computing, fog computing, distributed computing, data processing platforms, wireless communication networks, etc.) of smart and smarter cities have become relatively financially affordable, technically advanced, and widely deployed across urban environments. This has been enabled and fuelled by the most prevalent ICT visions of pervasive computing becoming deployable and achievable computing paradigms and thus the new reality in different parts of the world, especially Europe, Asia, and the USA. This new paradigmatic shift in computing as heralding a drastic change in ICT in its various forms and thereby giving rise to innovative solutions and sophisticated approaches increasingly pervading urban domains and environments has made the vision of building and living in sustainable smart cities an achievable and attainable reality [24]. Other driving factors for, or global shifts triggering, the wave of research and phenomenon in question, in addition to the rise, advance, prevalence, and convergence of ICT, is the unprecedented urbanisation of the world's population and the rising concerns over its multidimensional effects, coupled with the mounting challenges of urban sustainability [20]. In particular, as pointed out by Angelidou et al. [6], what has brought the two disciplines of smart urban growth and sustainable urban development closer than ever before, despite the different development trajectories followed until recently, is the growing realisation of the role of technological advancements in monitoring urban environments and making well-informed technical and policy decisions, as well as in reducing resource consumption whose unsustainability is bringing humanity closer to a future where basic goods will be unavailable to large parts of the population. In all, research on sustainable smart cities has attracted attention and evolved on the basis of these different, yet related, developments: smart cities, sustainable cities, ICT of pervasive computing, sustainable development, sustainability, and urbanisation.

Consequently, smart cities have gained traction among particularly many national governments and international policymakers as a promising response to the challenges of sustainable development in an increasingly technologised and computerised, yet unsustainable, urbanised world [20]. It is of particular relevance here to emphasise that it is not until more recently that the development of smart cities came to the fore as a sort of panacea for solving the kind of wicked and intractable problems that characterise the urban domain—thanks to the advent of big data analytics as a set of advanced technologies, coupled with the recognition of the untapped potential of their novel applications and services for advancing various aspects of sustainability (e.g., [5, 16, 18, 20, 93]). Worth noting is that ICT has in fact gained the recognition of offering unsurpassed ways to deal with the environmental, societal, and economic concerns of cities and hence to transform them into urban areas that can adapt to environmental, societal, and economic shocks since the mid 1990s, a few years after the widespread diffusion of the concept of sustainable development and the prevalence of ICT worldwide. Ever since, ICT has been socially and discursively constructed as having an enabling and catalytic role in sustainable development and in envisioning its future form in the context of sustainable smart cities [24]. In smart cities, ICT is proposed as a set of solutions to urban challenges and issues of a complex nature, including sustainability and living standards [16, 54]. In other words, and more detail, smart cities represent an urban development paradigm that emerged in the late twentieth century as a result of the drive of cities to be more responsive to citizen needs through offering conditions conducive to promoting and enhancing the quality of life in an increasingly globalised world [6], and then to become more sustainable in an increasingly urbanised world [60, 130] with support of advanced ICT.

The assessment of smart cities builds on 'the previous experiences of measuring environmentally friendly and livable cities, embracing the concepts of sustainability and quality of life but with the important and significant addition of technological and informational components' [93], cited in [2]. This relates particularly to big data technology and its diverse applications and services, which span many urban domains with regard to improving operational functioning, monitoring and optimising infrastructures and facilities, reducing resource consumption, providing efficient and faster services to citizens to enhance the quality of their life, and streamlining planning and decision-making processes, all in line with the goals of sustainable development [20]. By means of ICT innovations and thus advanced smart solutions, cities can well evolve in ways that can address environmental concerns and respond to socio-economic needs in a more strategic manner, as they are the incubators, generators, and transmitters of creative and innovative ideas [25]. Indeed, the clear prospects of many major cities to overcome the complex challenges pertaining to sustainability and urbanisation through the advanced forms of ICT is the key reason why smart cities of the future has recently gained traction as a holistic urban development strategy among universities, research instituters, policy makers, city governments, and industries. Besides, when discussing ICT solutions for improving the different aspects of sustainability, reference is made to smart cities of the future or smarter cities (e.g., [16, 20]) This is predicated on the assumption that ICT of pervasive computing offers great opportunities for monitoring, understanding, and analysing various aspects of urbanity for operating, managing, and planning urban systems in ways that can be leveraged in the needed transition towards, and the advancement of, sustainability. It is in smart cities of the future that the key to a better world—which is held by emerging and future ICT—will be most evidently demonstrated [16]. The underlying premise is that the use of ICT of pervasive computing and related big data analytics and its application is increasingly contributing to the further integration of urban systems and the effective assessment of their performance in terms of sustainability; facilitating collaboration and coordination among urban domains for energy and environmental efficiency gains; enhancing and mainstreaming ecosystem and public and social services; and pinpointing which kinds of networks need to be coupled or amalgamated. This is due to the merging wave of urban analytics for which big data constitute the fundamental ingredient, thanks to the opportunity of fashioning and utilising powerful intelligence and planning functions and simulation models in relation to urban monitoring, planning, and design [20]. In the meantime, the promises of smart cities is leading to an exponential increase in data by several orders of magnitude. Worth pointing out is that most of the sustainability benefits and opportunities of smart cities tend to be associated with what is labeled 'smarter cities'.

Smarter cities: characteristic features, social shaping aspects, and current issues of and future potentials for sustainability Smarter cities typically rely on the fulfilment of the prevalent ICT visions of pervasive computing, namely Ubiquitous Computing, Ambient Intelligence, Sentient Computing, and the Internet of Things. See Bibri [20] for a descriptive account of these visions. Big data analytics is one of the key prerequisite technologies for realising these visions in terms of the novel applications and services being in use in a wide variety of urban domains, such as transport, mobility, traffic, energy, environment, power grid, building, planning, design, governance, scientific research, innovation, and so on, to improve sustainability. Recent discoveries in computer science and its advanced ICT applications have given rise to those socially disruptive technologies and thus ubiquitous cities, ambient cities, sentient cities, cities as Internet-of-everything, and real-time cities. Of importance to note is that the orientation of these cities towards sustainability through embracing and incorporating the goals of sustainable development as part of national urban development initiatives and projects within technologically and ecologically advanced nations is considered as a new research endeavour that aims to leverage the informational landscape of smart cities in the needed transition towards sustainability [20]. In addition, these cities are associated with the core characteristic features of the future vision of technology in the sense that everyday objects communicate with each other and their surroundings in various ways and collaborate across heterogeneous and distributed environments to provide valuable information and limitless services in the form of intelligence to multiple, diverse urban entities in connection with operations, functions, activities, designs, strategies, and policies. For what this vision entails, the prospect of smarter cities is becoming the new reality with the massive proliferation of the core enabling technologies underlying ICT of pervasive computing [113]. Enabling diverse computationally augmented urban environments in modern cities and seeking to connect city constituents with each other together with their environments, the underlying technologies will enable different kinds of big data applications to usher in nearly very urban domain, thereby opening up new windows of opportunity for enhancing sustainability performance.

Visions of future advances in science and technology (S&T) (and predominately computer science and ICT) inevitably bring with them wide-ranging common visions on how societies and hence cities as social fabrics will evolve in the future, as well as the immense opportunities this future will bring [24]. This relates to the role of science-based technology in modern society in terms of its development, a subject area which is positioned within the research and academic field of Science, Technology, and Society (STS). This is concerned with the ways in which new technology emerges from different perspectives, why it becomes institutionalised and interwoven with politics and policy—cultural dissemination, as well as the risks it poses to environmental and social sustainability [24]. In this context, however, S&T is associated with ICT of pervasive computing and the increasing role it plays in advancing sustainability within contemporary cities. This rapidly evolving form of S&T and related role in sustainable smart cities has recently permeated urban and academic debates as well as politics and policy across the globe, as mentioned and documented above, and is accordingly seen as key for solving the environmental and socio-economic challenges pertaining to sustainability and urbanisation facing modern and future cities. ICT of pervasive computing is drastically changing long-standing forms of city structures, systems, and processes, and revolutionising city transformation models in terms of sustainability and the quality of life [16, 20]. In particular, major urban transformations are promised as a result of the advent of big data analytics and its application as an instance of ICT of pervasive computing. The existing evidence (e.g., [5, 6, 18, 20]) already lends itself to the argument that the use of big data technology and its novel applications across various urban domains makes this technology a salient factor for improving the goals of sustainable development and thereby advancing sustainability. If its research, development, and innovation continue further to be linked with the agenda of sustainable development and the goals of sustainability, i.e., to be utilised meaningfully and strategically, ICT of pervasive computing will have positive, profound, and long-term impacts on smarter cities or smart cities of the future. It is projected to yield hitherto unrealised environmental gains and socio-economic benefits, owing to its technological superiority in terms of the novel applications and services that provide high performance and concrete value [20].

In light of the above, smart cities are ever-changing and morphing into new faces characterised by the profusion of data and massive use of its analytics and related applications. This has been fuelled by the modern world becoming rapidly technologised and hence fully computerised. Adding to this is the increasing convergence and advance of ICT as a powerful enabler and driver for ecological modernisation and societal transformation, thereby playing a key role in addressing and overcoming the challenges of sustainability and containing the effects of urbanisation [24]. At the heart of ecological modernisation as an analytical approach, policy strategy, environmental discourse, and academic field is an established view of the potential of ICT innovations to bring about advanced solutions to complex environmental problems. Ecological modernisation as a theoretical concept is used to analyse those shifts in 'the central institutions and core practices of modern society deemed necessary to solve, avoid, or mitigate the ecological crisis' [19, p. 35]. One of its key dimensions is technology and the transformation of society [100], meaning particularly that environmental problems are most likely to be tackled through the development and application of advanced sophisticated technologies [100], such as big data analytics and related applications. Several ideas arising from the intended ecological switchover have gained footholds in the context of smart cities of the future. Indeed, the pertinence of such cities with that of environmental sustainability is reflected in the EU's urban development policy, whereby sustainable technology is seen as an asset toward optimising energy efficiency and thus reducing GHG emissions as well as fostering urban collective intelligence and innovation [48].

From a societal perspective, ICT is socio-culturally constructed to have a determinant role in instigating major social changes on multiple scales due to its transformational power residing or embodied in its disruptive, synergistic, and substantive effects, coupled with being of an enabling, integrative, and constitutive nature [24]. In relation to this, the coalescence of computing, data processing, and communication technology is unleashing a wealth of opportunities and proving a powerful driver for innovation and change, as well as blurring the boundaries between domains within different societal spheres [59]. In the meta-discourse of the information society and other derived discourses which metonymically represent it, such as smart cities and sustainable smart cities, advanced ICT is seen as a powerful driver for major transformations. As stated by ISTAG [59, p. ii], 'ICT offers a means to respond to many challenges. It is the "constitutive technology" of the first half of this century… ICT does not just enable us to *do* new things; it *shapes* how we do them. It transforms, enriches and becomes an integral part of almost everything we do. As ICT becomes more deeply embedded into the fabric of European society it is starting to unleash massive and far-reaching societal…change. ICT is essential for bringing more advanced solutions for societal problems. These constitutive effects amount to a paradigm shift in how our…society function.' ICT research plays a key role in unlocking the transformational effects of ICT for societal sustainability [59]. It is important not to underplay the radical social transformations that are likely to result from the implementation of ICT visions of pervasive computing [58]. For a detailed analytical account and deep discussion of the diverse dimensions of the social shaping of sustainable smart cities, the interested reader can be directed to Bibri and Krogstie [24].

Smarter cities or smart cities of the future are the product of socio-culturally-conditioned frameworks, including the way the related sustainable practices have emerged and become disseminated at the urban level and hence discursively constructed and materially produced through diverse socio-political institutions and organisations [24]. Therefore, as noted by Bibri [20], smarter cities should not be conceived of as 'isolated islands'; rather, the interplay between them and other scales and their relation to political and regulatory processes on a macro level ought to be recognised. Macro processes of political regulation and policy are deemed of crucial importance for the discursive-material dialectics of smarter cities as urban transformation. In this regard, political action is necessary for the production, insertion, functioning, dissemination, and evolution of smarter cities as an amalgam of innovation systems or a techno-urban discourse. Indeed, political practice is at the core of the theoretical framework of innovation system [32, 70, 71, 109] and the theory of discourse [50]. Recommendations for smarter cities as drastic urban transformations are unlikely to proceed without parallel political actions [116]. Drastic shifts to technological or sustainable regimes 'entail concomitantly radical changes to the socio-technical landscape of politics, institutions, the economy, and social values' [116]. Besides, technology and society and hence cities are shaped at the same time in a mutual process, i.e., the former develops dependently of the latter and then they affect each other and evolve in that process [19]. As succinctly put by McLuhan [97] many decades ago, we shape technology and thereafter it shapes us. This in fact is the kind of challenge that needs to be resolved in the development and implementation of smarter cities with regard to directing ICT towards enhancing their contribution to the goals of sustainable development. To put it differently, the intellectual challenge facing smarter cities lies in that advanced technologies such as big data analytics are not only developed to enable us to shape and alter how we create new and do things in many domains, but also to investigate and assess the processes of their own application and impact on cities as to their concrete contribution to sustainability [20]. Regardless, the way modern cities as complex systems and dynamically changing environments can be operated, managed, developed, and planned requires sophisticated approaches and innovation solutions to understanding and analyse them and to avoid and mitigate potential environmental and social impacts resulting from urban operational functioning, planning, and governance in the context of sustainability, respectively.

The current state of research in the realm of smarter cities shows that not enough focus has been given to the potential of ICT of pervasive computing for responding to the challenges of sustainability and containing the effects of urbanisation [20]. Such cities are mainly striving for smart targets instead of sustainability goals [25], just like current smart cities [2, 93]. In more detail, notwithstanding the relative increase of research on smarter cities—pushed particularly by big data analytics and its application across various urban domains—the bulk of work has tended to deal largely with the advancement of ICT of pervasive computing and its potential only in terms of the use of its novel applications to optimise economic efficiency in terms of productivity, management, cost-effectiveness, and time saving. As well as to improve the quality of life of citizens in regard to better, faster, and more efficient services. This leaves more relevant questions largely ignored or barely explored to date involving the rather untapped potential of emerging and future ICT in terms of big data analytics and its application for catalysing and boosting the process of sustainable development towards achieving the long-term goals of sustainability, including the integration of its dimensions [20]. To put it differently, despite the proven role of the advanced forms of ICT in enhancing urban sustainability performance, the evolving approaches to smarter cities raise several issues, involve special conundrums, significant challenges, and pose potential risks to the environment—when it comes to their development and implementation in the context of sustainability [25]. It is highly important that future studies should go beyond only passing reference to the role of big data competing in addressing and overcoming the challenges of sustainability to emphasise and exploit the numerous opportunities available in this regard. However, for a detailed review of the field of smarter cities in terms of its materialisation, characterisation, research issues, challenges, and risks, the interested reader can be directed to Chapter 10 of a recent book published by Bibri [20]. Overall, most of the critical issues discussed earlier concerning smart cities of today as to their inadequate contribution to the goals of sustainable development and thus poor sustainability performance do apply to the emerging smarter cities, so do the tremendous potential for advancing sustainability. The latter has indeed become a topic of major importance in recent years, a mainstream theme in the debate on ICT innovation for sustainability in the context of smart cities of the future, as well as a key research direction and new wave of urban thinking, as adequately discussed above.

Smarter cities, which are characterised by the infiltration of computer and information intelligence into the operating and organising processes of urban life, are extremely well positioned to do a lot more in respect of sustainability. Besides, it is high time for smart cities in their transition to smarter cities to go beyond the technical advancement and industrial competitiveness that have prevailed for more than two decades or so to start focusing their efforts towards solving the urgent problems and pressing issues pertaining to sustainability and urbanisation. Especially, future ICT will pervade urban operations, functions, designs, strategies, services, and policies in the context of smarter cities, thereby being in strong position in instigating major transformations. This is anchored in the recognition that it offers fascinating possibilities for monitoring, understanding, analysing, probing, and planning smarter cities to strategically improve and maintain their contribution to the goal of sustainable development [20]. The underlying premise is that future ICT blends, and its application is founded on, data science, computer science, and complexity sciences in terms of designing, constructing, and planning smarter cities capable of tackling the kind of intractable and wicked problems associated with sustainability and bringing about drastic transformations (e.g., [18, 20]). In reference to smart cities of the future, Batty et al. [16] note that future ICT is said to unleash the kind of science that can be mobilised to instigate profound changes. Already, emerging ICT is being leveraged in accelerating environmental sustainability in both smart cities and sustainable cities (e.g., [5, 16, 21, 82, 112]), making it possible to approach a range of issues around environmental sustainability in cities from a whole new perspective. Further, it has been suggested that as ICT pervades urban environments, i.e., data sensing, data processing platforms, cloud and fog computing infrastructures, and wireless communication networks become more and more embedded throughout urban systems and domains as well as in citizens' objects, smart cities can become smarter as to improving sustainability and enhancing the quality of life of citizens (e.g., [16, 20, 106, 113, 124]).

All in all, smarter cities will open new windows of opportunity for drastic sustainable change, especially they are still at the early stage of their development, and thus could, if planned strategically and implemented purposefully, do a lot more to advance sustainability and enhance the quality of life of citizens, including the mitigation of environmental risks and digital divides posed by ICT itself. In particular, the big data computing paradigm that is driving the transition from smart cities to smarter cities is noticeably in a penetrative path across various urban systems and domains towards safely fuelling unhindered progress on many scales, and hence paving the way for catalysing and accelerating sustainable development. However, failing to exploit the disruptive and substantive effects of ICT of pervasive computing on sustainability in an increasingly computerised and urbanised world means that the battle for sustainability will be lost in the world's major cities [20].

Big data analytics and its application in smart and smarter cities

Research status and data growth projection

Having recently, as a research wave and direction, permeated and dominated academic circles and industries, coupled with its research status being consolidated as one of the most fertile areas of investigation beyond the realm of smart and smarter cities, big data analytics has attracted researchers, scholars, scientists, experts, and practitioners from diverse disciplines and professional fields—given its importance and relevance for generating well-informed decisions and deep insights of highly useful value to many sectors of society. Therefore, big data analytics is a rapidly expanding research area merging computer science, data science, and complexity sciences [16, 20], and becoming a ubiquitous term in understanding and solving complex challenges and problems in such fields as sustainable urban development, engineering, economics, education, healthcare, medicine, and telecommunication. The big data movement has been propelled by the intensive R&D activities taking place in academic and research institutions, as well as in industries and businesses—with huge expectations being placed on the upcoming innovations and advancements in the field. This includes the high influence big data analytics and its application will have on many facets of smart and smarter cities and their citizens (e.g., [5, 16, 18, 20, 54, 73, 79, 83, 104, 124]). Further to the point, however, a large part of ICT investment is being directed by giant technology companies, such as Google, IBM, Oracle, Microsoft, SAP, and CISCO, towards creating novel computing models and enhancing existing practices pertaining to the storage, processing, analysis, management, modelling, simulation, and evaluation of big data, as well as to the visualisation and deployment of the analytical outcome for different purposes [20]. Adding to this is the active, ongoing research within so many universities across the globe, especially in relation to smart and smart cities, for the purpose of enhancing the acquisition of data from multiple distributed sources, the management of data streams, the integration of heterogeneous data into coherent databases as well as the definition of observables to extract relevant information from available datasets, data transformation and preparation, methods for distributed data mining and network analytics, the organisation and composition of the extracted models and patterns as well as the evaluation of their quality, tools for visual analytics to study the behavioural patterns and models, methods for the simulation and prediction of the mined patterns and models, and so forth. Big data analytics is considered as a prerequisite technology for realising the novel applications and services offered and promised by the ICT visions of pervasive computing, which is a determinant enabler and powerful driver for such cities.

The deluge of urban data is, and will continue to be, unfolding and soaring, amounting to hundreds of exabytes every year, if not more than that, and covering so many aspects of urbanity in its complexity, breath, depth, and heterogeneity as manifested in, among others, the nature of urban systems and their continuous integration, that of urban domains and their coordination, and that of urban networks and their coupling This urban data growth will undoubtedly continue in this direction, and expectedly, the resulting datasets are set to proliferate and be coalesced, integrated, and coordinated. Generally, the digital data are projected to grow from 2.7 Zettabytes to 35 Zettabytes by the year 2020 [90, 146]. Manyika et al. [91] projects a growth of about 45% in the global data produced per year. It is estimated that more data are produced every 2 days at present than in all of history prior to 2003 [79, 117]. This explosive data growth is due to a number of the core enabling and driving technologies of ICT of various forms of pervasive computing, and their ever-growing embeddedness into the very fabric of modern and future cities.

Research issues and future prospects

The past few years have witnessed extensive investments in the ICT infrastructure of smart and smarter cities in terms of large-scale deployments across the globe, especially in big data analytics and its core enabling technologies. This is making it increasingly feasible to collect, store, manage, and analyse large amounts of data throughout urban domains and to deploy the analytical outcome to serve many purposes, despite the limited capacities of the prevailing analytic systems or data processing platforms in use. This new development is opening new windows of opportunity for invigorating the application demand for the urban sustainability solutions that big data analytics can offer. Concurrently, the application of big data analytics has been expanded beyond the realm of business intelligence (e.g., [33, 107]) in the wake of this development to include the field of smart and smarter cities in terms of their domains (e.g., [5, 16, 18, 20, 54, 79, 83, 108]). However, research on big data analytics and its application tends to deal largely with economic development (i.e., management, optimisation, effectiveness, innovation, productivity, etc.) and the quality of life in terms of service efficiency and betterment (e.g., [15, 41, 54, 73, 77, 108]) while overlooking and barely exploring the issues related to the different dimensions of sustainability. This paucity of research pertains particularly to the untapped potential of big data technologies and their novel applications for enhancing the environmental and social aspects of sustainability [20]. This in fact relates to the deficiencies of smart and smarter cities in this regard. As discussed above, such cities have, irrespective of which ICT visions they tend to instantiate in relation to their operational functioning, management, planning, and development, been subject to much debate, generating a growing level of criticism that essentially questions their added value to sustainability due to the lack of incorporating the fundamental goals of sustainable development, as well as falling short in considering the environmental and social indicators of sustainability (e.g., [2, 20, 25, 55, 82, 92]). Consequently, a recent research wave has started to focus on enhancing smart and smarter city approaches to achieve the required level of sustainability through alining urban operations, functions, designs, strategies, services, and policies with the goals of sustainable development using big data applications under what is labelled 'sustainable smart cities' (e.g., [5, 16, 18]).

Data sensing and processing, cloud and fog computing, and wireless networking technologies associated with big data analytics are being fast embedded into the very fabric of cities badging or regenerating themselves as smart and smarter to pave the way for utilising and applying the upcoming innovative solutions to overcome the challenges of sustainability and urbanisation in the years ahead. Also, the increasing convergence and advance of ICT is giving rise to new computationally augmented urban spaces that are both drastically changing living and working modes as well as enabling sophisticated operating and organising processes of urban life, which are quite different from what has been experienced hitherto on many scales. This is in response to the event of cities becoming more and more complex as systems and dynamically changing environments together with their domains getting more and more coordinated, their systems integrated, and their networks coupled. This concern those domains, systems, and networks that rely heavily on complex technologies to realise their full potential for responding to the challenges of sustainability and urbanisation or, possibly, addressing them from the source. All the above points well to new opportunities and alternative ways to develop, operate, probe, plan, and govern smart cities of the future or smarter cities.

The expansion and success of big data computing trend is increasingly stimulating smart and smarter city initiatives and projects as well as research opportunities to an increasing extent, especially in technologically and/or ecologically advanced nations. However there are significant challenges to address and overcome prior to achieving a more effective utilisation of big data analytics and related applications in the realm of smart and smarter cities, including technological, computational, organisational, social, cultural, and political. These are the object of the next section.

Urban data deluge

Datafication The big data revolution will transform the way we live, work, and think in the city. Datafication has become a buzzword in the era of big data. This buzzword describes an urban trend of defining the key to core city operations and functions through a reliance on big data computing and underpinning technologies. There is no official definition of datafication, at least in terms of it being in the dictionary. In the context of this paper, the notion of datafication denotes that cities today are dependent upon their data to operate properly—and even to function at all with regard to many domains of urban life, especially in relation to sustainable development [23]. It also refers to the collective tools, processes, and technologies used to transform a city to a data-driven enterprise. In all, datafication involves turning many aspects of urban life into computerized data and transforming this information into useful knowledge and valuable insights.

Datafication is also known as datafy. A city that implements datafication is said to be datafied. To datafy a city is to put it in a quantified format so it can be structured and analyzed. The so-called quantifiable information is what the data miners or data analysts look for and rely on different sources to find it. Cities are taking any possible quantifiable metric and squeezing useful knowledge out of it for enhanced decision-making and deep insights pertaining to many domains of urban life. Thus, they require data and extract knowledge to perform critical urban processes related to the operation and organization of urban life. Datafication entails that in a modern data-oriented urban landscape, a city's performance is contingent on having control over the storage, management, and analysis of the data as well as on the extracted knowledge in the form of applied intelligence. Datafying cities occurs through the data obtained from the sensors that are deployed across urban environments so that issues that can arise will be noticed and tackled before they become serious as related to diverse urban systems and domains in terms of operations, functions, services, designs, strategies, and policies. Tackling sustainability issues is one of the key concerns of the datafication of the city. With these sensors, cities can have, for example, a more detailed understanding of the various problems of environmental sustainability and can enact new policy regulations based on real-time data.

In recent years, there has been a marked intensification of datafication. This is manifested in a radical expansion in the volume, range, variety, and granularity of the data being generated about urban environments and citizens (e.g., [20, 23, 79, 81, 120]), with the aim of quantifying the whole of the city. We are currently experiencing the accelerated datafication of the city in a rapidly urbanizing world and witnessing the dawn of the big data era not out of the window, but in everyday life. Our urban everydayness is entangled with data sensing, data processing, and communication networking, and our wired world generates and analyzes overwhelming and incredible amounts of data. The modern city is turning into constellations of instruments and computers across many scales and morphing into a haze of software instructions, which are becoming essential to the operational functioning, planning, design, development, and governance of the city [23]. The datafication of spatiotemporal citywide events has become a salient factor for the practice of smart sustainable urbanism.

Urban data potentials and sources There has been much enthusiasm in the domain of smart sustainable/sustainable smart urbanism about the immense possibilities and fascinating opportunities created by the data deluge and its extensive sources with regard to improving urban operational functioning, management, planning, and design in line with the goals of sustainable development as a result of thinking about and understanding sustainability and urbanization and their relationships in a data-analytic fashion for the purpose of generating and applying knowledge-driven, fact-based, strategic decisions in relation to such urban domains as transport, traffic, mobility, energy, environment, education, healthcare, public safety, public services, governance, economy, and science and innovation [20]. The exponentially growing amount of the data being constantly produced across many urban domains, whether separated or coordinated, is at such a high value that it has become of astuteness and strategic value for urban planners, strategists, and policymakers in collaboration with ICT experts and data analysts to exploit, harness, and analyze these data for the purpose of increasing the contribution of smart and smarter cities to the goals of sustainable development [20]. Within such cities, citizens, activities, movements, processes, physical structures, urban infrastructure, distribution systems and networks, natural ecosystems, spatial organisations, scale stabilisations, socio-economic networks, facilities, services, spaces, and citizen objects all contribute to the generation of the huge amounts of data collected from heterogeneous and distributed sources. Basically, virtually every aspect of urbanity has become open to, and instrumented for, data collection, processing, and analysis. As a result, vast troves of information have become widely available on numerous aspects of urbanity, including social trends, global shifts, environmental dynamics, socio-economic needs, spatial and scalar patterns, land use patterns, travel and mobility patterns, traffic patterns, energy consumption patterns, life quality levels, and citizens' lifestyles and participation levels [20, 27]. The data from these sources and on these aspects cascade into urban data deluge, which calls for prudent big data applications that can churn out useful knowledge and valuable insights from this huge deluge. The sustainability of smart and smarter cities as well as the smartness of sustainable cities are being digitally fuelled and driven by the enormous data collected for analysis and deployment for enhanced decision-making purposes.

The evolving data deluge resulting from the increasing availability of the data being generated in continuous streams on daily basis (e.g., [15, 23, 79]) is pushing research on and the use of big data analytics to expand remarkably and its technologies to proliferate in urban domains on a massive scale. The rationale is that it is increasingly enriching and reshaping our experiences of how smart and smarter cities can evolve and further advance at many levels, thanks to its analytics which is indeed offering new opportunities for generating well-informed decisions and enhanced insights with respect to our knowledge of how fast and best to advance sustainability [20]. This is due to the analytical power of big data as a fundamental ingredient for the next wave of city analytics with regard to the useful knowledge that can be extracted and immediately applied to improve sustainability performance. The increased use of big data analytics as well as the profusion and proliferation of data are being driven by the emerging core enabling technologies: techniques, algorithms, devices, systems, infrastructures, platforms, and networks, as advances in ICT of pervasive computing, and their continuous embeddedness into a wide variety of urban practices, enabling more effective accessibility, production, and sharing of data more than ever (e.g., [79]). Important to note, though, big data are about the way they are exploited and their analytics is applied, as well as how new innovations are facilitated and diffused throughout the domains of smart and smarter cities through data themselves, especially in the context of sustainability and in connection with urbanisation [20].

City analytics City analytics entails the application of various techniques, algorithms, models, and processes based on the fundamental concepts of data science—i.e., data-analytic thinking and the principles of extracting useful knowledge from large masses of data for decision making [20]. Big data analytics techniques include, but are not limited to, data mining, machine learning, statistical analysis, and database querying, and whose application involves significant challenges due to the interdisciplinary and transdisciplinary character of urban data. Also, their use depends on the nature of the problem to be tackled or solved in relation to a given urban domain. Worth noting is that the process of data mining is the most applied technique in urban analytics within smart and smarter cities (e.g., [16, 20, 73]). The main difference between data mining and other techniques is that it focuses on the automated search for or extraction of useful knowledge from large masses of data (e.g., [107]). However, while this technique has recently become of focus in city analytics in relation to various domains of smart cities of the future (e.g., [16, 73, 79]) as well as to those of sustainable smart cities of the future [20, 27], much of the existing knowledge of urban sustainability has long been gleaned from studies characterised by data scarcity ('small data' studies) and involving the use of traditional data collection and analysis methods [20]. This form of academic and scientific research in the domain of sustainable urbanism has prevailed for three decades or so. This has consequently impacted the robustness of the obtained research results and hence the way sustainability as underpinned by theoretical perspectives and empirical investigations based predominately on such methods has been adopted as a set of practices in urban planning and development [20, 26]. Commonly, in the academic and scientific research within smart sustainable urbanism domain, 'small data' studies are associated with high cost, quick obsolescence, infrequent periodicity, incompleteness, inaccuracy, and inherent biases; moreover, they capture a relatively limited sample of data that are tightly focused, restricted in scope and scale, time and space specific, and relatively expensive to generate and analyse [16, 20, 79]. Therefore, there is a need for advanced or sophisticated approaches into data collection and analysis in the domain of smart sustainable urbanism that can provide additional depth and insight with respect to complex urban phenomena and dynamics. Accordingly, using big data techniques in city analytics holds great potential for transforming the knowledge of sustainable smart and smarter cities through the creation of a data deluge whose analysis can provide, as part of big data studies, much more sophisticated, more inclusive, finer-grained, wider-scope and -scale, realtime understanding and control of different aspects of urbanity in terms of its complexity and intricacy [20].

Core enabling technologies

Strands and permutations Like many domains or areas to which big data analytics can be applied, smart and smarter cities require the big data ecosystem and its components to be put in place as part of their ICT infrastructure prior to designing, developing, deploying, implementing, and maintaining the diverse applications that support sustainability through enhancing and optimising urban operational functioning, management, planning, and governance accordingly. As a scientific and technological area, the research strand concerned with the core enabling technological components underlying the big data ecosystem involves such sub-areas as low-level data collection and fusion, intermediate-level data processing, and high-level application action and service delivery, adding to cloud and fog computing models for hosting the associated devises, systems, and networks [20]. These are under vigorous investigation in both academic circles as well as the ICT industry towards the development of computationally augmented urban environments and spaces in smart and smarter cities as part of their informational landscape and as a result of the ICT visions of pervasive computing becoming deployable and achievable computing paradigms. In this respect, big data analytics as a prerequisite technology for realising such visions entails a number of permutations of the underlying core enabling technologies pertaining indeed to various forms of pervasive computing, and also shaped by the way these forms can be applied and integrated depending on the urban domain concerned and the scale, complexity, and extension of the smart and smarter city projects and initiatives to be developed and implemented. Regardless of the several possible ways in which a set or number of the core enabling technologies can be arranged, it is necessary, as suggested by Chourabi et al. [36], to take into account flexible design, quick deployment, extensible implementation, comprehensive interconnections, and advanced intelligence. However, while there are various permutations of the core enabling technologies that may well apply to most domains, there are some technical aspects and details that remain specific to the area of smart and smarter cities, more specifically, to the requirements, objectives, and resources of the smart and smarter city projects that are to be developed and implemented, which are usually determined by the nature, scale, and extension of the endeavor within a given context [27]. Most of, if not all, the possible permutations, though, involve sensing technologies and networks, data processing platforms, cloud computing and/or fog computing infrastructures, and wireless communication and networking technologies. These are intended to provide a full analytic system of big data and related functional applications based on advanced decision support systems and strategies and the underlying intelligence functions and simulation models that can be directed towards improving the contribution of smart and smarter cities to the goals of sustainable development and thus achieving the required level of sustainability. On this note, Batty et al. [16] state that much of the focus on smart cities of the future, 'will be in evolving new models of the city in its various sectors that pertain to new kinds of data and movements and actions that are largely operated over digital networks while at the same time, relating these to traditional movements and locational activity. Very clear conceptions of how these models might be used to inform planning at different scales and very different time periods are critical to this focus… Quite new forms of integrated and coordinated decision support systems will be forthcoming from research on smart cities of the future'.

A survey of related work Many reviews or surveys have, over the last few years, been carried out on big data analytics and its core enabling technologies. They tend to offer different perspectives on, or emphasise various dimensions of, the topic, while overlapping in many computational, analytical, and technological aspects [21, 27] pertaining to such components as techniques, algorithms, models, software tools, data processing platforms, and application forms, adding to related research issues and opportunities as well as challenges (e.g., [34, 35, 68, 69, 115, 125, 145]). Regarding the orientation of most of these surveys and other studies conducted thus far, they tend to focus on the business domain (e.g., [33, 54, 107]). This implies that the literature and thus research addressing big data analytics and its core enabling technologies in relation to the domain of sustainable urban development literature and thus research remains scant. In response to this paucity of literature and thus research on the core enabling technologies of big data analytics and its application in the context of sustainable smart cities, Bibri and Krogstie [27] provide a thorough survey on the topic by identifying and reviewing such technologies, in addition to synthesising and illustrating the key computational and analytical techniques, processes, and frameworks associated with the functioning and application of big data analytics. In doing so, the authors bring together research directed at a more conceptual, technical, and overarching level, a multi-perspectival approach which is intended to stimulate new research opportunities within the city domain, with a particular emphasis on the use of big data analytics and its core enabling technologies for advancing sustainability, as well as to add more depth and rigour to the existing studies in the field. The topics of the core enabling technologies of big data analytics addressed in rather more detail by the authors in their topical literature review include, but are not limited to, the following:

- Pervasive sensing for urban sustainability in terms of collecting and measuring urban big data; the IoT and related RFID tags; sensor-based urban reality mining; and sensor technologies, types, and areas in big data computing.
- Wireless communication network technologies and smart network infrastructures.
- Data processing platforms.
- Cloud and fog/edge computing in terms of characteristics, benefits, commonalities, and differences.
- Advanced techniques and algorithms.
- Privacy mechanisms and security measures.
- Conceptual and analytical frameworks with a focus on the process of data mining.

It might be useful to elaborate on, for instance, data processing platforms as one of the key technological components of the ICT infrastructure of smart and smarter cities. To begin with, while there exist many data processing platforms that can be used to perform big data analytics in terms of storage, manipulation, management, analysis, and evaluation of large masses of data, Hadoop MapReduce platform tends to be the most commonly applied one in the realm of smart cities (sse, e.g., [73, 108]) and sustainable smart cities [20, 21] due to the suitability of its functionalities as to handling urban data as well as to its benefits related to load balancing, flexibility, processing power, and cost effectiveness [21]. Additionally, it has become the primary data processing platform given its simplicity, scalability, and fine-grain fault tolerance [145]. It has various extensions, including Co-Hadoop, Hadoop++, HadoopDB, Cheetahand, and Dare. And numerous technologies (e.g., Apache PIG, Apache Hive, Apache Tez, Apache Giraph, Apache Cassandra, Apache Spark, Apache Scoop, Apache Zookeepe, Apache HBase, Apache Flume, and Scribe) can, together with HDFS, be built on the top of the Hadoop system to form a Hadoop ecosystem to enhance efficiency and functionality [20]. Several reviews of data processing platforms have been carried out from different perspectives, including conceptual, technological, computational, analytical, and general (e.g., [69, 115, 145]). However, Spark is considered one of the more efficient data processing platforms in terms of real-time data handling. Apache S4 platform is designed for processing continuous data streams in real time [103].

In addition, data processing platforms, standalone or as part of cloud computing or fog computing model, have the function of collecting, storing, coalescing, processing, managing, analysing, evaluating, and interpreting large masses of data in relation to a given urban system or domain/sub-domain to discover useful knowledge in the form of intelligence intended primarily to enhance decision-making processes by deploying the obtained analytical outcome or feeding it into decision support systems pertaining to urban operations, functions, services, strategies, and policies. Accordingly, the value of resulting intelligence lies in optimising the efficiency of infrastructures and facilities, integrating and coupling networks, reducing resource consumption, enhancing service delivery, streamlining planning and governance processes, and smarting up urban forms and physical structures. These occur through such functions as control, automation, optimisation, management, modelling, and simulation in the context of sustainability. However, merely keeping up with data flood coming from a single urban domain or sub-domain and storing the more relevant bits are daunting enough, not to mention effectively managing and analysing colossal datasets to spot hidden patterns and discover meaningful correlations. Nevertheless, massive efforts are being deployed to further advance the existing data processing platforms in the context of smart and smarter cities in response to the emerging wave of city analytics for which big data are the fundamental ingredients, to reiterate, and the underlying role in tackling and responding to the challenges of sustainable development and urban growth [20]. That is, this advancement is necessary for both enhancing the operational functioning and planning of urban systems as well as facilitating the coordination and coupling of urban domains in line with the vision of sustainability in the context of smart and smarter cities.

Further to the point, other topical studies tend to address varied technological components of big data while focusing on their use in relation to specific technologies, especially the IoT. For example, Ahmed et al. [1] explore the recent advances in big data analytics for the IoT systems as well as the key requirements for managing and analysing big data in an IoT environment. Bibri [21] reviews and synthesises the existing literature with the main objective of identifying and discussing the state-of-the-art big data applications enabled by the IoT and related sensor technologies, data processing platforms, and cloud and fog computing models in the context of sustainable smart cities of the future. In establishing an IoT-based smart city using big data analytics, Rathore et al. [108] describe their proposed system by its architecture and implementation prototype using Hadoop ecosystem and a wide variety of sensors for different purposes. This system entails data generation and collection, aggregation and integration, filtration, classification, preprocessing, computational analytics, and decision making.

Enabling capabilities Big data analytics as a set of advanced hardware technologies: devices, systems, platforms, architectures, and networks, constituting a key component of the ICT infrastructure of smart and smarter holds great potential to alter how such cities can be operated, managed, designed, and developed with regard to sustainability. This prospect has become clear as the underlying core enabling technologies will be, in the near future, the dominant mode of monitoring, understanding, analysing, and planning such cities to improve their contribution to the goals of sustainable development [16, 20]. Moreover, the broad availability of urban data is pushing research ever more into further advancing software technologies, including methods, techniques, algorithms, models, simulations, and protocols towards enhancing the efficiency of the extraction of useful knowledge pertaining to sustainability for the purpose of enhancing related urban intelligence functions and simulation models associated with energy, transport, mobility, healthcare, education, planning, and so on [27]. In reference to smart cities of the future and in relation to planning, Batty et al. [16] point out that sustainability issues will be dealt with using more effective models and simulations in city planning; in the era of big data, and this new technology will be a salient factor for planning forms of operation and organisation.

Big data applications and their sustainability effects and benefits

A critical evaluation of topical studies The intent here is to point out the differences between the notable topical studies carried out on big data applications that are particularly significant. Critically evaluating this research entails providing opinions as to what extent the findings or statement within this research are true, or to what extent they can be agreed with, as well as providing evidence taken from a range of sources which both agree with and contradict the presented arguments. With that in mind, significant opportunities exist for big data analytics and its application in relation to modernising and advancing smart and smarter cities as urban development models in terms of sustainability dimensions, among other things, as there is a broad range of urban domains and subdomains that can utilise big data technology as an advanced form of ICT in connection with sustainable development processes (e.g., [6, 16, 20, 21]). In other words, there exist numerous big data applications whose effects are compatible with the goals of sustainable development, as the knowledge resulting from the analysis of urban data in the form of applied intelligence usher in nearly all the domains of smart and smarter cities. This is due to the ubiquitous nature of ICT of pervasive computing and the associated extensiveness of data and the massive use of its analytics. However, while some topical studies address big data applications, they tend to deal largely with their use in relation to the efficiency of the proposed solutions, and there only are a few recent studies that focus on their use, yet only, in relation to some aspects of sustainability, or pass reference on the role of big data application in improving environmental sustainability.

A short review conducted by Al Nuaimi et al. [5] describes only a few big data applications in smart cities, namely power grid, traffic lights and signals, and eduction, and also explores the opportunities, benefits, and challenges of incorporating big data applications in smart cities. The authors conclude that while many opportunities are available for utilising big data technology in smart cities, there are still many issues that need to be addressed to achieve better application of this technology. Hashem et al. [54] describe a few big data applications in terms of efficiency and sustainability, including power grid, transport and traffic, healthcare, and governance, and also discuss the visions of big data analytics as to supporting smart cities by focusing on how big data can change urban populations at different levels. Another detailed survey of big data applications provided by Bibri [21] includes more urban domains than the above reviews, including transport, mobility, traffic, energy, power grid, environment, buildings, infrastructure, and large scale deployment, yet only in relation to environmental aspects of sustainability and in the context of the IoT as one ICT vision of pervasive computing. In investigating the potential contribution of smart city to environmentally sustainable urban development, Angelidou et al. [6] analyse comparatively a total of 32 smart city applications that can be found in the Intelligent Cities Open Source (ICOS) community repository. The authors classify the applications according to, among other criteria, the environmental issue they address, namely high traffic density, high amount of waste, increasing air pollution, increasing energy consumption/sinking resources, loss of biodiversity and natural habitat, and sinking water resources. However, they neither specify, or provide any detail on, which of these applications, and how they, relate to big data analytics. Kumar and Prakash [83] investigate the real potential of using big data analytics by decision makers and city planners in smart cities using a large number of case studies across the globe and hence including many undergoing pilot project for making cities smarter along with well-being benefits, yet with only a focus on power grids and traffic congestion. Focusing on social sustainability issues in terms of digital divides, Gebresselassie and Sanchez [51] ask, in their recent study on smart tools for socially sustainable transport, how smartphone applications (apps) can address social sustainability challenges in urban transport, if at all, with a particular focus on transport disadvantages experienced by citizens due to low income, physical disability, and language barriers and based on a review of 60 apps. This study reveals that transport apps have the potential to address or respond to the equity and inclusion challenges of social sustainability by employing universal design in general-use apps, including cost-conscious features and providing language options, as well as by specifically developing smartphone apps for persons with disabilities. However, while this is not to imply that such apps are a panacea for the equity and inclusion issues related to urban transport—but only one of the tools that can be used to address them, there nevertheless are other urban domains where new apps of similar use need to be developed and mainstreamed to address the same issues, including healthcare, education, and public and social services, and so on. Moreover, while this study brings the social aspects of sustainability to the forefront, and helps to gain a better understanding of the application of smart tools for socially sustainable transport, there is no mention of the role of big data analytics in the functioning of such apps, or how they relate to it at all, despite the mention of some articles that in fact address big data analytics and its application in smart cities in terms of the new smart applications proliferating urban transportation systems. Indeed, their operation must be based on big data on travel behaviour, mobility models, and multimodal transport. Furthermore, Bibri [20] provides a list of the other domains where big data can be applied to reach the required level of the different dimensions of sustainability, including dematerialisation and demobilisation, water management, natural ecosystem management, public safety and civic security, ecosystem service provision, urban design and land use, urban planning, and participatory governance.

Furthermore, big data applications can be categorised into two classes in the realm of smart and smarter cities: real-time applications and offline applications. As elucidated by Bibri [20, p. 491] regarding the former, 'the input is instantaneous or near real-time, analysis is fast, and system behaviour or application action is based on real-time mining…

for decision-making since all real-time applications require immediate responses. This implies that if decisions, …based on analytical results…, cannot be made within a specific time line, they simply become of no value or effect. Hence, it is crucial in this regard to provide the kind of data necessary for mining in a timely manner and to conduct the analysis…in a fast and sound fashion for accurate decision-making purposes. As to the latter, the input tends to be periodic and thus analysis occurs sporadically. System behaviour or application action comes in the form of delayed responses. For example, traffic control requires immediate responses to mange traffic in real-time; while environmental monitoring and management is associated with more delayed responses, as decisions are generally made over medium or long-term period'. Mohamed and Al-Jaroodi [98] provide an account of real-time and offline applications in the context of smart cities, with a focus on big data analytics.

All in all, in smart and smarter cities, big data analytics and its application are associated with such diverse intelligence functions as control, automation, optimisation, management, prediction, and enhancement, which are involved in the operational functioning and planning of urban systems as part of various urban domains. Hence, big data applications are well positioned to enhance the sustainability, efficiency, and resiliency performance of such cities, as well as the life quality, well-being, and equity of their citizens. Yet, the literature and thus research on the uses of big data analytics and its application in relation to sustainable development remains scant in the context of smart and smarter cities. This implies that, to reiterate, the potential of big data computing for advancing sustainability remains untapped and underexplored in the context thereof, and therefore needs to be fully exploited and investigated, respectively.

The key practical and analytical applications of big data technology for multiple urban domains Big data technologies and their applications are increasingly permeating the systems and domains of smart and smarter cities due to their potential for enabling their needed transition to sustainable development in an increasingly urbanised world. The range of the emerging big data applications as novel analytical and practical solutions that can be utilised for enhancing their sustainability performance is potentially huge, as many as the case situations where big data analytics may be of relevance to enhance some sort of decision or insight in connection with their domains or sub-domains. Bibri [23] identifies and enumerates the most common big data applications in relation to these domains or sub-domains, and also elucidates their sustainability effects associated with the underlying functionalities pertaining to the operations, functions, services, designs, strategies, and policies related to these domains or sub-domains, which specifically include the following:

- Transport and traffic.
- Mobility.
- Energy.
- Power grid.
- Environment.
- Buildings.
- Infrastructures.

- Urban planning.
- Urban design.
- Academic and scientific research.
- Governance.
- Healthcare.
- Education.
- Public safety.

For a detailed account of the big data applications associated with these domains or sub-domains, the interested reader can be directed to Bibri [23]. The reason for not including the rather long table containing these applications and their description in the form of a series of bullet points in this paper is that it would make it an unusually long paper. However, those applications are by no means, or intended to be, exhaustive. Also, they are synthesised and distilled from many studies conducted in more recent years, the most notable of which in order of priority in terms of their contribution to the synthesis and extracted essential meaning below are: Bibri [20, 21], Batty et al. [16], Angelidou et al. [6], and Al Nuaimi et al. [5], including the other works that are referenced (credited) in these studies. Of relevance to add, as to the technical processes, tools, and other details underpinning the functioning of big data applications, the interested reader can be directed to Bahga and Madisetti [11], one of the many books available out there on the topic, for a detailed account from a general perspective, and to Bibri [20] for an overview focusing mainly on sustainable smart and smarter cities.

Towards data-driven sustainable smart cities

Data-driven smart sustainable cities' is a term that has recently gained traction in academia, government, and industry to describe cities that are increasingly composed and monitored by ICT of ubiquitous and pervasive computing and thereby have the ability of using advanced technologies by city operations centers, planning and policy offices, research centers, innovation labs, and living labs for generating, processing, and analyzing the data deluge in order to enhance decision making processes and to develop and implement innovative solutions for improving sustainability, efficiency, resilience, equity, and the quality of life. It entails developing a citywide instrumented system (i.e., inter-agency control, planning, innovation, and research hubs) for creating and inventing the future. For example, a data-driven city operations centre, which is designed to monitor the city as a whole, pulls or brings together real-time data streams from many different agencies spread across various urban domains and analyze them for decision making and problem solving purposes related to urban operational functioning. As cities are routinely embedded with all kinds of ICT forms, including infrastructure, platforms, systems, devices, sensors and actuators, and networks, the volume of data generated about them is growing exponentially and diversifying, providing rich, heterogenous streams of information about urban environments and citizens. This data deluge enables the real-time analysis of different urban systems and interconnects data across different urban domains to provide detailed views of the relationships between different forms of data that can be utilized for advancing the various aspects of urbanity through new modes of operational functioning, planning, design, development, and governance in the context of sustainability, as well as provides the raw material for envisioning more sustainable, efficient, resilient, and livable cities [23].

We are moving into an era where instrumentation, datafication, and computation are routinely pervading the very fabric of smart or smarter cities, coupled with the interlinking, integration, and coordination of their systems and domains. As a result, vast troves of contextual and actionable data are being produced and used to operate, regulate, manage, and organize urban life. At the heart of this emerging era of data-driven urbanism is a computational understanding of urban systems and processes that reduces urban life to a set of logic, calculative, and algorithmic rules and procedures. Such understanding entails drawing together, interlinking, and analyzing urban big data to provide a more holistic and integrated view and synoptic intelligence of the city. This is being increasingly directed for improving, advancing, and maintaining the contribution of smart or smarter cities to the goals of sustainable development. In other words, the data-driven approach to urbanism has become the mode of production for sustainable smart cities, which are accordingly becoming knowable, tractable, and controllable in new dynamic ways, responsive to the data generated about them by reacting to the analytical outcome of many domains of urban life in terms of enhancing and optimizing operational functioning, planning, design, development, and governance in line with the goals of sustainable development. In a nutshell, a new era is presently unfolding wherein sustainable smart urbanism is increasingly becoming data driven. For supra-national states, national governments, and city officials, smart cities of the future or smarter cities offer the enticing potential of environmental and socio-economic development—more sustainable, livable, functional, safe, equitable, and transparent cities, and the renewal of urban centres as hubs of innovation and research (e.g., [5, 16, 20, 23, 84]).

The main scientific and intellectual challenges and common open issues

While there is a growing consensus among urban scholars and applied urban science experts that big data analytics and its application will be a determining or salient factor in the operational functioning, management, planning, design, and development of smart cities of the future or smarter cities, there still are significant scientific and intellectual challenges as well as open issues that need to be addressed and overcome for building such cities based on big data computing and underpinning technologies, and then for accomplishing the desired outcomes related to sustainability and urbanisation. Such challenges and issues pose interesting and complex research questions, and constitute fertile areas of investigation awaiting interdisciplinary and transdisciplinary teams of scholars, scientists, experts, and researchers working in the field of sustainable smart urbanism.

The rising demand for big data analytics and its core enabling technologies, coupled with the growing awareness of the associated potential to transform the way urban systems can be operated, managed, planned, and designed in the context of sustainability, comes with major challenges and open issues related to the design, engineering, development, implementation, and maintenance of data-centric applications in sustainable smart cities of the future or smarter cities. The challenges are mostly computational, analytical, and technical in nature, and sometimes logistic in terms of the detailed organisation and implementation of the complex technical operations involving the installation and deployment of the big data ecosystem and its components as part of the ICT infrastructure of such cities. They include, but are not limited to, the following, as compiled in Table 2.

There are many studies available (e.g., [5, 15, 16, 20, 66, 68, 78–81, 85, 124, 132, 133]) that provide a descriptive or analytical account of some of the above listed challenges (and also some of the open issues addressed below) as related to big data analytics and its applications and uses in smart and smarter cities. For example, Bibri [20] provides an overview of some of those challenges and potential ways to address and overcome them in the context of sustainable smart cities of the future, including data management, database integration across urban domains, urban growth and data growth, data sharing, data uncertainty and incompleteness, data accuracy and quality, and data governance.

Most of the challenges of big data analytics and its application arise from the nature of the data generated in smart and smarter cities in terms of their attributes in terms of (e.g., [16, 20, 23, 79, 86, 95, 96, 146]):

- Consisting of exabytes or terabytes of data;
- Being structured and unstructured in nature;
- Being often tagged with spatial and temporal labels; being commonly streamed from a large number and variety of sources;
- Being mostly generated automatically and routinely; being created in, or near, real-time;
- Being exhaustive in scope and scale by striving to capture entire populations or systems;
- Dramatically exceeding sample sizes commonly in use for small data studies;
- Being relational in database systems by containing common fields that enable the conjoining and combination of different datasets;
- Being fine-grained in resolution by aiming to be very detailed and uniquely indexical in identification; and holding the traits of extensionality (can add new fields easily), evolvability (can change dynamically), and scaleability (can expand in size rapidly).

Adding to the above primarily technological challenges are the financial, organisational, institutional, social, political, regulatory, and ethical ones, which are associated with the implementation, retention, and dissemination of big data across the domains of sustainable smart and smarter cities of the future [20]. In this regard, controversies over the benefits of big data analytics and its application involve limited access and related digital divides and other ethical concerns about accessibility [49]. For a detailed discussion of the challenges of urban big data and sustainable development, the reader can be directed to Kharrazi e al. [144]. Kitchin [79] provides a critical reflection on the implications of big data and smart urbanism, examining five emerging concerns, namely:

1. The politics of big urban data.
2. Technocratic governance and city development.

Table 2 Computational, analytical, technical, and logistic challenges. Source: Bibri [23]

Computational, analytical, technical, and logistic challenges
Design science and engineering constraints
Data processing and analysis
Data management in dynamic and volatile environments
Data sources and characteristics
Database integration across urban domains
Data sharing between city stakeholders
Data uncertainty and incompleteness
Data accuracy and veracity (quality)
Data protection and technical integration
Fault tolerance and scalability
Data governance
Urban growth and data growth
Cost and large-scale deployment
Evolving urban intelligence functions and related simulation models and optimization and prediction methods as part of exploring the notion of smart cities as innovation labs
Building and maintaining data-driven city operations centres or citywide instrumented system
Relating the urban infrastructure to its operational functioning and planning through control, automation, management, optimization, enhancement, and prediction
Creating technologies that ensure fairness, equity, inclusion, and participation
Balancing the efficiency of solutions and the quality of life against environmental and equity considerations
Privacy and security

3. Corporatisation of city governance and technological lock-ins.
4. Buggy, brittle and hackable cities.
5. The panoptic city.

Furthermore, to effectively and successfully use big data analytics for smart and smarter city applications, there are some open issues that need to be addressed and resolved, which mostly stem from the different challenges mentioned above. These issues are currently under investigation by the relevant industry and research communities. Regardless, no full solutions and robust approaches based on big data analytics can be offered in the context of such cities, and therefore, there is always room for improvements and innovations in the field of data-driven sustainable smart urbanism in terms of operational functioning, planning, design, and development. However, as regards he key open issues, there is, and will be, a growing need or increased demand for well qualified professionals and experts to design, develop, deploy, implement, operate, and maintain smart cities of the future or smarter cities with regard to their infrastructures, platforms, and applications. Specialised education and focused training in the field need to be strategically planned, carefully designed, and widely offered to obtain the needed human resources for fulfilling the purpose and meeting the expectations. In addition, it is necessary to set common assessment methods, measurements, and control policies for big data applications in such cities. Monitoring, controlling, and managing initiatives and implementations using advanced techniques and procedures is of crucial importance for ensuring the effectiveness, viability, quality, and durability of big data applications in the context of sustainability. Furthermore, as discussed previously in relation to smarter cities, political action is determining in the functioning, insertion, and evolution of sustainable smart cities of the future or smarter cities as an academic discourse which epitomises a socio-technical transition that is of significance to society. The political effects on smart and smarter cities play a pivotal role in how they will perform in terms of sustainability [20]. Also, the privilege of access to data by different city constituents with different political positions or powers must be taken into account and addressed carefully [5]. For a detailed account and discussion on the shaping role of political action in sustainable smart cities of the future, the interested reader can directed to Bibri and Krogstie [24]. In addition, it is important to investigate the side or harmful effects of technology use by citizens on their health and living, and hence to consider all the possible risks and unintended consequences in this regard.

Another open issue requiring special attention and careful consideration in the context of smart cities of the future or smarter cities is security and privacy concerns. When all systems become integrated, networked, and ubiquitous, data will be shared among all urban entities. It is a commonly held view that the more technologies monitor urban environments and collect information, the larger becomes the privacy threats, and the larger the networks, the higher the security risks (see [27] for a discussion of privacy mechanisms and security measures). Therefore, the ICT infrastructure and related data processing and cloud/fog computing platforms and infrastructures must be secured, privacy must be preserved, and information must be protected and thus not abused. Privacy—to selectively reveal oneself to the world—remains though the most critical issue in the context of the use of big data analytics and related applications in such cities. In fact, privacy is considered a basic human right in many democratic states, enshrined in national and supra-national laws in various ways, and related debates concern acceptable practices as to accessing and disclosing personal and sensitive information about a person [81]. Such sensitive information can relate to a number of a personal facets and domains creating a number of inter-related privacy forms, including [94, 110]:

- Identity privacy (to protect personal and confidential data);
- Bodily privacy (to protect the integrity of the physical person);
- Territorial privacy (to protect personal space, objects and property);
- Locational and movement privacy (to protect against the tracking of spatial behaviour);
- Communications privacy (to protect against the surveillance of conversations and correspondence); and,
- Transactions privacy (to protect against monitoring of queries/searches, purchases, and other exchanges).

These forms of privacy can be threatened and breached through a number of what are normally understood as unacceptable practices, each of which produces a different form of harm, as compiled by Kitchin [81] (Table 3) and detailed by Solove [118].

Data-driven smart sustainable/sustainable smart urbanism, urban science, data science, and big data computing and underpinning technologies create a number of potential privacy harms for several reasons. Kitchin [81] addresses five reasons, each of which raises significant challenges to existing approaches to protecting privacy (privacy laws and fair information practice principles), namely:

1. Datafication, dataveillance and geosurveillance.
2. Inferencing and predictive privacy harms.
3. Anonymization and re-identification.
4. Obfuscation and reduced control.
5. Notice and consent is an empty exercise or is absent.

There are clearly a number of ethical issues that arise from the development, deployment, and implementation of smart or smarter city technologies and accompanying urban science. The ethical dimensions of big data computing and underpinning technologies and urban science need to be seriously addressed and much more thoroughly mapped out. As widely acknowledged, many smart urban technologies capture data without the consent of citizens—who ought actually to have full details of what data are being generated, for what purpose these data are being used for, what kind of insights are being extracted from them or additional data inferred from them, how they are being captured, in addition to having shared control and benefit in how all data concerning them are subsequently used. This necessitates full consent together with full transparency with regard to the actions of those who control, process, and analyze data. Urbanism researchers and urban scientists need to consider the ethical implications of their work with respect to privacy harms and citizen permissions, and the purposes their research is intended for—even in the context of sustainability. As suggested by Kitchin [81], 'Beyond complying with relevant laws and institutional research board requirements, analysts have a duty of care to their fellow citizens not to expose them to harm through their analysis. Admittedly, what constitutes harm is often difficult to define and harms can occur directly or indirectly but nonetheless there is a need to consider how research might be used and to act responsibly. In addition, professional bodies should review their ethical standards in the light of big data and revise accordingly. City managers need to consider the potential pernicious effects of the roll-out of smart [urban] technologies and that notice and consent are all but impossible in many cases and take a pro-active role in brokering privacy and security arrangements on behalf of citizens through relevant contracting procedures and parameters. Here, all vendors would be compelled to comply with service level agreements concerning the operation of systems, what data are generated and how these can be used and shared, and be subject to privacy impact assessments.'

From a social perspective, new ethical frameworks based on gifting or sharing, in which citizens swap their data for a tangible return, offer an alternative underpinning for smart cities of the future or smarter cities and urban science. However, the 'gifting' remains compulsory with no alternatives and is also done without consent, and the benefits of 'sharing' data are most often stacked in favour of those capturing the data [81]. From a technical perspective, while there are several solutions and frameworks (especially modelling and simulations) that have recently been proposed (e.g., [77, 85]), the problem persists in the quest for unconventional security

Table 3 A taxonomy of privacy breaches and harms. Source: compiled by Kitchin [81] from Solove [118]

Domain	Privacy breach	Description
Information collection	Surveillance	Watching, listening to, or recording of an individual's activities
	Interrogation	Various forms of questioning or probing for information
Information processing	Aggregation	The combination of various pieces of data about a person
	Identification	Linking information to particular individuals
	Insecurity	Carelessness in protecting stored information from leaks and improper access
	Secondary use	Use of information collected for one purpose for a different purpose without the data subject's consent
	Exclusion	Failure to allow the data subject to know about the data that others have about her and participate in its handling and use, including being barred from being able to access and correct errors in that data
Information dissemination	Breach of confidentiality	Breaking a promise to keep a person's information confidential
	Disclosure	Revelation of information about a person that impacts the way others judge her character
	Exposure	Revealing another's nudity, grief, or bodily functions
	Increased accessibility	Amplifying the accessibility of information
	Blackmail	Threat to disclose personal information
	Appropriation	The use of the data subject's identity to serve the aims and interests of another
	Distortion	Dissemination of false or misleading information about individuals
Invasion	Intrusion	Invasive acts that disturb one's tranquillity or solitude
	Decisional interference	Incursion into the data subject's decisions regarding her private affairs

measures and privacy-enhancing mechanisms [20]. In this respect, several researchers (e.g., [132]) have recently provided clear directions for further empirical research and theory development about privacy concerns, in addition to sensitising techniques to identify the emergence, absence, or presence of privacy concerns among citizens. The same directions apply to security concerns. Regardless, the generation, accumulation, and processing of various data streams across urban domains are projected to continue to raise privacy and security issues, which is in fact, of concern to all the city constituents and stakeholders. Therefore, there is a need for novel measures and mechanisms that can ensure trustable data acquisition, transmission, and processing, not least to legitimate service provisioning associated with transport, traffic, mobility, accessibility, healthcare, utility, and public and social services, while ensuring citizens' privacy and guaranteeing services' integrity in the context of sustainability. Of importance to also consider is to develop smart cities of the future or smarter cities and urban science that have a set of ethical principles and values at their heart, which in fact is at the heart of social sustainability. The challenge is to acknowledge that there are a number of real ethical issues that need to be addressed and overcome, and to search for and find the kind of solutions (i.e., privacy-enhancing mechanisms and security measures) that also enable the sustainability benefits of big data computing and underpinning technologies to be realized. This is no easy task, but one that needs urgent redress, supported by viable, strategic pathways.

Addressing different kinds of challenges and open issues, Kitchin [80] provides a critical overview of data-driven urbanism, and critically examines a number of urban data issues, namely:

- Data ownership, data control, data coverage and access.
- Data security and data integrity.
- Data protection and privacy, dataveillance, and data uses such as social sorting and anticipatory governance.
- Technical data issues such as data quality, veracity of data models and data analytics, and data integration and interoperability.

Discussion, conclusion, and contribution

The principal aim of this paper was to provide a comprehensive, state-of-the-art review and synthesis of the field of smart and smarter cities as regards sustainability and related big data analytics and its application in terms of the underlying foundations and assumptions, research issues and debates, opportunities and benefits, technological developments, emerging trends, future practices, and challenges and open issues. These issues were addressed through dividing the paper into many sections and sub-sections where the relevant conceptual and theoretical subjects as well as thematic and topical categories were adequately elaborated on and thoroughly discussed from a variety of perspectives. This interdisciplinary and transdisciplinary review explored a broad array of the literature at the intersection of various disciplinary and scientific fields and technological areas. As such, it is meant to facilitate collaboration among these fields and areas for the primary purpose of generating the kind of interactional and unifiable knowledge that is necessary for a more integrated and deeper understanding of the topic of smart and smarter cities in relation to sustainability and related big data analytics and its application, as well as new insights and perspectives. The outcome of this extensive review allowed to establish the status of current knowledge about the sustainability of smart and smarter cities in their current state, as well as to highlight the potential of big data analytics and related novel applications for advancing their sustainability in the future.

First, the conceptual theoretical, and discursive constructs that make up this study, namely smart cities, smarter cities, and big data computing, were identified, described, examined, and discussed while emphasising the relevant issues and aspects relating to the cross-disciplinary integration underlying the multidisciplinary topic of this study. Worth noting, however, is that despite the prevalence of the concept and phenomenon of smart city worldwide, there still is obscurity facing its definition; nevertheless, there seems to be an agreement on what the smart or smarter city should achieve as to sustainability and urbanisation, and how advanced ICT (particularly big data analytics and its application) should be utilised to mitigate or solve the associated challenges and issues.

Second, a detailed, two-part survey of the relevant work in terms of issues, debates, gaps, benefits, opportunities, and prospects was provided. The focus of the first part on smart cities was on general and particular research areas, deficiencies, and potentials with regard to sustainability, and that on smarter cities was on characteristic features, social shaping dimensions, and the current issues of and future potentials for sustainability. The review indicates that smart and smarter cities in their current state involve several issues, pose special conundrums, and present significant challenges as to their development and implementation with regard to their contribution to sustainability. Accordingly, there are many critical questions that are worth investigating, which pertain to conceptual, theoretical, analytical, empirical, practical, social, and environmental aspects as related to sustainable development and the role of advanced ICT (especially big data applications) in achieving its goals. These aspects constitute new research avenues and thus opportunities which need to be pursued and realised, respectively, to advance the sustainability of smart cities of the future or smarter cities based on big data applications. This is anchored in the growing recognition that emerging and future ICT is extremely well positioned to make substantial contributions in this regard due to its disruptive, innovative, substantive, and transformational effects on forms of urban operations, functions, services, designs, strategies, and policies.

Third, big data analytics and its application in smart and smarter cities was addressed in terms of research status and data growth projection, the urban data deluge in city analytics and its sources and enabling capabilities, research issues and future prospects, core enabling technologies, and big data applications and their sustainability effects and benefits. With respect to the latter, a set of varied topics was dealt with, which included a critical evaluation of topical studies, analytical and practical applications for multiple smart/smarter city domains, and data-driven sustainable smart cities. The review reveals that tremendous opportunities are available for utilising big data applications in smart cities of the future or smarter cities to improve their contribution to the goals of sustainable development by optimising and enhancing urban operations, functions, services, designs, strategies, and policies, as well as by finding answers to challenging analytical questions and thereby advancing knowledge forms. The most common data-centric applications identified concerning urban domains: transport and traffic, mobility, energy, power grid, environment, buildings, infrastructures, urban planning, urban design, academic and scientific research, governance, healthcare, education, and public safety. The potential of big data technology lies in enabling smart cities of the future or smarter cities to harness and leverage their informational landscape in effectively understanding, monitoring, probing, and planning their systems and environments in ways that enable them to achieve the required level of sustainability. To put it differently, the use of big data analytics is projected to play a significant role in realising the key characteristic features of such cities in terms of sustainability, namely the efficiency of operations and functions, the efficient utilisation of natural resources, the intelligent management of infrastructures and facilities, the improvement of the quality of life and well-being of citizens, and the enhancement of mobility and accessibility. In all, the untapped potential of big data applications is evident and needs to be unlocked and exploited within such cities. In all, the untapped potential of big data applications is evident and needs to be unlocked and exploited within such cities. Already, many major cities have, whether within ecologically or technologically advanced nations, started to implement big data applications to reap their sustainability benefits [23].

Fourth, the key scientific and intellectual challenges were identified and the common open issues associated with the use of big data analytics and related applications in (enabling, operating, managing, and planning) smart and smarter cities were examined and discussed. Just as there are many new opportunities and benefits ahead to embrace and exploit, there are significant challenges and open issues ahead to address and overcome in relation to big data analytics to achieve a successful implementation of related novel applications in the context of smart cities of the future or smarter cities. These challenges are mostly of computational, analytical, technical, and logistic kinds. While most of these challenges and open issues are currently under investigation and scrutiny by the relevant research and industry communities, supported by technology and innovation policies, deploying big data applications in smart cities of the future or smarter cities requires overcoming other organisational, institutional, political, social, ethical, and regulatory challenges. These are likely to hinder the development and implementation of big data applications in such cities. Nevertheless, with all the success factors in place, coupled with a deep understanding of the emerging phenomenon of smart cities and an acknowledgement of the potential of big data computing, making such cities smarter in achieving sustainability becomes an attainable goal in an increasingly urbanised world. Important to add, while smart city and big data computing research is still in its infancy, the solutions to the involved challenges and issues can make it a very practical field. Worth noting moreover is that, as smarter cities are still emerging and in the early stage of their development, could, if planned strategically and linked to the agenda of sustainable development as part of related research, do a lot more for sustainability before they become widely adopted.

Concerning the value of this review and synthesis, the findings enable researchers and scholars to focus their work on the identified real-world challenges and open issues and the existing knowledge gaps pertaining to smart and smarter cities as urban development strategies in the context of technology and sustainability, respectively. Practitioners and experts can make use of these findings to identify common weaknesses and potential ways to solve them as part of the ongoing and future endeavours of sustainable smart urban development. In view of that, this interdisciplinary and transdisciplinary review provides a valuable reference for researchers and practitioners in related research communities and the necessary material to inform these communities of the latest developments in the field. It moreover serves to inform various city stakeholders about the yet unexploited benefits of big data applications with regard to sustainability.

As an emerging field of research, data-driven smart urbanism is remarkably heterogeneous with a diversity of research problems, integrating various theoretical and disciplinary perspectives. Accordingly, there are many avenues for future research, and here, I identify a few of them as deemed highly relevant to this paper. Considering what this paper intended to establish and highlight, one area of future research should focus on exploiting the upcoming innovations in big data computing and underpinning technologies for enhancing and advancing the practice of sustainable smart urbanism, in addition to finding more effective ways of addressing the extreme fragmentation of and weak connection between smart cities and sustainable cities as landscapes and strategies, respectively, on the basis of big data computing. This is practiced within the field of urban science. Of particular relevance also is to address the various issues associated with the current approaches to smart and smarter cities, namely shortcomings, inadequacies, deficiencies, and misunderstanding with respect to sustainability. This specifically pertains to the question of the need for such cities to incorporate, or increase their contribution to, the goals of sustainable development in their conceptualization and operationalization as part of future pathways towards achieving sustainable smart cities. Furthermore, an enticing area of research is the exploration of the available opportunities towards new approaches to sustainable smart urbanism. Indeed, sustainable smart cities as a leading paradigm of urbanism tends to take multiple forms of combining the strengths of smart cities and sustainable cities based on how the concept of sustainable smart cities can be conceptualized and operationalized.

Lastly, this paper provides a form of foundation for further discussion to debate over the disruptive, substantive, synergetic, and transformational effects of big data analytics and its application on forms of the operational functioning, management, planning, and development of smart and smarter cities in terms of sustainability practices in the future. Also, it presents a sort of basis for stimulating more in-depth research on smart and smarter cities and big data computing in the form of both qualitative analyses and quantitative investigations focused on establishing, uncovering, substantiating, and/or challenging the assumptions and claims underlying the relevance and meaningfulness of big data applications as technological advancements with regard to advancing sustainability. For example, owing to the disciplinary origins of ICT-oriented literature which resorts to what is labelled 'normative bias' of smart city research [135], and thus respective authors' literacy in advanced sophisticated technologies, there is a fertile area of research that may challenge the promises and claims that new discoveries in big data computing as futuristic advances in ICT hold for urban spaces at the expense of the basic consideration of factors that hamper or facilitate the implementation of big data applications. Indeed, attempts at dwelling at this intersection regarding technological advancements exist in the body of research on smart cities (e.g., [57, 89, 131, 136]). Nevertheless, much more needs to be done to fully exploit it and thus promote sustainable interdisciplinary and transdisciplinary smart and smarter city research (e.g., [20, 23, 135]).

Abbreviations

ICT: Information and Communication Technology; IoT: Internet of Things; ITU: International Telecommunication Union; UNECE: United Nations Economic Commission for Europe.

Authors' contributions

The author read and approved the final manuscript.

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3. Master of Science in computer science with a major in informatics
4. Master of Science in computer and systems sciences with a major in decision support and risk analysis
5. Master of Science in entrepreneurship and innovation with a major in new venture creation
6. Master of Science in strategic leadership toward sustainability
7. Master of Science in sustainable urban development
8. Master of Science in environmental science with a major in ecotechnology and sustainable development

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3. Smart Sustainable Cities of the Future: The Untapped Potential of Big Data Analytics and Context-Aware Computing for Advancing Sustainability (660 pages), Springer, 03/2018.
4. Big Data Science and Analytics for Smart Sustainable Urbanism: Unprecedented Paradigmatic Shifts and Practical Advancements (500 pages).

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References

1. Ahmed E, Yaqoob I, Hashem IAT, Khan I, Ahmed AIA, Imran M, Vasilakos AV. The role of big data analytics in Internet of Things. J Comp Net. 2018;129:459–71.
2. Ahvenniemi H, Huovila A, Pinto-Seppä I, Airaksinen M. What are the differences between sustainable and smart cities? Cities. 2017;60:234–45.
3. Albino V, Berardi U, Dangelico R. Smart cities: definitions, dimensions, performance, and initiatives. J Urban Technol. 2015;22(1):3–21.
4. Al-Nasrawi S, Adams C, El-Zaart A. A conceptual multidimensional model for assessing smart sustainable cities. J Inf Syst Technol Manag. 2015;12(3):541–58.
5. Al Nuaimi E, Al Neyadi H, Nader M, Al-Jaroodi J. Applications of big data to smart cities. J Internet Serv Appl. 2015;6(25):1–15.
6. Angelidou M, Artemis P, Nicos K, Christina K, Tsarchopoulos P, Anastasia P. Enhancing sustainable urban development through smart city applications. J Sci Technol Policy Manag. 2017;9:1–25.
7. Angelidou M. Smart city policies: a spatial approach. Cities. 2014;41(S1):S3–11.
8. Angelidou M. Smart cities: a conjuncture of four forces. Cities. 2015;47:95–106.
9. Angelidou M. The role of smart city characteristics in the plans of fifteen cities. J Urb Technol. 2017;24(4):3–28.
10. Anthopoulos L. Understanding smart cities—a tool for smart government or an industrial trick? Public Administration and Information Technology, vol. 22. New York: Springer; 2017.
11. Bahga A, Madisetti V. Big bata science and analytics: a hands-on approach. Berlin: VPT; 2016.
12. Batty M. Technology highs. Guardian. 1989;22:29.
13. Batty M. Environment and Planning B. 1990;17:247.
14. Batty M. The computable city. Int Plann Studies. 1997;2:155.
15. Batty M. Big data, smart cities and city planning. Dialogues Hum Geog. 2013;3(3):274–9.
16. Batty M, Axhausen KW, Giannotti F, Pozdnoukhov A, Bazzani A, Wachowicz M, Ouzounis G, Portugali Y. Smart cities of the future. Eur Phys J. 2012;214:481–518.
17. Belanche D, Casaló L, Orús C. City attachment and use of urban services: benefits for smart cities. Cities. 2016;50:75–81.
18. Bettencourt LMA. The uses of big data in cities Santa Fe Institute. New Mexico: Santa Fe; 2014.

19. Bibri SE. The shaping of ambient intelligence and the internet of things: historico-epistemic, socio-cultural, politico-institutional and eco-environmental dimensions. Berlin: Springer; 2015.
20. Bibri SE. Smart sustainable cities of the future: the untapped potential of big data analytics and context aware computing for advancing sustainability. Germany, Berlin: Springer; 2018.
21. Bibri SE. The IoT for smart sustainable cities of the future: an analytical framework for sensor-based big data applications for environmental sustainability. Sustain Cities Soc. 2018;38:230–53.
22. Bibri SE. A foundational framework for smart sustainable city development: theoretical, disciplinary, and discursive dimensions and their synergies. Sustain Cities Soc. 2018;38:758–94.
23. Bibri SE. Big Data science and analytics for smart sustainable urbanism: unprecedented paradigmatic shifts and practical advances. Germany, Berlin: Springer; 2019.
24. Bibri SE, Krogstie J. On the social shaping dimensions of smart sustainable cities: a study in science, technology, and society. Sustain Cities Soc. 2016;29:219–46.
25. Bibri SE, Krogstie J. Smart sustainable cities of the future: an extensive interdisciplinary literature review. Sustain Cities Soc. 2017;31:183–212.
26. Bibri SE, Krogstie J. ICT of the new wave of computing for sustainable urban forms: their big data and context-aware augmented typologies and design concepts. Sustain Cities Soc. 2017;32:449–74.
27. Bibri SE, Krogstie J. The core enabling technologies of big data analytics and context-aware computing for smart sustainable cities: a review and synthesis. J Big Big Data. 2017;4(38):1–50.
28. Bifulco F, Tregua M, Amitrano CC, D'Auria A. ICT and sustainability in smart cities management. Int J Pub Sec Manag. 2016;29(2):132–47.
29. Castán JA, Martínez SI, Menchaca JL, Berrones MGT. Improving vehicular mobility in urban traffic using ubiquitous computing. J Comput Commun. 2016;4:57–62. https://doi.org/10.4236/jcc.2016.410006.
30. Caragliu A, Del Bo C, Nijkamp P. 'Smart cities in Europe' (series research memoranda 0048). Amsterdam: VU University Amsterdam, Faculty of Economics, Business Administration and Econometrics; 2009.
31. Carrasco-Sáez JL, Careaga Butter M, Badilla-Quintana MG. The new pyramid of needs for the digital citizen: a transition towards smart human cities. Sustainability. 2017;9:2258.
32. Chaminade C, Edquist C. Inside the public scientific system: changing modes of knowledge production. In: Smits R, Shapira P, Kehlmann S, editors. The theory and practice of innovation policy: an international research handbook. Cheltenham: Edward Elgar; 2010. p. 95–114.
33. Chen H, Chiang RHL, Storey VC. Business intelligence and analytics: from big data to big impact. MIS Q. 2012;36(4):1165–88.
34. Chen M, Mao S, Liu Y. Big data: a survey. Mob Networks Appl. 2014;19(2):171–209.
35. Chen F, Deng P, Wan J, Zhang D, Vasilakos AV, Rong X. Data mining for the internet of things: literature review and challenges. Int J Distrib Sens Networks. 2015;501(431047):1–14.
36. Chourabi H, Nam T, Walker S, Gil-Garcia JR, Mellouli S, Nahon K, Pardo TA, Scholl HJ. Understanding smart cities: an integrative framework. The 245th Hawaii international conference on system science (HICSS). Maui: HI; 2012. p. 2289–97.
37. Colldahl C, Frey S, Kelemen JE. Smart cities: strategic sustainable development for an urban world. Master thesis, School of Engineering, Blekinge Institute of Technology. 2013.
38. Dameri R, Cocchia A. Smart city and digital city: twenty years of terminology evolution. In: X Conference of the Italian chapter of AIS, ITAIS 2013, Università Commerciale Luigi Bocconi, Milan (Italy). 2013, p. 18.
39. David D. Environment and urbanization. Int Encyclop Geogr. 2017;24(1):31–46. https://doi.org/10.1002/9781118786352.wbieg0623.
40. Degbelo A, Granell Granell C, Trilles Oliver S, Bhattacharya D, Casteleyn S, Kray C. Opening up smart cities: citizen-centric challenges and opportunities from GIScience. ISPRS Int J Geo-Inf. 2016;5(2):16. https://doi.org/10.3390/ijgi5020016.
41. DeRen L, JianJun C, Yuan Y. Big data in smart cities. Sci China Inf Sci. 2015;58:1–12.
42. Dumreicher H, Levine RS, Yanarella EJ. The appropriate scale for "low energy": theory and practice at the Westbahnhof. In: Steemers K, Yannas S, editors. Architecture, city, environment, proceedings of PLEA 2000. London: James & James; 2000. p. 359–63.
43. Dutton WH, Blumler JG, Kraemer KL. Wired cities: shaping future communication. New York: Macmillan; 1987.
44. Erdmann L, Hilty LM (2010) Scenario analysis exploring the macroeconomic impacts of information and communication technologies on greenhouse gas emissions. J Ind Ecol 14(5):826.
45. Ersue M, Romascanu D, Schoenwaelder J, Sehgal A. Management of networks with constrained devices: use cases. IETF Internet. 2014.
46. Estevez E, Lopes NV, Janowski T. Smart sustainable cities. Reconn Study. 2016;1:330.
47. European Commission. Communication from the Commission EUROPE 2020. In: A strategy for smart, sustainable and inclusive growth. *Com (2010) 2020, Brussels* (3 March), Commission of the European Communities. 2010. https://doi.org/10.1016/j.resconrec.2010.03.010.
48. European Commission. Cities of tomorrow. Challenges, visions, ways forward. Publications Office of the European Union, Brussels. 2011.
49. Fan W, Bifet A. Mining big data: current status, and forecast to the future. ACM SIGKDD Explor Newsl. 2013;14(2):1–5.
50. Foucault M. The archaeology of knowledge. London: Routledge; 1972.
51. Gebresselassiea M, Sanchez TM. Smart' tools for socially sustainable transport. J Urban Sci. 2018;2:45.
52. Gubbi J, Rajkumar Buyya, Slaven Marusic, Marimuthu Palaniswami. Internet of things (IoT): a vision, architectural elements, and future directions. Future Gener Comput Syst. 2013;29(7):1645–60.
53. Han J, Meng X, Zhou X, Yi B, Liu M, Xiang W-N. A long-term analysis of urbanization process, landscape change, and carbon sources and sinks: a case study in China's Yangtze River Delta region. J Cleaner Prod. 2016;141:1040–50. https://doi.org/10.1016/j.jclepro.2016.09.177.

54. Hashem IAT, Chang V, Anuar NB, Adewole K, Yaqoob I, Gani A, Ahmed E, Chiroma H. The role of big data in smart city. Int J Infor Manag. 2016;36:748–58.
55. Höjer M, Wangel S. Smart sustainable cities: definition and challenges. In: Hilty L, Aebischer B, editors. ICT innovations for sustainability. Berlin: Springer; 2015. p. 333–49.
56. Hollands RG. Will the real smart city please stand up? City Anal Urban Trends Cult Theory Policy Action. 2008;12(3):303–20.
57. Ishida T, Isbister K. Digital cities: technologies, experiences, and future perspectives. Berlin: Springer; 2002.
58. ISTAG. Ambient intelligence: from vision to reality (for participation—in society and business. 2003. http://www.ideo.co.uk/DTI/CatalIST/istag-ist2003_draft_consolidated_report.pdf. Accessed 23 Oct 2009.
59. ISTAG. Shaping Europe's future through ICT. 2006. http://www.cordis.lu/ist/istag.htm. Accessed 22 Mar 2011.
60. International Telecommunications Union (ITU). Agreed definition of a smart sustainable city. Focus Group on Smart Sustainable Cities, SSC–0146 version Geneva, 5–6 Mar. 2014.
61. Jimenez CE, Solanas A, Falcone F. E-government interoperability: linking open and smart government. Computer. 2014;47(10):22–4.
62. Jabareen YR. Sustainable urban forms: their typologies, models, and concepts. J Plann Educ Res. 2006;26:38–52.
63. Joss S. Eco-cities: the mainstreaming of urban sustainability; key characteristics and driving factors. Int J Sustain Dev Plan. 2011;6(3):268–85.
64. Joss S, Cowley R, Tomozeiu D. Towards the ubiquitous eco-city: an analysis of the internationalisation of eco-city policy and practice. J Urban Res Pract. 2013;76:16–22.
65. Jucevicius R, Patašienė I, Patašius M. Digital dimension of smart city: critical analysis. Proc Social Behav Sci. 2014;156:146–50.
66. Kaisler S, Armour F, Espinosa JA, Money W. Big data: issues and challenges moving forward. In: Proceedings of 46th Hawaii International conference on systems sciences (HICSS). IEEE, Wailea, Maui. 2013, p. 995–1004.
67. Kärrholm M. The scaling of sustainable urban form: some scale—related problems in the context of a Swedish urban landscape. Eur Plan Stud. 2011;19(1):97–112.
68. Katal A, Wazid M, Goudar R. Big data: issues, challenges, tools and good practices. In: Proceedings of 6th international conference on contemporary computing (IC3), Noida, August 8–10. IEEE, US. 2013, p. 404–9.
69. Karun KA, Chitharanjan K. A review on hadoop—HDFS infrastructure extensions. In: IEEE, information and communication technologies (ICT). 2013, p. 132–7.
70. Kemp R. Environmental policy and technical change: a comparison of the technological impact of policy instruments. Cheltenham: Edward Elgar; 1997.
71. Kemp R, Rotmans J. The management of the co-evolution of technical, environmental and social systems. In: Weber M, Hemmelskamp J, editors. Towards environmental innovation systems. Berlin: Springer; 2005.
72. Khan M, Uddin MF, Gupta N. Seven V's of big data understanding: big data to extract value. In: 2014 zone 1 conference of the IEEE American society for engineering education (ASEE Zone 1). 2014, p. 1–5.
73. Khan Z, Anjum A, Soomro K, Tahir MA. Towards cloud based big data analytics for smart future cities. J Cloud Comput Adv Syst Appl. 2015;4:2.
74. Khan Z, Anjum A, Kiani SL. Cloud based big data analytics for smart future cities. In: Proceedings of the 2013 IEEE/ACM 6th international conference on utility and cloud computing, IEEE computer society. 2013, p. 381–6.
75. Khan Z, Kiani SL. A cloud-based architecture for citizen services in smart cities In: IEEE fifth international conference on utility and cloud computing ITAAC workshop. 2012, p. 315–20. (UCC), Chicago, IL, USA. IEEE.
76. Khan Z, Kiani SL, Soomro K. A framework for cloud-based context-aware information services for citizens in smart cities. J Cloud Comput Appl Adv Syst Appl. 2014;3(14):1–17.
77. Khanac Z, Pervaiz Z, Abbasi AG. Towards a secure service provisioning framework in a smart city environment. Future Gener Comput Syst. 2017;77:112–35.
78. Kharrazi A, Qin H, Zhang Y. Urban big data and sustainable development goals: challenges and opportunities. Sustainability. 2016;8(1293):1–8.
79. Kitchin R. The real-time city? Big data and smart urbanism. Geo J. 2014;79:1–14.
80. Kitchin, R. Data-driven, networked urbanism. 2015. https://doi.org/10.2139/ssrn.2641802.
81. Kitchin R. The ethics of smart cities and urban science. Philos Trans R Soc A. 2016;374:20160115.
82. Kramers A, Höjer M, Lövehagen N, Wangel J. Smart sustainable cities: exploring ICT solutions for reduced energy use in cities. Environ Model Softw. 2014;56:52–62.
83. Kumar A, Prakash A. The role of big data and analytics in smart cities. Int J Sci Res. 2014;6(14):12–23.
84. Kyriazis D, Varvarigou T, Rossi A, White D, Cooper J. Sustainable smart city IoT applications: heat and electricity management and eco-conscious cruise control for public transportation. In: Proceedings of the 2013 IEEE 14th international symposium and workshops on a world of wireless, mobile and multimedia networks (WoWMoM), Madrid, Spain. 2014, p. 1–5 Lane ND.
85. Lacinák M, Ristvej J. Smart city, safety and security. Proc Eng. 2017;192:522–7.
86. Laney D. 3–D data management: controlling data volume, velocity and variety. New York: META group research note; 2001.
87. Levy Y, Ellis TJ. A systems approach to conduct an effective literature review in support of information systems research. Inform Sci J. 2006;9:1–32.
88. Lombardi P, Giordano S, Caragliu A, Del Bo C, Deakin M, Nijkamp P, Kourtit K. An advanced triple-helix network model for smart cities performance. Amsterdam: Vrije Universiteit, Research Memorandum; 2011. p. 2011–45.
89. Lytras MD, Aljohani NR, Hussain A, Luo J, Zhang XZ. Cognitive computing track chairs' welcome & organization. In: Proceedings of the companion of the web conference, Lyon, France. April 2018, p. 23–27.
90. Malik P. Big data: principles and practices. IBM J Res Dev. 2013;57:4.
91. Manyika J, Chiu M, Brown B, Bughin J, Dobbs R, Roxburgh C, et al. Big data: the next frontier for innovation, competition, and productivity. New York: McKinsey Global Institute; 2011.
92. Marsal-Llacuna M-L. City indicators on social sustainability as standardization technologies for smarter (citizen-centered) governance of cities. Soc Indic Res. 2016;128(3):1193–216. https://doi.org/10.1007/s11205-015-1075-6.

93. Marsal-Llacuna ML, Colomer-Llinàs J, Meléndez-Frigola J. Lessons in urban monitoring taken from sustainable and livable cities to better address the smart cities initiative. Technol Forecast Social Change. 2015;90(2):611–22.
94. Martínez-Ballesté A, Pérez-Martínez PA, Solanas A. The pursuit of citizens' privacy: aprivacy-aware smart city is possible. IEEE Commun Mag. 2013;51:136–41.
95. Marz N, Warren J. Big data: Principles and best practices of scalable realtime data systems. Manning: MEAP edition; 2012.
96. Mayer-Schonberger V, Cukier K. Big data: A revolution that will change how we live, work and think. London: John Murray; 2013.
97. McLuhan M. Understanding media: the extensions of man. New York: McGraw Hill; 1964.
98. Mohamed N, Al-Jaroodi J. Real-time big data analytics: applications and challenges. In: 2014 international conference on high performance computing & simulation (HPCS). 2014, p. 305–310.
99. Morinière L. Environmentally influenced urbanization: footprints bound for town? Urban Studies. 2012;49(2):435–50.
100. Murphy J. Ecological modernization. Geoforum. 2000;31:1–8.
101. Nam T, Pardo TA. Conceptualizing smart city with dimensions of technology, people, and institutions. In: Proceedings of the 12th annual international conference on digital government research. 2011
102. Neirotti P, De Marco A, Cagliano AC, Mangano G, Scorrano F. Current trends in smart city initiatives—some stylized facts. Cities. 2014;38:25–36.
103. Neumeyer L, Robbins B, Nair A, Kesari A. S4: distributed stream computing platform. In: ICDM workshops. 2010, p. 170–177.
104. Pantelis K, Aija L. Understanding the value of (big) data. In: Big data 2013 IEEE international conference on IEEE. 2013, p. 38–42.
105. Perera C, Zaslavsky A, Christen P, Georgakopoulos D. Sensing as a service model for smart cities supported by internet of things. Trans Emerg Telecommun Technol. 2014;25:1–12.
106. Piro G, Cianci I, Grieco LA, Boggia G, Camarda P. Information centric services in smart cities. J Syst Softw. 2014;88:169–88.
107. Provost F, Fawcett T. Data science for business. Sebastopol: O'Reilly Media Inc; 2013.
108. Rathore MM, Won-HwaHong AP, Seo HC, Awan I, Saeed S. Exploiting IoT and big data analytics: defining smart digital city using real-time urban data. J SSC. 2018;40:600–10.
109. Rånge M, Sandberg M. Windfall gains or eco-innovation? "Green" evolution in the Swedish innovation system. Soc Environ Econ Policy Stud. 2015;18:1–20.
110. Santucci G. Privacy in the digital economy: requiem or renaissance? Privacy Surgeon.See. 2013. http://www.privacysurgeon.org/blog/wp–content/uploads/2013/09/Privacy-in-the-Digital-Economy-final.pdf (accessed 12 November 2015).
111. Scott J. A matter of record. Cambridge: University of Cambridge Press; 1990.
112. Shahrokni H, Årman L, Lazarevic D, Nilsson A, Brandt N. Implementing smart urban metabolism in the Stockholm Royal Seaport: smart city SRS. J Ind Ecol. 2015;19(5):917–29.
113. Shepard M, editor. Sentient city: ubiquitous computing, architecture and the future of urban space. Cambridge: MIT Press; 2011.
114. Shin D. Ubiquitous city: urban technologies, urban infrastructure and urban informatics. J Inf Sci. 2009;35(5):515–26.
115. Singh J, Singla V. Big data: tools and technologies in big data. Int J Comput Appl. 2015;112(15):0975–8887.
116. Smith A. Transforming technological regimes for sustainable development: a role for alternative technology niches? Sci Public Policy. 2003;30(2):127–35.
117. Smolan R, Erwitt J. The human face of big data. New York: Sterling; 2012.
118. Solove DJ. A taxonomy of privacy. Univ Penn Law Rev. 2006;154:477–560.
119. Song H, Srinivasan R, Sookoor T, Jeschke S. Smart cities: foundations, principles, and applications. New Jersey: Wiley; 2017.
120. Strandberg KL. Monitoring, datafication and consent: legal approaches to privacy in the big data context. In: Lane J, Stodden V, Bender S, Nissenbaum H, editors. Privacy, big data and the public good. Cambridge: Cambridge University Press; 2014. p. 5–43.
121. Su K, Li J, Fu H. Smart city and the applications. In: Electronics, communications and control (ICECC), 2011 international conference on IEEE. 2011, p. 1028–1031.
122. Taghavi M, Bakhtiyari K, Taghavi H, Olyaee Attar V, Hussain A. Planning for sustainable development in the emerging information societies. J Sci Technol Policy Manage. 2014;5(3):178–211.
123. Thrift N. The 'sentient' city and what it may portend. Big Data Soc. 2014;1:2053951714532241.
124. Townsend A. Smart cities—big data, civic hackers and the quest for a new utopia. New York: Norton & Company; 2013.
125. Tsai CW, Lai CF, Chao HC, Vasilakos AV. Big data analytics: a survey. J Big Data. 2015;21:2.
126. United Nations. World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352). New York, United States of America. 2014. https://doi.org/10.4054/DemRes.2005.12.9.
127. United Nations. Transforming our world: the 2030 agenda for sustainable development, New York, NY. 2015a. https://sustainabledevelopment.un.org/post2015/transformingourworld.
128. United Nations. Big Data and the 2030 agenda for sustainable development. Prepared by A. Maaroof. 2015b. http://www.unescap.org/events/call-participants-big-data-and-2030-agendasustainable-development-achieving-development.
129. United Nations. Habitat III Issue Papers, 21—Smart cities (V2.0), New York, NY. 2015c. https://collaboration.worldbank.org/docs/DOC–20778. Accessed 2 May 2017.
130. UNECE. Key performance indicators for smart sustainable cities to assess the achievement of sustainable development goals, vol. 1603. Geneva: UNECE; 2015.

131. Van de Voorde T, Jacquet W, Canters F. Mapping form and function in urban areas: an approach based on urban metrics and continuous impervious surface data. Landsc Urban Plan. 2011;102:143–55.
132. van Zoonen L. Privacy concerns in smart cities 2016. Gov Inf Quart. 2016;33(3):472–80.
133. Vinod Kumar TM, Dahiya B. Smart economy in smart cities. In: Vinod Kumar TM, editor. Smart economy in smart cities international collaborative research: ottawa, St. Louis, Stuttgart, Bologna, Cape Town, Nairobi, Dakar, Lagos, New Delhi, Varanasi, Vijayawada, Kozhikode, Hong Kong. Singapore: Springer; 2017.
134. Visvizi A, Lytras MD, Editorial MD. Policy making for smart cities: innovation and social inclusive economic growth for sustainability. J Sci Technol Policy Mak. 2018;9:1–10.
135. Visvizi A, Lytras MD. Rescaling and refocusing smart cities research: from mega cities to smart villages. J Sci Technol Policy Mak. 2018;9:134–45.
136. Visvizi A, Mazzucelli C, Lytras M. Irregular migratory flows: towards an ICT' enabled integrated framework for resilient urban systems. J Sci Technol Policy Manag. 2017;8:227–42.
137. Wall R, Stravlopoulos S. Smart cities within world city networks. Appl Econom Lett. 2016;23(12):875–9.
138. Warleigh-Lack A. Greening the European Union for legitimacy? A cautionary reading of Europe 2020. Innov. Eur. J. Soc. Sci. Res. 2011;23:297–311.
139. Webb J, Hawkey D, Tingey M. Governing cities for sustainable energy: the UK case. Cities. 2016;54:28–35. https://doi.org/10.1016/j.cities.2015.10.014.
140. Webster J, Watson RT. Analyzing the past to prepare for the future: writing a literature review. MIS Quarterly. 2002;26(2):13–23.
141. Wheeler SM. Constructing sustainable development/safeguarding our common future: rethinking sustainable development. J Am Plan Assoc. 2002;68(1):110–1.
142. Williams K, Burton E, Jenks M, editors. Achieving sustainable urban form. London: E & FN Spon; 2000.
143. Zanella A, Bui N, Castellani A, Vangelista L, Zorzi M. Internet of things for smart cities. IEEE Int Things J. 2014;1(1):22–32.
144. Zhang C. Fog and IoT: an overview of research opportunities. IEEE Int Things J. 2016;3(6):854–64.
145. Zhang Y, Cao T, Tian X, Li S, Yuan L, Jia H, Vasilakos AV. Parallel processing systems for big data: a survey. Proc IEEE. 2016;104(11):2114–36.
146. Zikopoulos PC, Eaton C, deRoos D, Deutsch T, Lapis G. Understanding big data. New York: McGraw Hill; 2012.