

TECHNICAL ARTICLE

A Novel Model for Data-Driven Smart Sustainable Cities of the Future: A Strategic Roadmap to Transformational Change in the Era of Big Data

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The conscious push for sustainable cities to be smarter and thus more sustainable in the era of big data is due to the problematicity surrounding their development planning approaches and operational management mechanisms, as well as the fragmentation of their designs and technologies. This has a clear bearing on their performance with respect to the contribution to and balancing of the goals of sustainability. This situation is compounded by the negative consequences of the expansion of urbanization, an irreversible global trend involving a multitude of environmental, social, economic, and spatial conditions that pose unprecedented challenges to policymakers and planners. The underlying argument is that more innovative solutions and sophisticated methods are needed to enable sustainable cities to tackle the kind of problems and complexities they embody. This in turn brings us to the question related to the weak connection between sustainable cities and smart cities as approaches as well as their extreme fragmentation as landscapes, both at the technical and policy levels. Therefore, sustainable cities need to embrace and leverage what smart cities have to offer so that they can optimize, enhance, and maintain their performance and thus achieve the desired outcomes of sustainability. This paper aims to develop a novel model for data-driven smart sustainable cities of the future, and in doing so, it provides a strategic planning process of transformative change towards sustainability. This model combines and integrates the prevailing paradigms of sustainable urbanism and the emerging paradigms of smart urbanism—based on the outcomes of the four case studies conducted on compact cities, eco-cities, data-driven smart cities, and environmentally data-driven smart sustainable cities. As the core of this aggregate model is how to bring about the different forms of infrastructural transformations needed to reach a vision of a sustainable future in the era of big data. Especially, it has become feasible to attain important improvements and advancements of sustainability by amalgamating sustainable cities and smart cities thanks to the proven role of advanced ICT and the untapped potential of data-driven technologies.

Keywords: Data-driven smart sustainable cities; sustainable cities; smart cities; compact cities; eco-cities; infrastructure; strategic planning; sustainability; data-driven technologies

1. Introduction

Cities are a mark of human civilisation and play a central role in the pursuit of new paradigms of thinking to bring about major transformations to the way people live. Sustainability has, over the last four decades, been one of the most influential paradigms of thinking within urbanism. Modern cities holding unparalleled potential to address and overcome the challenges of sustainable development largely depends on how they can be planned, designed, and managed in response to global trends, scientific discoveries, and technological advances. This is clearly reflected in the Sustainable Development Goal (SGD 11) of the United Nations' 2030 Agenda—Sustainable Cities

and Communities (UN 2015a). Appropriately redesigning and restructuring urban places as sustainable cities and adopting innovative solutions to make urban living more sustainable is a continuous endeavor towards achieving the long-term of goals sustainability.

Compact cities and eco-cities are the central paradigms of sustainable urbanism and the most prevalent and advocated models of sustainable cities. Numerous recent national and international policy reports and papers state that these two models contribute, though to varying degrees, to resource efficiency and reliability, environmental protection, socio-economic development, social cohesion and inclusion, quality of life and well-being, and cultural enhancement (Bibri 2020a). It is argued that the compact city model is able to contribute to and support the balancing of the three goals of sustainability (e.g., Bibri, Krogstie and Kärrholm 2020; Burton 2002; Jenks and Dempsey 2005; Hofstad 2012; Jenks and Jones 2010; OECD 2012), and that the eco-city model is able to achieve the goals of environmental

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sustainability and to produce some economic and social benefits of sustainability (Bibri and Krogstie 2020a; Joss 2010; Joss, Cowley and Tomozeiu 2013; Kenworthy 2006; Mostafavi and Doherty 2010; Pandis and Brandt 2011; Rapoport and Vernay 2011; Suzuki et al. 2010).

Transformative processes within sustainable cities have been in focus for some time now. The motivation for achieving the United Nations' SGD 11 has increased the need to understand, plan, and manage sustainable cities in new and innovative ways (UN 2015a). In this respect, the United Nations's 2030 Agenda regards advanced 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 (UN 2015b). This relates to the multifaceted potential of smart cities, which has been under study with respect to the role of big data technologies and their novel applications in strategic sustainable development within the framework of 2030 Agenda (UN 2015c). The abundance of urban data, coupled with their analytical power, opens up for new opportunities for innovation in sustainable cities. This in turn means tackling the problems and challenges facing sustainable cities in their endeavor to make actual progress towards achieving the vision of sustainability.

Big data technologies are heralding a new era wherein sustainable cities are morphing in response to what has been identified as data-driven urbanism. This transformation—which entails how sustainable cities are being monitored, understood, analyzed, and thus organised, planned, controlled, and regulated—is manifest in the increasingly level of the development and implementation of data-driven technology solutions in their management mechanisms and development planning approaches. In fact, big data technologies have, in the context of sustainability, become as essential to the functioning of smart cities (e.g., Angelidou et al. 2017; Bibri 2019a; Bibri and Krogstie 2020b, c; Bettencourt 2014; Eden Strategy Institute 2018; Hashem et al. 2016; Kumar and Prakash 2016; Nikitin et al. 2016; Perera et al. 2017) as to that of sustainable cities (e.g., Bibri 2018, 2020b, c; Bibri and Krogstie 2017a, b, 2020a, c; Pasichnyi et al. 2019; Shahrokni et al. 2014; Shahrokni, Levihn and Brandt 2014; Shahrokni et al. 2015; Shahrokni, Lazarevic and Brandt 2015; Sun and Du 2017; Thornbush and Golubchikov 2019).

The conscious push for sustainable cities to be smarter and thus more sustainable in the era of big data is due to the problematicity surrounding their development planning approaches and operational management mechanisms, as well as the fragmentation of their designs and technologies. This has a clear bearing on their performance with respect to the contribution to and balancing of the goals of sustainability. Over the last two decades, research within the field of sustainable urban forms, especially compact cities and eco-cities, has produced conflicting, uncertain, and non-conclusive results (e.g., Bibri 2020b, c; Bibri and Krogstie 2017a; Cugurullo 2016; Jenks and Dempsey 2005; Kaido 2005; Kärrholm 2011; Lim and Kain 2016; Neuman 2005; Williams 2010) concerning the actual benefits they claim to deliver. This is compounded

by the unprecedented issues engendered by the escalating urbanization and their implications for jeopardizing sustainability. Today, urbanization is one of the greatest environmental, economic, and social challenges that sustainable cities are facing. In recent decades, urban growth has been dramatic, a climate which has made it more challenging for sustainable cities to reconfigure themselves more sustainably without the use of advanced ICT. In a nutshell, new circumstances require new responses. Bibri and Krogstie (2019a) provides a comprehensive review of sustainable urban forms (eco-cities and compact cities), highlighting their inadequacies, shortcomings, struggles, and bottlenecks, as well as the role and potential of advanced ICT in addressing these issues and problems. Most of which tend to relate to how sustainable cities have long been studied, understood, and planned. This pertains to data scarcity, inherent limitations of traditional research methods, inefficient management processes, and long-term planning approaches. This is dramatically changing thanks to the multifaceted potential of smart cities as enabled predominately by the IoT and big data technologies. As a result, many opportunities are yet to explore as to integrating sustainable cities and smart cities in terms of their operational management and development planning on the basis of advanced computational data analytics, thereby mitigating their extreme fragmentation and weak connection (e.g., Ahvenniemi et al. 2017; Angelidou et al. 2017; Bibri 2019b, 2020b, c; Bifulco et al. 2016; Kramers, Wangel and Höjer 2016) under what is labelled “data-driven smart sustainable cities.”

This paper aims to develop a novel model for data-driven smart sustainable cities of the future, and in doing so, it provides a strategic planning process of transformative change towards sustainability. This model combines and integrates the prevailing paradigms of sustainable urbanism and the emerging paradigms of smart urbanism – based on the outcomes of the four case studies conducted on: (1) compact cities (Bibri, Krogstie and Kärrholm 2020), (2) eco-cities (Bibri and Krogstie 2020a), (3) data-driven smart cities (Bibri and Krogstie 2020b), and (4) environmentally data-driven smart sustainable cities (Bibri and Krogstie 2020c). The case study research is associated with the empirical phase of a futures study that consists of 6 steps, each with several guiding questions to answer. This paper reports the outcome of Step 6, which involves answering the following five guiding questions:

1. What built infrastructure changes are necessary for reaching the vision of the desired future?
2. What sustainable urban infrastructure changes are necessary?
3. What smart urban infrastructure changes are necessary?
4. What social infrastructure changes are necessary?
5. What technological infrastructure changes are necessary?

Important to note is that the framing of this paper as a set of planning actions and policy measures is justified by the fact that it is concerned with the decisive steps and strategic pathways that should be taken to attain the vision

of the desirable future. The primary intent is to provide recommendations for government officials, policymakers, planners, designers, developers, industry experts, and other stakeholders on how to build a data-driven smart sustainable city of the future.

This paper is organised into four sections: Section 2 briefly introduces the methodological framework for the futures study. Section 3 presents the results, detailing the strategic planning process of backcasting in terms of its objectives, targets, vision, and strategies and pathways. Section 4 discusses the results. This paper ends, in Section 5, with some concluding remarks.

2. Research Methodology

The methodological framework applied in the futures study combines and integrates normative backcasting

and descriptive case study as qualitative approaches. The backcasting approach was employed to achieve the overall aim of the futures study. The case study approach, which is associated with the empirical phase of the futures study, was adopted to examine and compare two of a total of six cases from the ecologically and technologically leading cities in Europe within each of the frameworks of compact cities, eco-cities, data-driven smart cities, and environmentally data-driven smart sustainable cities. Bibri (2020d) dedicates a whole article to the methodological framework for strategic data-driven smart sustainable city planning whose core objective is clarifying which city model is desired and working towards that specified outcome. **Table 1** presents the guiding questions for each of the six steps in the futures study, and highlights the five questions addressed by this paper in bold.

Table 1: The guiding questions for each step in the backcasting-oriented futures study.

The guiding questions for the backcasting-oriented futures study	Methods and tools
<p>Step 1: Detail strategic problem orientation (Part 1)</p> <ol style="list-style-type: none"> 1. What is the model of urbanism to be studied? 2. What are the aim, purpose, and objectives of the backcasting study in relation to this model? 3. What are the long-term targets declared by the goal-oriented backcasting approach? 4. What are the objectives these targets are translated to for backcasting analysis? 	Research design and problem formulation
<p>Step 2: Detail strategic problem orientation (Part 2)</p> <ol style="list-style-type: none"> 1. What are the main prevailing trends and expected developments related to the model to be studied? 2. What are the key sustainability problems associated with the current model of urbanism and what are the causes? 3. How is the problem defined? 	Trend analysis and problem analysis
<p>Step 3: Generate a sustainable future vision</p> <ol style="list-style-type: none"> 1. What are the demands for the future vision? 2. How does the future model of urbanism look like? 3. How is the future model of urbanism different from the current model of urbanism? 4. What is the rationale for developing the future model of urbanism? 5. Which sustainability problems have been solved and which technologies have been used in the future vision? 	Creativity method
<p>Step 4: Conduct empirical research</p> <ol style="list-style-type: none"> 1. What is the justification for the methodological framework to be adopted? 2. Which category of case study design is most relevant to investigating the dimensions of the future model of urbanism? 3. How many case studies are to be carried out and what kind of urban phenomena should they illuminate? 4. To what extent can this investigation generate new ideas and illustrate the theories applied and their effects, as well as underpin and increase the feasibility of the future vision? 	Case study method
<p>Step 5: Specify and Integrate the components of the future model of urbanism</p> <ol style="list-style-type: none"> 1. What urban and technological components are necessary for the future model of urbanism? 2. How can all these components be integrated into a framework for strategic sustainable urban development planning? 3. What are the key benefits, potentials, and opportunities of the future model of urbanism? 	Creativity method
<p>Step 6: Perform backwards-looking analysis</p> <ol style="list-style-type: none"> 1. What built infrastructure changes are necessary for attaining the future vision? 2. What sustainable urban infrastructure changes are necessary? 3. What smart urban infrastructure changes are necessary? 4. What social infrastructure changes are necessary? 5. What technological infrastructure changes are necessary? 6. What institutional changes are necessary? 	Backcasting analysis

Source: Bibri (2020d).

2.1. Backcasting as a Strategic Planning Process

The term “backcasting,” which was coined by Robinson in 1982, can denote a concept, a study, an approach, a methodology, a framework, or an interactive process among stakeholders. Hence, it has been defined in multiple ways. Robinson (1990, p. 823) defines backcasting as a normative approach which works “backwards from a particular desired end point to the present in order to determine the feasibility of that future and what policy measures would be required to reach that point.” Thus, backcasting is a planning process by which a desired outcome is envisioned and articulated, followed by the question: “what do we need to do today to reach that specified outcome?” (Figure 1) This question is about figuring out the “next steps,” which are quite literally the next concrete actions to undertake.

In recent years, backcasting has been mostly applied in the futures studies that deal with long-term problems and sustainability solutions (see, e.g., Åkerman 2005; Åkerman and Höjer 2006; Höjer, Gullberg and Pettersson 2011; Miola 2011; Quist et al. 2011; Quist 2007; Vergragt and Quist 2011; Wangel 2011). The backcasting process in the futures study represents a strategic planning tool for facilitating the progress towards achieving the goals of sustainability for those cities that are badging or regenerating themselves as sustainable, or manifestly planning to be or become smart sustainable in the era of big data.

2.2. Descriptive Case Study

The descriptive case study approach was applied in the four case studies to investigate the prevailing models of sustainable urbanism and the emerging models of smart urbanism (Step 4). The intention of this investigation is to identify the underlying components of the new model of urbanism in terms of its core dimensions, strategies, and solutions, and then to integrate these components into an applied framework for strategic sustainable urban development planning (Step 5). This is in turn intended to guide the strategic planning process of transformative

change towards sustainability, which represents the novel model for data-driven smart sustainable cities of the future (Step 6). Overall, by carefully studying any unit of a certain universe, we find out about some general aspects of it, at least a perspective that guides subsequent research. Case studies often represent the first scholarly toe in the water in new research areas.

The case study is a descriptive qualitative methodology that is used as a tool to study specific characteristics of a complex phenomenon. The descriptive case study approach, as defined by Yin (2009, 2014, 2017), was identified as the most suitable methodology for the empirical phase of the futures study. This methodology has been chosen considering the nature of the problem being investigated, the research aim, and the present state of knowledge with respect to the topic of data-driven smart sustainable cities. In this context, it involves the description, analysis, and interpretation of the four urban phenomena, with a particular focus on the prevailing conditions pertaining to plans, projects, and achievements. That is, how the selected cities behave as to what has been realized and the ongoing implementation of plans based on the corresponding practices and strategies for sustainable development and technological development. Accordingly, the four case studies examine contemporary real-world phenomena and seek to inform the theory and practice of data-driven smart sustainable urbanism by illustrating what has worked well, what needs to be improved, and how this can be done in the future. They are particularly useful for understanding how different elements fit together and (co-)produce the observed impacts in a particular urban context based on a set of intertwined factors.

3. The Results: The Strategic Planning Process of Backcasting

As a roadmap to transformational change, the backcasting process articulates strategic thinking—the why—behind both the vision of the future and the plan for getting

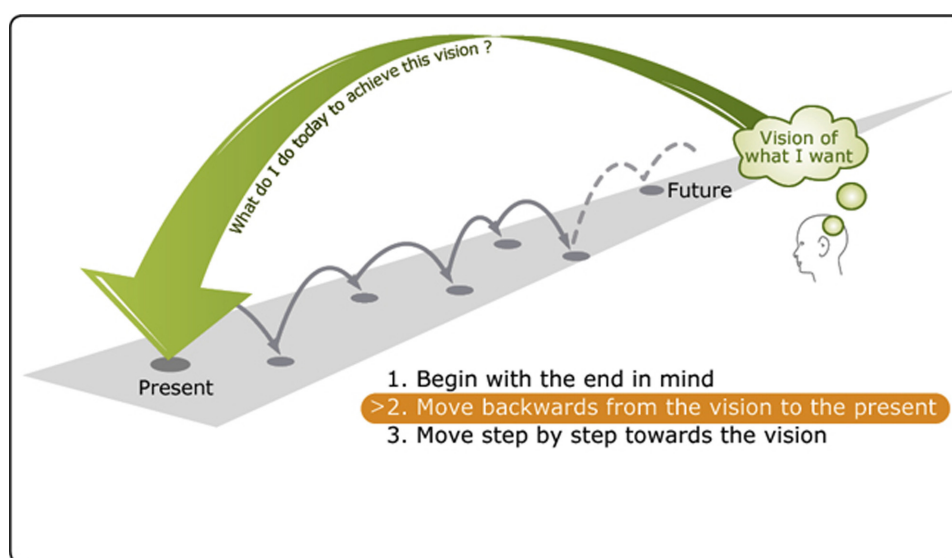


Figure 1: The backcasting process from the Natural Step. Source: Holmberg (1998).

there. Strategic planning denotes a systematic process of generating a vision of a desirable future and translating it into broadly defined objectives and targets, and then identifying a sequence of actions and measures to achieve that specified future. Accordingly, this section is structured into three main phases, (1) the vision of the future, (2) the objectives and targets of sustainable development, and (3) the strategies and pathways for transformative change.

3.1. The Future Vision

The vision of the future is where the problems, issues, and challenges related to sustainable cities (Bibri and Krogstie 2019a) have been solved by means of the data-driven technologies and solutions offered by smart cities of the future. However, the overall goal, which builds the vision of what the future should look like once manifested, is the indicator established to determine whether the objectives have successfully been achieved. The data-driven smart sustainable city is envisioned as (Bibri and Krogstie 2020d, p. 89):

“A form of human settlements that secures and upholds environmentally sound, economically viable, and socially beneficial development through the synergistic integration of the more established strategies of sustainable cities and the more innovative solutions of data-driven smart cities towards achieving the long-term goals of sustainability.”

In constructing the future vision, we have attempted to retain the best of what we already have that have been successfully enacted in real-world cities, making use of the things that have been demonstrably better in the past, while being selective in adopting the best of what is emerging and promising, making use of the things that will add a whole new dimension to sustainability in terms of harnessing its synergic effects, balancing its dimensions, and thus boosting its benefits.

3.2. The Objectives and Targets

The future vision is translated into broadly defined objectives and targets, which are of a long-term nature. The objectives and targets can also be used to develop the future vision. The targets are established first as specific desired outcomes that support the achievement of the objectives. These define an endpoint of concern and the direction of change that is preferred. The targets and objectives are to be—specific, measurable, achievable, relevant, and targeted when adopting the future model of urbanism. They are decided on according to what the data-driven smart sustainable city of the future aspires to achieve, an ambition which can be adapted to existing sustainable cities in their own contexts.

The objectives describe the measurable contribution of the data-driven smart sustainable city of the future as to achieving the overall goal of the future vision. Therefore, they define what is to be achieved and should have a specified timescale and be linked to the performance of the data-driven smart sustainable city of the future to ensure that policy commitments are prioritized and addressed in terms of improving and advancing the environmental,

economic, and social goals of sustainability. This improvement should also be continual in line with sustainability policies in relevance to the national and local context of existing sustainable cities so that new objectives can be agreed on when the original objectives have been met. However, the objectives are of a qualitatively descriptive nature because the future vision is not concerned with a given sustainable city, or departs from a basic standard in mind accordingly. With that in regard, the data-driven smart sustainable city of the future aims to achieve the objectives of sustainable development, the most prominent among them are presented in **Table 2**.

The targets are the indicators that are established to determine how successfully the objectives have been achieved by providing relevant benchmarks for the compact, ecological, and technological components of the data-driven smart sustainable city of the future. This involves how synergistically these components are integrated, cooperate, and beneficially complement one another. The targets can quantify or qualify the objectives over time. The specific targets set in relation to the future vision are specified in terms of the dimensions, strategies, and solutions of the four investigated models of urbanism. They help to set up a clear course of action and guide the future vision. The target-setting here denotes the strategic process to establish performance goals for the physical, environmental, economic, social, and technological areas of the data-driven smart sustainable city of the future. Each area uses a different tool that starts with establishing a baseline, e.g., how much energy is currently being used, or how dense and diverse is a given urban area or district. In the context of the futures study, the targets are of a qualitatively descriptive nature because the future vision is not concerned with a given sustainable city, or departs from a basic standard in mind accordingly. Nonetheless, the qualitative targets should, when planning the development of the data-driven smart sustainable city of the future, be turned into quantifiable targets that can be achievable within an agreed timescale in accordance with the objectives. This in turn depends on the nature of the areas targeted (e.g., GHG emissions reduction, energy efficiency, well-being, etc.), the level of progress already made in these areas, and so forth. As to the level of progress, for example, the targets should be set in the areas where improvement is most needed or prioritized in order to meet the requirements for regulatory compliance, to improve performance, to reduce risks, and so on.

Table 2: The prominent objectives of sustainable development.

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- Reduced energy consumption and carbon footprint
 - Improved resource efficiency with minimal environmental impacts
 - Minimized waste
 - Increased use of sustainable materials
 - Reduced air and noise pollution
 - Reduced automobile use
 - Preservation of open space and sensitive ecosystems
 - Improved social justice and equity
 - Enhanced quality of life and well-being
 - Liveable and community-oriented human environments
-

The future vision as a long-term goal represents the set of targets that should move the city from its current state (sustainable) to its future state (data-driven smart sustainable). Hence, these targets incorporate the objectives of sustainable development as well as the objectives of technology associated with the readiness of the city to introduce data-driven technology in, and the implementation of applied technology solutions for, city operational management and development planning with regard to sustainability. Accordingly, they should be based on the synergistic integration of the strategies and solutions of the four investigated models of urbanism (see **Table 3**).

Furthermore, one objective may involve the different categories of the targets, e.g., reducing energy usage includes targets related to building density, green energy, smart energy, passive and net-zero energy building, sustainable transport, smart transport, and so forth. Each of these targets may in turn include a set of sub-targets. Generally, a strategic vision can have multiple goals and each goal can have many objectives. At the same time, each objective can be linked to multiple targets and each target can be linked to various key performance indicators (KPIs). The targets specified represent the key areas that drive urban sustainability performance and the way it can be improved and advanced with the support of data-driven smart technologies and solutions. Finding a way to measure these areas is normally followed by, as a natural next step, starting setting performance targets.

The data-driven smart sustainable city of the future should establish CityScore as an online dashboard to show how the city government is performing against its targets in the areas identified on a wide range of metrics. The metrics measured can be used as a gauge of how well the city government is serving its citizens and responding to their concerns in regard to the three dimensions of sustainability. The daily activity updates make performance and progress transparent to the public and city administrators. A single, combined number can summarize how the administration is performing overall. Tracking performance against targets enables problem areas to be quickly identified

and remedied, and offers citizens the opportunity to hold administrators to account. Aggregating and dividing the data collected automatically by sensors as well as by city workers using their mobile devices by the target figure can generate a daily, weekly, or quarterly score: above 1 means the city is exceeding its targets, below 1 means it is falling short.

The targets should be clear and there should be no ambiguity about the objectives that should be prioritized. This ensures that stakeholders understand how the different objectives are being attained and balanced. This in turn can help secure stakeholders' buy-in and support. In particular, the ICT infrastructure should be planned, implemented, and managed while being dependent on the initiative by and interest of the other stakeholders involved in the sustainability efforts, including planners, developers, architects, building owners, utilities, energy cooperatives, and citizens. The initiatives of these stakeholders should be coordinated in order for them to be able to work together more effectively and support each other. Among the benefits of setting the targets in this context are:

- Establishing clear goals for various stakeholders and purposes (e.g., organisations, institutions, projects, investments, etc.)
- Motivating people (planners, developers, industry experts, citizens, etc.) by clarifying their expected performance and how they can measure progress
- Providing a benchmark against which improvements can be measured
- Demonstrating commitment to the agenda and policies of sustainable development

Worth noting is that the above stated targets embody the targets of the SDG 11 (**Table 4**). These are slightly adapted from the United Nations (2015a) as the focus of the futures study is on the cities that are already badging or regenerating themselves as sustainable, or manifestly planning to be or become smart sustainable.

Table 3: The core compact, ecological, and technological targets of the future model of urbanism.

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- Increased compactness of urban space
 - High density and diversity of buildings
 - Multidimensional mixed uses: social mix, physical land use mix, economic mix, and temporal mix
 - Prioritized sustainable transportation and its integration with smart transportation
 - Multifunctional green infrastructure for ecosystem services and biodiversity
 - Balanced mixture of low-energy, energy-efficient, and passive buildings
 - Large-scale net-zero and locally produced solar energy houses
 - Sustainable energy system and its integration with smart energy system
 - Sustainable waste system and its integration with smart waste system
 - High degree of the readiness of the city to the integration of advanced technology in its management:
 - High availability and development level of the infrastructure and big data analytics competencies required for the functioning of the city
 - New and extensive sources of data and a high level of support for open and standard data
 - High degree of the implementation of applied technology solutions for the city management:
 - High level of the development of applied data-driven solutions for the city operational management and development planning related to the various areas of sustainability
 - Established data-oriented competences pertaining to research, innovation, strategic planning and policy, education, and professional training.
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Table 4: The SDG 11 targets embodied in the future vision.

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1. Ensure access for all to adequate, safe, and affordable housing and basic services.
 2. Provide access to safe, affordable, accessible, and sustainable transport systems for all.
 3. Enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management.
 4. Strengthen efforts to protect and safeguard the natural and cultural heritage.
 5. Reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.
 6. Provide access to safe, inclusive and accessible, green and public spaces.
 7. Substantially increase the number of human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation of and adaptation to climate change, and resilience to disasters.
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Source: Adapted from United Nations (2015a).

3.3. The Strategies and Pathways for Transformative Change

This phase entails building a feasible and logical path between the state of the future and the present based on the criteria defined for the future vision. Such path represents a set of strategies and pathways to be pursued in order to bring about the needed transformative change towards sustainability. Determining the strategies and the specific pathways to execute them is the main part of the effort to achieve the overall goal of the future vision by meeting the specified objectives and targets. At the heart of these strategies and pathways is the practice-oriented process of designing and developing the data-driven smart sustainable city of the future. Different multiple strategies are needed in order to attain the future vision. To employ each of these strategies in turn requires a set of specific actions, sequences of actions, and agendas within each strategy, ways of achieving specified results. However, as cities generally need to be able to respond to new global trends and shifts, it is important for the future vision, strategies, and pathways to have flexibility as well as some firmness. The future vision needs to remain firm and should be the anchor that holds all the rest together. The strategies as a form of long-term plan may need to pivot in response to external factors such as global trends and technological shifts. The pathways are the most flexible in terms of adjustment and modification, especially the future vision does not pertain to a given sustainable city. In a nutshell, the goal needs to be developed and planned strategically, held to be achieved, and the pathways that can help move towards fulfilling the strategies need to be flexible. The key strategies and pathways are presented next in accordance with the five dimensions of the landscape of the data-driven smart sustainable city of the future, namely:

1. Built infrastructure
2. Sustainable urban infrastructure
3. Smart urban infrastructure
4. Social infrastructure
5. Technological infrastructure

3.3.1. Built Infrastructure

The built infrastructure involves the patterns of the physical objects in the city pertaining to the built-up areas as well as those areas planned for new development and

redevelopment together with transport, communication, energy, and waste systems. The compact and ecological dimensions of urban design characterize most of the built infrastructure as regards its buildings, blocks, streets, open space, public space, green space, and essential urban infrastructure.

3.3.1.1. Compact Design of Urban Form

Urban form denotes the physical aspects that characterize the built-up areas. The form of the city is seen as a salient factor for enacting more sustainable, efficient, equitable, and livable urban environments through design. It is associated with the development strategies related to urbanization dimensions, namely physical (land use change), geographical (population), economic (agglomeration), and societal (social and cultural change). These largely pertain to the design strategies of the compact city, namely compactness, density, multidimensional mixed-land use, sustainable transformation, and green open space.

The strategies for development planning are based on a number of important challenges, notably increasing population, plans to create more jobs, new demands from the business sector, the possibility of a simpler daily life for more people, measures to decrease social inequality and socio-spatial segregation, the development of urban areas for a more closely connected city, plans to enhance transport infrastructure, and the even distribution of green areas and parks. These are at the core of the compactness of the built form.

Main Directions for Compactness

To attain the compactness of the built form of the data-driven smart sustainable city of the future with the expected benefits of sustainability, there are four main directions to take:

- Develop central points:
 - Densify and supplement with more housing and businesses around the central points to make use of the particularly good conditions for a more local city life based on the idea of enabling people to manage day-do-day life by walking, cycling, and public transport.
 - Gather shops and services so that the central points function as local magnets.

- Make good use of the situation at the central points, with densification in mind.
- Use the land in a carefully thought-out and efficient manner so that the places take on more city character.
- Make use of what already exists:
 - Use existing resources and investments already made as efficiently as possible.
 - Reinforce, supplement, and further develop in the closely connected building structure already in place.
 - Use the existing infrastructure more efficiently to reduce the effects of traffic on the environment.
 - Counteract traffic congestion.
 - Coordinate the locations of new houses, workplaces, and services with extensions and reinforcements in public transport.
 - Retain and reinforce closely connected public walk-ways between the areas, functions, and buildings.
- Make the biggest effort and muster strength where it makes a difference at most:
 - Prioritize between development areas.
 - Promote brownfield development.
 - Develop new areas on the basis of a holistic approach and overall way of thinking, instead of smaller or scattered supplementary projects.
 - Create variety through more functions in each district, quarter, and building.
 - Cooperate on a broad scale with other stakeholders.
 - Involve different stakeholders in planning measures over a longer period of time to ensure an overall perspective.
- Regulate compact urban development:
 - Increase the effectiveness of regulatory tools.
 - Set minimum density requirements for new development.
 - Establish mechanisms to reconcile conflicts of interests.
 - Strengthen urban rural linkages.
 - Harmonize business policies with compact city policies.

Staged Expansion and Intensification of Urban Fabrics

To pursue these directions, it is important to stage an expansion of the city based on the current level of its compactness with respect to the extent to which land areas can be used close to existing development, or urban development can take place adjacent to existing urban fabrics and structures. This relates to the intensification strategy of compaction, which encompasses a range of substrategies for urban renewal, infill, development, and redevelopment. These substrategies in the context of the data-driven smart sustainable city of the future are to be applied on the six specific urban fabrics that were identified based on the case studies conducted on compact cities and eco-cities (Bibri, Krogstie and Kärrholm 2020; Bibri and Krogstie 2020a). An urban fabric denotes the physical characteristics of urban areas in terms of com-

ponents, materials, buildings, spatial patterns, scales, streetscapes, infrastructure, networks, and functions, as well as socio-cultural, ecological, economic and organisational structures. The identified urban fabrics together with the applied substrategies of the intensification strategy are presented below:

Build and Develop Centrally

The Central Renewal Area

- Build mixed developments.
- Create attractive meeting places and new parks.
- Prioritize public transport, walking, and cycling.
- Create robust and interconnected urban structure by improving connections.
- Enhance the cultural environment.

The Inner City

- Strive for a living center with attractive and safe city spaces.
- Develop a mix of densely built dwellings, workplaces, shops, businesses, facilities, and public services together with well elaborated public spaces for a pleasant and comfortable everyday life.
- Increase the number of homes.
- Prioritize public transport, walking, and cycling.
- Protect cultural heritage and be respectful in new development.
- Improve green areas and parks.

Concentrate on Strategic Nodes

- Analyze the potential for greater density, which should be based on the existing housing forecast in order to be able to plan for a long-term development of the city.
- Develop brownfield sites first.
- Create and complement with a mix of functions combined with varied public.
- Build with higher densities around interchanges (with good accessibility) and public transport corridors.
- Prioritize density close to the central points of strategic nodes.
- Encourage high quality design to lower perceived density.
- Create good opportunities for walking and cycling.
- Improve transport infrastructure and services and increase accessibility.
- Implement multi-modal travelling to support the density and mixed land use of the central points of strategic nodes
- Make use of valuable green areas and corridors.
- Recognize that the green areas are important for the preservation of nature's own integrity, and a significant recreational factor for inhabitants.

Complement and Mix

- Complement the areas that have good access to public transport and are easy to reach by walking and cycling by additional homes, workplaces, and commercial functions, thereby greater variety and a more vibrant city.

- Ensure a mix of housing types and forms as well as of functions.
- Increase diversity and vitality through new development and re-development.
- Improve the match between residents and local services and jobs.
- Encourage the greening of built-up areas.

Reserve Outer Areas for Future Consideration

The outer area, which is not yet developed or about to be developed, should be strategically planned based on the core strategies of the compact city in terms of density, diversity, mixed land use, sustainable transportation, green space, and other design features pertaining to the eco-city with respect to various types of sustainable buildings.

- Unlock the potential for the development of new homes and workplaces in the areas located on the outer edges of the city.
- Provide the opportunity for new development in the long term.
- Invest in urban infrastructure and services prior to new development, especially transport.
- Ensure the feasibility of high quality public transport in order to achieve a certain level of density.
- Have regard to valuable natural, cultural, and recreational heritage.
- Consider developing passive, low-energy, net zero energy, energy efficient, and green buildings.

Build New Districts

Building new districts should be based on the integration of the core strategies of the compact city and the eco-city as planning systems as regards designs and buildings, with support of new technologies.

- Create great diversity of the scales and designs of building densities.
- Make larger and medium scale buildings more frequent as to the distribution of building footprints.
- Create great variety of buildings and building techniques, notably passive solar, low energy, net-zero, energy efficient, and green buildings.
- Use sustainable materials in building construction.
- Use recycled material with the potential of future reuse and long life span in the underlying layers of the streets, alleys, and public spaces.
- Develop multidimensional mixed land use: physical land use mix, economic mix, and social mix.
- Encourage focused investment in public space and foster a sense of place.
- Support various types of housing tenures: the conditions under which buildings or dwellings are held or occupied, with a planning approach focused greatly on safety and equality aspects via the design of different meeting places.
- Develop and implement measures to stimulate the development of affordable housing for all income groups, not too high to serve low and moderate in-

come residents through inclusionary zoning.

- Create a diversity of job–housing balances, household sizes, household structures, cultural diversity, and age groups.
- Invest in and continuously work on reducing socio-economic disparity and social segregation within the new city districts to unlock its full potential and the city's population and cultural structure.
- Create robust and interconnected urban structure by developing good connections: physical links within and between the different parts of the new city districts, as well as their connection with the existing city districts.
- Forge the physical links between communities within the different parts of the new city districts.
- Remove physical barriers isolating certain areas by improving public transportation infrastructure and services.
- Prioritize public transport, walking, and cycling.
- Make use of valuable green areas Recognize that the green areas are important for the preservation of nature's own integrity, and a significant recreational factor for inhabitants.
- Protect national parks with regard to their specific and sensitive flora and fauna and their cultural heritage
- Create new and evenly distribute parks across the new city districts.
- Develop relevant structures for collaboration between these stakeholders within the city departments.
- Involve local communities in planning and decision-making processes in ways that enable the residents to have a say in the development of the new city districts by inviting them to attend a series of planning workshops, e.g., exploration of strategic options, community planning sessions, and capacity building.
- Collect and analyze data on the movement of residents to plan the new city districts.

3.3.1.2. Ecological Design of Urban Form

Ecological design is a design form which integrates itself with living processes to minimize environmentally negative or destructive impacts. It is associated with the green structure in the city and how it should be developed, distributed, and managed (e.g., Austin 2013; Bibri and Krogstie 2020a; Beatley 2010; Beatley 2000; Farr 2008; Mostafavi and Doherty 2010). The green and blue structure strategy can be broken into eleven substrategies, namely:

1. Greening
2. Rainwater harvesting
3. Ecological diversity
4. Biodiversity
5. Green parks
6. Green streets and alleys
7. Green factor and green points
8. Green roofs
9. Rain gardens
10. Bioswales
11. Permeable Pavements

The green structure strategy relates to the idea of letting nature do the work by designing multifunctional green structure to provide important ecosystem services of various categories, including provisioning, regulating, cultural, and supporting services. To let nature do the work entails ensuring that greenery and water are used as active components in the design and operation of the city. The green structure replaces and complements technical systems, creates a richer plant and animal life, and contribute to human health and well-being. Important to note is that the green structure strategy as an integrated approach is best to be implemented in new urban areas or outer areas with development potential. Also, a number of the aforementioned substrategies can be implemented as part of the individual urban development projects related to the other urban fabrics mentioned earlier, when it is feasible from a design perspective. However, below are the key pathways needed for executing the green structure strategy:

- Ensure the use of greenery and water as active components in the design and operation of the city districts.
 - Provide incentives to the residents in the existing city districts to install their own rainwater harvesting systems.
 - Design the drainage system in the new city districts to be aesthetically pleasant, with waterfalls, canals, ponds, and various elements for purifying and buffering the water.
 - Divert the rainwater through aboveground gutters surrounding the buildings of the new city districts as part of public space design.
 - Build permeable pavements to reestablish a more natural hydrologic balance and reduce runoff volume by trapping and slowly releasing precipitation into the ground instead of allowing it to flow into storm drains and out to receiving waters as effluent.
 - Build bioswales to slow and reduce stormwater runoff while removing debris and filtering out pollutants.
 - Build rain gardens to collect and hold rainwater from downspouts, driveways, and sidewalks for a short time, allowing the water to slowly seep back into the ground.
 - Implement 'green space factor' as an instrument to guarantee a certain volume of greenery in residential courtyard and to ensure that green qualities are achieved in connection with the city's new construction projects.
 - Use green space factor where appropriate.
 - Monitor and improve the effects of green space factor pertaining to such ecosystem services as recreation, reduced risks of flooding, improved local climate, and noise reduction.
 - Reinforce ecosystem services in urban various urban practices so that their benefits and functions do not deteriorate.
 - Supplement the green factor system with green points, a list of a number of wide-ranging environmental measures, that can be implemented to promote biodiversity in the existing and new city districts.
- Transform the existing green and water views across the new city districts into liveable waterfront areas offering plaza, green space, and promenade, allowing for a variety of activities to take place and providing great opportunities for the social mix and interaction of the residents of the new city districts.
 - Use the waterfront footpath as linkages to several landscape nodes.
 - Create and distribute parks across the new city districts by ensuring 100% of the existing apartments have access to a park and natural environment within 200 meters, as well as by reserving a sufficient number of hectare for parks and dividing them between these apartments.
 - Develop and implement advanced technologies for monitoring the condition and composition of green space in the city districts.
 - Develop and implement new technologies to stimulate biological and ecological diversity and conservation.

3.3.2. Essential Urban Infrastructure: Smart and Sustainable Systems

As a wide-ranging term, infrastructure is the basic structure which supports the operation of a city. This makes economic and social development possible. The focus here is on the essential sustainable and smart infrastructures that make up the city, including transportation systems, communication systems, energy systems, waste systems, lighting systems, sewage systems, and waste disposal systems. These are associated with the basic facilities, services, and installations needed for the functioning of the city in terms of engineered systems. Worth pointing out is that the essential urban infrastructure embodies economic infrastructure, the internal facilities of the city that make business activity possible or promote economic activity, such as communication, transportation, distribution networks, and energy supply systems.

The essential urban infrastructure involves six key strategies:

1. Smart sustainable transportation
2. Smart sustainable energy
3. Smart sustainable waste management
4. Smart urban metabolism
5. Smart street lighting
6. Smart urban infrastructure

3.3.2.1. Smart Sustainable Transportation

To be able to effectively improve and strategically advance the contribution of the city to the goals of sustainability, it is necessary to fully integrate sustainable transportation system with smart transportation system. Accordingly, the smart sustainable transportation strategy encompasses seven substrategies, namely:

1. Walking and cycling
2. Public transport
3. Car-pooling (biogas and electric)
4. Electric vehicles

5. Smart transport management
6. Smart traffic management
7. Smart mobility management

Sustainable transportation: Sustainable transportation is a major strategy for achieving sustainability. It denotes any means of transportation that is green and has low impacts on the environment. Below are the key pathways for executing the sustainable transportation strategy.

- Implement the hierarchy of sustainable transportation, namely walking and cycling, public transport, car pools, and private cars.
- Set clear targets for reducing car journeys with the long-term objective of establishing the hierarchy.
- Provide a range of opportunities for walking and cycling through increased densities and short distances, i.e., proximity to workplaces, shops, services, and facilities in densely residential areas.
- Improve the public transport system by creating new connections, enhancing existing networks, and influencing habits and movements through soft measures.
- Improve the capacity, comfort, waiting time, and service quality of the public transport system.
- Build and enhance pedestrian paths/walking tracks and bike paths/cycle lanes linking different areas of the city districts to local workplaces, shops, businesses, and facilities.
- Build new cycle bridges linking the new city districts to the city center and the inner city.
- Make good availability of bicycle parking throughout the city.
- Provide incentives that give priority to cycling by offering a higher than average number of cycle parking spaces per apartment, house, and building.
- Restrict car parking by limiting parking spaces per apartment, house, and building.
- Close public spaces to cars and provide further opportunities for walking and cycling along pleasant routes.
- Provide incentives for electric and biofuel cars and taxis.
- Develop and implement strategic plans for the transition from private-owned cars to a plug-in hybrid, to mobility as a service with electric taxis, to biofuel diesel, and to public transport:
 - Private cars can be changed to a plug-in hybrid and then replaced by mobility as a service with electric taxis, a small alteration of self-driving electric taxis. An important precondition for the expansion of this traveling mode is the charging stations for electric cars that should be in place across the city.
 - Private cars can be changed to a biofuel diesel cars and then to public transport for everyday mobility and renting or sharing a biodiesel for longer trips.
 - Gradually increase the percentage of the private cars leaving the different districts of the city and allow a fleet of more and more self-driving electric taxis to circulate in these districts.

- Make bus stops within reasonable distance from blocks of building and with shortest possible running time intervals (e.g., operating on a five-minute schedule).
- Provide hassle-free usage of multiple modes of shared and public transport.
- Use biogas-fuel powered and hybrid busses as well as solar-powered screens showing times of arrival at bus stops.
- Combine measures and initiatives for shaping the physical structure of sustainable transportation as well as influencing behavior.
- Implement mobility management as a soft measure to build, develop, and maintain transport infrastructure and to create and keep the dialogue with different stakeholders as to how to make choices for travel modes.
- Introduce economic, social, and environmental policies through the congestion charges and Ultra Low Emission Zone (ULEZ), and allow the residents to tangibly see the impacts of automobile use across all three pillars of sustainability.

Smart Transportation: Smart transportation is one of the main ways modern cities can improve the daily lives of citizens and sustainability. It involves information systems that collect data about traffic, vehicles, and the use of different modes of transport for further processing and analysis in city operations center. Transport and traffic management is one of the most common areas that use data-driven technology solutions. The key pathways for executing the smart transportation strategy are:

- Develop and implement the unified public transport system with ticketing system.
- Develop and implement the bus transit system based on the orthogonal network of bus lines.
- Manage all the transport services of the city in real-time based on the data received from the situational centers.
- Develop and implement the smart traffic light system.
- Develop and implement the smart parking system.
- Encourage businesses and consumers to use vehicles equipped with telematics.
- Raise awareness of the options and benefits of intelligent transport systems.
- Apply disincentives to alter demand for carbon intensive vehicles. Equip public transport with advanced sensors to monitor mobility and movement and collect related data (e.g., precise geo-positioning, times, delays, number of passengers, etc.) for mining and visualization
- Use mobility and movement data for planning in terms of determining the need for launching new public transport routes or developing new road infrastructure.
- Implement the smart board for displaying information about the roads conditions in real time.
- Ensure seamless, efficient, and flexible multi-modal transport system.

- Support equity and inclusion using smartphone apps in sustainable urban transport.
- Develop and implement new business models for “Mobility-as-a-Service” for sharing systems.
- Develop and implement the bicycle sharing system for short trips across the city.
- Develop and promote smart apps for other modes of sustainable mobility to keep the citizens up-to-date and connected.
- Use sensed mobility data to understand how mobility behavior and traffic variation from one day to another is linked to the network topology for developing smart apps to influence travel behavior towards sustainable mobility.
- Integrate real-time mobility data and large-scale datasets that simultaneously record and calibrate dynamical traces of individual and collective movements across various spatial scales and over different temporal scales to understand the dynamic interplay between individual and collective mobility and social interactions.

3.3.2.2. Smart Sustainable Energy

The smart sustainable energy strategy aims to reduce energy consumption, increase renewable energy adoption, and decrease carbon footprint. Here technological innovations can play a prominent role in the light of the high predicted rate of urbanization. Integrating sustainable energy with smart energy will drive data-driven smart sustainable cities of the future to become fossil fuel-free and climate positive. Therefore, the energy system should combine green energy technologies and energy efficiency technologies. Accordingly, the smart sustainable energy strategy involves five key substrategies, with some overlaps among them, namely:

1. Renewable energy sources and technologies
2. Smart power grid and advanced metering infrastructure technologies
3. Smart building technologies
4. Smart home monitoring technologies
5. Smart environmental monitoring technologies.

The key pathways for executing the four last substrategies have already been addressed in (Bibri 2020e). This paper specifically provides the key strategic pathways for achieving the goals of energy efficiency and pollution reduction. The identified data-driven smart solutions are found to have significant potential to improve and advance environmental sustainability in the context of emerging smart sustainable cities.

Renewable Energy Sources and Technologies: It is important to strongly advocate renewable energy generation and usage in order to enable the city to become fossil fuel-free by 2050. Renewable energy is derived from naturally replenished and zero-emission sources such as solar, wind, biomass, hydropower, and geothermal), using a number of industrial and technological systems. Below are the key pathways needed for implementing the substrategy of renewable energy sources and technologies:

- Install solar collectors on the top of new and retrofitted buildings throughout the city to produce heat (see **Figure 2**).
- Install pumps (aquifer and sea water) to produce heat.
- Use aquifer and heat pumps for cooling.
- Combine solar collectors and pumps to aggregate heat production.
- Promote and install solar panels/photovoltaic cells throughout the city to produce electricity.
- Install stations of wind turbines to produce electricity for heat pumps as well as dwellings.
- Complement windmill farms by installing wind generators, smaller versions of massive power generators, in the different parts of the city districts.
- Perform solar thermal installations for energy monitoring to aid in understanding the solar thermal energy produced and consumed.
- Link diverse energy plants to the city’s energy system for district heating, district cooling, and power grid.
- Build large scale bio-fueled combined heat and power (CHP) system for producing electricity and heat by renewables and organic household waste. The incineration of waste is used to produce energy for heating systems.

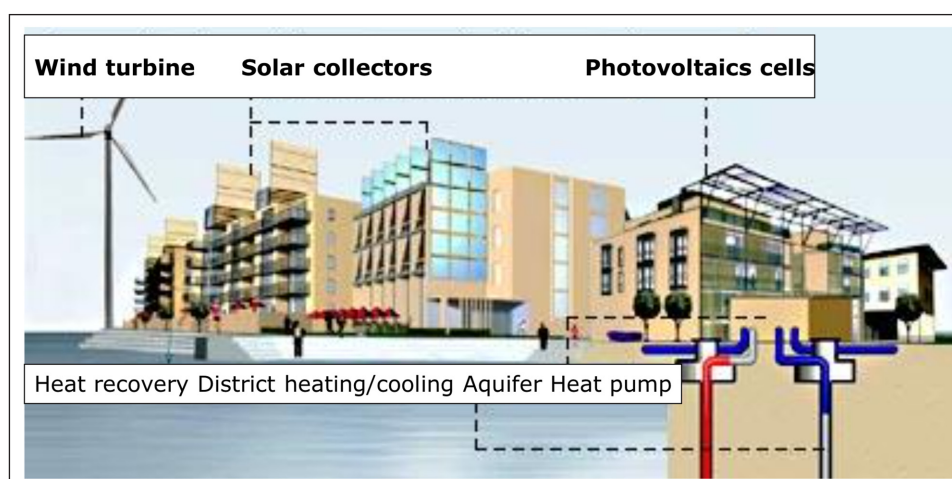


Figure 2: Heating and cooling based on renewables in Western Harbor District, Malmö, Sweden.

It is worth noting that some of the above installations depend on the geographical location and climate of the city as well as its energy needs. **Figure 2** illustrates an example of a renewable energy system integrating wind turbine, solar collectors, and photovoltaics cells for heating and cooling. Today, solar panels often cost less than on-grid electricity. Moreover, if all buildings' electricity is produced with solar energy, carbon emissions can be reduced by more than 50% compared to baseline in sustainable cities by 2030. Therefore, it is important to aim for shifting electric supply from 100% large-scale to 100% local solar power.

The main goal of the renewable energy sources and technologies strategy is to phase in renewables and phase out fossil fuels by 2050, resulting in 100% locally produced electricity and heat from clean sources in most districts and ultimately supporting the entire geographical area of the data-driven smart sustainable city of the future. This kind of transformational change requires a strategic roadmap, i.e., a time-based plan that defines a future outcome and determines and assesses the decisive steps needed to reach it.

3.3.2.3. Smart Sustainable Waste Management

To achieve far more resource-efficient use of waste that has minimal impacts on the environment requires developing and implementing a number of measures and solutions as part of smart sustainable waste management. This strategy encompasses seven substrategies, namely:

1. Convenient and smart waste collecting system
2. Vacuum waste chutes
3. Food waste disposers
4. Biogas digesters
5. Wastewater and sewage treatment system
6. Biological waste separation procedures

Sustainable waste management: The key pathways needed for executing the sustainable waste management strategy are:

- Standardize the planning of sorting facilities for separating packaging, food waste, and mixed waste, and ensure that all properties have access to these facilities.
- Build and evenly distribute large waste sorting stations throughout the city districts, and connect them to the city's waste infrastructure.
- Create and implement the relevant regulatory instruments with respect to waste management, and monitor progress to ensure the effective use in terms of the extent they yield desired results.
- Adhere to the waste hierarchy that reduces the quantity of the produced waste and the hazard it poses and prioritizes material-efficient products, thereby placing emphasis on recycling, reuse, and minimization of consumption in all its cycles.
- Use ICT to substitute for physical products.
- Design the waste sorting system in a way that is accessible and makes it easy for the residents to sort their waste in a safe and sustainable manner.

- Develop and disseminate easy-to-understand guidelines for sorting waste at the source.
- Ensure a high degree of waste separation in the city districts.
- Consider converting the food waste collected throughout the city districts into bio-fertilizer that can replace artificial fertilizer on agricultural fields.
- Build wastewater and sewage systems in the city districts, and integrate them in the city treatments plants
- Recognize that wastewater and sewage fractions are important energy resources (i.e., biogas fuels) and integrate them in the sustainable energy system.
- Develop and implement measures for influencing behaviors through engaging residents as part of environmental stewardship, as well as promoting sustainable habits and lifestyles.
- Set the following targets for sustainable waste management when planning new districts:
 - 100% of the kitchen of the dwellings have waste disposal units.
 - 100% of the properties have access to a vacuum waste chutes system in the residential courtyards that is able to transport non-organic waste underground.
 - Waste separation units are close to home for sorting paper and packaging materials, food waste, and mixed waste.
 - Wastewater and sewage treatment systems are installed and operate effectively in the city.
 - Closed eco-cycles function properly.

Smart Management of Waste Collection: Smart waste collection systems are becoming more and more widespread, and many cities across the globe are already implementing this solution in the city management programs. Typically, smart management of waste collection involves adopting data-driven resolutions intended to improve the efficiency of the city management, especially in relation to the city districts with no vacuum waste chutes systems. The key pathways for executing the strategy of smart management of waste collection are:

- Install smart waste collection system in the city districts:
 - Use sensors to allow to determine the degree of the fullness of waste containers, the level of the collected waste, independent of the nature of the recoverable waste.
 - Transmit the information received from these sensors via the mobile network to cloud storage for processing, analysis, and visualisation.
 - Use the obtained results to allow the sanitation workers to plan the collection routes of their waste disposal trucks in the real-time mode based on the degree of fullness.
- Implement the smart waste collection system where needed.
- Develop and implement the BigBelly solution.

3.3.2.4. Smart Urban Metabolism

As a model used for describing and analysing energy and materials flows in the city and their relationship with its infrastructure and activities, urban metabolism serves to maintain the functional and evolutionary states of the city as a socio-technical organism. Looking at the data-driven smart sustainable city of the future through a metabolic lens, a framework through which to successfully model the flows of its systems becomes of high importance and interest. This aids in understanding the relationship between human activities and the natural environment by studying the interactions of human systems and natural systems in the sphere of the city. Indeed, urban metabolism provides a platform through which the implications of the different dimensions of sustainability can be considered.

- Develop and implement a smart urban metabolism framework based on real-time data, high temporal resolution, high spatial resolution, and continuous visualization of materials and energy flows to different city stakeholders and at different social scales.
- Use multiple key performance indicators (KPIs) which need to be based on real-time data generation from heterogeneous sources and to be fed back on five spatial scales (household, building, neighborhood, district, and city) on the relevant interfaces developed for different audiences.
- Use dynamic and high resolution meter data for the evaluation of energy consumption in households and buildings. This is to increase the level of detail in the evaluation results and ease the detection of deviations in the performance of structures.
- Find more effective and innovative ways to deal with the challenges, barriers, and issues pertaining to the smart urban metabolism framework:
 - Access to and integration of siloed data from the different owners of data.
 - Privacy to motivate people to be actively involved in providing data.
 - The technical issues related to sensor technology, big data analytics, and emission factors.
 - Shortcomings concerning the use of dynamic and high resolution meter data for the evaluation of energy consumption, data collection and management, preservation of personal integrity, and incentives to react to the given evaluation information.
- Use diverse communication tools and methods for behavioral change, including:
 - Sustainable human computer interaction (HCI);
 - Eco-visualization;
 - Augmented reality;
 - Computers and smartphones;
 - Persuasive technology; and
 - Climate pervasive services.
- Use data-intensive scientific methods for studying urban metabolism to provide harmonized indicators for environmental sustainability assessment and for quantifying GHG emissions of the city, as well as for urban planning and policy analysis.

3.3.2.5. Smart Street Lighting

The city-wide street lighting system provides tremendous opportunities for modern cities to collect huge amounts of data from urban environments and to transfer them to special centers for their subsequent processing and analysis for enhancing decision making associated with numerous uses and applications. This can be used to make urban living more environmentally sustainable and to enhance the quality of life for citizens. Street lighting is one of the most interesting pathway to using and exploiting the IoT and big data analytics in future cities. Thus, it can be expanded beyond what is originally used for. The key pathways needed for executing the strategy of smart street lighting:

- Develop and implement the smart street lighting system and integrate it into the city-wide lighting infrastructure to enable the use of numerous innovative solutions related to transport, traffic, mobility, air and noise pollution, parking, safety, public Wi-Fi, and so on.
- Leverage the city-wide lighting infrastructure in achieving ambitious environmental goals at a lower cost given the pervasiveness, high visual impact, and cost-effectiveness of the street lighting system, in addition to its connection to the smart power grid system.
- Replace the street lights across the city with LED-based lighting system together with an IoT-based sensor network for advanced programmable features related to energy and the environment.
- Use the smart street lighting system to reduce the operational costs and optimize the energy efficiency of public-lighting system, as well as to reduce the risk of traffic collisions.
- Use smart street lights for night-time cycling based on context-aware technologies.

3.3.2.6. Smart Urban Infrastructure Management

Advanced ICT will be focussed on defining critical problems and events that might emerge rapidly and unexpectedly across the city. Analysing and identifying such problems and events is of great importance to urban sustainability and resilience. The smart management of the essential urban infrastructure involves monitoring and controlling its structural conditions in terms of potential changes that can increase risks and hazards as well as compromise safety and quality. In this context, data-driven smart technologies and solutions tend to be mostly justified by the high significance of the natural resources such infrastructure utilizes or involves in its operation. The key pathways needed for employing the strategy of the smart management of urban infrastructure:

- Support smarter transport, electricity, water, waste, and lighting networks in ways that can optimize resource efficiency and reliability and achieve more benefits with less expenditure and investment.
- Develop and implement new technologies for enhancing incident management, improving emergency

response coordination, harnessing synergies between different components, minimizing risks, ensuring safety and service quality, and reducing operational costs.

- Develop and implement new technologies for coordinating activities between various operators and service providers of the essential urban infrastructures in regard to scheduling repair and maintenance in a more efficient and effective way.
- Relate sustainable and smart urban infrastructures to their operational functioning, operational management, and short-term planning through monitoring, automation, control, optimization, and improvements using advanced ICT, especially the IoT and big data analytics.
- Analyze and investigate longer term sustainable and smart urban infrastructure needs and demands up to 2050—and use new technologies to meet them in a timely manner.
- Use joined-up planning to develop and implement new urban intelligence and planning functions that generate the kind of structures, systems, and forms that improve and maintain the sustainability, efficiency, and resiliency of the city.

3.3.3. Social Infrastructure

Social infrastructure is the development and maintenance of the basic facilities combined that are necessary for human development. It is a subset of the infrastructure domain and typically includes assets that accommodate social services. These are provided by a city government, either through the public sector (or related entities) or the financing of private provision of services. A huge part of new digital technologies, innovative solutions, interactive platforms, and diverse forms of public-private cooperation have become of critical importance to overcome the social challenges and to bring about the needed transformations in a number of social domains that sustainable cities and smart cities are facing. This is at the core of the assets of the social infrastructure of the data-driven smart sustainable city of the future, particularly in relation to citizen participation, public safety, healthcare, and education and training. Other assets are part of the built infrastructure, the essential urban infrastructure, and the technological infrastructure, such as facilities, community support, housing, sewerage, water and wastewater treatment, transport, public space, recreation, and so forth. In a wider sense, the data-driven smart sustainable city of the future also has a variety of sustainable development institutions and competence centers whose mandate is improving social, economic, and environmental aspects. The role of political and civic institutions and urban centers lies in maintaining the planning, development, governance, and functioning of the city as a data-driven smart sustainable entity in the future. However, the social infrastructure focuses on three strategies:

1. Smart citizens: participation and consultation
2. Smart public safety
3. Smart healthcare

3.3.3.1. Smart Citizens: Participation and Consultation

The social infrastructure is about people. Therefore, the involvement of citizens in the management and planning of the data-driven smart sustainable city of the future using information systems is crucial to the progress towards its ultimate goal. Such involvement is associated with the adoption of the most important resolutions related to living, which intend to improve the level of satisfaction and increase the level of confidence and trust among citizens in the city administration. The strategy “participation and consultation” aims to stimulate citizens’ interest in taking part in the planning and development of the city. Research, knowledge development, and experience feedback are important preconditions for solving complex challenges. The key pathways for executing the participation and consultation strategy are:

- Develop online platforms to engage citizens and make it easier for them to find out about different issues of planning and land use.
- Develop crowdsourcing platforms to address important city issues related to different areas.
- Establish a platform to enable citizens to influence their experience of the city by providing feedbacks and ratings.
- Create a platform where citizens can participate in the surveys organized by the city administration which can use the related data to adopt the resolutions in relation to the different domains of city life.
- Create a platform to engage more citizens in dialogue so as to gather input on their needs and demands (e.g., buss timing, playgrounds, parking lots, parks, ICT system reliability, and mobile coverage indoors), to evaluate all their suggestions, and to identify and solve important issues. Citizens can suggest ideas which can be put to a vote among the registered users of digital platforms for polls.
- Create a platform to enable citizens to communicate as well as track the status and control the execution of their complaints related to city issues.
- Create special portals to enable citizens to report the economic problems existing in the city in response to the adverse effects of urbanisation, pandemics, and disasters.
- Create diverse platforms to allow citizens to participate in urban technologies and policies, including:
 - Classrooms for learning about the uses and applications of and innovating in emerging digital technologies;
 - Entrepreneurial spaces for attracting startups and skilled innovators to create and promote new technologies;
 - Co-innovation centers for enabling close collaboration among different city stakeholders;
 - Participatory platforms for connecting city stakeholders to support decision-making processes; and
 - Democracy platforms for enabling citizens to discuss government proposals as well as submit their own.

- Create city councils for remote service provision by public agencies and mobile kiosks.
- Develop and implement new technologies which offer the prospect of ending the digital divide, provided that they do not open up other kinds of divides.
- Develop data-driven projects to identify public trends that can be considered when developing programs and initiatives for urban development.
- Support and strengthen the technologies that ensure widespread citizen participation through enhanced security measures and privacy mechanisms.

3.3.3.2. Smart Public Safety

It is highly important to develop a much deeper and more informed understanding of the risks, threats, and hazards surrounding the city. This requires a new set of data-driven technologies and collective decision-making processes. Data-driven approaches to urbanism enables understanding the city as strongly interlinked and coupled systems that generates unexpected and surprising dynamics. Emerging technologies are increasingly changing the nature of such dynamics by predicting them on multiple scales in terms of the properties and processes which stimulate change within the city system, thereby outsmarting it. The key pathways needed to execute the smart public safety strategy are:

- Use cutting-edge tools through established platforms to create awareness of situations, provide realistic scenarios for hazards, and strengthen resilience by integrating artificial intelligence, expert knowledge, and human experience.
- Make use of data-intensive science in decision-making processes with respect to natural disaster preparedness, responsiveness, and recovery.
- Monitor urban environments to inform authorities as well as alert citizens of potential risks, hazards, and vulnerabilities.
- Use environmental monitoring systems to track air pollution (e.g. harmful substances) in real time to prevent or mitigate adverse effects on public health.
- Use advanced simulation models to predict disease outbreaks and act accordingly to save lives and resources through taking preventive measures.
- Use data-driven approaches to hazard identification and risk assessment to provide immediate responses to potential threats.
- Use data-driven sentient computing to improve security by denying access to suspicious users to public places.
- Use data analytics to investigate transportation-related safety and health issues and inform the responsible public and private entities to make improvements accordingly.

3.3.3.3. Smart Healthcare

One of the key areas targeted by technological advancements and innovations is human health. Medical systems and healthcare services are at the core of the IoT and big

data applications. Healthcare management is one of the areas where the highest level of technology development and adoption is observed. The use of data analytics and personal wearable devices in medicine for the diagnosis and treatment of patients is one of the most promising areas of applied data-driven solutions in modern cities. Therefore, the focus should be on the electronization of medical services to enhance the quality of healthcare provided to all citizens and thus their well-being, as well as to upraise the effectiveness and efficiency of health system management. This entails using advanced tools, powerful computational processes, and innovative systems, such as embedded sensors and actuators, database system integration, management and monitoring software, simulation models, and decision support systems. The key pathways for executing the smart healthcare strategy are:

- Inform citizens about new healthcare policies and medical discoveries and rapidly disseminate information about disease outbreaks.
- Use advanced analytics techniques to analyze and interpret the huge datasets on health to improve the outcomes of healthcare with respect to those conditions that play out over longer times.
- Implement applied data-driven solutions in medicine for diagnosis and treatment by actively involving healthcare institutions, medical agencies, think tanks, and biotechnology companies as partners.
- Implement applied data-driven solutions to influence legislators on changes in regulating the medical and pharmaceutical industry.
- Encourage public and private medical organizations to adopt big data technology in their activities in terms of the implementation of eHealth platforms to accumulate, store, and deliver access to information about citizen health and medical history. The state-of-the-art technologies of big data analysis can be used to:
 - Perform accurate forecasts of the load on medical services and activity planning;
 - Evaluate the efficiency of educational programs, the quality of the obtained data, and the level of satisfaction of employers; and
 - Conduct health trend analysis of citizens.
- Connect medical centers, doctors, and patients with health data repositories and management software programs and sensing and communication capabilities to optimize the efficiency and performance of healthcare systems in terms of monitoring, traceability, and accessibility.
- Employ monitoring medical devices to remotely detect anomalies, gather patients' behavioral information, detect changes in their normal parameters to help improve the quality of recommendations and the accuracy of diagnosis.
- Gather all information about human health and treatment in electronic health record (EMRs) to allow physicians from different medical institutions to access patients' medical records and to enable patients to participate fully in healthcare decisions.

- Gather and analyze information on health indicators from non-specific devices, such as bracelets, smart watches, and sensors, as well as special medical devices.
- Establish a situation center to monitor the availability of and demand for medical services by analyzing the amount of appointments to doctors.
- Define inspection priorities and schedules based on the analysis of data on health standards in terms of checking the condition of hospitals and procedures and the execution of business rules.
- Inspect the recipients of health benefits based on the analysis of data to determine the level of compliance.
- Develop and implement the unified medical information and analytical system for healthcare. Such system comprises communication center, electronic registry, electronic health record, electronic prescription, disability certificates, laboratory services, and personalized record-keeping. It allows combining a variety of medical services and digitally collecting and analyzing data.
- Set the following targets prior to implementing the large-scale system of electronization:
 - Increase the transparency of medical facilities for citizens.
 - Raise the trust of citizens in health care system
 - Reduce queues in polyclinics by collecting and analyzing information on the flow of patients and the demand for medical services using a system of electronic records to set up appointments.
 - Distribute workers and doctors in healthcare centers based on data-driven decisions.

3.3.4. Technological Infrastructure

Generally, an ICT infrastructure includes hardware, software, networking, data storage, as well as an operating system. These are used to deliver applied solutions to the different stakeholders of the city. The ICT infrastructure of the data-driven smart sustainable city of the future must be able to integrate numerous application domains for sustainability across various spheres of its administration. Vital elements in this regard are the IoT, big data analytics, and artificial intelligence. These are to be used and integrated in more innovative ways to solve the problems related to the city management.

The ICT infrastructure can be deployed within the city's own facilities or within cloud computing. The ICT infrastructure strategy includes the following substrategies:

- Sensor infrastructure and digital network for data transfer
- IT architecture layers
- Data sources and open data

The competencies associated with the ICT infrastructure pertain to the process of big data analytics in terms of generating, processing, analyzing, and visualizing data for enhancing decision making across the various domains of the city (transport, traffic, energy, environment, health-

care, public safety, etc.). They depend on the scale and quality of the instrumentation, datafication, and computation dimensions of the city. This in turn determines the nature and range of the solutions provided to optimize, enhance, and maintain the performance of the city with regard to sustainability. Digital instrumentation produces huge amount of data, which are transformed into datasets and thus become easily conjoined and shared and highly appropriate for handling. These datasets allow real-time analysis of the different aspects of urbanity to generate deep insights that can be used in decision-making processes and in developing simulation models for managing, planning, and designing more sustainable cities. The essence of digital instrumentation lies in coordinating and integrating technologies (and hence the strategies of sustainable cities and the solutions of smart cities) that have clear synergies in their implementation within development planning and operational management. This opens up and enables realizing many new opportunities in the context of sustainability. The key pathways needed for executing the ICT infrastructure strategy are:

3.3.4.1. Sensor Infrastructure and Wireless Network for Data Transfer

- Develop and implement measures for modernizing the infrastructure of the city to make it ready to integrate data-based management.
- Implement and exhaustively deploy the sensor infrastructure and increase the number of Wi-Fi hotspots to cover the city areas to form a dense network of sensors.
- Build and extend the city Wi-Fi to increase the communication capabilities of the sensors deployed across the city areas as well as the data transfer processes.
- Ensure the fastest rate of wireless networks across the city areas.
- Ensure that all citizens have access to the Internet.
- Provide free Wi-Fi to all public buildings and facilities.
- Prioritize affordable high-speed digital connectivity for the city and provide free Wi-Fi to all citizens.
- Digitize businesses and organizations and increase the number of people working in the technology and service sectors.

3.3.4.2. IT Architecture Layers

- Set the basics of the IT architecture defining the strategies and policies allowing the sustainable city to become a data-driven smart sustainable city. This endeavor should be based on the joint cooperation of the city government, ICT companies, and academic institutions.
- Design, develop, implement, and maintain the IT architecture of the data-driven smart sustainable city of the future based on three main layers, namely (1) the information layer, (2) the middleware layer, and (3) the application layer:

1. The information layer is based on the whole complex of data sources, data routinely generated

about the city and its citizens by a range of public and private organizations. This layer collects raw data from different sources within the framework of the data-driven smart sustainable city of the future. These sources include sensors, cameras, transponders, meters, actuators, GPS, transduction loops monitoring various phenomena, and computerized databases, as well as a multitude of smartphone apps and sharing economy platforms generating a range of real-time location, movement and activity data. This layer also includes technologies and solutions allowing the transfer of the collected data for their further processing and analysis. The sensor platform of this layer isolates the applications that are to be developed to exploit the information generated by the city of the future. It also provides openness and interoperability. The data infrastructure standardization and data integration in a unified system significantly simplify the further usage of data.

2. The middleware layer collects raw data from the information layer and standardizes them for further processing and analysis. It provides tools for the storage, processing, and analysis of the collected data, which allow interpreting data, making forecasts on their basis, and identifying interconnection between different data ranges. This set of data analytics techniques enables obtaining the meaningful information from the resulting vast deluge of real-time, fine-grained, contextual, and actionable data for numerous applications. It represents the operation system for the data-driven smart sustainable city of the future, a platform that offers a comprehensive and transversal connectivity to serve citizens and other stakeholders. It is an open-code IoT platform that is accessible and open for use by third parties to download, develop, and/or modify data.
3. The application layer is the set of applications that use the meaningful information made available from the lower layers, and that provides services for the data-driven smart sustainable city of the future. It serves for the exchange of data among all the interested parties and the adoption of solutions based on the obtained data. It is based on the idea of using data to predict situations in order to make better decisions and reactions. This layer includes platforms with open data and tools of data visualization (e.g., dashboards and smart board) applied by the city administration for control over the city management system, automated systems of response to city-wide events (e.g., situation centers and control rooms), as well as a plethora of application developers, including city governments, state agencies, and private developers.

The ICT infrastructure for the data-driven smart sustainable city of the future comprises a collection of smart solutions for various spheres of its administration. It includes novel applications and services for city agencies and departments to serve different stakeholders, and dem-

onstrates the innovative use and integration of the IoT, big data analytics, and artificial intelligence to solve problems within the aforementioned domains of urban life.

3.3.4.3. Data Sources and Open Data

Data sources characterize the availability of the actually used and potentially to be used sources of data. Based on the analysis of these data, the data-driven smart sustainable city of the future will be able to make countless and support complex decisions pertaining to planning, design, and operational functioning. However, some data are open and thus accessible to the public for use, while other data are confidential and thus pose privacy issues. Also, some data are available virtually for free, while other data require effort to obtain. Still not all the data needed for the development and implementation of applied data-driven solutions for sustainability exist. However, the key pathways needed for executing the strategy of data sources and open data are:

- Support cooperation between the public and private sectors regarding the open data initiatives.
- Define rules and guidelines for the open data platforms to work with the public and private sector organizations:
 - Stimulate the publishing of dynamic data and the uptake of Application Programme Interfaces (APIs).
 - Limit the exceptions which allow public bodies to charge more than the marginal costs of dissemination for the re-use of their data. This involves the data held by public undertakings, under a specific set of rules in terms of the data made available for re-use.
 - Develop regulatory frameworks for open access to publicly funded research data. New rules should also facilitate the re-usability of research data already contained in open repositories.
 - Strengthen the transparency requirements for public-private agreements involving public sector information, thereby avoiding exclusive arrangements.
 - Identify and espouse a list of high-value datasets to be provided free of charge. These datasets have a high commercial potential and can speed up the emergence of value-added information products. They should also serve as key data sources for the development of Artificial Intelligence in relation to sustainability.
 - Develop ancillary projects in the form of organizations, institutions, and enterprises to arrange the collection and storage of data, providing the necessary support to the primary activities of the city stakeholders.
- Enable and promote common data standards (open, semi-open, proprietary, etc.).
- Develop and implement principles and measures to facilitate the integration of the different cross-thematic categories of data into coherent databases prior to large-scale data analytics. This relates to the public

policy domain of big data in terms of:

- How to collect, store, and coalesce various types of data in the city data warehouse;
 - Which stakeholders should be involved within each of existing city domains;
 - What concerns are relevant for the diffusion of big data technologies and platforms;
 - How to exchange or make use of data standards;
 - How the residents should be involved in the decision-making process pertaining to the selection and deployment of big data innovations; and
 - The legal and ethical dimensions in terms of data access and control and privacy and security.
- Develop strategic initiatives related to data protection and regulation:
 - City data analytics office as a platform for sharing the information generated or stored by public bodies with individuals and organizations.
 - Data commons city as an open-source policy toolkit regarding ethical digital standards for the city to develop digital policies that put citizens at the center and make governments more open, transparent, and collaborative.
 - Use open data to promote transparency and build trust in government decision-making and official policies.
 - Develop mayoral institutions for the governance of big data for situating the application of related innovations and financially supporting critical urban datasets.
 - Open up data to improve policymaking and to encourage innovation:
 - Make data publicly available for businesses and citizens to use, as well as provide tools for visualization and analysis.
 - Use data to inform the making of policies and decisions.
 - Make data available to the general public to drive innovation and collaboration in the development of new urban solutions, e.g., the formation of startups and the launching of new software applications to create economic and social value.

Up till now, the four models of sustainable urbanism and smart urbanism investigated are weakly connected as approaches and extremely fragmented as landscapes at the technical and policy levels. The compact city and eco-city models of sustainable urbanism, which have been around for over four decades or so, have many overlaps among them in their ideas, concepts, and visions, as well as distinctive concepts and key differences in terms of planning practices and design strategies. The overlap is justified by the fact that they both represent the central models of sustainable urban development. Therefore, they are, to some extent, compatible and not mutually exclusive. As to the data-driven smart city, which is an emerging paradigm of smart urbanism, it shares the challenges of sustainable development with the two models of sustainable urbanism, with the main difference being that it focuses more on the use and adoption of data-driven tech-

nologies and solutions and related technical and institutional competences to overcome these challenges—than on the planning practices and design strategies of urban sustainability. Concerning the environmentally data-driven smart sustainable city model, it emphasizes the dimension of environmental sustainability and employs data-driven technology solutions to reach environmental targets. In this sense, this model combines concepts and ideas from both the eco-city and the data-driven smart city. The two models are increasingly being merged on the basis of the IoT and big data analytics technologies in a bid to overcome the significant challenges posed by climate change in the face of the escalating trend of urbanization. However, while both implement data-driven technology solutions to improve and advance environmental sustainability, they remain significantly divergent with respect to their priorities, values, visions, policies, strategies, and goals, thereby the meaningfulness of their integration in the fourth case study.

4. Discussion

The main outcome of this study is the strategic pathways developed to bring about the preferred future. This involves identifying a set of planning actions and policy measures that enable to build a data-driven smart sustainable city in terms of the built infrastructure, sustainable urban infrastructure, smart urban infrastructure, social infrastructure, and technological infrastructure of its landscape. Developing strategic pathways is at the core of most of the backcasting approaches applied in the futures studies that address the various topics of sustainability transitions, or deal with long-term problems and sustainability solutions. This study is concerned with a pathway-oriented category of backcasting (e.g., Bengston Westphal and Dockry 2020; Wangel 2011), which is about identifying the planning actions and policy measures that connect a desirable state of the future to the present. At the core of this category, in the context of this paper, is how to bring about changes to the landscapes of the data-driven smart sustainable city of the future through different, yet interrelated, transformations related to the compact, ecological, and infrastructural designs of the city. Such transformations are of a complementary nature in line with the requirements of the future vision. However, setting strict goals in perspective of this category is of less importance (Vergragt and Quist 2011; Wangel 2011) compared to the other categories of backcasting, such as action-oriented backcasting, target-oriented backcasting, and participation-oriented backcasting (e.g., Akerman, Höjer 2006; Höjer, Gullberg and Pettersson 2011; Quist et al. 2001; Wangel 2011).

We identified the key strategies and pathways needed to move from the current state of sustainable cities to the future state of data-driven smart sustainable cities. This new integrated model of urbanism provides an important planning tool for facilitating the endeavor to build various models of sustainable cities that respond to the ongoing shifts brought by big data science and analytics and the underlying enabling and driving technologies. This means allowing sustainable cities to enhance, optimize,

and potentially maintain their performance in regard to supporting, balancing, and integrating the three dimensions of sustainability thanks to emerging and future data-driven technologies and their uses and applications in many urban domains and across several spatial scales. The construction of the vision of the future based on broadly defined objectives and targets is about setting priorities, incorporating values, and adopting principles pertaining to sustainability while taking advantage of what the multifaceted potential of advanced ICT through its innovative solutions for a large number of sustainability areas. This has indeed been demonstrated by several studies addressing the environmental, economic, and social aspects of sustainability (e.g., Angelidou et al. 2017; Bettencourt 2014; Bibri 2020b; Bibri and Krogstie 2017b; Kramers, Wangel and Höjer 2016; Nikitin et al. 2016; Pasichnyi et al. 2019; Thornbush and Golubchikov. 2019; Trencher, G. 2019; Shahrokni et al. 2014; Shahrokni, Levihn and Brandt 2014) through innovative operational management mechanisms and enhanced development planning practices.

The technological facets of the futures study have been addressed in more detail in the two case studies conducted on the emerging paradigms of smart urbanism. One of the key aspects to highlight in this regard is the role of smart cities in connecting the aforementioned infrastructures associated with the transformations needed to attain the future vision through the identified strategies and pathways. This connection, as enabled by advanced ICT as essentially network-based, is a way to leverage the collective intelligence of the data-driven smart sustainable city of the future through the synergic nature of ICT in regard to producing the tripartite benefits of sustainability. In other words, in making sustainable cities cleaner, safe, and more efficient through the new urban intelligence functions enabled by joined-up and short term planning approaches. This can be accomplished by harnessing the vast troves of data that can be generated from across many urban domains thanks to advanced computational analytics techniques as well as urban operation systems and analytical centers (e.g., Batty et al. 2012; Bibri 2019b; Kitchin 2014, 2016; Kitchin, Lauriault and McArdle 2015; Nikitin et al. 2016). Sustainable cities involve the kind of challenges that are enormous enough to call for a data-driven approach to planning as a function of many diverse city stakeholders. Joined-up planning is a form of integration and coordination that enables the city-wide effects associated with environmental, economic, and social sustainability to be monitored, understood, and embedded into the designs and responses of sustainable cities in terms of their operational functioning, i.e., forms, structures, spatial organisations, activities, and services as embedded in space and time.

The compact and ecological facets of the futures study characterize sustainable cities in terms of urban design. While the environmental goals of sustainability tend to dominate in the discourse of the eco-city (e.g., Mostafavi and Doherty 2010; Holmstedt et al. 2017), the discourse of the compact city emphasizes the economic goals of sustainability (e.g., Hofstad 2012; Jenks and Jones 2010), with the social goals of sustainability being of less focus in the eco-city than in the compact city (see, e.g., Bibri

2020b, c; Lim and Kain 2016; Heinonen and Junnila 2011; Bramley and Power 2009; Raporport and Verney 2011). In view of that, it is of significant importance to integrate both models of sustainable urbanism so as to strengthen their design strategies and green technology solutions to deliver the best outcomes of sustainability. Several studies have supported the idea that the compact city has the ability to support and balance the three dimensions of sustainability (e.g., Bibri, Krogstie and Kärrholm 2020; Burton 2002; Dempsey 2010), but it needs to strengthen the influence of the environmental and social goals of sustainability over urban planning and development practices (e.g., Bibri 2020c; Hofstad 2012). The ultimate goal is to create sustainable cities that can contribute to resource efficiency and reliability, environmental protection, socio-economic development, social cohesion and inclusion, the quality of life and well-being, and cultural enhancement. In fact, the two models tend to overlap in their principles, priorities, objectives, policies, and visions. In short, they are not mutually exclusive. Other attempts undertaken in this direction represent ideal approaches with inherent limitations of practical implementation (e.g., Roseland 1997; Harvey 2011). Farr (2008) discusses an integrated approach combining some elements of ecocities, some elements of compact cities, and sustainable urban infrastructure. However, this approach lacks empirical basis and is not grounded in specific planning actions and policy measures for implementing it in a real-world setting. Kenworthy (2019) focuses on strengthening the eco-city through a number of urban sustainability principles related to design, strategic planning, and transport.

The idea of integrating the two models of sustainable urbanism in question is based on fully merging their dimensions and strategies, with some flexibility concerning what to emphasize in urban planning and design and how this can be done depending on the characteristics of the urban areas that demonstrate the potential for future development. The novelty of this integrated approach to sustainable urbanism lies in incorporating sustainable energy systems, waste management systems, passive and low-energy buildings, and green structure in the built environment of the compact city to enhance its contribution to the environmental goals of sustainability. This is predicated on the assumption that these structures create the infrastructure needed to provide the ecosystem services and natural environmental processes, which can bolster compaction strategies to achieve better outcomes.

The nature of the integration of sustainable cities and smart cities is to be determined by the way in and the extent to which the dimensions and strategies of the former are pertinently extended and strengthened by those of the latter in the sense of creating a consolidated approach to data-driven smart sustainable urbanism that harnesses the synergistic effects and boosts the benefits of sustainability while supporting the balancing of its dimensions. This depends on the level of progress and how this can be assessed in regard to the different areas of sustainability within a given city that is badging or regenerating itself as sustainable or sustainable smart. Regardless, underlying the data-driven smart sustainable city of the future is the idea of its conception as processual outcomes

of urbanization (building, living, consuming, and producing), rather than as stable unchanging structures. Indeed, the model of the city is no longer predicated on the basis of this conception—rather, it is as much dominated by information flows as material flows. Besides, sustainable cities as complex systems evolve and change dynamically as urban environments in response to emergent proprieties and factors. Accordingly, cities need to be processual in conception, dynamic in planning, scalable in design, and optimisable in operational functioning in order to be responsive to population growth, environmental pressures, changes in socio-economic needs, discontinuities, and societal transitions. And the best way forward is to adopt advanced technologies to deal with the complexities inherent in their development planning and operational management.

Sustainable cities growing ever bigger in terms of their populations and knowledge base lie at the core of the future model of urbanism. ICT will be most clearly demonstrated in large sustainable cities. Building sustainable cities enabled by big data technologies is increasingly seen as a strategic move for containing and tackling the rather mounting challenges of sustainability in the face of the expanding urbanization. This is justified by the influence these advanced technologies can have on the way we control, manage, regulate, govern, and plan sustainable cities. In particular, while planning cannot reproduce the compact and ecological characteristics of sustainable cities that have been developed based on incremental and interactive processes involving many stakeholders over time, the primary role of big data lies in enabling information flows and channels, coordination mechanisms, powerful analytics, well-informed and evidence-based decisions, and learning and sharing processes involving divergent constituents and heterogenous collective and individual actors as data agents. These are indeed the most significant challenges that are currently facing sustainable cities, coupled with the dispersion of power. These complex conditions are continuously exacerbated by the unpredictability of environmental, socio-economic, and demographic changes.

However, sustainable cities are so characterized by their specificities as regards their compact and ecological dimensions and how and the extent to which these are integrated in a given city area or district. This in turn shapes the way in which the IoT and big data technologies can be embedded in the fabrics of sustainable cities, as well as how they can be applied in their operational management processes and development planning practices. In more detail, sustainable cities essentially exhibit key differences in the way they prioritize and implement their strategies and solutions depending on many intertwined factors, notably physical, geographical, socio-political, economic, environmental, and historical. In particular, the IoT and big data technologies might work in one sustainable city in a way that is different in another. Hence, they should sometimes be dramatically reworked to be applicable in the context where they are embedded. Besides, sustainable cities do not have a unified agenda as a form of strategic planning, and data-driven decisions are unique to each sustainable city, so are environmental, economic,

and social challenges. Big data are the answer, but each sustainable city sets its own questions based on what characterize it in regard to visions, policies, strategies, pathways, goals, and priorities. Regardless, it is important for sustainable cities to make the best use of their local opportunities and capabilities as well as to assess their potentials and constraints from a more integrated perspective when it comes to the operational management and development planning related to their compact, ecological, and technological landscapes and approaches.

In view of the above, the new model of urbanism is not meant to be universal in its nature, and it follows that the proposed strategic planning process of transformative change towards sustainability should look at the wider picture and be flexible in its means. In this respect, it is important to acknowledge the fact that universal urban models, whether compact, ecological, smart, or a combination of these, are problematic and cannot be applicable in the same manner all over the world (see, e.g., Bibri and Krogstie 2020c; Hofstad 2012; Karvonen, Cugurullo and Caprotti 2019; Rapoport and Vernay 2011; van Bueren et al. 2011). Therefore, urban models should be adapted to the multidimensional context specific to each city. In addition, while automation, big-data analytics, and artificial intelligence can bring numerous advantages to sustainable cities, it is equally important to acknowledge the fact that these advanced technologies can be problematic, and therefore, policy-makers and planners should be careful when employing them. Many recent studies have discussed the potential urban problems and issues triggered by automation, big-data analytics, and artificial intelligence in the context of smart sustainable urbanism (e.g., Bibri 2019a, c; Cugurullo 2020; Yigitcanlar and Cugurullo 2020).

5. Conclusion

Working with long-term images of the future is meant to increase the possibilities and stimulate the opportunities to attain the kind of sustainable cities that last thanks to emerging and future technologies. Sustainable cities are always about citizens. Being data-driven smart about sustainable cities requires to connect directly to the concerns and feelings of people with respect to environmental protection, economic regeneration, and social justice. Historically, people have always moved to and preferred to live in sustainable cities to improve their lives, and smart urbanism is being embraced anew as a strategic move to create sustainable cities that make urban living more sustainable over the long run. Towards this end, sustainable cities have to learn faster and identify strategies that work. Therefore, it is scholarly worthy to venture some thoughts about where it might be useful to channel the efforts now and in the future in what has been termed “data-driven smart sustainable urbanism.”

This paper developed a novel model for data-driven smart sustainable cities of the future, and in doing so, it offered a strategic planning process of transformative change towards sustainability in the era of big data. It identified a series of actions and measures pertaining to the built infrastructure, sustainable urban infrastructure, smart urban infrastructure, social infrastructure, and technological infrastructure of the landscape of the

data-driven smart sustainable city of the future. This empirically grounded model of urbanism is meant to be clearly specific in terms of the underlying components based on the prevailing paradigms of sustainable urbanism and the emerging paradigms of smart urbanism. The essence of this new integrated model lies in providing the needed tools, techniques, methods, systems, platforms, and infrastructures enabled by the core enabling and driving technologies of the IoT and big data analytics for the current model of urbanism to optimize, enhance, and maintain its performance with respect to the contribution to and balancing of the goals of sustainability.

In terms of the practicality of the new model of urbanism, the feasibility of the future vision is underpinned and increased by the outcomes of the four case studies. The case study approach as a research strategy facilitates the investigation and understanding of the underlying principles in the real-world phenomena involved in the construction of the future vision in the futures study (Bibri 2020d). This pertains to:

- The extent to which the compact city and the eco-city support the balancing of the goals of sustainability
- The design strategies of the compact city and the environmental design and technology solutions of the eco-city
- The practice of the data-driven smart city in regard to the development and implementation of innovative applied solutions for development planning and operational management to improve and advance sustainability
- The role and potential the emerging data-driven technology solutions have in improving and advancing environmental sustainability within the frameworks of sustainable cities and smart cities.

The suitability of backcasting for the kind of problems that are associated with sustainable cities in terms of their contribution to and balancing of the goals of sustainability stems from the problem-solving and goal-oriented character of backcasting that is embedded in its process of strategic planning. Backcasting is useful in studying problems that are complex and associated with persisting trends that contribute to the problems' complexity. Moreover, it allows to imagine the impacts of the future vision, which should be highly significant and entail extensive and ambitious improvements and advancements compared to the current trend. The advantage of using this framework lies in its foundation and efficacy with regard to providing insights into and developing pathways for sustainability transitions, as well as in its ability to produce desired outcomes. This is of high relevance and importance to policy-makers as to informing strategic plans for achieving the objectives of sustainable development and thus making actual progress towards sustainability. Here, backcasting can be viewed as a process of transformative change in the sense of how sustainable cities can be designed and developed so that they become able to monitor, understand, analyze, and plan their infrastructures more effectively

so as to enhance and maintain their performance with respect to their contribution to sustainability in terms of its tripartite value. All in all, the new model of urbanism can be seen as an important arena for sustainability transitions in the era of big data. It offers a clear prospect of instigating a major transformation by synergistically connecting the agendas of urban development, sustainable development, and technological development for a better future.

Competing Interests

The authors have no competing interests to declare.

Author Contributions

S.E.B. designed the research, conducted the literature review, collected and analyzed the data, and wrote the manuscript. J.K. reviewed the manuscript. The authors read and approved the published version of the manuscript.

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