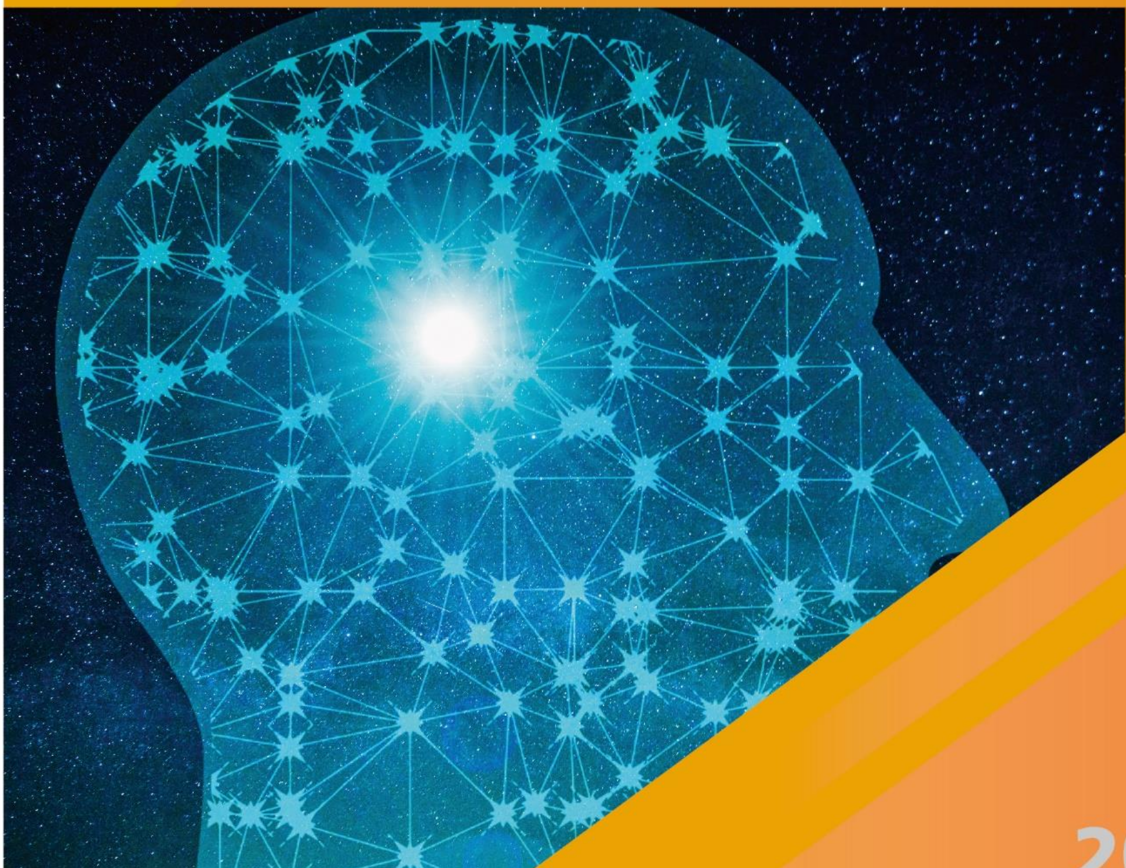
China Council for International Cooperation on Environment and Development

SPECIAL POLICY REPORT

Digitalization and Green Technologies for Sustainable Development



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Digital-Green Dual Transformation and the Sustainable Development of Cities

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Project Team

Team leads*:

- Chinese team lead:
  - Prof. Ke Gong, Past President of WFEO, Executive Director of the Chinese Institute of New Generation Artificial Intelligence Development Strategies
- International team leads:
  - Prof. Dirk Messner, President, German Environment Agency
  - Gim Huay Neo, Managing Director, World Economic Forum

Coordinators:

- Chinese coordinator:
  - Pei Lei, Office manager of Binhai Development Institute, Nankai University
- International coordinators:
  - Stephan Thurm, International Affairs Officer, German Environment Agency
  - Xie Xi**,** Project Lead, China, Ocean Action Agenda, World Economic Forum
  - Dr.-Ing. He Ling, Research and Policy Officer, German Environment Agency

Core experts*:

- Chinese team:
  - Liu Gang, Professor in the Innovation Economics and Innovation Policy, Ph.D. supervisor, and Director of Nankai Institute of Economics
  - Shao Chaofeng, Professor and doctoral supervisor of the College of Environmental Science and Engineering NKU
  - Dai Shuanping, Professor and doctoral supervisor, School of Economics, Jilin University, China
  - Wang Yu, Professor and doctoral supervisor, School of Economics, Jilin University, China
  - Liu Dian, Associate Researcher of China Institute, Fudan University, Director of the Strategic and Macro Research Program, Institute for AI International Governance, Tsinghua University
  - Liu Jie, Lecturer of the Chinese Institute of New Generation Artificial Intelligence Development Strategies
  - Nick Hajli, Professor and Chair of Strategy and Innovation at Loughborough Business School
  - Markus Taube, Professor, Chairman for East Asian Economic Studies, faculty member of the Mercator School of Management at the University of Duisburg-Essen, Germany
  - Mina Tajvidi, Assistant Professor in Marketing at Queen Mary University of London, School of Business and Management
  - Luo Chun, Postdoctoral fellow of the Chinese Institute of New Generation Artificial Intelligence Development Strategies
- International team:
  - Prof. Felix Creutzig, Head of working group Land Use, Infrastructure and Transport; Chair of Sustainability Economics, Technische Universität Berlin

- Prof. Keywan Riahi, Program Director and Principal Research Scholar, IIASA
- Dr. Guoyong Liang, Senior Economist, United Nations
- Dr. Leila Niamir, Research Scholar, Transformative Institutional and Social Solutions Research Group, IIASA
- Prof. Phillip Misselwitz, Architect and Urban Planner, Partner of Urban Catalyst GmbH, Berlin
- Alice Schröder, Lead on Sustainable Spatial Development and Environmental Assessments, German Environment Agency
- Anna Eckenweber, Formerly Consultant at Urbanizers Consulting
- Marie Neumüllers, Founding Partner, Urbanizers Consulting
- Jan-Peter Glock, Project Manager, Policy Advisor and Mobility Researcher, German Environment Agency
- Katja Becken, Expert on Circular Economy, Building, and Production, German Environment Agency
- Daniel Hausmann, Portfolio Manager, Cluster Climate, Energy, Environment, and Biodiversity at the East Asia Regional Office - Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
- Josefine Hintz, Doctoral Researcher, Hertie School - AI and Climate Technology Policy Group, Mercator Research Institute for Global Commons and Climate Change
- Tommaso Piseddu, Research Associate, SEI Headquarters – Societal Transitions Unit

Advisory experts:

- Chinese team:
  - Chirantan Chatterjee, Reader in Economics of Innovation at Science Policy Research Unit (SPRU) at University of Sussex Business School
- International team:
  - Dr.-Ing. Robert Wagner, AI and Digitalization Expert, Lead of the UBA AI Lab

Project management team:

- Chinese team:
  - Shen Mingzhe, Office manager of Chinese Institute of New Generation Artificial Intelligence Development Strategies
  - Wang Guanyi, Partnership & Programme Manager, Office of International Affairs, Nankai University
  - Jing Ran, Administrative staff of Chinese Institute of New Generation Artificial Intelligence Development Strategies
  - Zhang Lin, Administrative staff of Chinese Institute of New Generation Artificial Intelligence Development Strategies
  - Zhang Hanyin, Administrative staff of Chinese Institute of New Generation Artificial Intelligence Development Strategies
  - Liu Chang, Administrative staff of Chinese Institute of New Generation Artificial Intelligence Development Strategies

- International team:
  - Jan-Hendrik Eisenbarth, Advisor, Sino-German Environmental Partnership III - Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
  - Dai Min, Project Manager, Sino-German Environmental Partnership III - Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
  - Dr. Niels Thevs, Project Director, Sino-German Environmental Partnership III - Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

* The team leads and members of this special policy study (SPS) serve in their personal capacities. The views and opinions expressed in this SPS report are those of the individual experts participating in the SPS Team and do not represent those of their organizations and CCICED.

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- World Economic Forum: Zhou Hailing, Zhu Chunquan, Na Na, Xia Bing
- Technische Universität Berlin: Ge Ke
- Jinan University: Wang Chunchao, Professor and Dean of the School of Economics
- Chinese Academy of Sciences (CAS): Chen Weiqiang, Professor, Researcher and Group Leader of the Institute of Urban Environment (IUE)
- Chinese Academy of Sciences (CAS): Song Lulu, Associate Researcher, Institute of Urban Environment (IUE)
- Ralph Wollmann, Scientific Officer, International Academy – Transformations for Environment and Sustainability, German Environment Agency

Executive Summary

1. Research significance

Cities are crucial to achieving the 2030 Agenda for Sustainable Development and the Sustainable Development Goals (SDGs). Currently, more than 50% of the world's population lives in cities. By 2050, 68 % of the global population will live in cities and urban areas. Today, cities take up only about 3% of land area, but are responsible for 50% of waste generation, 60-80% of GHG emissions and 75% of resource consumption, with the construction sector alone using 40-50% of the resources extracted globally.

During the urbanization process, China has seen the emergence of mega-cities with populations exceeding 10 million, including Shanghai, Beijing, Shenzhen, Chongqing, Guangzhou, Chengdu, Tianjin, Dongguan, Wuhan, and Hangzhou. This rapid urbanisation has resulted in an increased consumption of resources, energy and materials and led to negative environmental effects.

China has made significant strides in smart city developments, marked by initiatives dating back to 2005 with the introduction of digital city management. Subsequent policies, such as the 2014 "Guiding Opinions on Promoting the Healthy Development of Smart Cities" and the 2023 "Plan for the Overall Layout of Building a Digital China," have driven the nation's smart city agenda. These efforts have resulted in improved urban efficiency, including smarter transportation systems that reduce congestion and emissions.

While China's advancements in smart city development are impressive, it becomes apparent that the integration of digitalization and the green transition (here also referred to as the "dual transformation") has not yet been formally implemented in China. Against this backdrop, we argue that the shift towards net-zero cities will fundamentally depend on the strategic execution of the dual transformation towards smart sustainable cities. Therefore, the "Smart Sustainable City" concept should be adopted as the leading paradigm of urban development.

2. Research focus

This CCICED Special Policy Study (SPS) explores the holistic integration of digitalization and sustainability at the city level in China. The study aims to provide strategic insights and policy recommendations for creating sustainable smart cities by combining well-established sustainability practices with cutting-edge digital technologies. It presents a blend of theoretical analysis and empirical studies, including case studies of both Chinese and international cities which provide useful benchmarks and best practices, highlighting the potential for innovative approaches to urban development.

The study advocates for a holistic understanding of smart sustainable cities, based on a United Nations' definition. A smart sustainable city uses information and communication technologies (ICTs) to improve urban operations, enhance the quality of life, and ensure the long-term sustainability of economic, social, and environmental systems. The core of the report outlines strategies for integrating digitalization and sustainability across key domains of urban development. This includes transforming the urban economy, energy systems, and industry through digital solutions, while also fostering civic participation, socially inclusive urban planning, and gender-sensitive policies. The design of compact, green cities with efficient public transport and sound environmental governance is also emphasized.

In its concluding chapter, the report provides a set of policy recommendations for the Chinese government. Central to these recommendations is the concept of the "City Brain", a digital platform that harnesses data to optimize urban management, which could play a key role in China's transition to smart sustainable cities. The study emphasizes that the dual transformation is not only crucial for China's future urbanization but also serves as a global model for achieving sustainable development in cities worldwide.

3. Key policy recommendations

This report provides a set of key policy levers paving the way towards the implementation of smart sustainable cities. Our prioritized areas of action include: 1) data and AI governance, 2) energy and industrial infrastructure, 3) smart and sustainable urban planning, 4) social participation and inclusion, 5) knowledge generation and access, and 6) monitoring and learning. Overall, these practical recommendations adhere to a rationale of three overarching strategies:

First, implement a people-centered "Smart Sustainable City" strategy
Chinese cities should adopt the "Smart Sustainable City" concept as the key paradigm for their next phase of smart city development. To achieve this, we recommend municipalities establish a dedicated Smart Sustainable City Committee and fully integrate sustainability into all aspects of city planning and management. This includes addressing environmental concerns (such as green AI-infrastructure, emissions, energy use in data centers, pollution, and electronic waste), social issues (such as gender equality, privacy protection, and support for digital disadvantaged groups), and governance (such as scientific decision-making, transparency, and public participation). Sustainability needs to be considered at every stage of smart city construction, from digital investment to data governance, emphasizing citizen participation and community strengthening to embrace a people-centered approach.

Second, enhance digital capabilities for sustainable solutions
The development of Smart Sustainable Cities should focus on building digital capabilities and providing smart, sustainable solutions. Digital capabilities include ICT infrastructure (hardware, software), ICT services, and urban AI systems (like city brains and intelligent urban management centers). Smart and sustainable solutions encompass general applications such as digital twin cities, smart transportation, smart energy, and smart industrial parks, as well as tailored solutions for specific urban challenges and the needs of vulnerable groups. Enhancing digital capabilities for sustainability demands both technological advancements and institutional innovation.

Third, advance key technologies that integrate digital and green innovations

Digital and green innovation is crucial for driving economic and social transformation. Integrating digital technologies, such as artificial intelligence, with green technologies is key to sustainable urban development in Chinese cities. This integration enables more efficient resource use, faster planning processes, and the strategic utilization of new and existing infrastructure to build resilient urban spaces. To develop and implement these key technologies, national and sectoral innovation systems need to be further enhanced.

Under these overarching strategies, the six prioritized areas of action are:

AI and Data Governance

A people-first strategy is essential to undergo a digital transformation. Cities should prioritize ethical use of artificial intelligence, ensuring that algorithms are under human control, transparent and serve public interest. Data governance needs to be improved, and environmental and social risks associated with digitalization need to be mitigated.

Energy and Industrial Infrastructure

Cities should direct financial investments toward green technologies and digital services to foster sustainable urban economies, including green energy and industrial infrastructure. Government policies should support technological and infrastructural development to accelerate this transformation.

Smart and Sustainable Urban Planning

Focus on the design of compact, green cities with mixed-use districts, eco-friendly mobility options, and reduced noise levels. Central to this vision is a new approach to managing limited urban space. Cities should integrate the "City Brain" technology utilizing AI and big data to simulate and predict the environmental impacts of urban planning decisions. AI can help optimize mobility, buildings, and climate adaptation, guiding sustainable urban development and reducing environmental damage.

Social Participation and Inclusion

To ensure digital inclusivity, cities should offer green and digital literacy programs to equip citizens with an understanding of sustainability and its relation to quality of life as well with the skills needed to understand algorithmic systems. Governance needs to be developed that is capable and motivated to incentivize change. For disadvantaged groups, such as the elderly, children, and economically vulnerable populations, cities should provide training to help them access digital city services. Gender equity need also to be integrated at various stages of technology development.

Knowledge Generation and Access

Cities should create data portals that allow public access to sustainability-related metrics. This enhances transparency and encourages public engagement in sustainability efforts, supporting evidence-based climate action and making data usage methods more accessible. Social innovations in areas of sustainable behavior and development of business models focused on the circular economy and sustainability need to be supported through different measures and incentives.

Monitoring and Learning

Cities should develop and adopt city-specific indicators to measure progress in digital and green development. These indicators help define long-term visions, track performance, and adjust strategies for continuous improvement. Cities should also seek synergies between different monitoring systems to identify effective sustainability indicators.

Keywords: Urbanization, digitalization, green development, city brain, dual transformation, green growth, smart, sustainable, climate resilient, green-blue infrastructure, social inclusion, energy transformation, urban planning, urban environment

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Introduction

This CCICED Special Policy Study (SPS) aims to provide insight on how to holistically integrate the digital and green transformations at the city level in China. For the creation of smart sustainable cities, we propose combining well-tested sustainability capabilities with innovative and visionary digital appliances. Through theoretical and empirical studies, the study provides policy recommendations to the Chinese government for promoting the coordinated advancement of digitalization and green transformation, thereby contributing more effectively to sustainable development. The empirical studies include case studies on specific cities both at home and abroad, as well as an exploration of cutting-edge practices in the urban digital-green dual transformation around the world. These studies at the global level provide useful benchmarking and learning from best practices for Chinese cities.

Cities are crucial to achieving the 2030 Agenda for Sustainable Development and the Sustainable Development Goals (SDGs). Currently, more than 50% of the world's population lives in cities, and by 2050, 68 % of the global population is expected to live in cities and urban areas [1]. The construction of new infrastructure will consume the majority of the CO_2 budget (1.5 ℃ scenario) if conventional materials such as steel and cement are used. In recent decades, the construction sector has already become responsible for around 34% of global energy demand and 37% of energy and process-related CO2 emissions, making it the largest emitter [2][3].

Today, cities take up only about 3% of land area, but are responsible for 50% of waste generation, 60 – 80% of greenhouse gas (GHG) emissions and 75% of resource consumption [4]; the construction sector alone uses 40-50% of the resources extracted globally[5][6]. In 2022, China's urbanization rate reached 66.16 % and could rise to 70% in the next five years[1]. During the urbanization process, China has seen the emergence of megacities with populations exceeding 10 million, including Shanghai, Beijing, Shenzhen, Chongqing, Guangzhou, Chengdu, Tianjin, Dongguan, Wuhan, and Hangzhou.

Marked by the digital city management pilot project, the practices of smart city construction started in China in 2005. In 2014, the National Development and Reform Commission (NDRC) issued the *Guiding Opinions on Promoting the Healthy Development of Smart Cities*, and the associated mechanism of inter-ministerial coordination was established later in the same year. Since then, smart city construction has become an official policy at the national level in China. In 2017, the NDRC, together with the Cyberspace Administration of China and the National Standards Administration, formulated the *Evaluation Index for New Smart Cities*, which has been subsequently updated several times. In 2023, the Chinese government issued the *Plan for the Overall Layout of Building a Digital China*, which means that smart city construction has entered a new and more important stage.

Over the past two decades, China has strategically invested in smart cities, ranging from dense networks of urban sensors to cloud-based AI computations, to smart applications, resulting in much more efficient car transport and reduced congestion. However, while Chinese smart city capabilities are impressive, and China upholds the philosophy of harmonious coexistence between humanity and nature by prioritizing CO_2 emission reduction, pollution control, biodiversity conservation and seeking green development, cities are still one of the major sources of CO_2 emissions and air pollution in China.

Our field research demonstrates that integration of digital technologies and sustainability capabilities (here, also referred to as the "dual transformation") has not yet been implemented in China and, as we will argue hereafter, that the transformation toward net-zero cities will fundamentally depend on the strategic execution of the dual transformation toward sustainable smart cities.

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[1] Reuters. (2024, July 31). China expects urbanisation rate near 70% in next five years. Reuters. https://www.reuters.com/world/asia-pacific/china-expects-urbanisation-rate-near-70-next-five-years-2024-07-31/.

Hence, we recommend exploring how to mobilize digital technologies to address planetary challenges in cities. Specifically, we suggest investigating the following: 1) how to direct digital infrastructure toward sustainability; 2) how to improve digital capabilities for providing effective sustainable solutions; 3) which indicators could help to monitor progress; and 4) how to manage risks related to digitalization.

We propose mainstreaming a holistic understanding of the smart sustainable city in the planning and development of smart cities in China. According to the United Nations, a smart sustainable city is "an innovative city that uses ICTs and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social, environmental as well as cultural aspects" [7].

As visible in Figure 1, the main body of the study will lay out the most important strategies to integrate sustainability and digitalization across important domains of city development. The first section of this report discusses the current state of the development of Chinese cities and the fundamental changes they undergo in the era of digitalization and climate change. Section 2 addresses the sustainable transformation of the urban economy, energy system, and industry through digital means. Section 3 discusses civic participation, human-centred urban planning, and the consideration of social inclusion and gender biases before Section 4 touches upon the design of compact and green cities, public transport, and environmental governance. Throughout the study, short case studies based on our study research trips to Ordos (Inner Mongolia), Beijing, Vienna (Austria), and Helsinki (Finland) illustrate the application of digital and sustainable best practices on the ground.

The report finishes in Section 5 with a set of key policy levers and operationalized policy recommendations that pave the way to the implementation of sustainable smart cities. The leverage points provide guidance on 1) data and artificial intelligence (AI) governance, 2) energy and industrial infrastructure, 3) smart and sustainable urban planning, 4) social participation and inclusion, 5) knowledge generation and access, and 6) monitoring and learning by integrating well-tested sustainability capabilities and digital technologies—including the City Brain, whose enormous potential for sustainable development will be elaborated.

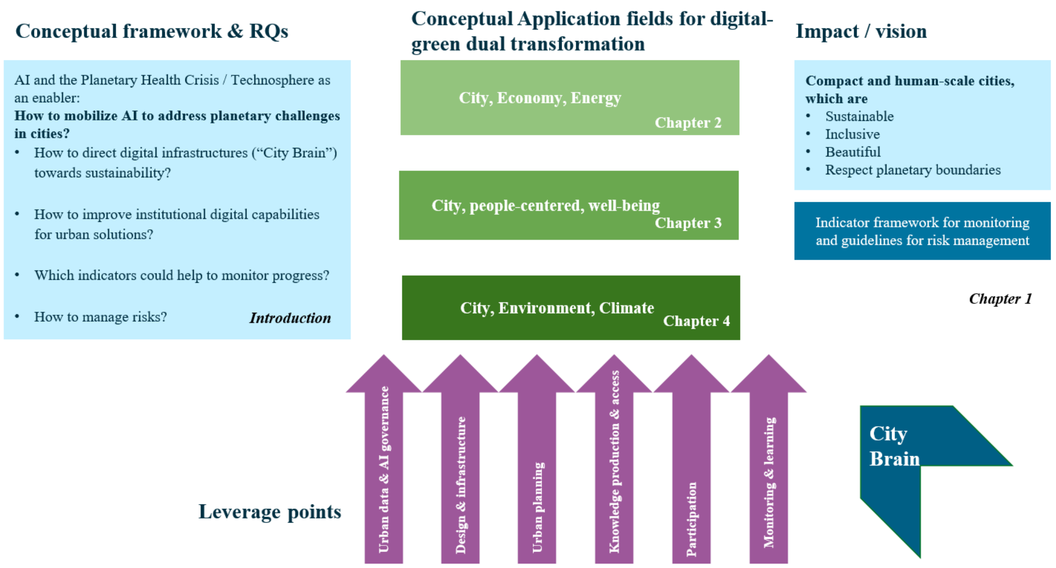

Figure 1. Digital-green dual transformation and the sustainable development of cities: A conceptual and analytical framework

1. Digital Capabilities for a Sustainable Urban Future

In the face of the climate crisis, economic turmoil and social tensions, urban development is encountering increasingly severe challenges. In the meantime, digitalization provides unprecedented opportunities to enhance municipal capacities and expand the boundaries of urban development. Establishing the conceptual framework of the SPS study, Section 1 is organized as follows: Section 1.1 discusses the drivers and boundaries of urban development and introduces the concept of the “City Brain”; Section 1.2 presents major sustainability capabilities that cities have at their disposal; and Section 1.3 addresses the most important potentials and risks that come with the digitalization of our cities.

1.1 Cities as Complex Technology-Economy-Society Systems in the Age of Digitalization

Cities are highly complex systems comprising numerous subsystems including technology, economy, politics, society, culture, and ecology. Infrastructure and the ecological carrying capacity present limiting factors for urban development. Meanwhile, the potential for technological innovation and industrial transformation arising from the interaction between technological and economic systems is key to breaking through the borders of urban development. Entering the second quarter of the 21st century, global technological innovation is increasingly focusing on AI, which is forming a new innovation paradigm and production mode of human-machine collaboration. This creates the conditions for building digital capabilities that enable the coordinated and balanced development of urban economy, society, and ecology.

1.1.1 Drivers and boundaries of urban development

Edward Glaeser argues that the key to urban development lies in the increased density of economic activity, which stimulates transaction growth and efficiency improvements [8]. The spatial concentration of population and economic activities promotes wealth creation through mechanisms such as sharing, matching, and learning [9]. Sharing primarily involves the communal use of public infrastructure, like urban transportation. Matching refers to the alignment between supply and demand, particularly the fit between people and jobs. Learning encompasses the formal and informal flow of information and knowledge that results from agglomeration, serving as the basis for technological innovation. Cities, especially megacities, are responsible for generating over 80% of global wealth and nearly all technological innovations [10].

While the concentration of population and economic activity in cities drives wealth growth, it also introduces new problems and challenges, such as rising crime rates, disease transmission, traffic congestion, and environmental pollution. The negative externalities of agglomeration drive the migration of population and economic activities from city centres to suburbs, thereby setting limits on urban expansion. Moreover, with the emergence of climate change and ecological crises, urban development faces increasingly severe challenges.

From an economic perspective, if the concentration of population and economic activities is the fundamental driving force behind urban development, growth will stagnate when the marginal benefits of agglomeration equal the marginal costs. Building on this basic principle, several factors can be identified that affect the expansion of urban boundaries:

- **Limitations in infrastructure development.** On the one hand, infrastructure construction requires significant capital investment; on the other hand, there is a limit to how much infrastructure can be expanded within a given urban area.
- **The ecological and environmental carrying capacity.** The ecological and environmental carrying capacity determines the availability of resources in the environment, which limits the size of the population and economic activities that can be supported in a certain area.
- **Technological innovation.** Throughout urban development history, technological innovation has consistently driven progress. Improvements in infrastructure and enhanced environmental carrying capacity resulting from technological advances not only facilitate further concentration of population and economic activities but also contribute to ongoing enhancements in economic efficiency.

Among these factors, with the assumption that ecological and environmental carrying capacity remains constant, infrastructure and technological innovation are the fundamental determinants of urban expansion. Under existing technological conditions, infrastructure investment and development tend to exhibit sublinear growth, meaning their effect on the concentration of population and economic activities results in diminishing returns. Conversely, technological innovation demonstrates linear growth, leading to increasing returns in its impact on population and economic activity concentration.

The effect of technological innovation on urban development potential, characterized by increasing returns on investment, manifests in three main areas: first, it creates new opportunities for infrastructure investment, thereby reducing costs and enhancing the efficiency of existing infrastructure; second, it improves the efficiency of economic activities, including both production and transaction efficiency; and third, it strengthens the ecological and environmental carrying capacity, as evidenced by the adoption of green energy and the expansion of the sharing economy.

1.1.2 Digital capability and the expansion of boundaries in urban development

In general, technological changes that impact urban development fall under the category of general-purpose technology innovation. Through innovative applications across various urban networks, general-purpose technology not only enhances productivity but also influences social and ecological development.

AI is the core engine of the Fourth Industrial Revolution and is set to profoundly impact urban development. As a general-purpose technology, AI signifies a transformation in technological, economic and social systems:

- As a substitute for human intellect, AI involves a highly complex technological system that includes intelligent chips, computing architectures, machine learning platforms, and key hardware.
- AI is a form of data intelligence that has emerged from cyberspace. By optimizing and controlling physical and social spaces through data and algorithms from cyberspace, AI can revolutionize urban resource allocation.
- AI can drive structural changes in both the economy and society. The extensive application of AI not only transforms existing industrial structures but also fosters innovations in paradigms, production methods, and lifestyles, making it a crucial driver of structural changes in the economy and society.
- AI can enhance ecological and environmental carrying capacities. So far, AI has been extensively applied in fields such as smart transportation and water pollution control, contributing to the improvement and protection of the ecological environment.
- AI promotes the coordinated and balanced development of urban economies, societies, and ecosystems. So far, AI has not only improved economic efficiency but also addressed pressing social issues and supported ecological protection.
- The innovative application of AI can enhance urban resilience and adaptability to environmental changes. Especially in the context of increasingly frequent extreme weather events, more advanced and intuitive urban sensing and decision-making systems enable cities to respond swiftly to natural disasters and pandemics.

AI-driven urban digital transformation is a process of building digital capabilities. For cities, digital capability means the ability to utilize digital technologies to address challenges in the coordinated development of urban economies, societies, and ecosystems. Digital capability is universal, capable of tackling issues related to economic efficiency, as well as social and ecological development. Recent advancements in smart city development in China illustrate that the City Brain serves as the foundational element and vehicle for developing digital capabilities in cities.

1.1.3 The city brain

In response to escalating urban traffic issues, Chinese scientist Wang Jian introduced the concept of the City Brain in April 2016. He described the City Brain as an urban digital infrastructure that integrates data and computational power, leveraging advancements in cyberspace [11]. This approach aims to dismantle traditional silos and transition from localized to holistic optimization by applying data resources to urban management. Ultimately, the goal is to promote coordinated development across economic, social, and ecological dimensions.

The City Brain is a complex technological system composed of interwoven technologies, including the Internet of Things, big data, AI, cloud computing, edge computing, 5G, cyber-physical systems, and digital twins. The intelligence developed through the AI technology system belongs to the category of brain-like intelligence. The synergy between human wisdom and machine intelligence is the fundamental driving force behind the development of the City Brain and smart cities. Supported by AI, cities develop perceptive neural networks, decision-making systems, and execution systems to offer support and assistance for human decision-making from a holistic perspective.

Moreover, the City Brain is a resource allocation method. It optimizes and controls economic and social activities in physical and social spaces through interactions among cyberspace, physical space, and social spaces to achieve overall resource optimization. The City Brain leverages big data connections and algorithms to achieve holistic optimization and enhance overall efficiency.

Since 2016, several Chinese cities, including Beijing, Shenzhen, Shanghai, Hangzhou, Guangzhou, Chongqing, Chengdu, Qingdao, Tianjin, Nanjing, Zhengzhou, Wuhan, Xi’an, and Jinan, have each launched City Brain initiatives tailored to their own developmental needs. While these initiatives are government-driven, technological innovation is led by enterprises. In China, AI companies like Huawei, Alibaba Cloud, China Mobile, and China Unicom are the main innovators in the construction of City Brain.

Leading tech companies like Huawei are at the forefront of developing fundamental software and hardware technology systems and innovation ecosystems. The City Brain innovation ecosystem led by these tech giants includes not only major technology firms but also universities, research institutions, startups, and traditional industries. This innovation ecosystem fosters the application of City Brain technology across various sectors. In China, the City Brain initiative impacts a wide array of fields, including urban governance, smart transportation, smart government, new infrastructure, smart security, smart energy, smart communities, smart parks, smart campuses, smart buildings, smart water management, smart environmental protection, and smart meteorology.

The development of City Brain initiatives has facilitated the accumulation of digital technologies and capabilities, encompassing both foundational and vertical hardware and software systems. The collaboration between leading tech firms and AI small and medium-sized enterprises (SMEs) creates a network that builds these digital technologies and capabilities. This accumulation supports the coordinated development of urban economies, societies, and ecologies while fostering continued population and economic agglomeration. Importantly, AI-supported cyberspace industry systems break traditional geographic constraints in resource allocation, establishing new connections between cities and between urban and rural areas. The City Brain construction is a crucial factor in shaping the future of cities.

1.2 Pathways towards Urban Sustainability

There are many ways for cities to develop key capabilities to improve their sustainability, and thus, the overall quality of life for their citizens. Here, we introduce three central concepts, namely a vision for tomorrow’s cities, the compact city as a focal point for sustainability, and New European Bauhaus as an integrative sustainable urban development pathway, part of which is discussed in further detail in Section 4.

1.2.1 A vision for tomorrow’s cities

German Environment Agency’s *Tomorrow’s Cities* provides a vision of the future of urban living, focusing on creating cities that are sustainable, liveable, and efficient and emphasizing the need for an integrated approach to urban development that balances environmental, social, and economic factors. It proposes 10 coordinated bundles of measures to implement cities with compact housing and mixed-use districts, accessible green spaces, environmentally friendly mobility, and low noise levels (see Section 4.1).

1.2.2 The compact city as a focal point for sustainability

An important paradigm of sustainable urban development is the compact city, where distances are short, and the reliance on cars is minimized. The compact city provides multiple benefits. Compact and well-connected cities that provide accessibility without cars offer significant advantages for environmental sustainability, public health, and social equity. In compact cities, keeping distances short ensures that essential services and destinations are within walking or cycling distance. This reduces the need for long commutes, lowers transportation emissions, and promotes physical activity. Furthermore, optimizing building designs for energy efficiency helps significantly reduce energy consumption, leading to lower GHG emissions and operating costs. Encouraging a shift from car usage to walking and cycling can drastically reduce urban air pollution, decrease traffic congestion, and improve public health through increased physical activity (see Section 4.1).

1.2.3 New European Bauhaus as an integrative sustainable urban development pathway

The New European Bauhaus (NEB) is a process-oriented vision of future urban living with a human-centred theory of change. Launched by EU Commission President von der Leyen during her 2020 State of the Union address, the NEB aims to integrate cultural and creative aspects into the European Green Deal. Von der Leyen described it as a way to "shape the world we want to live in" (2020) rather than passively allowing unexamined social and technological developments to shape it.

The initiative focuses on envisioning and achieving an environmentally sustainable, inclusive, and beautiful urban future. It promotes change as a democratic, co-creative process, encouraging bottom-up approaches at various scales, from designing sustainable furniture to redeveloping socially disadvantaged neighbourhoods. This approach leverages a vast pool of social and technological innovations while emphasizing sustainability, inclusivity, and beauty as the core parameters of future urban living. However, the implementation of innovations in urban buildings, transportation, and blue-green infrastructure depends on local enabling conditions, which are largely influenced by local and state-level governance [12].

The Neues Bauhaus Erde (New Bauhaus Earth) initiative addresses the urgent need to revolutionize the construction sector, which significantly contributes to global CO2 emissions. Key aspects of Neues Bauhaus Erde include sustainable construction: it promotes the use of organic and renewable building materials, such as wood and bamboo, instead of traditional materials like concrete and steel. This shift can significantly reduce the carbon footprint of buildings and create a large CO_2 sink.

1.3 Nexus of Digitalization and Sustainability: Synergies and Risks

To expand the potential of sustainability capabilities for urban development, we propose to integrate them with digital technologies, such as the AI-driven City Brain introduced above. While integration will bring about improvements in urban sustainability, the digitalization of cities as such poses risks that deserve further elaboration.

1.3.1 Potentials of digitalization for sustainable city development

Coordinating digitalization and greening is an inherent requirement of the ecological civilization strategy. It emphasizes using digital technology to achieve green development, which in turn drives and leads digitalization, ultimately fostering sustainable development. From an industrial development perspective, this coordination involves not only smart and low-carbon production but also upgrading products and industries to higher standards. The coordination of digitalization and green development has double implications. First, it indicates that digitalization serves as the technical basis for achieving green development. By leveraging data-driven optimization and control of physical spaces through cyberspace, digital technology provides pathways and solutions for green and low-carbon development. Particularly, holistic optimization through cyberspace is crucial for energy conservation and emission reduction, enhancing the integrated benefits across economic, social, and ecological dimensions. Second, it denotes that green development offers practical scenarios for the application of digital technologies, thereby promoting the growth of digital technology and the digital economy. Green development includes both the application of new energy and low-carbon technologies and the improvement of existing energy efficiency. In both areas, digital technologies play a significant role.

At the same time, the use of green technologies within core sectors of the digital industry must be given high priority. Notably, with the innovative application of generative AI models, the focus on computing power and its associated green technologies has become a critical issue in the development of these sectors. Thus, in the era of the digital economy, the synergy between digitalization and green development holds significant strategic value for the long-term advancement of the global economy.

1.3.2 Energy demand for digitalization and AI

While digital-driven socio-economic development improves energy efficiency, it also results in a carbon footprint [13]. Statistics in 2021 show that the total electricity consumption of national data centres reached 216.6 billion kWh, with carbon emissions amounting to 135 million tonnes accounting for approximately 1.14% of the country's total CO_2 emissions. According to *China's Comprehensive Computing Power Index (2023)*, released by the China Academy of Information and Communications Technology, China's computing power industry has maintained high-speed growth, with AI computing power exceeding 25% of the whole computing power structure. As of June 2023, the total scale of the country's computing power has reached 1.080 Eb.

Since the introduction of OpenAI's ChatGPT in 2022, domestic AI research and development have surged, increasing demand for AI computing power. This growth, while advancing urban digital transformation, also increases the carbon footprint, highlighting the need for green energy development despite challenges in cost, technology, and market acceptance. Incentive policies and AI applications can help reduce these barriers (see Section5).

1.3.3 Systematic risks of AI deployment

AI deployment in smart cities and cloud operations presents significant yet uncertain systemic risks. These technologies can concentrate economic power, widening the gap between the wealthy and the poor, destabilizing social structures, and exacerbating urban tensions [14]. AI-driven misinformation and polarization can undermine social cohesion, leading to civil unrest. Additionally, while AI can enhance institutional decision-making and efficiency, it can also create dependencies that weaken independent functioning, making governance vulnerable to failures and cyber-attacks.

In the context of China's smart cities like Shenzhen, Hangzhou, Beijing, and Shanghai, careful management is necessary to mitigate these risks. Policies promoting AI literacy, universal basic income, and reskilling programs can help distribute AI benefits equitably. Robust fact-checking algorithms and transparent mechanisms are essential to combat misinformation. Ensuring privacy and human rights in AI surveillance through anonymized data and synthetic population data can prevent data misuse. Proper oversight, empowered institutions, and safeguards for human autonomy are crucial for leveraging AI;s full potential while protecting societal interests.

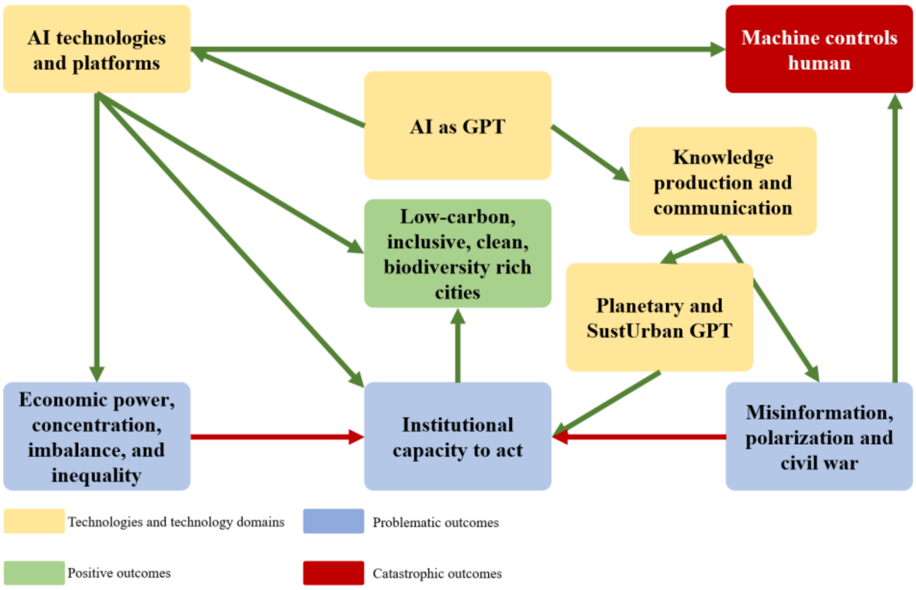

Figure 2. The systemic risks of the digitalization of cities

1.3.4 AI as both an enabler and a solution in the technology space

AI super-platform enterprises like Huawei, Baidu, Tencent, and Alibaba are extensively deploying AI in green energy and societal sectors. Huawei's Digital Energy division focuses on transforming energy, intelligence, and mobility in the carbon neutrality process, emphasizing intelligent photovoltaic storage generators and integrating photovoltaics, wind power, and energy storage to construct high-quality, digital clean energy bases. Huawei plans to build at least 100,000 supercharging stations by 2024 to support the growth of new energy vehicles. In education and health, Huawei is promoting digitalization through technological innovation. The synergy between digitization and greening is essential for sustainable development, optimizing and controlling physical space via digital pathways to achieve low-carbonization. Greening provides scenarios for applying digital technology, enhancing energy efficiency, and supporting the digital economy. The integration of green technology in digital industries, particularly with large AI models, is critical for China's economic development in the digital era.

1.3.5 Gender data gap and bias

Digital technologies, especially AI, and how they are designed are not gender-neutral – they include a bias. Gender bias can be understood as "prejudiced actions or thoughts based on the gender-based perception that women are not equal to men in rights and dignity" [15]. Such bias is part of a given socio-cultural context and the data that serves as a basis for analysis, algorithms. These influence the design of digital technology [16]. For example, generative AI tends to reproduce existing stereotypes and recent experiments to remedy this effect have not yet succeeded.

Gender bias in digital technologies is often the result of the gender data gap, meaning the absence of robust data disaggregated by gender, resulting in an incomplete understanding of reality [17]. As such, non-existent data on gender differences means that urban planning is often gender-blind [18]. Currently, the gender data gap, according to UN estimates, is at 78 % for performance on SDGs in China, complicating the sustainable and inclusive use of AI on a large scale [19]. Bias is also induced bythe pre-dominantly male workforce in software engineering, which is responsible for designing and developing AI solutions. If systems are not developed by diverse teams, they likely do not cater to the needs of all [20].

While there is no one-size-fits-all solution to close the gender data gap and manage gender bias, key approaches include gender-disaggregated open datasets and the proactive management of biases. Addressing the gender data gap and bias in the context of smart sustainable cities leads to increased urban safety and liveability for all [21].

2. Dual Transformation and Sustainable Economic Development

Section 2 aims to shed light on the green and digital transformations of the urban economy, focusing on the economic dimension of sustainable development. After addressing the demand and supply sides of sustainable economic growth at the city level in the first section, Sections 2.2 and 2.3 discuss the implications of the dual transformation for the urban economic structure and employment, as well as for the sharing and circular economies, respectively. The importance of technological innovation is highlighted throughout the section.

2.1 Sustainable Economic Growth through Technological Innovation

Sustainable economic growth can be significantly advanced through technological innovation, addressing both the supply and demand sides of urban development. On the supply side, investing in renewable energy sources and digitalized energy systems enhances efficiency and reduces carbon footprints, driving cleaner and more resilient energy infrastructures. Simultaneously, on the demand side, cities can leverage digital platforms to optimize resource use, improve public services, and promote sustainable practices among residents. By integrating smart technologies into urban planning and service delivery, cities can boost economic performance, create green jobs, and foster a more sustainable urban environment, thus harmonizing economic growth with environmental stewardship.

2.1.1 Renewable and digitalized energy systems

Digitalization offers significant opportunities to enhance the efficiency, sustainability, and reliability of energy supply systems. Key measures in energy supply include:

- **Grid Managemen**t. AI can optimize the integration of renewable energy sources into the grid in multiple ways. It can help predict production patterns from wind, solar, and other renewables and thus ensure a stable and reliable energy supply despite the inherent variability of renewable sources.
- **Smart Appliances.** Smart appliances, utilizing AI, can reduce household energy demand and carbon footprint. It can better match demand with intermittent renewable energy supply, reducing the precarious and expensive need for coal reserve power. AI can thus help further make demand more “flexible” and thus compatible with variable renewables.2
- **Predictive Maintenance.** AI-driven predictive maintenance identifies potential failures in the energy infrastructure before they occur, ensuring uninterrupted energy supply and extending the lifespan of grid components.
- **Improved Forecasting and Planning.** AI models predict future energy demand based on historical data and real-time inputs, enabling better planning and allocation of resources to meet anticipated needs.
- **Resource Management.** AI optimizes the supply chain for energy production by managing the procurement and distribution of raw materials, such as fuel for power plants, ensuring timely and cost-effective delivery.
- **Logistics and Distribution.** Digital tools streamline logistics and distribution networks, enabling circularity, reducing delays, and minimizing the carbon footprint associated with transporting energy resources.

By leveraging these digital and AI-driven innovations, digitalization can be a key enabler of electrification. While energy supply systems can become more efficient, reliable, and sustainable, they contribute to the urban energy transition, ensuring a stable energy supply in the face of increasing demand and environmental challenges.

In order to enable this transition, governance innovations and new infrastructure will be critical. Modern and digitally integrated cities will be characterized by much higher power and data densities, requiring up-front

[2] This could for example include putting high-capacity appliances such as heat pumps under the control of utilities so that they become active resilience providers for the grid. Digital solutions can further help manage energy storage systems, such as batteries, to store excess renewable energy when production is high and release it when production is low, thus balancing supply and demand.

investments in electricity grid and data connection infrastructure. Leveraging the finance will need to be complemented by electricity market reforms to permit incentive schemes and real-time pricing, as well as sharing appliance controls with actors that manage systems reliability and resiliency.

2.1.2 Demand-side measures in buildings and transport

Achieving sustainable cities requires rapid and extensive systemic transformation across various sectors, such as buildings, transport, urban planning, and industry. This transformation involves several key strategies, including “Avoid” strategies, which aim to significantly reduce energy and material demands—for example, promoting teleworking to decrease the need for transportation. “Shift” strategies involve utilizing sharing and circular economy platforms for resource sharing and collaborative consumption. “Improve” strategies focus on enhancing the efficiency of existing technologies, including efficient design, construction, retrofitting, and strategies to minimize energy and material consumption through material substitution and electrification in transportation.

Buildings and construction contribute to nearly 40% of global energy-related CO_2 emissions [23]. These emissions stem from various stages: during construction, where carbon-intensive materials such as cement and steel are used; during operation, when energy is consumed for heating, cooling, and other purposes and from refrigerant leaks in cooling systems; and during demolition [24].

Implementing sufficiency measures is crucial; this includes strategies such as restricting the growth of floor area and optimizing room temperatures for heating and cooling [25]. Reducing the floor space of buildings can significantly lower the material requirements for construction, as well as the energy needed for space heating and cooling. Promoting co-working and co-housing can further reduce per-capita floor space and facilitate the sharing of services [26][27][28]. Encouraging behavioural and lifestyle changes, such as adjusting room temperatures, can also play an important role in driving energy demand reductions [27]. Urban planning should support compact buildings and urban forms, shifting from single-family to more compact multi-family housing to avoid sprawl and leverage synergies in mitigation across the buildings and transport sectors [29][30]. Circular approaches offer significant opportunities to avoid waste and reduce the need for virgin raw materials. Repurposing existing buildings, which can generate significantly fewer emissions than new construction, should be prioritized [26][31]. Additionally, strategies such as dematerialization, lightweighting design, and urban mining, which include the recycling and reuse of materials from urban buildings at the end of life, can help reduce both demolition waste and the need for new materials [32]. Nature-based solutions have a high potential to address both mitigation and adaptation challenges while offering a range of co-benefits [33]. Green roofs and facades absorb CO2, improve air quality, and improve urban well-being [34]. To more effectively promote energy efficiency behaviour, strategies such as behavioural nudges and neighbourhood competitions can utilize social and psychological influences to encourage households to adopt more efficient practices. Zoning laws should favour multi-family housing, and investments should be made in infrastructure that supports compact urban development. Tax incentives or subsidies for repurposing buildings, mandates for using recycled and reused materials, and urban mining programs are all essential components of a comprehensive policy approach to enhance sustainability in the built environment.

Strategies in buildings should focus on accelerating the transition from fossil-fuel-based systems to efficient renewable energy sources and electrification for heating, cooling, cooking, and lighting, which is essential for reducing GHG emissions [35][36]. This transition involves adopting technologies such as heat pumps, solar PV, and efficient appliances [37]. Moving away from traditional biomass and coal, particularly in low-income areas, is crucial not only for mitigation but also for alleviating poverty and improving public health by reducing indoor air pollution [38]. Policies should encourage the use of on-site renewables like solar PV, wind turbines, and city-integrated distributed generation, which can enhance energy supply reliability and reduce carbon footprints. Additionally, implementing district heating and cooling systems in densely populated urban areas can sustainably meet building energy demands while further minimizing environmental impacts [27][39].

“Improve” strategies and policy recommendations for reducing GHG emissions in buildings should focus on enhancing the efficiency of existing technologies, which can account for 30% to 70% of potential emission reductions [40]. Prioritizing energy-efficient building envelopes and passive houses, which include insulation and climate-adapted design strategies, can significantly reduce operational energy demand while improving indoor comfort [35][41][42]. Key areas for improvement include adopting low-emission technical systems such as advanced heating, ventilation, and air conditioning systems and promoting energy-efficient appliances and lighting. Both new and existing buildings can achieve net-zero-energy standards at costs comparable to conventional construction, making them crucial for meeting net-zero targets [43]. Building retrofitting strategies should be tailored to specific climates to effectively reduce heating and cooling needs. Governments should support these efforts by renovating public buildings to zero-energy standards and utilizing smart home technologies and the Internet of Things to optimize building operations and encourage energy-saving behaviours. The adoption of low-carbon and bio-based materials, such as timber, bamboo, and biomass, can reduce embodied emissions and offer long-term carbon storage, with well-managed bio-based materials potentially reducing sector emissions by up to 40% by 2050 [35][44][45]. Financial and policy support is necessary to promote these materials, alongside efforts to decarbonize conventional materials like concrete, steel, and aluminium, which are significant sources of global emissions. Electrifying production with renewable energy, increasing the use of recycled materials, and fostering innovation are essential steps for transforming the built environment and achieving substantial emissions reductions.

Digitalization greatly boosts the effectiveness of shift measures, such as electrification and on-site and city-integrated renewables. While digitalization plays a moderate role in "avoid" and "improve" measures, such as dematerialization and energy-efficient building envelopes, its most pronounced impact is in advancing high-efficiency smart home technologies, thereby promoting economic growth and reducing environmental impacts (see Table 1).

Table 1. Impact of digitalization on maximizing the potential of buildings demand-side measures for energy and emissions reduction and economic growth

Demand-side measures		**Impact of digitalization on maximizing potential**
Avoid	Reducing the floorspace	Medium (through telecommuting)
	Behavioural and lifestyle changes	Medium (through new smart appliances and gadgets)
	Compact buildings and urban forms	Low
	Avoid material waste, repurposing	Low*
	Dematerialization, lightweighting design	Medium-high (through 3D printing)
	Nature-based solutions	Low (through smart design)
Shift	Electrification	High
	On-site renewables like solar PV	High
	City-integrated distributed generation	High
Improve	Energy-efficient building envelopes	Medium-high
	Smart home technologies	High
	Low-carbon and bio-based materials	Low

* A higher outcome is envisioned for the future, but there is currently insufficient study to support this

The transport system is central to reducing GHG emissions, improving city air quality, and lowering urban temperatures by minimizing anthropogenic heat. Therefore, transforming urban transport is crucial for developing sustainable and liveable cities. There are several strategies for decarbonizing the urban transport sector, following the ASI approach, include:

Key "avoid" strategies involve telecommuting and teleworking, although total emission savings are estimated at no more than 1% of total transport GHG emissions [40][46]. Urban planning, the reallocation of street space, smart logistical systems, and increased street connectivity, which shorten travel distances, hold significant potential for reducing travel needs [40]. For newly built cities, these strategies could lead to a 25% reduction in urban energy use by 2050. Urban planning and zoning strategies are essential for reducing the need for long commutes and encouraging sustainable transportation methods. Designing cities with mixed land use, high-density development, and close proximity to public transportation hubs supports walking and cycling. Expanding the implementation of concepts like the 15-minute city or superblocks can further enhance these benefits [48][49]. Developing active mobility infrastructure—such as safe and convenient facilities for walking and cycling—encourages non-motorized transportation, which reduces short car trips and improves public health. This approach is particularly effective in compact and walkable cities.

Promoting efficient and accessible public transportation systems, such as buses, trams, subways, and light rail, encourages the use of shared modes of transport over private vehicles, leading to lower overall emissions. Shared mobility solutions, including car-sharing and bike-sharing, further support decarbonization by reducing car ownership and promoting higher load factors. Integrating various transportation modes into a unified mobility system, facilitated by Mobility as a Service, can streamline urban travel and encourage a shift away from private cars. Implementing urban freight logistics solutions such as electric cargo bikes, consolidated delivery routes, and safe non-motorized last-mile delivery infrastructure can substantially cut emissions. Additionally, developing urban logistic micro-hubs and consolidation centres helps further reduce emissions by increasing the proportion of non-motorized deliveries. These strategies are particularly effective in well-planned, compact urban areas.

Electrification is a crucial strategy for reducing transportation emissions. Encouraging the shift to electric vehicles (EVs) for private passenger, commercial, and delivery fleets can significantly cut emissions. To promote this transition, offering incentives such as subsidies, tax breaks, and free parking for EVs is effective in increasing adoption among individual owners. Additionally, electrifying buses, taxis, and other shared transportation modes can further lower emissions, particularly in auto-centric cities where other solutions may be less immediately impactful. Harmonizing these policies can create more liveable cities. Successful decarbonization of urban transport requires a comprehensive approach that integrates urban planning, technology, policy, and community engagement tailored to the specific needs of each city.

In summary, digitalization has a high impact on “avoid” measures such as telecommuting and teleworking, which can significantly reduce energy use and emissions, with benefits that extend to the building sector. For shift measures, digitalization substantially improves the effectiveness of public transport, shared mobility infrastructure, and urban freight logistics solutions. When it comes to improving existing systems, electrification of vehicles greatly benefits from advancements in digital and technology, offering high potential for increased energy efficiency and reduced environmental impact (see Table 2). Industry sector strategies, from a material perspective, are discussed in the building sector. Strategies related to supply and structural adjustments will be addressed in the following section.

Table 2. Impact of digitalization on maximizing the potential of transport demand-side measures for energy and emissions reduction, as well as economic growth

Demand-side measures		**Impact of digitalization on maximizing potential**
Avoid	Telecommuting	High
	Urban planning and zoning strategies	Low (through new smart applications and sensors)
	Active mobility	Medium (through smart applications and platforms)
Shift	Public transport	Medium-high
	Shared mobility	Medium-high
	Urban freight logistics solutions	Medium-high
Improve	Electrification (EVs)	High

2.2 Dual Transformation and Industrial Structure Adjustment

Sustainable and digital technologies not only enhance performance and efficiency but also reshape the structure of cities. In particular, the dual transition of cities might have a significant impact—positive and negative—on quality of life.

2.2.1 Economic structure change

The dual transition of cities has been beneficial for the development of new technological segments and thus the creation of new-tech-empowered sectors, such as new-generation telecommunications, big data, and AI [50][51]. Such dynamics invite innovative actors to restructure economic incentives, especially in the emerging technological segments and new technology-driven economic sectors [52]. In the economy, new business models and frameworks [52] and digital platforms [54] will prevail in cities.

Meanwhile, urban decision makers will be forced to develop governance frameworks to adapt to the dual transition [55]. In this new scenario, the application of data and digital technology can enable the improvement of conventional sectors (such as green buildings, waste management, water management, and smart healthcare). Against this backdrop, smart city appliances provide opportunities and challenges for urban decision-making. For example, big data analytics has become an advanced tool for solving urban hazardous materials transportation [56] and city brain projects [57].

The integration of digital technologies into urbanization secures future capital revenue at large, including financial, physical, and social dimensions [58]. Capital reallocation from other sectors to digital sectors also has a significant impact on the economic dynamics ofcities [59]. Cities will be increasingly dependent on external data management and energy supply. Hence, the spatial interconnectedness among cities and rural areas will increase, and positive spillovers will be more frequent.

Box 1. Case study on the German Ruhr region

In 2020, a new major initiative started with the vision to transform the Ruhr area into the "greenest industrial region in the world." This green infrastructure strategy is based on the concept of creating a strategically planned network of natural or semi-natural green and open spaces that connect the various industrial and residential districts of the Ruhr area. Under the leadership of the government of North Rhine-Westphalia, the project is to be developed in a flexible, participatory development process. About 100 individual projects are to be set up and implemented in a step-by-step process. Central fields of action are defined as: "Networked mobility - short distances," "Successful economy - good work," "Living diversity - strong cohesion," "Secure Energy – Healthy Environment," and "Best Education - Excellent Research." It must be noted that digitalization is not earmarked as a separate field of action but only has a supportive function for other specific goals.

Note: See Annex 3 for the whole German Ruhr region case study.

2.2.2 Employment structure

Intensive investments and the expansion of new technologies and infrastructure in cities might result in higher unemployment [60]. Digitalization drives firms to substitute human work with advanced tools to save costs, in particular, reducing the number of low skilled workers and personnel in non-production departments [61]. Nevertheless, digital appliances will create new job opportunities [62] and facilitate employment expansion [63].

Even more so, the transition to smart sustainable cities will create more green jobs [64], which will produce goods or services that improve environmental protection and natural resource conservation. Additionally, the green transition will reallocate work to greener sectors, such as renewable energy, green buildings, and new infrastructures for energy and transport sectors [65].

Additionally, regions will have to react to altered labour market demands and skills needed by diversifying education and developing stronger resilience in the labour force. However, as we are still in the early stage of this transition, firms and industries will have to continuously analyse and adapt to a fast-changing economic environment [66]. In this context, cities and employers will have to look out for their most disadvantaged groups in the work force – young people with low qualifications [67]. The transition will impact young people after a long economically painful decade since 2008 and will, eventually, pressure them to expand their skill sets yet again [68].

2.3 The Impetus of Digital Solutions for the Sharing and Circular Economy

The adoption of digital solutions in the Chinese market has delivered on the promises that this so-called "fourth industrial revolution" [69][70] would provide enormous contributions to the economic development of the country. Several attempts have been made to measure these, and the figures hovered around 4.8% of GDP in 2011 before jumping to more than 20% in 2016 [71]. The review proposed by[72] reveals substantial benefits for economic growth and for total productivity performance: the information and communication technology (ICT) sector and manufacturing activities heavily relying on it significantly outgrew all other economic sectors, with annual growth of 15.7% and 11.4%, respectively, in the 2001–2018 period. The same sectors also show the largest contribution to the growth in total factor productivity. The impact on this last variable has been further confirmed by additional research using a pane of Chinese provinces. The previous literature has also evidenced the improvements that the digital economy has helped generate on the environmental side. While the direction of this impact and the heterogeneity with which it manifests itself should pose a caveat, data from all Chinese provinces reflect a positive contribution to the environment, stemming from the use of digital technologies [72]. Some of the channels through which digital technologies provide such a positive impact include, for instance, improvements in the output of energy, a reduction in energy losses, and a decrease in energy demand [74][75].

The reasoning behind the idea of the sharing economy stems from the recognition by Botsman & Rogers (2010) that a significant share of goods and resources in developed countries are held privately and are often misallocated or significantly underused [76]. Guaranteeing access to these resources for multiple users would then, the authors suggest, reduce wastes and inefficiencies. No country has so far been able to exploit the economic potential of the sharing economy to the extent that China did. At a level of $15 billion in 2014, the Chinese sharing economy is projected to skyrocket to $335 billion by 2025 [77][78]. The relevance of the sharing economy for the country can also be understood by noticing that China is home to the world's largest company in the sharing economy: as of 2023, Meituan employs about 115,000 full-time people and had total revenues of RMB 276 billion, tripled from the 2019 figures.

Adopting digital solutions has the potential to significantly contribute to the development of both the sharing and circular economies. For instance, one of the main challenges faced by companies active in the circular economy is guaranteeing the traceability of their sources [79][80][81]. The creation of digital product passports can help address the issue of traceability and make consumers more aware of the origin of the materials in the products that they purchase so they can hold companies more accountable for their supply chain strategies [81]. Most of these solutions are based on blockchain technology, a field where China has already established itself as the global research and development leader [83]. However, even though blockchain has been able to deliver on its promises to improve firms' performances, Chinese companies seem to still have not been able to exploit this technology at its full potential [84]. Insights from developers from the carbon markets industry in China may suggest the domains that can still pose a challenge for the full exploitation of this technology: common attitudes and societal norms, data accuracy and authenticity, funding opportunities to stimulate the adoption, and functional characteristics of the technology that would make it easier for users and non-experts to increase their uptake [85]. A wider adoption of blockchain technology, or any other tech-enabled monitoring and tracking service, also has the potential to deal with the level of trust that is needed for sharing economy initiatives but that may often be lacking [86].

Digital solutions also have the potential to help deal with the vast production of municipal solid waste (MSW), a characteristic byproduct of rapid urbanization [87]. And China's fast urbanization has exacerbated the problem in the country [88][89]. Providing a boost for the development of a local circular economy and dealing at the same time with issues of limited space within its municipal boundaries, the city of Hong Kong has been praised for its use of digital solutions to improve the collection, sorting and cataloguing of MSW [90]. Drawing on a comparison with the city of Xiamen, the authors conclude that the potential to adopt digital solutions in MSW in China's major cities is still ample.

3. Dual Transformation and Sustainable Social Development

Sustainable social development is of paramount importance for achieving a successful dual transformation. Cities are not only agglomerations of physical units but complex systems of entities that are supposed to respond to the needs of their inhabitants. The promotion of green and digital transformation must be related to aspects of urban quality of life, including, for instance, education, healthcare, and mobility. It is against this backdrop that we propose sustainability terminology that includes social aspects and promotes a sustainable smart city that is people-centred. To ascertain how to enhance the intertwining of data and AI-driven urban development with the involvement of people in creating habitable cities, this section looks at several key aspects that are closely linked to ethical considerations for cities in the age of AI.

3.1 Ethical Considerations

In the digital age, robust privacy and security frameworks are essential for building trust between governments and citizens. Prioritizing these measures ensures ethical standards, increases public confidence, and supports social inclusion and effective stakeholder engagement. Trust is a cornerstone of social inclusion and effective stakeholder engagement, and it hinges on the assurance that personal data is handled with the utmost respect and protection. Policy-makers must prioritize stringent privacy safeguards and robust security measures to prevent unauthorized access and misuse of sensitive information. By doing so, they not only comply with ethical standards but also enhance public confidence in digital initiatives. This trust is essential for encouraging active community participation and ensuring that technological advancements contribute positively to social equity and inclusion, thus reinforcing the foundational values of transparency and accountability in the digital age.

3.2 Digitalization of Government Services

Urban infrastructure accessibility, equity, and inclusiveness refer to the fair enjoyment of infrastructure services by all residents in a city, regardless of their socio-economic status, gender, race, age, or disability. Digitalization of government services refers to the process of transforming traditional, paper-based government operations and services into digital formats that can be accessed and used online. This transformation aims to make government services more efficient, accessible, and user-friendly for citizens, which can have huge impacts on urban infrastructure accessibility. Stakeholder collaboration is critical to this process, with different roles shaping and implementing digital initiatives.

Accessibility gaps in urban digital infrastructure often manifest as disparities in connectivity, digital literacy, and equitable use of technology. To effectively bridge these gaps, it is imperative to evaluate the role of key stakeholders and the complexities they face in the digitalization process because these advancements may inadvertently widen the digital divide if not inclusively designed and governed [91] — for instance, the integration of emerging technologies like smart cities, the Internet of Things (IoT), and AI.

First, an integrated service system. Successfully digitally transformed government services feature full-process online handling, with government service matters being received and processed to the same standards both online and offline, without differentiation. This requires consistency in service content and organizational structure in system construction, achieving interconnected information from the highest administrative department of government services down to offline service windows, self-service terminals, service centres, convenience service centres, and mobile terminal apps. Digital and physical operations have equal validity, enabling real-time interactive verification and collaborative online-offline operation.

Second, a standardized service operation. The construction of government service systems should follow unified standards. Vertical integrated service platforms at various levels of government services and function-based service platforms should be built to unified standards. Otherwise, information bottlenecks or even information silos may occur, leading to poor information flow in government services and affecting user experience. System construction standards include various business processes, data application terminals, and management of government service platforms. Various government service matters should be implemented with detailed standardization, clarifying basic content such as names, codes, types, and bases of government service matters, incorporating them into a unified management system for consistent management and release. Meanwhile, government service agencies should update relevant content and information on government service matters promptly according to regulations and timely disclose service guidelines to the public.

Third, a convenient user service system. Government service platforms and terminals should be adaptively deployed on various applicable devices, including but not limited to mobile devices. Government service agencies should promote the introduction of government service matters to mobile platforms and self-service terminals based on practical situations. Multiple application materials, unclear information leading to multiple trips and long processing times, receiving units, acceptance conditions, required materials, and lists of materials that can be temporarily omitted should be clearly indicated on government service terminal platforms at all levels and updated dynamically. Special attention should be given to special groups, such as the elderly and other digitally disadvantaged groups, providing accessible, convenient government services and application instructions.

Challenges in digital transformation arise from issues such as data privacy, cybersecurity, the cost of technology, and a lack of infrastructure, particularly in marginalized communities [92][93]. To overcome these barriers, a stakeholder-driven approach is essential. This includes fostering public-private partnerships, where government agencies devise policies that encourage digital inclusion, while private entities offer infrastructural support and innovation [95] digital divide [95]. Another critical strategy for inclusivity lies in the deliberate engagement of underrepresented groups in the design and implementation of digital services. This includes non-discriminatory access to digital IDs and ensuring women and girls benefit from digital public infrastructure projects [96].

Box 2. Case study on Vienna: priorities and collaborative efforts

With the ambition to be an open, digital city, Vienna incrementally digitalizes all its procedures. When deciding which procedures to prioritize over others, the impact on climate change and the needs of citizens are two critical factors. More specifically, the city agreed on 12 digital principles, such as gender equity or environmental sustainability. These principles are put into practice across various digital strategies and projects, such as “Digital health” or the digital platform Sag’s Wien (Tell Vienna), where citizens can report any infrastructure faults or issues that will then be taken care of by the city.

The city holds digital capacity and continues to advance and adapt it. For example, the city has a Chief Technology Officer and a Chief Innovation Officer, who fosters collaborations between departments, and closely works with Urban Innovation Vienna (an innovation company), and other companies. For example, in collaboration with the innovation company, the city uses satellite data to monitor green space, land cover changes, or car park utilization and machine learning to detect patterns in the use of public spaces.

Note: See Annex 4 for the whole Vienna case study.

3.2.1 Government structures and key stakeholders

In the digitalization process, from a data perspective, any individual or organization that provides data or is affected by data should become a stakeholder in digital government services. Stakeholders who provide data offer decision-making based on accurate information for the specific implementation of digital government services. While maximizing stakeholder utility, the implementation of government services incentivizes stakeholders to continuously provide relevant data to support subsequent government services. From a societal perspective, the openness and sharing of individual information data will ultimately produce externalities, and whether these externalities are positive or negative is determined by the quality of government service provision.

One of the critical aspects of digital transformation initiatives in the public sector is the dynamic engagement of key stakeholders, including government authorities at various levels, private sector partners, civic groups, academic institutions, and the general public. Each plays a distinctive role in shaping and directing the outcomes of digitalization projects.

For instance, government entities often initiate and fund digital transformation efforts driven by the need to enhance service delivery and operational efficiency. At the same time, the private sector contributes technological expertise and innovative solutions that are fundamental to modernizing aging infrastructure and processes [97][98]. The synergistic collaboration between public institutions and private companies can lead to more robust and effective digital infrastructures, exemplified by the successful implementation of e-procurement systems in Ghana as noted in a study of Agbeko et al. [97].

Civic groups and the local community play a pivotal role in providing grounded feedback and advocating for the inclusivity of digital services. Their involvement ensures that digital transformations do not just cater to technological aspects but also address societal needs and accessibility concerns. The general public, as end-users of digital government services, are perhaps the most critical stakeholders. Their adoption and acceptance of digital platforms gauge the success of transformation efforts. Feedback mechanisms such as surveys, user feedback platforms, and public forums enable policy-makers to gather insights on user experience and areas needing improvement.

The engagement of these key stakeholders not only brings diverse perspectives and expertise to the table but also ensures broad-based support and the adoption of digital initiatives. It underscores the complex interdependencies and collaborations essential for the successful digital transformation of urban infrastructure.

3.2.2 Digitalization and strategies for inclusivity

Digital transformation is a multifaceted and intricate process, especially when considering the transformation of urban infrastructure to bridge accessibility gaps. In analysing the role of stakeholders in this digitalization process, it’s crucial to understand that stakeholders include not just government entities but also private sector participants, NGOs, communities, and international organizations. Their collaboration is instrumental in accelerating a stakeholder-driven digital transformation that prioritizes accessibility and inclusivity.

For instance, the establishment of dedicated national offices for digital inclusion can serve as a powerful coordinating body, advocating for policy changes and ensuring accountability, as suggested by Ehimuan [99]. These offices can monitor digital inclusion initiatives closely, adjusting as needed to ensure that the goals of inclusivity are being met.

Further, leveraging public-private partnerships, as outlined by both Ehimuan (ibid.) and Monika Palani (2023)[99][92], can aggregate resources and expertise from various sectors to extend connectivity to underserved populations, which is a significant challenge. Such partnerships often result in innovative solutions like community networks or promoting the adoption of digital health innovations [100], which can enhance access to healthcare and other critical services.

Moreover, addressing the affordability of internet services and devices is essential for bridging the digital divide, as Nick Awad points out (ibid.).[100] Programs like the FCC’s Lifeline Program can lessen the financial burden on low-income households, promoting a more equitable distribution of digital access.

Gustavo Streger’s insights indicate that marginalized communities face significant disadvantages due to inequitable access to digital resources [101]. Strategies that focus on expanding broadband infrastructure, enhancing digital literacy, and implementing affordability measures are critical components of a comprehensive approach to digital inclusion.

The conclusion that can be drawn is that a stakeholder-driven approach to digital transformation involves concerted efforts aimed at increasing digital literacy, fostering innovation, and implementing policy reforms to support an inclusive digital ecosystem. Strategies should be context-specific and address the unique challenges faced by different demographic groups, ensuring that technological advances do not leave anyone behind but instead work as a bridge that closes the gap between the digitally empowered and the underserved.

3.2.3 A digital future for government services

The benefits of digitalization in government services are multifaceted and expansive, profoundly revolutionizing the way government agencies interact with citizens and manage their operations. At its core, digitalization aims to increase efficiency, drive cost savings, and significantly enhance customer satisfaction [102]. The adoption of online platforms, e-signatures, and chatbots, for example, streamlines service delivery and fosters a more responsive engagement between governmental institutions and the citizenry (ibid.).

Beyond the immediate improvements in service transactions, digital transformation extends its benefits to deeper, strategic layers of governance. By embracing advanced data management technologies, such as data lakes and AI, governments can analyse large data sets effectively, leading to better-informed policy decisions and service enhancements (ibid.). This shift not only bolsters the capacity to serve but also fortifies cybersecurity measures, offering robust protection against the rising threats posed by cybercriminals, a concern that is of paramount importance given the sensitive nature of government-held information (ibid. 2005).

Digitalization also opens the gates to unparalleled transparency and accountability. Governments can now offer open data platforms and online performance dashboards, sharing vital information on service delivery and policy decisions with the public, thus engendering a climate of trust and collaborative governance (ibid.). Automation and the digitalization of back-end processes not only refine internal workflows but also present a significant opportunity for achieving quick wins that can generate public goodwill and trust in digital initiatives [103].

Therefore, digital government is not merely a technical upgrade but a fundamental reconceptualization of public sector service design, delivery, and interaction with society. It promises to reshape sectors pivotal to social welfare, including healthcare, education, infrastructure, and broader governance, ensuring that these critical services can adapt, sustain, and thrive in an increasingly digital world [104].

Engagement of key stakeholders in the digital transformation of urban infrastructure is crucial for ensuring inclusivity and bridging accessibility gaps. The engagement of key stakeholders in bridging accessibility gaps in urban digital infrastructure requires a multifaceted approach. It demands collaboration across government, the private sector, community organizations, and residents. Each group plays a unique role in ensuring that digital urban services are inclusive, accessible, and responsive to the needs of all community members. This collaborative approach not only enhances the efficacy of digital services but also fosters a sense of community ownership and empowerment, contributing to more equitable and inclusive urban environments.

3.3 Impact of Digitalization on Social Urban Planning in the Context of Green Transformation

Social urban planning plays a central role in the dual transformation. Through socially acceptable approaches to urban planning and process design that incorporate the experiences and knowledge of various actors, there is great potential to combine green and digital developments that do justice to the living conditions of all population groups. It should be emphasized that the dual transformation into a green and digital city is not just decided at the national or even at the city level – the neighbourhood level needs to be taken into consideration. Green and digital cities of the future will be “closer”, “more public”, and more agile [105].

Box 3. Qixia District: using WeChat for innovative governance

Qixia District's government faces considerable challenges in managing and servicing their diverse population. Qixia leadership was at first lost in terms of how to implement new directives from their superiors in the municipal government under the "Five-in-One" scheme.

To achieve their goals, young officials in Qixia took the initiative in 2016 and established 747 WeChat groups that cover all 119 neighbourhoods and communities within the entire district. While WeChat is a social media platform for informal and private networking, the district officials saw the opportunity to utilize it for innovative governance. By 2018, it had already attracted more than 150,000 subscribers from the district, and it uses multi-functions of WeChat to create bulletin boards, specialized groups, and other service functions. For questions, comments, and reports, the officials promise timely responses within two hours. They have also kept a promise of providing responses to each request. As predicted in our discussions above, these younger officials, who are much more dependent on merit performance for career development, have remained proactive and innovative in their administrative choices.

3.3.1 The digital urban twin as an instrument for strengthening the involvement of local communities

Essentially, the extent to which a Digital Urban Twin can serve as an instrument for improving the quality of life for local communities depends on the quality and quantity of the integrated data. With regard to this secion's focus on the social aspects of sustainable development, it might first be important to remember that all data in question is either personal (related to a person), public (collected or paid for by government bodies), enterprise (collected by market bodies but not related to personal information), or commercial (proprietary data commercialized by a company).

Thus, the question of who controls the collection and the use of data becomes paramount. To make Digital Urban Twins meaningful and useful for communities, the data included should be community-orientated. For example, the digital-green dual transformation will not succeed without distinctively shortening travel distances and without shifting mobility towards inter-modality and more active travel. Planning data for this kind of shift can only be collected with the help of individuals. China has successful examples of using Participatory GIS (PGIS) and Public Participation GIS (PPGIS) in planning processes at the local level. This could be systematically integrated into Digital Urban Twins on the local level. Encouraging citizen science-based projects in order to engage communities and collect data regarding noise and other health-threatening issues would shift this to the next level.

The rapid increase in the use of AI in connection with complex urban systems fosters the necessity of formulating a set of rules and also addresses the question of who is in control of the algorithm. This is especially true if—like for the City Brain—private companies provide the software and public bodies provide the data used to train the system and to keep it running. To build people's trust in green and digital transformation, they need to know their rights, they need to know that their rights are respected, and they need to know that their data is used for the right purposes. The Personal Information Protection Law provides important guidelines here, but it will have to be constantly reviewed and updated.

The focus of the worldwide and Chinese smart city discourse on megacities, big cities, and newly developed settlements means that small communities with a lack of resources and know-how in information technology are in danger of being left behind. This is contrary to the belief that the digital-green transformation needs closeness and neighbourhoods as key factors of success.

The development and use of Digital Urban Twins for social purposes require a holistic approach that balances technological advancements with social equity, privacy, and ethical considerations. By prioritizing stakeholder engagement, data accessibility, and continuous improvement, cities can leverage Digital Urban Twins to enhance urban resilience, sustainability, and quality of life for all residents.

3.3.2 The involvement of local communities in green smart cities design-processes

Digital technologies have the potential to serve people and their communities and improve living conditions for all (People-Centred Smart Cities, n.d.). For digital technologies to be used in a targeted and people-centred way, everyone needs to be involved. In addition, both digital and climate issues are very closely linked to social issues. These should always be taken into account. The neighbourhood level plays a central role here, not only in terms of the planning itself but also because neighbourhoods are considered to be the nuclei of social cohesion and bring with them key factors for a successful transformation. By involving local communities, local conditions ("Eigenart") can be better understood, and solutions can be human-centred.

One lever to meeting the dual transformation lies in the involvement of communities. A just transformation considers the needs and concerns of the community and responds to needs by enabling involvement in development processes. The goal of transformational processes should be to strengthen the social fabric and improve community well-being. All citizens should be able to benefit equally from progress and equally enjoy the advantages of digital and sustainable development. Without sufficient consideration of social aspects, the dual transformation can lead to certain population groups being cut off from the possibilities of technology and existing inequalities being exacerbated (see Section 3.3).

In China, digital technologies have participatory potential to change environmental policy. This is shown by the study ICT-based environmental participation in China: Same, same but digital? According to the study, the instruments (ICTs) improve transparency, accountability, and communication between citizens and the government, as well as efficiency and service provision. However, this potential is mainly used by groups that are already digitally and environmentally active. The instruments do not involve new social groups in processes. This poses the risk that digital technologies could reinforce socio-political inequalities. Last but not least, the study shows that Chinese citizens often attribute responsibility for solving environmental problems to the government, thereby shirking personal responsibility [108].

Added value for cities through the involvement of communities in smart city design-processes. Digitalization offers the opportunity to better explain complex relationships to a broader public, to create awareness and sensitize people to their own impact, and to interact with the population as part of data collection (citizen science). This can be achieved, for example, through transparent information and presentation of planning processes via digital planning tables, the transfer of knowledge through visualizations, augmented reality tools or gamification, the visualization of problems through the mapping of scenarios, the networking of stakeholders via digital participation platforms or participation through the contribution of data via mapping apps (see Annexes) [108]. The use of new digital methods and formats is accompanied by an enormous demand for knowledge acquisition and transfer. The aim should therefore be to supplement the existing analogue formats and tools for the involvement of communities with new digital forms. This will make it possible to reach a wider range of target groups within urban society. The prerequisites for this are that access to these new digital infrastructures must be simple and intuitive. They should be fun to use and offer personal added value. In addition, the tools should serve the community and urban planning alike to make it easier to understand the city and its processes and to be able to shape the city sustainably together.

The key objectives associated with the involvement of communities are inclusion and integration. This applies in particular to people with disabilities, older people with no experience in digital media, people with insufficient language skills, or women. On the one hand, this means providing diverse digital offerings that take into account people's different abilities (design for all) (Smart City Charter, Making Digital Transformation at the Local Level Sustainable, 2017). Before digital tools are used for smart city design processes, it is important to understand the needs of citizens in terms of their knowledge of how to use them, the associated fears and concerns, and also, generally, acceptance of the use of digital solutions. In order to involve new groups in design processes, target group-specific support is needed—for example, through support structures, mentoring, and networks. In addition, the accessibility of devices and software in public spaces is central, and people should be able to rely on the use of digital structures. Cities should enable their residents to receive services by non-digital means and continue to provide analogue structures in this respect [109].

Box 4. Case study on Vienna: decarbonizing the city's building stock

While many other city administrations struggle to scale up climate action in the building sector due to private ownership, Vienna historically owns a significant number of buildings in the city—about 220,000 buildings. This gives the city an advantage for implementing large-scale decarbonization programs in the building stock independent from the private market, such as the Raus aus Gas program (to phase out fossil fuels in building heating by 2040).

Note: See Annex 4 for the whole Vienna case study.

3.4 Intersectionality: Women, Migrant Workers, and the Elderly

The historical trend of wealth and income distribution over a period of more than 200 years indicates that there is a slow trend toward equality. However, the last decade has seen inequalities increase globally [110]. The goal of this section is to provide a balanced account of how smart cities, data, and digital technologies could contribute to this trend, closing with an outlook showing how these technologies could also be remedies. The key concepts in this section are intersectionality and gender equality. Intersectionality denotes when two or more identities overlap, resulting in certain types of inequality. For example, elderly women might experience different or combined forms of inequality on the basis of their gender and their age. Gender equality is achieved if people of all gender identities have the same rights, responsibilities, and opportunities.[3] In our view, intersectionality brings gender inequality sharply into view. In China, the trend across the board is that inequalities are rising and intersecting more strongly. Since the 1980s, China's Gini coefficient rose from roughly 0.25 to over 0.4, making China one of the most unequal countries globally. However, China made huge advances compared to the 1980s and succeeded in raising 770 million Chinese out of absolute poverty.

3.4.1 Women

In lockstep with the national trend, gender equality has deteriorated in China over the last 50 years, although the situation of women in terms of access to education, health care, and wealth has improved significantly in absolute terms. China is one of the few countries that does not follow a U-curve: women's relative societal position typically improves with the transition from an industrial to a service-based society. Instead, China's development resembles more of an "L" with no sign of a relative improvement [111]. The development of smart cities so far contributes to this trend. For example, women's share in the high-paid sections of the STEM workforce necessary to develop and manage a smart city makes up less than 30%.

Urban experiences vary significantly between genders. Women often juggle multiple roles requiring efficient transport systems to meet different needs and usually have less budget for transport [113]. While men primarily show linear mobility patterns, women combine several purposes during their journeys [114]. For example, only 39.67% of all trips made by women in Beijing are commuting trips, while men make 10% less. 35% of women's trips are for shopping, 13% more than for men, and 8.91% of trips are for picking up people, 2% more than for men [114][113]. In addition, many digital mobility services do not cater to the demands of the mobility of care such as bike sharing which is unsuited for transporting goods or children [115].

Safety in urban environments is a central concern for gender mainstreaming. A comparative survey in Wuhan and Urumqi found that 70% of women expressed anxiety in public transport [113]. At the same time, the reported incidents of sexual harassment are high, 24.6% in Wuhan and 19.3% in Urumqi while the number of unreported cases is most likely much higher [114]. Most incidents of sexual harassment and violence experienced by women occur in public vehicles, but many women have also been assaulted at the stations or on the way [116]. These dynamics explain the preferences of middle- and high-income women for safer modes of private transport [117].

[3] https://www.un.org/womenwatch/osagi/conceptsandefinitions.htm (accessed July 9, 2024).

Finally, many women enter the "gig economy", which is an integral part of today's smart cities, offering opportunities such as flexible work and a low bar to re-enter the work force after pregnancy. In 2021, approximately 200 million people were employed in China's gig economy, and the number is expected to double by 2036 [118]. While there are no reliable overall figures on the gender ratio in the gig economy, 2.37 million of DiDi Chuxing's 13 million employees were female in 2021, just over 18% [119]. In the gig economy, women are often exposed to misogynistic stereotypes and violence. Disadvantages that disproportionally affect women are precarious employment, no residency, and the sole responsibility of raising children in addition to their jobs. A recent study has found that many economic platforms are unresponsive to claims of sexual harassment in the workplace and generally not easily held accountable [119].

3.4.2 Migrant workers

Migrant worker households[4] have two major challenges: first, a strong focus on smart cities may channel resources to the already rich cities. Second, nearly 300 million of China's 734-million-person labour force are migrant workers who may be left behind since they work in sectors threatened by the advance of digitalization. Among migrant workers, women are particularly vulnerable with, on average, a higher concentration in low-skilled jobs and lower health levels than men.

A key metric to understand the situation of migrant workers is education. In all of China, only 36.6% of the working-age population (25–64) has attained upper secondary education (OECD average: 83%), 10% have a bachelor's degree (OECD average: 19%), and 1% have a master's or doctoral degree (OECD average: 14%) (OECD, 2022). Even though data on the rural-urban education divide are not readily available, some estimates suggest that 21% of female migrant workers have primary education or below, but only 9% of the men do. However, fewer female migrant workers use computers at work – only 44% of women compared to 50% of men [122]. Overall, Scott Rozell's research on "invisible" rural China has made it abundantly clear that China's low position in the OECD is mainly due to the rudimentary education of its rural population and, thus, also of migrant workers. Since automation and smart city developments not only require a lot of talent (see section 2) but may also reduce the need for low-skilled labour, the comparatively unskilled rural workforce, many of whom are migrant workers, are at risk of being left behind [123].

Many unskilled and migrant workers find themselves in the gig economy. In addition to an economically precarious situation, gig workers report the breakdown of social relations due to the platform economy. To take DiDi drivers as an example, cab drivers used to have regulated working hours, which meant some time was shared with other cab drivers. Also, they had to retrieve and hand back their cars, again opportunities to meet and chat. Now, everyone has their own car, and work starts with leaving the home [124].

3.4.3 Elderly population

Between the years 2020 and 2022, the share of over 60-year-olds in the Chinese workforce rose from 8.8% to 12.8%. The number of people aged over 60 in the total population is expected to rise from just over 20% to approximately 30%. Base state pensions are low, at a minimum of 123 yuan per month, and many of those retiring now have only one child to support them. Older rural women are particularly disadvantaged, as their average income covers only 21% of their expenses [125]. Elderly women tend to live longer than men but are more likely to suffer from chronic diseases and generally have poorer health compared to their male counterparts [126]. Women also have higher unmet elderly care needs [127].

The emergence of digital tools, smart cities, and platforms has so far not been a remedy but threatens to leave the elderly further behind. The literature on the so-called "grey digital divide" distinguishes four main barriers to including older people in the digital transformation – motivation, material barriers, skills and usage. The elderly in urban environments use a wide variety of digital devices, but many report problems. These range

[4] Migrant workers in China are generally understood to be workers residing in cities with a rural household registration.

from a lack of health, such as sight, to a lack of understanding. In particular, the speed and depth of the digital transformation create anxiety among older people about a future with a place for them.

Government interventions to remedy this situation face a tricky challenge brought about by a mixture of expectations and reluctance. On the one hand, the elderly expect the government to intervene and support them, but on the other, many of them are reluctant to turn to people outside the family and, in particular, do not to turn to government programs for help [128].

3.3.4 The value of inclusive multi-stakeholder planning and digital tools

This section recommends basing urban design on inclusive multistakeholder planning processes and using digital tools to facilitate the creation of sustainable smart cities.

First, inclusive multi-stakeholder planning. Smart cities in China are often implemented in a command-and-control style. As a result, local communities and interest groups are rarely included in planning and decision-making. However, there are exceptions: the UNDP developed a method together with Guizhou to involve local communities in incorporating their immediate needs into indicators reflecting these needs. This approach differs clearly from the Chinese government standard for smart cities, the recently ratified GB/T 33356-2022. In addition, many sectors, often represented by individual government institutions, such as the environment, social cohesion, and better living, are not yet systematically included in planning and decision-making processes. As a result, local government institutions sometimes lack the opportunity to share information, including relevant data needed to make decisions and plan sustainable interventions.

Box 5. A collaborative multi-stakeholder data platform in India

The India Urban Data Exchange (IUDX) platform is driving the development of future Indian cities by enabling secure, real-time data sharing between cities and various stakeholders. As an open-source project, IUDX fosters collaboration among city officials, private sector partners, and civil society in over 40 cities across India. IUDX depends on maintaining high data quality, collaboration between stakeholders and educating them about the value of data and promoting policies that foster data sharing. For instance, in Pune, IUDX supports an app that helps citizens find the safest paths by using data analytics. It integrates real-time data from various sources, including community feedback, street lighting, and crime statistics, to recommend routes that minimize exposure to unsafe conditions, particularly for women and children. The app has been rolled out in many Indian cities and is also being used globally, for example in Bogota, Colombia.

Second, digital technologies can play a pivotal role in integrating gender mainstreaming into urban planning, ensuring cities are equitable and inclusive [129][21][130]. Gender mainstreaming and socially equitable planning involve embedding specific needs into all facets of policy and decision-making [21]. Digital tools can help planners to understand and analyse these dynamics [118].

Box 6. AI-supported City Planning in Manila

With the support of the GIZ Data Lab, the GIZ projects ‘NDC Transport Initiative Asia’ and the ‘TUMI Women Mobilise Women’ used an AI-based approach to look at urban planning in an inclusive and intersectional way, creating AI-generated images of real locations in Manila. These images incorporated elements like safety features (e.g., lighting, cameras, female security personnel), accessible infrastructure for persons with disabilities (e.g., ramps, tactile pavements), and public amenities that cater to the diverse needs of the population (e.g., accessible restrooms, green areas) to help participants and decision-makers to better visualize potential improvements in urban spaces. Thus, AI can play a crucial role in advancing the conversation about creating safer and more inclusive urban environments.

To circle back to this section's initial question about whether smart cities, data, and digital technologies will contribute to the globally increasing inequalities or be remedies, it has become abundantly clear that technology alone will not be the solution, but its careful, socially conscious, and—above all, inclusive—use could pave the way for socially equitable results.

4. Dual Transformation and Sustainable Environmental Development

Multiple environmental challenges, such as climate change, overconsumption of raw material, or high land take, illustrate the need for a transformation for sustainable urban development including compact, safe and healthy settlements, sustainable and efficient mobility, and resilience against climate change [131]. The sustainable environmental development of cities worldwide needs to be accelerated to safeguard liveable and climate-resilient urban areas in the face of climate change, environmental pollution and biodiversity loss. Digitalization can boost this development. From an environmental perspective, it is necessary to analyze how digitalization can benefit sustainable development, and how technical innovation and digitalization can be linked with sustainability. This section showcases digital infrastructures and tools as means to reach predefined sustainable environmental development objectives through urban planning. It gives recommendations on how to unlock the potential of digitalization while directing it into the right channels.

4.1 Integrative Urban and Environmental Planning and Development for Tomorrow’s Cities

Since the implementation of the 17 SDGs of the 2030 Agenda for Sustainable Development on January 1, 2016, the UN Secretariat and major international organizations have been committed to assessing the progress of the SDGs. According to available assessments, the resilience and well-being of the planet, its people, and environment and ecosystems are being degraded, and the world is “seriously off track” to meet the 2030 deadline for achieving the SDGs. The *Sustainable Development Goals Report* 2024 shows that, of the 7 SDGs and 33 indicators involved in China’s ecological environment, life below water (SDG14), and life on land (SDG15) are assessed as “red,” while clean water and sanitation (SDG6), affordable and clean energy (SDG7), and sustainable cities and communities (SDG11) are assessed as “orange.” And there are no green SDGs, which puts China’s ecology and environment SDGs in a relatively backward position in the global ranking. There is an urgent need to push the green transformation forward, with pollution reduction and carbon reduction as the main focus; promote the building of a modernized and intelligent urban environmental infrastructure; improve the efficiency of natural resources use; protect and restore freshwater ecosystems; and curb the reduction of the ecological habitat and biodiversity. The purpose is to deepen international data cooperation under the framework of the Global Development Initiative, help implement the United Nations 2030 Agenda for Sustainable Development through “data governance,” and work together to build an open and win-win international cooperation pattern in the field of data, so as to provide new impetus and vitality for sustainable development.

German Environment Agency sets out a vision for Tomorrow’s Cities [132] that aims to develop compact and green cities, mixed-use districts, environmentally friendly mobility, and noise reduction. It provides a vision of the future of urban living, focusing on creating cities that are sustainable, liveable, and efficient, emphasizing the need for an integrated approach to urban development that balances environmental, social, and economic factors. It proposes 10 interconnected packages of measures designed to tackle these issues systematically, addressing core challenges like traffic congestion, air pollution, noise, and the lack of green spaces.

- **Compact and Mixed-Use Cities.** The vision promotes denser, mixed-use urban development to minimize long commutes and strengthen community bonds. This approach, known as “double inner development,” aims to create neighbourhoods where residential, commercial, and recreational spaces coexist. For example, cities can target a car density reduction to 150 vehicles per 1,000 inhabitants.
- **Urban Green Spaces and Public Areas.** Increasing green spaces is essential for better air quality and recreation. The vision includes parks, green roofs, and vertical gardens, suggesting the conversion of underutilized areas into green zones, for instance, transforming old industrial sites into community parks that provide significant environmental and social benefits.
- **Noise Reduction.** Strategies to combat noise pollution include speed limits, noise-reducing road surfaces, and quiet zones. The vision sets ambitious targets, such as adhering to WHO recommendations of a 40 dB(A) night-time noise level. Implementing these measures can reduce stress and improve urban living conditions.

- **Active Mobility Networks.** Enhancing infrastructure for walking and cycling is crucial. The vision calls for continuous, safe, and attractive networks of footpaths and cycling routes. For example, developing a network of bike lanes and pedestrian paths can significantly reduce reliance on cars, promoting healthier lifestyles.
- **Integrated Mobility Services and Electromobility.** Future urban mobility should integrate various transport modes into a seamless system accessible via digital platforms. The vision supports EVs and car-sharing programs, coupled with a robust charging infrastructure. Cities like Oslo have successfully implemented widespread EV charging points, supporting a transition to electric mobility.
- **Improving Public Transportation.** Enhancing public transport quality and accessibility is fundamental. The vision includes increasing service frequency and reliability and transitioning to electric buses and trains. For instance, cities like Freiburg im Breisgau have integrated electric trams and buses, significantly reducing urban emissions.
- **Sustainable Urban Logistics.** Urban logistics should be environmentally friendly, reducing delivery vehicles and their impact. The vision promotes electric cargo bikes for last-mile deliveries and urban consolidation centres. Amsterdam, for example, has adopted electric cargo bikes to streamline deliveries and reduce traffic congestion.
- **Managing Motorized Traffic.** Strategies for managing traffic include congestion charges, parking management, and low-emission zones. The vision aims to reduce traffic volume and promote sustainable transport. London’s congestion charge zone is an example, effectively reducing central city traffic and emissions.
- **Eco-Friendly and Digital Urban Planning.** Digital tools and smart city concepts are crucial in modern urban planning. The vision encourages open data, intelligent traffic management, and digital platforms to enhance public participation. Barcelona’s smart city initiatives use real-time data to manage traffic and public services efficiently.
- **Participatory and Cooperative Planning.** Involving citizens in the planning process is essential for creating responsive urban environments that meet the needs and desires of its inhabitants (see Section 3.3). The vision advocates for participatory approaches, like urban transition labs and dialogue forums, ensuring community engagement. It also proposes using digital tools and platforms to facilitate this engagement, making it easier for residents to contribute to planning and decision-making processes. Examples include Vienna’s participatory urban planning projects, which involve residents in decision-making processes.

The implementation of these measures needs collaborative efforts between central and local governments, as well as private sector and community involvement. Implementing these measures requires substantial investment, supportive legal frameworks, increased funding from both the central and local levels, and the reallocation of existing funds. As public finance is limited, central measures include eliminating environmentally harmful subsidies and redirecting those funds toward sustainable urban development initiatives. At the municipal level, integrated urban planning is a key mechanism for cities to implement these goals.

The compact city together with multifunctional and space-efficient use of the limited resources of urban spaces is key to a climate-friendly urban development [133]. Strategies include harnessing the potential of re-densification and the preservation, renovation, and conversion of existing buildings. At the same time, compact building structures must be combined with sufficient and accessible open and green space to avoid trade-offs with regard to health, climate resilience (e.g., the urban heat island effect), and quality of life (see Section 4.5). The urban planning model of triple inner urban development is an integrated planning and design solution that aims at a new spatial distribution of areas for building, mobility and green space [134]. The goal is to link compact building development in cities with securing and qualifying green and open spaces and with the reduction of private motorized traffic in favour of public transportation and active mobility. (Re)designing and redistributing traffic areas has a crucial influence on climate protection and adaptation, the provision of recreational areas and urban nature, air quality, and noise pollution, and thus on human health. Triple inner urban development benefits from comprehensive and up-to-date geodata as a source for land registers for buildings and vacant lots, green space information systems, traffic modelling, and even digital twins.

Cities are increasingly developing smart concepts for climate, environmental, and resource protection, in addition to traditional integrated urban planning instruments such as zoning plans and integrated urban development concepts. The German Smart City Charter presents guidelines and recommendations on how municipalities can shape digitization in a sustainable and active way [135]. There are different dimensions in which digital tools can support urban planning. First, the digitalization of urban and environmental planning offers new and more economical possibilities for data collection and environmental monitoring to identify and implement measures based on new and robust data (see Section 4.2). Second, digital tools can be part of measures themselves, which is most prominent in mobility (see Section 4.3). Third, they can support new forms of communication of all relevant stakeholders and public participation in planning processes (see Section 3.3).

A case study analysis of digitization and sustainable urban development shows that smart solutions can only make a significant contribution to achieving overarching climate and environmental policy goals in combination with non-digital measures of sustainable urban development, such as the conversion or expansion of urban infrastructure [136]. For example, a modal shift to cycling requires the expansion of the cycling infrastructure in addition to smart traffic lights. In conclusion, the following recommendations were drawn to better integrate concepts for smart cities and urban environment protection (ibid.):

- Smart solutions should be designed to be environmentally friendly, making use of their potential and avoiding possible risks and rebound effects.
- Urban environmental monitoring and evaluation systems for smart cities should be implemented to ensure transparency and comparability.
- Issues of the protection of the urban environment should be addressed in funding programs for digitization and smart cities.
- The opinion and information exchange of all relevant stakeholders (city administration, infrastructure companies, service providers, citizens, etc.) for the development of environmentally friendly smart solutions should be strengthened.
- Test beds for environmentally friendly smart solutions should be provided.

Box 7. AI for sustainable urban planning

Increasing access to big data and scalable AI models enables a new era for urban sustainability solutions [137], with high-resolution and highly contextualized approaches. The synergy of increased data availability, advanced analytical models, and prospective capabilities represents a significant leap forward in our ability to design and implement effective, localized urban sustainability strategies. For example, AI-based urban planning can identify sustainability and climate solutions tailored to the specific needs and contexts of distinct urban areas while integrating additional priorities into the analysis i.e., around biodiversity, green development, or inclusiveness.

4.2 Digital Innovations to Re-Invent Urban Environmental Protection and Development

Environmental governance is the extension and application of the concept of “governance” in the field of ecological environment. It aims to solve g prominent problems such as environmental pollution, ecological damage, climate change, biodiversity loss, and so on, to achieve a harmonious coexistence between humans and nature. Making digital innovation and smart environmental protection important components of smart cities is a common demand and trend for global urban environmental governance.

4.2.1 Digital innovations and urban environmental governance

Digital technologies innovate ecological governance pathways and modes to provide systematic environmental services for the public and intelligent environmental decision-making for the government. As a modern way of urban ecological environment governance, digitally oriented smart governance of ecological environment integrates digital technologies such as big data, 5G, AI etc., into urban environmental protection. The advanced integration between digitalization and greening keeps improving the scientific, precise, and intelligence level of the environmental governance of urban ecology. The key to smart governance of the ecological environment lies in coordinating the relationship between digitalization and greening, promoting their mutual reinforcement and coordinated development. The promotion of digitalization and the use of technologies such as AI to discover the patterns behind data can be an important driving force for ecological environment governance and help achieve its efficient and sustainable effects. The promotion of green development is, on the other hand, an essential part of building a digital ecological civilization.

Expand the path of urban eco-environmental governance through digital technology innovation to implement the "data governance" of the urban eco-environment. With the help of massive data and powerful arithmetic, the use of big data, cloud computing, and AI, among others, we can effectively enhance systematic, synergistic, and precise ecological environmental protection and promote the integrated protection of mountain-water-forest-farmland-lake-grassland-sand and their systematic governance. For example, in order to promote precise, scientific and legal pollution control, some cities in China use mathematical statistics, digital simulation, genetic algorithms, big data, machine learning, etc., and integrate multi-dimensional environmental data to build a complete data chain from emissions at the pollution source to environmental quality changes, which provides powerful technical support for achieving precise traceability and prediction in environmental pollution prevention and control. Widespread application of digital technology can equip ecological environmental governance with efficient monitoring and active early warning, provide scientific analysis and effective response, and expand the path of ecological environmental governance.

Promote the transformation of ecological environmental governance toward systematization and synergy through digital technology innovation. For a long time, due to the insufficient sharing of ecological environmental data and information among regions, departments, and units, ecological environmental governance has been fragmented to a certain extent, and the problem of "repeated governance" has been more prominent in some regions. Through efficient data aggregation and advanced technologies, such as AI, cloud computing and digital twins, the ability to have a comprehensive overview of the situation, top-level design, monitoring and sensing, early warning and forecasting, intelligent decision-making, and emergency response can be effectively enhanced, providing intelligent support for the ecological governance and systematic environmental services for citizens. Taking the urban water system as an example, with the acceleration of urbanization, it is facing challenges, such as security risks, ecological damage, shortage, and pollution. Through the establishment of the intelligent control system based on AI and big data for the urban water environment to connect the urban plant-station-network-river system and consider resources, environment, ecology, safety and the culture of urban water in a comprehensive manner, the integrated management, comprehensive protection, and systematic use of surface water, wastewater, ecological water use, natural precipitation, and groundwater can be implemented.

Promote the green upgrading of urban development methods and assist enterprises in advancing the green transition. The rapid development of digital technology has provided new ideas and methods for advancing the synergistic reduction of pollution and carbon emissions; promoting pollution prevention and control at the source instead of end-of-pipe treatment; establishing a sound economic system for green, low-carbon and circular development in a synergistic digital and green transformation; and promoting a comprehensive green transformation of economic and social development. Digital technology helps with energy saving and emission reduction. Through the collection, processing and handling of production data, digital technology can monitor the whole chain of production in real-time, precisely regulate the production management mode according to changes in demand, improve the efficiency of resource allocation, and reduce the consumption and waste of resources and energy. For example, in terms of energy transformation and upgrading, digital technology and intelligent energy technology are used to build a new type of electric power system in Ordos (see Annex 1).

Box 8. Eco-industrial parks in Tianjin

Regarding the construction of eco-industrial parks, the Economic and Technological Development Zone in Tianjin comprehensively employs the industrial IoT, identification resolution, AI, and other technologies to build an “industrial environment brain” that combines diversified supervision, such as safety supervision, environmental protection, energy etc., and emergency joint control. It has gathered valuable experience for the construction of the resource-friendly, green, and sustainable development of smart industrial parks. Digital technology can provide a platform for enterprises to share information, reduce the uncertainty of R&D innovation, support innovative activities, enhance production efficiency, and reduce carbon and pollutant emissions per unit of economic output. The digitization of production and operation has become an important carbon reduction focus for enterprises. The proportion of AI-related technologies for carbon reduction increases year by year, playing an increasingly important role.

Promote the adoption of sustainable lifestyles and consumption patterns among urban residents through digital applications. Green development implies both a change in the production mode and a change in lifestyle. Along with the development of digital technology, digital applications in green consumption, travelling, and homes have become more popular in daily life and are attracting more and more people to join the green and smart living trend. At present, the building of smart communities in Shenzhen is guided by public demand. The application service scenarios of digital technology have been actively expanded, and the focus has been placed on the innovation of governmental and public services, such as the so-called “fingertip office,” “online office,” or “nearby office” for employment, healthcare, sanitation, or medical services. By letting data do the work, efficiently aggregating service resources around the neighbourhood community and building convenient and beneficial smart services, the diversified needs of community residents can be better met. In addition, the application of the online classroom, intelligent medical care, smart library, and other digital technologies brings convenience to social life, meets increasingly diversified and personalized needs, and strengthens the whole of society's awareness of conservation, environmental protection, and ecology from a technical level.

4.2.2 Applying big data analysis and AI in sustainable environmental development

The application of AI and big data technologies brings new opportunities to improve the quality of the urban environment. Applications such as intelligent transport systems, waste treatment, and environmental monitoring can effectively reduce traffic congestion, improve waste treatment efficiency, and optimize environmental pollution control. At the same time, scientific urban planning, refined environmental governance, and smart city management can be achieved through the analysis of big data. The building of eco-environmental smart governance can focus on synergistic efforts of platform construction, data mining, digital integration, policy protection, etc., to form a so-called “one network” or “one map,” research data value, develop algorithms, promote in-depth application of digital technology in the field of ecological environment, and elaborate the fundamental and leading role of digital ecosystem technology.

Based on local characteristics, representative provinces and municipalities have been selected in China since 2016 to carry out the innovative application of eco-environmental big data, explore the application model, and promote the replication and implementation of the pilot results. After nearly a decade of development and practice, big data and AI have proven to be effective measures for environmental regulation and governance and have been widely promoted as a new model for environmental protection and management.

- Build a monitoring system for all elements of the ecological environment, covering the air, water, soil, solid waste, noise, etc., to realize comprehensive monitoring functions. Through the scientific deployment of sensor terminals and networks, a monitoring network covering all ecological environment elements within the administrative regions is established, and real-time transmission of sensor data is realized.
- Establish a comprehensive application system for the ecological environment to carry out the functions of management, evaluation, supervision, and law enforcement. Taking the supervision and management of the whole life cycle of pollution sources as the central theme, it carries out accurate

supervision, management, assessment, and evaluation of government departments, emission point sources, pollution control companies, etc., and establishes a grid-based, full-coverage environmental supervision system e.g. a mobile law enforcement system for environmental monitoring, environmental grid management system, IC card total emission control system, and “one enterprise, one file” system for pollution sources.

- Develop a support and management system for ecological environment decision-making to achieve a decision-making command function. Integrating ecological environment monitoring data resources and other professional data resources establishes a so-called “one map for environmental protection” system for intelligent decision-making management, which provides accurate and timely data information and a scientific and efficient command platform for government departments. For example, Suzhou Industrial Park has set up an emergency monitoring, warning, and command platform for comprehensive environmental management. In the event of an environmental incident, this system can provide real-time information about on-site situations, an emergency response plan, pollution traceability management, and other functions to assist environmental decision-making.
- Build intelligent livelihood service systems for environmental protection to achieve public service functions. Through the open application of the intelligent environmental protection platform for the release of environmental quality statements, complaints on environmental issues, applications for administrative licences, and public announcements of administrative penalties, it provides positive interaction and sharing between the government and the public.
- Explore the application scenarios of big data and AI in environmental governance. Through computer vision technology and machine learning algorithms, AI technology can classify and identify waste, realize automated processing, and improve the efficiency and accuracy of waste classification (see Annex 8 for the listed examples).

Box 9. Application Scenarios of Big Data and Artificial Intelligence in Environmental Governance

The SUEZ Group from France develops an innovative technology “Autodiag” for smart identification of waste and applies it in a solid waste treatment centre, which is responsible for the collection and sorting of solid waste in more than 100 cities in the Paris region. It is reported that with this quality control technology, which works continuously and automatically directly on the waste sorting line, waste sorting will be more efficient, and the results will be more reliable. This “Autodiag” intelligent recognition technology has been successfully applied to the sorting and detection of plastic waste with a success rate as high as around 98.5 %. In 2023, 127 units of intelligent monitoring system for waste sorting have been put into operation in Miaocheng township of Huairou District, Beijing. The staff can monitor the situation of 127 waste sorting stations in 20 communities (villages) in real time, so as to carry out the classification work in a targeted manner. The manual supervision has been replaced by the 24-hour intelligent monitoring mode, which saves on labor and material resources while improving the sorting rate of municipal solid waste. In the Jingdu Jiayuan, Caoqiao Street, Pinghu City of Zhejiang Province, AI robots replace staff for 24-hour intelligent supervision on waste classification, which reduces labor cost. Through the closed-loop management of problem identification, evidence collection and consciousness-raising as well as the establishment of a long-term supervision mechanism for waste classification, it solves the problems of the community in waste classification such as high labor cost of supervision, difficulties in getting evidence of violation and enforcing law, untimely rectification or inaccurate data. It also opens up a new mode of waste classification for the city, and helps accelerate waste classification towards intelligence, digital governance and precision.

AI helps environmental protection organizations and related companies carry out environmental monitoring, waste classification, carbon emission monitoring, environmental planning, and governance more efficiently and accurately and has a wide range of application prospects. However, there are some challenges to its large-scale application. For example, data is of great significance to the environment, and overall control can only be carried out properly with accurate knowledge of the current situation. However, AI technology requires a large amount of data for training and learning. At present, AI also needs to strengthen the collection and management of environmental data and improve the quality and quantity of data to support its application. At the same time, the initial investment in AI is huge, and there is extremely high demand for technology, manpower, and hardware infrastructure. Moreover, the building of the framework takes a certain amount of time, and the cost during operation is also very high, which is a major burden for cities with small populations and weak economies.

4.3 Sustainable Urban Mobility for All

Traffic areas are key to urban environmental development for three reasons (see [139]. First, they are comprised of a large share of urban space that could be used for, for example, climate adaptation. Second, the mostly strongly sealed traffic areas increase climate risks themselves (e.g., precipitation run-off or heat island effect). Furthermore, they are mostly used for motorized individual transport as a spatially inefficient and emissions-intensive transport mode that amplifies climate change as the driver for the aforementioned risks. The mobility transition is the process of addressing these three effects, in addition to local environmental problems (e.g., air pollution or noise), traffic safety, or social justice and gender issues (e.g., accessibility, spatial distribution) associated with traffic. It can be summarized as aiming to avoid unnecessary traffic (e.g., by planning compact cities), shift from motorized individual to public transportation or active mobility (walking, cycling etc.), and improve the efficiency of (fossil) fuel-based individual transportation (e.g., by switching to EVs [140][141], see Section 2.1.2). Yet, improvement measures rarely have beneficial spatial effects.

The mobility transition as a means of sustainable urban development can benefit from digitalization in a number of ways. Automated and connected driving will lead to changes in mobility behaviours and create new business models that will have an enormous impact on the transportation system [142]. Whether this impact is in line with the goals of sustainable urban development depends on the use and impact of the tools. Potential risks can be avoided by making technology assessments across transport modes mandatory in order to prevent negative effects on environmentally friendly transportation. Utilizing digital tools makes a difference: self-driving vehicles can increase the attractiveness of individual and public transport. This can be governed by regulations that come along with technological advances. For example, harmonizing data and regulations emphasizing open data will likely increase the beneficial impacts of multimodal mobility apps and platforms that depend on shared data and promote a shift from individual motorized to public transportation (ibidem). But it could also be governed through funding, such as when public research funds prioritize the R&E of automation for public transportation as opposed to motorized private transportation. In addition, unwanted rebound effects and efficiency gains from digital innovation should be accompanied by tailored policies aiming to reduce car ownership, such as regulating empty running or tax reductions for shared vehicles.

On the other hand, unregulated digitalization in mobility could lead to increased urban sprawl and longer travel distances since commuting in automated vehicles becomes more attractive.

Box 10. Using machine learning to deduce transport emissions from the built environment

A recent study by Nachtigall et al. [143] addresses the challenge of accurately estimating the impact of the built environment on induced transport CO_2 emissions while considering residential self-selection biases. The study proposes a double machine learning framework that incorporates the following two machine learning models: one to estimate residential self-selection bias and another to predict induced transport CO_2 emissions while accounting for this bias. The findings of the study demonstrate the effectiveness of the proposed double machine learning approach in accounting for residential self-selection and improving the accuracy of estimating induced transport CO_2 emissions associated with the built environment.

For example, based on a case study for Berlin and the travel diaries of 32,000 residents, they found that the built environment causes household travel-related CO_2 emissions to differ greatly between central and suburban neighbourhoods in Berlin, mainly due to the different accessibility of destinations. By properly accounting for residential self-selection biases, the models provide more reliable estimates of the causal impact of built environment factors on transport emissions. This has significant implications for urban planning and policymaking, as it enables more informed decisions to be made. Overall, the study underscores the importance of incorporating advanced machine learning techniques in urban sustainability research.

4.4 Carbon Emission Reduction, Resource Efficiency, and Zero Pollution in Urban Development

This section provides an overview of how digitalization and AI can help to unlock and mainstream tools and approaches to achieve built environment transitions at the scale of buildings and infrastructures. According to the Intergovernmental Panel on Climate Change (IPCC), it is possible to reduce GHG emissions by up to 90% in industrialized countries and by 80% in developing countries by mitigation measures within the building sector [3]. This section will outline how digitalization can make a decisive contribution in shaping pathways toward a resource-efficient, climate-friendly, and pollutant-free urban development and thus achieve positive outcomes for people and the environment. Digital tools, along with standardized methods and processes, can help to manage the increasing complexity by systematically mapping and evaluating the information required for addressing the challenges with regard to refurbishing the existing building stock and setting standards for energy, materials used, and pollution for refurbishment and new-built structures—and thus contribute to achieving the political goals in the EU of achieving GHG neutrality in the building sector by 2050 as part of the European Green Deal, and in China of peaking CO_2 emissions before 2030 and achieving CO_2 neutrality before 2060.

Understanding the full environmental costs of buildings as a basis for development. As already addressed in Section 2, a key lever for change is to refocus the building economy on addressing key societal needs while disincentivizing unnecessary overproduction resulting in underused or vacant structures at high environmental and societal costs. Needs can often be met within the already existing building stock. Policies should disincentivize demolition and remove regulatory hurdles for repurposing structures, reuse, adaptation, extension, and densification, fostering compact, mixed-use, and people-centred cities while avoiding or at least reducing carbon emissions, material investments, and further environmental disturbances connected with newly built structures and urban expansion (Table 1 in Section 2 gives an overview on the impact of digitalization on demand-side measures). A key policy lever is obligating environmental impact assessments at the planning stage, which acknowledge and value the embodied carbon of existing structures on site to disincentivize demolition. Innovative planning legislation in countries like Denmark [145] have shown how easy-to-access digital tools can help to mainstream whole-life carbon accounting, create the basis for tying planning permissions to carbon budgets (locally determined maximum carbon emission and resource consumption targets) and help to: a) favour the reuse, renovation, and/or extension of existing structures over demolition where this will save emissions and resources and b) incentivize the prioritization of sustainable nature-based materials and recycled products over conventional high-energy and carbon-intensive materials wherever possible.

Planning and designing with a new material palette. As the proportion of GHG emissions in the building sector caused by the operation of buildings (heating, cooling, hot water, etc.) is falling continuously due to improved insulation and other measures [4] (forecast: to 50% from 70% today), the embodied emissions, i.e., the emissions attributable to the extraction and production of the materials required for the construction and erection of buildings, will become an increasingly important factor in the environmental footprint of a building. The choice of materials for new construction and renovation is therefore of great importance for the envisaged goal of carbon emission reduction, resource efficiency, and zero pollution. Guidelines and digital planning and assessment tools can be essential in mainstreaming climate-friendly, and resource-efficient design to ensure that the carbon emissions of buildings are minimized throughout their life cycle, material efficiency and waste minimization are optimized, and a broad range of sustainable material choices will become available.

A climate friendly material palette should follow an avoidance-replacement-improvement paradigm. While demand levers should be used to avoid unnecessary material investment, efforts to decarbonize an urban building material palette that consists largely of concrete and steel should be fully exploited. Both measures are unlikely to reverse the building sector's impact on our climate in the short term since most decarbonization options and low- to zero-GHG intensity production processes remain at the pilot to near-commercial stage [159] and are costly and not yet proven at scale. In addition to efficiency gains whenever concrete and steel are used, a systemic overhaul of the construction sector is needed to simultaneously replace a significant amount of the carbon-intensive material demand needed to address the urgent housing and infrastructure needs as well as the retrofitting needs for the existing global housing stock with a broad range of regenerative, bio- and geo-based materials. This would embrace the power of nature-based carbon capture and the potential of construction-based carbon storage instead of focusing on largely unproven technology solutions with potentially significant impacts on the production and construction phases.

A transition from a fossil economy to a bioeconomy in construction offers an opportunity to more evenly distribute socioeconomic access and opportunity. Roswag-Klinge et al. [146] confirm that the building sector can be designed to be GHG-neutral under certain conditions through the intensive use of wood and wood-based materials in the construction and long-term maintenance of buildings. The GHG emissions from the largely minimized, necessary concrete components in the construction phase can be offset by the use of wood. Digital tools and AI, such as remote sensing, are currently being developed to better assess and guide the sustainable sourcing of nature-based materials, assess volumes, and secure supply chains, or help to understand how to optimize the application of a broader range of nature-based materials. Standardized systems for digitally assessable environmental product declarations ensure that only construction products made from sustainably sourced renewable raw materials, such as bio-based materials or secondary materials and, in some cases, decarbonized mineral materials, that meet the requirements on circularity given below are placed on the market.

Ensuring circularity. Beyond the design stage, relevant data recording and long-term availability of all relevant data are key to ensuring that the material investment in refurbishment or new structures will not be wasted. Easy-to-use, standardized procedures, and documents such as product and building passports, building databases, or digital twins can be key enablers to manage the cycle of building materials in an economically viable way. These digital protocols can be part of design-for-disassembly approaches to planning in advance for future reuse and subsequent cascading use of building components in successive buildings to maximize material life and recyclability. The mainstreaming of these tools needs to be accompanied by regulatory interventions: the only construction products that should be placed in the market should be fully recyclable or have at least an increased proportion of recycled material, low in harmful substances, reusable several times, durable and repairable [147]. Methods and principles are needed for a relevant assessment of the recyclability of building materials and structures, as well as of building materials and products. These must be further developed, made available, and communicated to stakeholders in a way that is as generally applicable as basic data [160]. Digitally supported, modular, serial construction and refurbishment is particularly promising for the refurbishment of generic building types. Cost savings, shorter construction times, efficient material procurement for factory production, elimination of construction site waste, higher utilization rates of recycled materials and the reuse of modules are frequently cited advantages.

Addressing pollution. Buildings and their construction, operation, and dismantling also contribute to the pollution of air, water and soil, which can lead to relevant pollution, particularly in urban centres. The requirement that building materials for refurbishment and new construction must be guaranteed to be largely free of harmful substances addresses pollution from chemicals. Examples include organic additives that leach out of plasters, façade paints (e.g., biocides), or roof waterproofing membranes (e.g., root protection agents). Building products are also a major source of indoor pollutants. As building products are difficult to replace afterwards, knowledge of the substances contained in building products is already required when selecting materials and building products in the planning phase. This may include the testing of building products in advance, the only way to make informed decisions and prevent cost-intensive dismantling measures later. Moreover, pollutant-free building materials are a prerequisite for their recycling [147].

Generating social acceptance and creating momentum. Even if much is already technically possible today, social discussion and acceptance are important, as are political instruments and measures. Sustainability certificates, best practice examples, eco-labels or awards can increase public awareness. Market-based instruments, such as CO_2 shadow prices, sustainable finance instruments, or monetary incentives, can support building owners in choosing sustainable materials and construction methods. Specifications for public building owners are one option for influencing the market. In addition, there is quite a bundle of possible regulatory measures, e.g. carbon footprint thresholds, low-emission requirements, and energy performance requirements.

4.5 Green-Blue Cities for Climate Adaptation, Biodiversity Conservation, and Human Well-Being

Given ongoing worldwide urbanization and multiple crises, such as climate change and the loss of biodiversity, urban green spaces have been internationally gaining more importance [148][149][150][151]. Nature-based solutions incorporating blue (water) and green (vegetation) infrastructure are vital for mitigation, adaptation, human well-being, and urban biodiversity. They provide multiple ecosystem services, such as regulating temperature, water balance, improving air quality, and offering spaces for recreation and social encounters [152]. Therefore, urban green-blue infrastructure is a crucial factor for the quality of life and environment in cities and is as important as technical, digital, and social infrastructure.

Urban green-blue infrastructure must be strategically developed and maintained according to five planning principles that include the improvement of qualities, creation of green-blue urban networks, promotion of multiple uses, development of green and grey infrastructure in tandem and encouragement of cross-institutional cooperation and collaboration [153]. Means for implementation comprise instruments of urban, open space, and sectoral planning, as well as adequate funding for the establishment and management of urban green-blue infrastructure. Other important instruments are quantitative levels of open space provision and accessibility of green and blue spaces in combination with qualitative requirements. A best practice example is the city of Vienna, which sets out parameters for green space and open space provision as quantitative minimum requirements for both urban expansion projects and the existing urban fabric.

With regard to the inevitable effects of climate change, the dense population and overlapping infrastructures in cities increase climate-induced risks, especially from heatwaves or heavy rainfall. At the same time, cities offer many opportunities to utilize synergies between climate adaptation, public services, and environmental protection, if climate adaptation is understood as a transformative process, rather than the ability of any urban infrastructure, to withstand external impacts [139]. The sponge city concept focuses on the functions of urban green-blue infrastructure for the urban water circle and aims at urban resilience [154]. It marks a paradigm shift from the traditional approach to removing water as fast as possible away from the city and rethinks urban space concerning the ability to decentralize the storage of rainwater, allow it to seep in, or drain it at a reduced rate. This relieves the wastewater infrastructure and makes it more resilient [155][156]. Also, rainwater can be used to manage urban vegetation, thus saving freshwater resources.

Digital solutions can support the modelling, planning and monitoring of urban biodiversity, nature-based solutions and green-blue infrastructure in many ways. Remote sensing helps to map the urban green-blue infrastructure as a data-base for green space information systems that support urban planning processes. For example, the German UrbanGreenEye project aims to establish satellite data for the determination of climate adaptation-relevant parameters as a tool for municipal administration and planning processes [157]. Digital climate modelling tools help to estimate future climatic effects of existing and new building structures. Also, digital solutions can support the management of urban green infrastructure, e.g., with regard to optimized rainwater management by coupling to weather forecasts or the monitoring of tree conditions with sensors.

Box 11. Understanding urban form features and temperature variation with machine learning

A recent study investigates how urban form characteristics influence the spatio-temporal variation of ambient temperature in Berlin, Zurich, and Seville [158]. The study addresses the importance of understanding the urban heat island effect and its impact on local climate conditions. By comparing different urban forms, the authors aim to identify key features that contribute to variations in ambient temperature across the studied cities. To conduct their research, the authors analyzed the relationship between urban form characteristics and ambient temperature variation using a machine learning model. The presented modelling enables the mapping of temperature differences and spatial warming patterns within cities and provides valuable insights for decision-making in terms of affected areas.

The analysis of the effects of land use during the daytime and night-time revealed that water bodies and vegetation in Berlin have a significant impact and can reduce temperatures by up to 2 ℃ during the day. Conversely, the presence of dense development was evident in the night-time temperature fluctuations, which contributed to significant warming effects in the city. The heat maps produced provide a detailed understanding of the microclimate at the urban unit level and facilitate the identification of priority areas that require targeted climate solutions to reduce heat intensity, especially in communities prone to adverse effects.

4.5.1 Quality and stability of biological systems in urban areas

An urban ecosystem is a type of functional network structure formed by the interaction between urban residents and the surrounding biotic and abiotic environments. It is also a special artificial ecosystem established by humans on the basis of transforming and adapting to the natural environment. It is composed of natural systems, economic systems, and social systems, which are interconnected through highly dense material flow, energy flow, and information flow. Among them, human management and decision-making play a decisive regulatory role. As an artificial ecosystem dominated by humans, the vulnerability of urban ecosystems is determined by their artificiality, openness, and incompleteness. Increasing the species quantity and complexity of nutritional structures of different species can enhance the resilience and stability of urban ecosystems. At present, the focus of improving the quality of urban ecosystems is to increase urban biodiversity, reduce hard surfaces, develop sponge cities, increase research on urban metabolic pathways, maintain the stability of urban ecosystems, and enhance their resilience.

Based on the requirements of ecological protection, agricultural production, and urban construction, a differentiated evaluation system to integrate the six individual elements of land resources, water resources, mineral resources, environment, ecology, and disasters into the carrying capacity level of national territory under the three functional directions of ecological protection, agricultural production, and urban construction needs to be built. The positioning and scale of urban development need to be determined; the natural and green infrastructure, and the lifeless grey infrastructure need to be integrated; and an ecological network that combines biodiversity protection; security of water, soil, and gas; disaster prevention and avoidance; and cultural and leisure functions needs to be built. This enhances the connectivity of urban spatial ecological landscapes; promotes the connection between urban water systems, green spaces, and peripheral rivers, lakes, forests, and cultivated land; and forms a collaborative and symbiotic production and living ecological support system.

4.5.2 Urban park construction and management based on biodiversity

The process of industrialization and urbanization in the world has created enormous material wealth and spiritual culture, but it has also generated serious challenges, such as the expansion of urban space without boundaries, inefficient occupation of elemental resources, insufficient supply of public services, and same urban forms (so-called 1,000 cities with one face). A brand-new urban concept and form are urgently needed to provide a “holistic solution.” The park city is an important way to meet the needs of the people in the new era. It has green space, landscape, history, culture, parks, and neighbourhoods. The construction of urban parks should aim to meet the development needs of park cities, coordinate the needs of urban management and service, build application scenarios for green living and ecological consumption, and implement small-scale neighbourhoods, humanized spaces, compact road networks, and pocket parks.

Traditional urban parks are often used as urban landscapes or green infrastructure to meet the leisure needs of urban residents, providing places for rest, sightseeing, exercise, interaction, and a variety of collective cultural activities. The construction of urban parks is often driven by government financial investment, which is investment-oriented, but it has not generated good economic results. Park city[5] is to show the real characteristics of the city through digital technology and improve the quality of the city through the integration, deployment, and design of various resource elements so that urban residents can improve their living, business, and travel experiences. The core of a park city is to make full use of digital technology to generate spatial form schemes; establish the interaction path between "pedestrian activities" and "urban spatial form"; coordinate the ecological, cultural, and industrial construction of urban space; promote the integration of industry and city through digital industry and ecological living; and explore the future city where nature and people coexist without boundaries.

[5] One definition of "park city" can be found on https://www.hanspub.org/journal/paperinformation?paperid=28511.

5. Policy Recommendations

Cities are central to human civilization, generating over 80% of social wealth and 90% of technological achievements. However, the concentration of populations and economic activities in urban areas brings challenges such as social pain points and environmental degradation. As we enter the second quarter of the 21st century, technological innovation, particularly in the field of AI, has become increasingly important and opens up new opportunities to better understand urban processes and adapt them to future requirements through targeted impulses. For China, facing the impacts of climate change and geopolitics on the economy, figuring out how to promote the digital-green dual transformation to achieve green economic growth of more than 5% is a challenge. However, it is important to strike a right balance between economic development and the environment and society, without sacrificing the latter two aspects in pursuit of growth. This section lists central operationalized policy recommendations – allocated to six core action areas or leverage points that can assist city officials and policy-makers in integrating the sustainable and digital transformation of cities. This is followed by a set of overarching strategies.

There is no one-size-fits-all solution for the development of smart sustainable cities. The population, development level, economic structure, history, and culture of each city are different, which determines the variations in the paths of smart city construction. In the process of improving the top-level design of smart cities, it is therefore necessary to emphasize adapting to local conditions, adhering to a pragmatic orientation, and implementing the principle of inclusive and sustainable development. At the level of practical policy-making, Chinese cities should strategically identify the most important policy and strategic levers that will enable them to achieve their SDGs. As to this, it should be noted that digitalization is no “silver bullet”; sometimes *smart* simply means well-thought-through. In many cases, technical efficiency is not sufficient, while vibrant social networks and local communities are crucial for sustainable development at the city level. As the experience during the COVID-19 pandemic demonstrates, these networks and communities can respond quickly to emerging challenges and mobilize various resources. As powerful sources of urban resilience, they should be strengthened in the digital-green dual transformation.

Action Area 1: AI and Data Governance

Strengthening urban data governance requires addressing both capacity and control. Key interventions include enhancing digital infrastructure, which ensures robust and secure data collection, storage, and processing capabilities. To further strengthen municipal data governance, it is crucial to institutionalize human decision-making and leadership. Ensuring that decision-makers are well-informed and capable of interpreting complex data sets helps maintain transparency and accountability. Additionally, fostering collaboration between various stakeholders, including academia, industry, and civil society, can enhance the governance framework by incorporating diverse perspectives and expertise. This helps, for example, to take different scenarios into account in municipal planning projects or to organize low-threshold participation procedures. Specifically, cities can implement the following policies to develop strong data and AI governance:

- **Put people first and make their needs the starting point to promote AI application and data governance**

In the process of urban digital transformation, we should put people first and make efforts to meet their growing physical and mental needs. With the development of cities, the needs of city residents are diversifying and of higher standards, as exemplified by the increasing demand for green transportation and education. Sustainable development at the city level can be effectively promoted, by solving residents’ growing needs through digital and green technologies, while giving them a sense of increased life quality.

- **Maintain control over algorithms, ensuring they serve the public interest and are used ethically and transparently**

First, ensure algorithmic transparency by requiring vendors and developers to provide clear documentation on how algorithms function, decisions are made, and data is used. This transparency should be accessible to both city officials and the public. Second, apply regulatory frameworks to oversee algorithmic use, including guidelines for ethical AI, regular audits, and independent oversight bodies to monitor compliance and prevent biases. Third, adopt open-source algorithms to enable community scrutiny and collaboration. This approach builds trust by allowing citizens and experts to review and improve these systems. Fourth, establish feedback and redress mechanisms to allow citizens to report concerns about algorithmic decisions and ensure these issues are effectively addressed. Finally, develop and implement comprehensive digital privacy and security frameworks that prioritize the protection of citizens' personal data, ensuring transparency, accountability, and robust safeguards against unauthorized access and misuse. This framework should include clear guidelines for data collection, storage, and sharing, as well as stringent measures for securing data against breaches. It should also mandate regular audits and assessments to ensure compliance with privacy standards.

- **Improve data governance and optimize data resources**

Data is central to the operation of smart cities, linking digital capabilities and solutions. The *"Plan for the Overall Layout of Building a Digital China"* points out that to consolidate the foundation of Digital China, on the one hand is to build sufficient and efficient digital infrastructure, and on the other hand, is to smooth the circulation of data resources. This is also applicable to the construction of new smart cities, which need to balance the construction of digital infrastructure and the optimization of data resources while strengthening the enabling role of data as a key factor of production. Data governance should be improved, with an open data management system established to avoid duplicate data collection and closed use, which result in isolated data islands and a waste of resources. In terms of data gathering, it is necessary to strengthen the collection of sustainability-related data like "carbon footprint" and "carbon credits" at the individual, household and organization levels, which are often related to the systems of smart transportation and smart energy consumption. In the meantime, while enhancing efficiency and transparency, it is crucial to establish a comprehensive digital privacy and security framework at the city level.

- **Mitigate environmental and social risks**

First, promote transparency in data collection and algorithm design to mitigate the gender data gap and bias by requiring the sharing of smart city data with research institutions focused on gender equality. Implement measures to ensure that AI systems are designed with diverse datasets, reducing gender bias and improving inclusivity in urban development. Second, regularly assess the environmental impact of AI and digitalization efforts within smart cities, implement a green AI infrastructure. Establish monitoring systems to track energy consumption and carbon emissions from data centres and AI operations, adjusting policies as needed to maintain a balance between digital growth and sustainability goals.

Action Area 2: Energy and Industrial Infrastructure

Ensure that energy demand and energy supply meet flexibly, supporting the integration of intermittent renewables into the energy system by relying on smart industrial and smart home systems, supplemented by dynamic pricing.
Specifically, cities can implement the following policies to transform their energy sectors and industrial base using digitalization:

- **Target financial structures and flows for the green and sustainable transformation of the urban economy**

First, target subsidies and tax incentives to encourage the widespread adoption of digital services and green technologies. Mandate that all data centres must be powered by newly constructed renewable energy (solar, wind, and batteries). These financial incentives can play a crucial role in accelerating the transition to sustainable practices and modern technological solutions. Second, direct both public and private investments toward research and development (R&D) in green and digital technologies. Establishing innovation hubs and forming strategic partnerships can help drive technological advancements, with co-investment opportunities designed to attract additional private investors. Third, promote collaboration between the public sector, businesses, and academia to develop sustainable business models. Restructure taxation to encourage green practices and digital solutions.

- **Develop governance and policy for technology and infrastructure development**

First, implement market reforms to remove barriers to applying green and digital technology. Update regulations to integrate renewable energy, support decentralized production, and foster innovation in sectors like industry, transport, and waste management. Second, coordinate efforts across local, regional, and national levels ("multi-level governance") to ensure policy coherence, efficient resource allocation, and alignment with climate goals. Third, invest in AI and data-driven platforms for optimizing industry system and urban sustainability, while ensuring data privacy and promoting open data policies.

Action Area 3: Smart and Sustainable Urban Planning

Integrate the City Brain technology into urban planning to enhance sustainability by utilizing AI to simulate and predict the impact of interventions on GHG emissions in mobility and buildings, and on climate resilience. Cities should leverage AI for transit-oriented development and climate adaptation strategies, using high-resolution spatial data to guide sustainable urban development and reduce environmental impacts. The use of advanced data-driven methods allows cities to tailor their planning efforts to their unique characteristics, ensuring that urban development aligns with sustainability objectives and enhances the quality of life for residents. The integration of these technologies provides a powerful toolset for addressing the complex challenges of urban climate change mitigation and adaptation. Specifically, cities can seize the means of digitalization for sustainable urban planning by implementing the following policies:

- **Design environmentally sustainable smart cities by following the Tomorrow City vision**

First, focus on the design of compact, green cities with mixed-use districts, eco-friendly mobility options, and reduced noise levels. Central to this vision is a new approach to managing limited urban space. The planning model of "triple inner urban development" promotes a reallocation of urban land, aligned with the sponge city concept[6]. AI-based urban planning tools (the sustainability area of the City Brain) that can rapidly monitor, evaluate, predict and guide low-carbon and resilient settlement structure have high potential.

Second, encourage digital innovation in public transport and active mobility, while also addressing any rebound effects that may arise from increased efficiency. Public transport and active mobility form the backbone of a sustainable urban transport system and are essential for reducing the demand for urban traffic space. The investigation of urban mobility data can support the efficient identification of locations that provide safe (physically separated from car traffic) bicycle lanes. These sectors can significantly benefit from digitalization if legal and fiscal mechanisms are implemented to maximize their potential while mitigating potential risks.

Third, achieve a climate- and people-friendly built environment through the standardization and mainstreaming of digital planning and assessment tools for building stock and easy-to-access life cycle carbon accounting tools to identify the most important levers in the construction sector to decarbonize, minimize hazardous substances and optimize resource consumption, as well as for deriving, setting and monitoring targets and indicators for the envisioned transformation.

Fourth, anchor environmental targets for a decarbonized, dismantlable, zero-pollution building stock in legislation, support their implementation financially and through other instruments. Crucially this involves the decarbonization of cement/steel construction and a transition to laminated timber and other renewable building

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[6] The sponge city concept focusses on the functions of urban green-blue infrastructure for the urban water circle and aims at urban resilience [154].

materials advanced by education programs in architecture schools, as well as financial support and derisking for construction companies taking up new materials. To develop a smart and sustainable city, goals for urban environmental protection must become part of regulatory measures, and the transformation of building must be accompanied by sustainable financing and/or monetary incentives, e.g. sustainability certificates, and/or non-monetary incentive systems, e.g. best practice examples and eco-labels.

Fifth, protect, develop and qualify networked, multifunctional and accessible urban green-blue infrastructure on all levels from residential environments to urban regions. This can be achieved through integrated green infrastructure planning and management, anchorage of quantitative values for open space provision and accessibility, and sustainable financing. Digital tools should support the modelling, planning and monitoring of urban green-blue systems.

Sixth, promote the systematization and synergizing of urban ecological environment management with the help of digital technology innovation. Future city construction should consider organically embedding urban ecological and environmental governance through digital technologies such as AI. As to this, support the collection of ecological and environmental data and encourage urban residents to adopt sustainable lifestyles and consumption patterns. This will provide a strong impetus for the development of a beautiful China and sustainable development of urban environments.

Action Area 4: Social Participation and Inclusion

Offer green and digital literacy programs to equip citizens with an understanding of sustainability and its relation to quality of life as well with the skills needed to understand algorithmic systems. Implementing participatory design processes and involving community members, experts, and city officials, ensures that algorithms are developed with diverse input, addressing potential biases and aligning with community values as well as contributing to sustainable urban development. Engaging citizens through public consultations, workshops, and forums further demystifies technology, empowering them to actively participate in the governance process. Specifically, cities can ensure digital participation and socially inclusive development by adhering to the following policies:

- **Prevent the exacerbation of inequalities and promote socially equitable planning**

First, provide training to disadvantaged groups such as older people, children and residents of economically disadvantaged areas to ensure their access to digital city services. Second, integrate aspects of gender equity at different stages of the development process of digital technologies used to solve urban challenges and foster urban development. By including perspectives of all genders, smart appliances can balance the biases embedded in the data they use.

- **Develop governance that is capable and motivated to incentivize change**

First, provide municipalities with scientific results to support smart sustainable city design processes with the involvement of communities (top-down knowledge distribution). In this context, peer reviews between cities are very useful as a support. Second, support civil servants to become enablers of sustainable smart city design processes. Training programs to qualify employees can be designed and disseminated at the national level. Active participation formats should engage all relevant stakeholders and require a sufficient budget i.e. gender budgeting.

Action Area 5: Knowledge Generation and Access

Establish data portals that provide access to sustainability-relevant metrics, enabling evidence-based climate action through predictive AI modelling. By making data accessible and engaging the public, cities can foster transparency and inclusivity in urban sustainability efforts. In addition to data access, it is also about making the methods of data utilization more accessible. Cities of the future have workshops and experimental spaces to enable different actors (citizens, companies, scientists and city employees) to create knowledge with data for their needs. Specifically, cities can generate knowledge and make it accessible by implementing the following policies:

- **Generate and provide access to urban sustainability-relevant data**

First, develop predictive models for low-carbon urban planning to further energy efficiency utilizing high-resolution spatial data and AI. AI methods can identify low-carbon urban planning strategies, e.g., by minimizing newly induced traffic as a result of new settlements. Algorithms can also analyse building morphology to infer construction ages and identify older structures that would benefit most from energy retrofits. This kind of data-driven insight enables cities to allocate resources more effectively, ensuring that retrofitting efforts deliver maximum environmental benefits. Second, allow access to comprehensive mobility data, such as GPS and transportation usage patterns, to allow urban planners to design more efficient public transport networks. By analysing this data, cities can identify underserved areas and optimize transit routes to reduce travel-related GHG emissions. Finally, enhance climate adaptation through urban heat mapping. Detailed spatial data on urban temperatures can help cities identify areas most vulnerable to heat stress during extreme weather events. Machine learning models can analyse temperature variations and correlate them with urban form features, such as green spaces and building densities. This approach allows cities to implement targeted interventions, such as increasing urban greenery in heat-prone areas, to mitigate the effects of heatwaves.

- **Support social innovations for technology adoption**

First, encourage sustainable behaviour through public campaigns, education, and incentives that promote energy conservation, sustainable transport, and waste reduction. Second, support the development of business models focused on the circular economy and sustainability, leveraging digital platforms to reduce waste and create new economic opportunities.

Action Area 6: Monitoring and Learning

Smart city indices or indicators are important tools for defining a clear long-term vision and direction for the dual transformation, measuring progress, making agile adjustments in the process and evaluating results. Smart City indices or indicators ought to take into account a wide range of criteria to assess a city's digital and green progress. One of the future tasks of cities should be to work out synergy effects between existing monitoring systems of individual disciplines and to identify smart sustainable indicators. Specifically, cities can advance the monitoring and learning process on their way towards a smart sustainable city by implementing the following policies:

- **Develop city-specific indicators that monitor the digital and sustainable transformation**

First, develop indicators at an early stage in order to not only measure developments (inputs and outputs) but also to influence them in advance. The findings should then be used as a targeted planning, information and decision-making basis for politicians and administration, and should contribute to informing, communicating and raising public awareness. Second, reflect the specific characteristics of each city ("Eigenart") and ensure their relevance and effectiveness. Cities should carefully select their own indicators. The development of suitable indicators and their collection should be co-designed by various stakeholder groups. Finally, include ethical considerations in the frameworks that monitor cities' greening and digitalization processes. This perspective reveals issues related to intergenerational justice, social justice, environmental justice, financial justice, degree of autonomy, honesty and accountability and the current state of scientific evidence.

- **Improve the existing system of evaluation index**

The *"Evaluation Index for New Smart Cities"* (the latest version in 2022, implemented on 1 May 2023) evaluates smart city construction from two angles: one is objective indicators, including public services, governance structure, ecological liveability, information infrastructure, information resources, industrial development, information security and innovative development; the other is subjective indicators, namely citizen experience. This index system covers all major aspects of smart city construction, targeting mainly cities at the prefecture level and above. In 2019, a total of 275 cities participated in the evaluation. At present, it is worth considering how to improve the contents and weights of the "ecological liveability" part of the "*Evaluation Index for New Smart Cities*".

Overarching Strategies

China's smart city projects have covered all provinces, municipalities, and autonomous regions. All sub-provincial-level cities, above 95% of prefecture-level cities, and more than 50% of county-level cities have planned to develop smart city-capabilities. Recently, the construction of smart cities is accelerating in combination with "new infrastructure buildup" covering, for instance, 5G, big data centres, AI, and industrial internet. China's rapid smart city construction has been driven by a large amount of investment, the scale of which amounted to RMB 875 billion (about USD 120 billion) in 2023. Despite significant investments and achievements, the developments of smart cities and green cities remain on two separate tracks in China. Cities should prioritize sustainability considerations, provide smart and sustainable solutions, and advance key technologies that promote the coordinated advancement of the digital and green transformation.

- **Implement a people-centred "Smart Sustainable City" strategy**

Chinese cities should switch to the concept of the "Smart Sustainable City" as the leading paradigm of smart city development. To do so, municipalities should establish a specific Smart Sustainable City Committee and comprehensively integrate sustainability considerations into the work of smart city construction. These considerations include the environmental dimension (such as GHG emissions, data centre energy consumption, environmental pollution, electronic wastes, etc.), the social dimension (such as gender equality, privacy protection, "digitally disadvantaged groups", etc.), and governance (scientific decision-making, public participation, transparency, etc.). Sustainability considerations can be incorporated into various stages and aspects of smart city construction, including, for instance, the investment in digital capabilities, the provision of sustainable solutions, and the governance of data resources. This should involve the active participation of citizens and relevant organizations as well as the strengthening of social networks and local communities to make it a people-centred approach.

- **Enhance digital capabilities for sustainable solutions**

The construction of Smart Sustainable Cities needs to consider both the buildup of digital capabilities and the provision of smart and sustainable solutions. Digital capabilities cover aspects such as relevant ICT infrastructure (hardware, software), ICT services, and urban AI systems (city brains, intelligent urban management centres), while smart and sustainable solutions include general application scenarios, such as digital twin cities, smart transportation, smart energy, and smart industrial parks, as well as specific application scenarios for dealing with unique urban problems and pain points for certain localities and the specific needs of various vulnerable groups. The improvements in digital capabilities for sustainable solutions require both technological empowerment and institutional innovation.

- **Advance key technologies that integrate digital and green innovations**

Digital and green innovation plays a vital role in driving economic and social transformation and upgrading. The integration of digital technologies, e.g. AI, with green technologies is essential for achieving sustainable urban development in Chinese cities. This can be achieved through a more efficient use of resources, rapid planning processes and the strategic use of new and existing infrastructure to strengthen resilient urban spaces. To develop and deploy key technologies in this regard, the national and sectoral systems of innovation need to be further improved.

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The City Brain is at the core of smart city operation. Powered by AI, big data and cloud computing, the City Brain can greatly improve the efficiency of urban operations, which lays the foundation for sustainable development. As to this, it will be critical to not only test the City Brain in pilots and isolated application fields, but to collect and analyse evidence of its integration with urban sustainability capabilities. However, it is not enough for a city to have only an efficient brain—it also needs a warm heart. The heart cares about the environment and nature and loves everyone in the city. Having both an efficient brain and a loving heart is the key to the city's successful digital and green dual transformation. In addition, to most effectively serve the people in their pursuit of a better life, both effective markets and capable governments should play a role. Under the command of an efficient brain and a loving heart, the invisible and visible hands shall work together, and, only through collaboration between the two, can we create a sustainable urban future.

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Annexes

Annex 1. Artificial Intelligence Promotes the Green Energy Transformation of Ordos

1.1 Basic situation of Ordos City and its vision of energy industry transformation

Ordos is located in the middle reaches of the Yellow River in the west of Inner Mongolia Autonomous Region. The average annual temperature is 5.3℃ -8.7 ℃, and the average temperature in July is 21℃ -25 ℃. The climate is cool and pleasant, very suitable for living. It has jurisdiction over 2 municipal districts and 7 banners, covering a total area of 87,000 square kilometres, accounting for 7.35% of the total area of the Inner Mongolia Autonomous Region. By 2023, Ordos will have a permanent population of 2220.3 thousand, an urbanization rate of 79%, annual GDP of 81.542 billion US dollars, and per capital GDP of 365 thousand US dollars, ranking first in China. In the vast territory of China, Ordos City has a unique geographical position and resource endowment and is an important national energy base. Natural gas reserves in Ordos exceed 10 trillion cubic meters, coal bed gas resources are 4.21 trillion cubic meters, and the annual output of natural gas has exceeded 30 billion cubic meters. With more than 10 million kilowatts of solar and wind energy available for development, Ordos is the country's largest energy output prefecture-level city, one of the 14 large coal bases, one of the nine coal power bases, one of the four national modern coal chemical industry demonstration zones, and has been approved to build 2 new energy bases of 10 million kilowatts, with obvious resource advantages.

Facing the severe environment of global climate change, the high-quality development of energy industry in Ordos is full of challenges. In 2023, the added value of the production and supply of electricity, heat, gas and water in Ordos increased by 18.0 percent year on year, and the supply of energy products was stable. However, for a long time, the traditional energy industry represented by coal accounted for more than 50% of the total economic output in Ordos, and mainly relied on low-end industries such as "selling coal and mining coal" to drive economic growth. This low-end production and operation mode are not sustainable. In response to the new demands for the development of resource-based cities, Ordos initiated a shift in its economic development model, with traditional resource industries such as coal and emerging energy sectors progressing in tandem. Conforming to the new trend of information development and taking the development of artificial intelligence as an important measure for industrial transformation and upgrading.

The concept of green development reflects the multi-dimensional improvement of Ordos' urban energy structure. By fully promoting 5G technology into mines, building smart mines and green mines, Ordos has promoted the development of the coal industry to fine and deep processing, and steadily improved the energy efficiency of the coal industry. And build a set of energy production, equipment manufacturing, application demonstration in one of the "wind and solar power, hydrogen storage, and electric vehicles" industrial cluster. Taking into account the growth of non-coal industries, the development of high-tech enterprises and the development of green energy. Ordos is in a new stage of transformation to transform its development mode and optimize its energy industry structure and is moving toward a model of pursuing high-quality growth.

1.2 Challenges and difficulties on the way of energy transformation in Ordos

The per capital GDP of Ordos is nearly three times that of the national per capital GDP, but its per capital carbon emission is also much higher than the national average. Ordos is a typical city heavily dependent on coal resources. By the end of 2023, Ordos has a total installed power capacity of 45.99 million kilowatts. Among them, the installed thermal power capacity is 35.59 million kW, accounting for 77.4 percent of the total installed capacity, and the installed renewable energy capacity is 10.4 million kW, accounting for 22.6 percent of the total installed capacity. On the one hand, Ordos's economic development has long relied on the coal industry, and its energy structure is unitary; On the other hand, abundant energy resources is a huge endowment advantage, Ordos needs to find a "balance point" where traditional energy industry and green energy industry go hand in hand, instead of blindly rejecting traditional energy industry. Under the "dual carbon" goal, Ordos faces great pressure on energy transformation and environmental governance. Continuous high-intensity coal energy exploitation has brought a series of resource and environmental problems, which are manifested as serious air pollution, aggravated soil erosion and sharp decline in ecological carrying capacity. For example, Zhangjialiang Coal Company stacked 950 square meters of coal prone to dust in the open air, and did not carry out airtight treatment; Four coal mining enterprises in the Chizhjing area of Etoke Banner have overdrained about 7 million cubic meters in the production process, resulting in a drop in the groundwater level around the coal mine and serious damage to the groundwater ecological environment.

Ordos accounts for about 1/6 of the country's proven coal reserves and 1/3 of the country's proven natural gas reserves, and its energy and chemical industries are at a high level of development. In 2022, Ordos's annual carbon emissions will be 193 million tons, with per capita carbon emissions 6.9 times that of the national per capital level. In 2023, the structure of the three industries in Ordos will be 3.5:67.3:29.2, with the added value of secondary production accounting for 67.3% of GDP, and most of the products produced are primary products. Although solar energy, wind energy and other new energy industries are also steadily set sail, but the current energy status of Ordos determines that the coal-based energy structure and the economic development situation dominated by the secondary industry cannot be fundamentally changed in a short time. How to get rid of the "resource curse" is a major test that Ordos faces on the road of realizing the transformation of energy industry.

At present, Ordos new energy business has not yet formed a complete integrated industrial cluster, the number of high-tech, high value-added technology-intensive enterprises is small, the independent research and development ability of enterprises is limited, coupled with the price of green energy raw materials continues to rise, the operating cost of enterprises has increased significantly, especially the photovoltaic power generation in the production process of high energy consumption, heavy pollution, scrap disposal cost is relatively large. The development pressure of green energy projects is great. Factor input and innovation are the driving forces of economic growth, while talent is the main body of innovation. Ordos has weak human capital advantage and lacks high-level talents, especially those who need to continue the transformation and development of energy industry. Ordos has advantages in resources and infrastructure, but there are shortcomings in supporting capabilities such as technology, capital and talents. Therefore, there are many obstacles in the transformation from traditional energy industry to green energy industry, and it is difficult to find a sustainable and healthy development path.

1.3 Solutions about AI promoting the transformation and development of energy industry

Ordos benchmarks against advanced domestic or industry standards, promote the green transformation of the industrial industry, take the integration of artificial intelligence and coal mining technology as an opportunity to promote the intelligent construction of coal mines and improve the automation level of coal mining. All new coal mines in Ordos are built in accordance with green mine standards, so as to give full play to the demonstration role of successful restoration of green mines and create a national green mine construction model area.

Relying on rich green energy resources, Ordos promotes the development of renewable energy such as scenery with a high proportion, promotes the project of doubling new energy, optimizes the layout of scenery power generation projects, and makes full use of desertification governance area[1], arid hard beam area[2], open dump in coal mining subsidence area[3] and both banks of the tributary[4] to speed up the construction of large-scale centralized wind power and photovoltaic power generation base. For example, the former 500,000 kw coal mining subsidence area of Wulan Mulun town, Yijin Horo Banner, has been transformed into an intelligent photovoltaic garden complex covering an area of about 42,000 mu, forming a positive development model of green power generation on the board and planting and breeding under the board. The project is the epitome of the construction of green mines in Ordos, aiming to maintain the balance of regional ecological environment.

▲ Erdos photovoltaic industry

To transform the traditional energy industry, one is to give play to the backbone of state-owned enterprises, support the city Digital Investment Co., Ltd. to establish a state-owned network freight enterprise oriented by market and customer demand, and rely on the digital coal production and marketing service platform to provide services for more logistics enterprises. The Municipal Digital Investment Co., Ltd. actively participates in digital construction projects such as smart energy, and takes the initiative to undertake the development, operation and maintenance services of information projects of government agencies and enterprises and institutions. The second is to promote the integration construction of safety production standardization, intelligent production and green mining in the coal industry, and accelerate the intelligent construction of the coal industry. Inner Mongolia Intelligent Coal Company Ma Diliang Coal Mine uses 10 smart mine systems such as full video scheduling communication system, 5G+ intelligent coal mining system, 5G+ intelligent tunnelling system, etc. Committed to the transformation and development of coal industry from human-driven to technology-driven. Ordos city plans to make all coal mines in normal production intelligent by the end of 2024, and all qualified coal mines will be intelligent by the end of 2025.

The city will integrate the traditional energy industry with the development of the green energy industry to support the coupled development of modern coal chemical industry and green hydrogen. It supports modern coal chemical enterprises to reduce the total carbon emission and intensity of projects through the integrated development of "coal chemical industry + green hydrogen". Take wind power, photovoltaic fusion green hydrogen demonstration project, which located in Wu Shen Banner as an example, the project is the world's largest and the first green hydrogen coupled coal chemical project in the whole autonomous region, aiming to replace the "coal hydrogen" in the original process with "green hydrogen", and help enterprises promote the work of coal to olefin, as well as downstream high-end material industry.

From the macro level, it will promote the overall intelligent development of the city, carry out research on key technologies of low carbon, zero carbon and negative carbon, and build carbon neutral technology platform and industrial chain. With the CIM basic platform as the base, Ordos has accelerated the IoT perception and digital supervision application of urban infrastructure around the four major fields of smart engineering, smart housing, smart city construction and smart urban management. Deepen the application of building information modelling (BIM) technology and strengthen the management of the whole life cycle of buildings.

▲ Ordos City Information Modelling (CIM)

1.4 The actual effect of energy industry transformation in Ordos

In the aspect of traditional energy industry, the intellectualization process is promoted through the localization of industrial operating systems and the construction of intelligent mines. The country's first domestic industrial operating system "Kuang Hong" has been put into use in Ordos, and 70 intelligent coal mining faces and 41 intelligent driving faces have been built, 52 coal mines have been connected to 5G network, and seven green and intelligent land ports have been built in the city's main coal producing areas to drive development. At present, a total of 178 qualified coal mines in Ordos are listed in the intelligent construction list, and the intelligent coal mine covers a production capacity of 600 million tons/year, accounting for 70% of the city's coal mine production capacity.

In the aspect of green energy industry, the capacity of new energy consumption and the scale of project grid connection have expanded, and the layout has been rapid. Ordos has introduced artificial intelligence technology into the urban power grid main grid project to improve the intelligence level of the power system. Taking the green microgrid project of zero carbon Industrial Park in Mengsu Economic Development Zone as an example, the project has achieved 100% on-site consumption of green electricity, and the utilization rate of industrial surplus energy is as high as 70%. The grid-connected scale of the city's new energy projects has doubled year by year, and the total grid-connected scale will exceed 24 million kilowatts in 2024, with 2 million kilowatts of energy storage built and 118,000 tons of green hydrogen production capacity. By 2025, the total grid-connected scale will exceed 50 million kilowatts, with 6 million kilowatts of energy storage and 200,000 tons of green hydrogen production capacity.

▲ Kubuqi Desert water ecological governance has achieved remarkable results

In terms of industrial structure, a new industrial chain has been built through digital and green transformation. Ordos has made every effort to build the whole industrial chain of "wind and solar power, hydrogen storage, and electric vehicles" integrating energy production, equipment manufacturing and application demonstration, with a strong industrial foundation and good consumption conditions. At present, Ordos has built a high-quality wind power base along Hangjin Banner, Otuoke Banner and Otuoke Front Banner, and the city's new energy installed grid connected scale has exceeded 10 million kilowatts, and a total of more than 70 million kilowatts of new energy power generation projects have been approved. In the first half of 2024, Ordos's photovoltaic equipment manufacturing industry increased 5.6 times year-on-year, and solar power generation reached 4.9 billion KWH, up 112.2 percent year-on-year. According to the plan, by 2025, the installed capacity of new energy in Ordos will exceed 50 million kilowatts, accounting for more than 50% of the total installed capacity of electricity, and the total output value of the five industrial chains of "wind and solar power, hydrogen storage, and electric vehicles" will exceed 69.785 billion US dollars. In 2020, clean energy power generation in Ordos City accounted for only 5.8% of the total power generation, by 2030, the total installed capacity of renewable energy power generation reached 100 million kilowatts, and clean energy power generation accounted for 50% of the total power generation.

▲ Wind power generation in Ordos

In terms of industrial benefits, the development of green energy industry has made significant economic benefits and ecological contributions. Taking Dalat Banner with an annual output of 5 million meters of prestressed concrete photovoltaic pipe pile project as an example, the project can achieve an annual output value of 3489.2 thousands US dollars after completion, and can pay taxes of 3,489,200 US dollars. The project has a considerable input-output ratio and high economic efficiency, and can be used as a stable tax source for local finance. Kubuqi Desert in the application of photovoltaic power generation leading base, has stable power generation of 1.6 billion KWH, while fixing and controlling desertification, so that the Kubuqi Desert vegetation coverage rate reached 53%. The damage of wind and sand and soil erosion in Ordos have been basically brought under control.

▲ Dalat Banner photovoltaic power generation application leading base

1.5 Ordos experiences and best practices

- **Increase policy support and institutional development.** Ordos City has formulated several policies to support the green transformation of the energy industry, actively strives for special and policy support related to the industrial transformation of the state and the autonomous region, coordinates the transformation of the production mode in Ordos and the transformation and development of the energy industry, and promotes the construction of urban artificial intelligence public service platform and the cultivation of system solution suppliers.

- **Carry out talent introduction and scientific and technological innovation.** Jointly with well-known energy research institutions, carry out research on the green energy industry, and actively create conditions to introduce outstanding talents and teams from home and abroad in the field of green energy industry. By building a state-level innovation laboratory, introducing high-end innovation platforms and talents, and promoting intelligent and green development, Ordos has built an interconnected market environment and promoted the free flow of land, labor, capital, technology, data and other elements within the region, which has significantly improved the scientific and technological content and competitiveness of the energy industry.
- **Build a smart infrastructure system.** To optimize and upgrade the existing digital coal production and marketing service platform, smart Internet of Things technology service platform, and comprehensive coal trading service platform, to provide coal enterprises with whole-process, whole-chain, whole-cycle, traceable digital closed-loop comprehensive services, and effectively regulate the coal trading market.
- **Create a digital government and promote a low-carbon society.** By promoting the construction of urban intelligent agents, comprehensively promoting the construction of digital government affairs, and promoting the construction of a first-class business environment, the task of building a new type of digital government is realized. By strengthening the digital management of water ecology, strengthening the digital management of forest and grass wet ecology, and developing high-efficiency industries to enrich the people, we will establish important measures to improve the digital level of ecological protection in the Yellow River Basin. Through the four important works of digital intelligence for air pollution prevention, water pollution prevention, soil pollution prevention and solid waste pollution prevention and control, we will establish important measures to strengthen the digital intelligence ability of environmental pollution comprehensive remediation. By promoting the intelligent development of circular economy, vigorously developing green energy, promoting the management of energy conservation in the whole area, and promoting the construction of pilot cities for national carbon testing, we will encourage low-carbon life, make green and low-carbon behaviors become common in the whole society, and provide the public foundation for the development of green economy.

1.6 Summary and conclusion

- **Government departments create requirements for AI application scenarios.** The energy industry transformation in Ordos City is currently in the promotion stage, primarily driven by government departments to stimulate demand, attract market enterprises to offer artificial intelligence services, establish artificial intelligence testing sites through large-scale government procurement, encourage various industries to adopt artificial intelligence technology for intelligent applications that satisfied societal needs, and actively facilitate the transition of traditional energy industry towards green energy. This will advance the city's objective of achieving "carbon neutrality and carbon peak".
- **Give full play to the integrated innovation characteristics of artificial intelligence, in order to provide smart solutions for urban energy transformation.** With its powerful computing power and complex algorithm design, artificial intelligence can replace traditional manual and partial machine production. The biggest highlight of multi-modal artificial intelligence technology is that it can seamlessly integrate and efficiently process diversified data from different perception fields, and can penetrate, diffuse and apply new energy technologies such as wind power and photovoltaic to traditional industries represented by coal, and carry out technology integration, which greatly reduces the transformation cost of the traditional energy industry and makes it easier to change the dominant technology and production mode. In addition, artificial intelligence technology is used to improve the intelligent level of urban pipe networks and microgrids, build a collaborative supply system of various forms of energy, directly combine renewable energy and high-load energy industries, and promote the leap-forward development of the energy industry.

- **Use the ability of artificial intelligence to solve complex problems and choose the best technical route to promote urban energy transformation.** The aspects of enterprise technology application, organization and coordination, and structural adaptation level should be measured, while choosing new energy enterprises with advanced digital intelligence technology. According to the screening of the diversity of technical routes in different application scenarios of enterprises, combined with the current transformation and development planning of China's energy industry, comparative analysis is carried out, and the optimal technical route is summarized that is conducive to the overall profit of enterprises, the development of artificial intelligence technology and the maturity of energy industry, and actively promote the test, demonstration and promotion of the technical route.

Notes and references:

[1] Desertification governance area refers to the area where desertification has occurred or is about to occur, through afforestation, grassland restoration, soil and water conservation and other measures, ecological restoration and govern.

[2] Arid hard beam area refers to an area with hard surface, sparse vegetation and poor soil formed in arid or semi-arid areas due to long-term water shortage and soil erosion.

[3] Open dump in coal mining subsidence area is the surface subsidence area formed by underground coal mining resulting in the movement and deformation of the surface rock.

[4] Both banks of the tributary refer to the land area on either side of a river or gully in an arid and semi-arid region.

Annex 2. Wuhan's Autonomous Driving Experiences

2.1 China's intelligent connected vehicle road testing and demonstration applications continue to expand

By the end of 2023, China has built 17 national level testing demonstration zones, 16 pilot cities for the coordinated development of smart cities and intelligent connected vehicles, 7 pilot zones for the Internet of Vehicles, and a total of 22000 kilometres of open testing roads nationwide. More than 5200 testing demonstration licenses have been issued, with a total testing mileage of 88 million kilometres. Multi scenario demonstration applications such as autonomous driving taxis, unmanned buses, autonomous passenger parking, mainline logistics, and unmanned distribution are being carried out in an orderly manner.

More than 10 cities, including Beijing, Shanghai, Guangzhou, Shenzhen, Chongqing, Wuhan, and Changsha, allow autonomous vehicle to engage in commercial trial operation of taxis, urban public buses (electric vehicles), and other vehicles in specific regions and periods, and the application scale is expanding. Among them, Beijing started earliest, and Wuhan landed the fastest. At the end of April 2022, the Beijing Intelligent Connected Vehicle Policy Pilot Zone was the first to release the first batch of "unmanned demonstration application road testing" notices. In August 2022, Wuhan also released a pilot policy for the commercialization of fully autonomous driving, with autonomous vehicles without safety personnel being the first to provide commercial services on public roads; Subsequently, Guangzhou, Shanghai, Shenzhen and other places have also started unmanned manned road testing and demonstration applications.

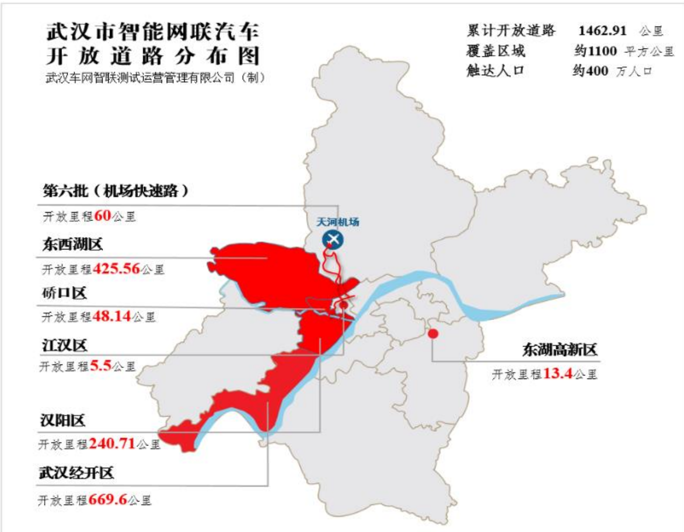
In terms of policies and regulations, with the accelerated development of testing and demonstration, the promotion of unmanned testing and commercial operation, breakthroughs in local legislation, and the continuous promotion of mutual recognition of test results, intelligent connected vehicles are evolving towards a new stage of large-scale demonstration. Relevant departments are strengthening the supply of industrial development innovation policies. Beijing, Shanghai, Guangzhou, Shenzhen, Wuhan, and Chongqing have all issued policies and regulations regarding the application, operation, and supervision of autonomous vehicle testing and demonstration applications.

2.2 The application of intelligent connected vehicles in Wuhan has been rapidly implemented

In November 2016, the Ministry of Industry and Information Technology of the People's Republic of China and Hubei Province signed and built the project of "Smart Car and Smart Transport Application Demonstration Based on Broadband Mobile Internet" and settled in the Economic Development Zone. "China Wuhan Smart Connected Car Demonstration Zone" became the sixth smart connected car demonstration zone in China. On September 22, 2019, the National Intelligent Connected Vehicle (Wuhan) Testing Demonstration Zone was officially unveiled, and companies such as Baidu, Hailiang Technology, and Shenlan Technology were awarded the world's first batch of commercial license plates for autonomous vehicles by the transportation department of Wuhan. As of September 5, 2023, Wuhan City has issued the 1000th autonomous driving test license plate for the National Intelligent Connected Vehicle (Wuhan) Test Demonstration Zone to Baidu Group. After years of construction and development, the National Intelligent Connected Vehicle (Wuhan) Testing Zone has established a three in one intelligent connected vehicle testing system of "open+closed+simulation".

In December 2019, Wuhan Economic Development Zone was the first in the country to establish a 108 kilometre 5G covered vehicle road collaborative autonomous driving test road. Afterwards, Wuhan gradually expanded about 321 kilometres of open test roads in three batches. In January 2023, Wuhan will open the fifth batch of intelligent connected vehicle test roads, with all 344 kilometres of roads located in the Wuhan Economic Development Zone. The cumulative open road mileage of Wuhan Economic Development Zone is 669.6 kilometres, making it the first region in central China to fully open intelligent connected vehicle roads.
In July 2023, Wuhan City released the sixth batch of 60 kilometre intelligent connected vehicle test roads. For the first time, highways and cross river routes have been included in the testing scope of intelligent connected vehicles on newly opened roads. Extending from Hanyang District to Tianhe Airport, it includes 40.1 kilometres of expressway and 18.9 kilometres of urban elevated road.

In August 2023, the seventh batch of 651.35 kilometres of test roads will be opened in Wuhan, covering an area of approximately 500 square kilometres, which is the largest number of open roads and coverage area in the same batch of roads in Wuhan. Mainly distributed in three administrative districts of Wuhan, including 48.14 kilometres of open roads in Qiaokou District, 177.65 kilometres of open roads in Hanyang District, and 425.56 kilometres of open roads in Dongxihu District. The Dongxihu District and the area within the Third Ring Road of Hanyang District are almost fully open, gradually extending from the new urban area to the central urban area. Among them, Hanyang District and Hankou District have achieved cross district connected road opening. As of December 2023, Wuhan has opened 3378.73 kilometres (one-way mileage) of intelligent connected vehicle test roads, covering an area of 3000 square kilometres and a population of 7.7 million; The Wuhan Intelligent Connected Vehicle Closed Test Field, covering an area of 1312 acres, is the only closed test field in the world that combines a T5 level test field with an F2 level track; A total of 1581 test licenses have been issued to 19 autonomous driving companies, and the Checheng Network platform has connected 675 intelligent connected vehicles; The total mileage of intelligent connected vehicle testing has reached 7.8 million kilometres, with a total testing time exceeding 530000 hours; More than 387 intelligent connected vehicles have undergone regular testing and operation, and in 2023, the number of autonomous driving travel service orders exceeded 732000, serving 900000 people, ranking among the top in the country. There are 300 fully autonomous vehicles, with a maximum one-way distance of 95 kilometres. Among them, by July 2024, Baidu's "Apollo Go" automatic driving demonstration operation vehicles had reached 400. So far, Wuhan has the highest number of commercial orders for autonomous driving.



▲ Distribution of Test Roads in Wuhan Intelligent Connected Vehicle Demonstration Zone
(As of August 2023)

On the basis of continuously strengthening road testing, in early 2022, Wuhan City released the first national city level intelligent connected road construction standard ("General Principles for Intelligent Connected Road Construction"), providing a basis for risk assessment and open testing of intelligent connected roads throughout Wuhan. The formulation of this standard not only fills the gap in local standards for intelligent connected road construction in China, but also provides prior experience and reference for the formation of provincial standards, industry standards, and even national standards for intelligent connected roads.

In 2021, in order to enhance the intelligence level of China's urban infrastructure, accelerate the development of the intelligent connected vehicle industry, and form replicable and promotable experience, the Ministry of Housing and Urban Rural Development and the Ministry of Industry and Information Technology jointly designated Beijing, Shanghai, Guangzhou, Wuhan, Changsha, and Wuxi as the first batch of six "dual intelligence" pilot cities in China. Since the launch of the "dual intelligence" pilot program, Wuhan has actively promoted the construction of intelligent infrastructure and vehicle city network platforms, as well as the demonstration application and commercial operation of autonomous driving. On October 31, 2023, the Ministry of Housing and Urban Rural Development and the Ministry of Government and Information Technology announced the acceptance and assessment results of the first batch of six "dual intelligence pilot cities" in China. Wuhan's comprehensive score was 87.47 points, ranking second only to Shanghai. As the core carrier area of the "dual intelligence" pilot program, Wuhan Economic and Technological Development Zone actively explores the demonstration of the "dual intelligence" pilot program, promotes technological innovation, standard setting, testing and verification, and demonstration application of intelligent connected vehicles.

In terms of "dual intelligence" urban infrastructure construction, Wuhan Economic Development Zone has built a total of 1014 5G base stations, achieving full coverage of 5G signals. A 106 km 5G full coverage vehicle road cooperative automatic driving open test road has been built, which has the test operation conditions for autonomous vehicle above L4 level. It is the largest, richest and first open road automatic driving demonstration area with full 5G access in China at present. At the same time, Wuhan Economic and Technological Development Zone has built an "open, inclusive, and shared" vehicle city network platform based on vehicle road collaboration, constructing a high-precision 3D urban spatial model of 160 square kilometres to achieve interconnectivity between people, vehicles, roads, objects, and clouds.

In the comprehensive capability evaluation of the National Intelligent Connected Vehicle Demonstration Zone in 2023, Wuhan was rated as the leading unit in the comprehensive capability evaluation of the 2023 Intelligent Connected Vehicle Testing Demonstration Zone, ranking second in the country. The National Intelligent Connected Vehicle and Intelligent Transportation (Beijing Hebei) Demonstration Zone and the National Intelligent Connected Vehicle (Changsha) Testing Zone ranked first and third respectively. In the "Closed Site Testing Capability Assessment", it was rated as the "2023 Intelligent Connected Vehicle Testing Demonstration Zone Closed Site Testing Capability Assessment Passing Unit" and ranked among the top three in the National Intelligent Connected Vehicle and Intelligent Transportation (Beijing Hebei) Demonstration Zone, National Intelligent Connected Vehicle (Changsha) Testing Zone, and National Intelligent Connected Vehicle (Wuhan) Testing Demonstration Zone.

2.3 Wuhan's intelligent connected vehicle industry ecology

As the main battlefield for technological innovation and economic development in Wuhan, the Economic and Technological Development Zone is an important gathering place for China's traditional automobile, new energy vehicle, and intelligent connected vehicle industries, known as the "China Car Valley". In recent years, Wuhan Economic and Technological Development Zone has seized the opportunities of electrification and intelligence development in the automotive industry and has rapidly grown into a cluster of new energy vehicles and intelligent connected vehicles in China through the aggregation of innovative and industrial resources. As of June 2023, "China Auto Valley" has gathered 9 complete vehicle enterprises, 13 complete vehicle factories, and more than 500 parts supporting enterprises, making it one of the regions with the highest concentration of China's automotive industry. In 2021, the automobile industry in Wuhan Economic Development Zone achieved a production value of 229.88 billion yuan, with a total vehicle output of 943000 vehicles, accounting for 67.7% of Wuhan City, 45% of Hubei Province, and 3.6% of the country. In 2022, with "China Auto Valley" as the leader, the "Wu Xiang Ten Sui" automobile industry cluster was awarded the national level "Advanced Manufacturing Cluster" by the Ministry of Industry and Information Technology.

Wuhan Economic and Technological Development Zone has taken intelligent connected vehicles as its main direction, focusing on the construction of intelligent connected vehicle demonstration zones, forming a nationally ranked industrial cluster and a dynamic industrial innovation ecosystem. In 2022, Wuhan Economic Development Zone issued the "Action Plan for Strategic Enhancement of New Energy and Intelligent Connected Vehicle Industry in Wuhan Economic Development Zone (2023-2025)" (referred to as the "Action Plan"), focusing on the intelligence of the automotive industry. The Action Plan proposes to achieve five major goals for the development of the new energy and intelligent connected vehicle industry by 2025. One is to increase the scale of automobile production. The automobile production capacity has reached 3 million units, including 1.5 million units of new energy vehicles. The total production of automobiles has exceeded 1.5 million units, of which the production of new energy vehicles has exceeded 600000 units, striving to exceed 1 million units; The second is to significantly enhance brand influence. Create more than 10 distinctive brands of new energy and intelligent connected vehicles and key components; The third is to achieve breakthroughs in core technologies. Key technologies such as new energy and intelligent connected vehicle three electric systems, vehicle grade chips, etc. have achieved domestic leadership, and terminal system technologies such as intelligent driving and intelligent cockpit are accelerating industrialization; The fourth is to improve the industrial ecology. Cultivate and optimize the entire industry ecosystem of research and development, design, manufacturing, testing, and application of new energy and intelligent connected vehicles; The fifth is to innovate and take the lead in application. A number of new energy and intelligent connected vehicle demonstrations and typical application scenarios have emerged, forming a normalized and sustainable commercial operation scenario, promoting the large-scale commercial application of L4 level intelligent connected vehicles.

The Action Plan proposes that in the next three years, Wuhan Economic Development Zone will make every effort to create new energy and intelligent connected vehicle demonstration and typical application scenarios, support Wuhan to apply for the national intelligent connected vehicle access and road access pilot cities, open 2500 kilometres of test roads, continuously increase the investment in autonomous vehicle, form a scale of 1000 commercial operations, and issue more than 1800 relevant licenses. The formulation and implementation of the Action Plan have clarified the strategic points for the development of intelligent connected vehicles in Wuhan Economic Development Zone and provided direction for further development.

Since 2016, Wuhan Economic Development Zone has firmly grasped the opening up of intelligent connected vehicle application scenarios, attracted and gathered technological innovation resources, integrated existing automotive industry resources, accelerated the development of artificial intelligence industry, and formed a relatively complete intelligent connected vehicle industry chain and industry innovation ecology.

The open application scenarios have driven the entry and development of intelligent connected vehicle enterprises and research institutions. So far, Wuhan has gathered more than 130 core enterprises in the intelligent connected vehicle industry chain, including Dongfeng Yuexiang, Yikatong, and Xinqing Technology (including 4 unicorn enterprises), and has established multiple research institutions, including joint innovation laboratories and national intelligent transportation technology innovation centres. With the expansion of open testing road networks and the increase of autonomous vehicles, enterprises in the fields of 5G communication, Beidou positioning, and smart transportation are accelerating their gathering. Intelligent connected vehicle enterprises and research institutions have joined forces with 195 related enterprises to form the "Intelligent Vehicle and Smart City Collaborative Development Alliance", forming an innovative industrial ecosystem for intelligent connected vehicles that includes various links such as "research and development + testing + application".

In the development process of the intelligent connected vehicle industry in Wuhan Economic Development Zone, a group of enterprises with high growth potential have begun to emerge. In the "Announcement of the List of the Fifth Batch of Specialized, Refined, Special and New 'Little Giant' Enterprises and the Second Batch of Specialized, Refined, Special and New 'Little Giant' Enterprises Approved by the Hubei Provincial Department of Economy and Information Technology in 2023", 11 Wuhan Economic Development Zone enterprises including Dongxi Boze Automotive System Co., Ltd., Dongfeng Mahler Thermal System Co., Ltd., Wuhan Institute of Technology Hydrogen Electric Technology Co., Ltd., Hualizhixing (Wuhan) Technology Co., Ltd., and Hubei 3611 Emergency Equipment Co., Ltd. were successfully selected. As of June 2023, a total of 217 enterprises in Hubei Province have been included in the list of specialized, refined, and new "Little Giant" enterprises. A total of 103 enterprises in Wuhan have been selected, and 11 new enterprises have been added to the Wuhan Economic Development Zone, bringing the total to 37. In the field of intelligent connected vehicles, startups including Huali Zhixing (Wuhan) Technology Co., Ltd. have become an important part of the industrial innovation ecosystem through research and development accumulation.

On September 19, 2023, KPMG China released the 6th China Automotive Technology 50 List, with companies from Wuhan Economic and Technological Development Zone including Huali Zhixing, Neusoft Ruichi, Boreton, Majia Technology, and Qingzhou Zhihang selected. Among them, Neusoft Ruichi Wuhan Company mainly engages in the research and development of intelligent driving, vehicle cloud integration, and automotive basic software products. Through cooperation with Lantu, we will focus on developing the next generation of autonomous driving controllers.

On January 30, 2023, Forbes China released the list of new unicorn companies for 2022, with four new unicorns added in Hubei Province and two seats exclusively held by Wuhan Economic Development Zone, namely Lantu Automobile and Xinqing Technology. In 2021, Wuhan Economic Development Zone enterprises Yikatong Technology and Lotus Technology became unicorn companies. Lantu Automotive, Lotus Technology, Yikatong Technology, and Xinqing Technology all belong to the field of intelligent connected vehicles.

Relying on the National Intelligent Connected Vehicle Demonstration Zone, Wuhan Economic Development Zone has gathered intelligent connected vehicle industry enterprises and joint laboratories including Dongfeng Navigation, Dongfeng Yuexiang, Yuanrong Qixing, Yikatong, Tsinghua University, and Wuhan University, forming an industrial innovation ecosystem covering key and core technologies such as autonomous driving solutions, chips, LiDAR, millimetre wave radar, high-precision maps, and V2X. Especially the emergence of industry chain leading enterprises with strong research and development and radiation capabilities has laid a solid foundation for the development of Wuhan's intelligent connected vehicle industry.

As the main enterprise in the intelligent connected vehicle industry chain, Xinqing Technology specializes in the research and production of high-performance automotive grade chips and solutions. It has successfully mass-produced the first 7nm automotive grade intelligent cockpit in China, "Longying No.1", achieving a technological breakthrough in the field of domestic high-end automotive chips. The Lynk&Co 08, Ryzen 7, and Lynk&Co 06EM-P models equipped with the "Dragon Eagle One" have achieved mass production and market sales. In early 2024, Xinqing Technology plans to launch the advanced autonomous driving chip AD1000, which will benchmark against the most advanced international products. The AI computing power will reach 256POPS, providing strong technical support for the integrated cabin driving technology architecture of automotive enterprises.

Since 2016, Wuhan has achieved the aggregation and development of innovative resources in the intelligent connected vehicle industry through the opening of application scenarios, and has initially formed an industrial innovation ecosystem, creating conditions for the next step of development. How to further accelerate the opening of application scenarios, promote technological innovation and the gathering of industrial resources, achieve breakthroughs in key core technologies, and improve the industrial chain and innovation ecology is a strategic choice for Wuhan to further promote the development of the intelligent connected vehicle industry.

Annex 3. Digital-Green Dual Transformation and Sustainable Development in the Ruhr Area, Germany

With more than 5 million inhabitants and an area of almost 4,500 square kilometres, the Ruhr region is the largest conurbation in Germany and the fifth largest in the European Union. The starting point for this prominent position was the transformation of the originally agrarian region into a heavy industry cluster with extensive local coal production, which began around 1870. The successful development of a powerful coal and steel industry, which brought together companies in the coal, iron and steel industry with steel-related companies in the manufacturing industry (mechanical engineering, automotive, etc.), led to a massive influx of capital and labor. At the same time, however, there was also a catastrophic overexploitation of environmental resources and a serious degradation of natural resources. Coal mining hollowed out the bedrock and led to precarious sinkholes and generally unsafe ground conditions. The use of toxic chemicals and the build-up of waste products that were hazardous to health and the environment as part of local industrial production resulted in excessive, widespread pollution. As early as the beginning of the 20th century, the Emscher, which flows through the Ruhr area, gained the dubious distinction of being Europe's most polluted river. A naturally flowing river had become a man-made system of open sewers.

Against this backdrop, the digital-green dual transformation and the establishment of sustainable development structures is, on the one hand, a highly complex mammoth task. On the other hand, the successes and experience gained in this process in the Ruhr area are also of particular value for similar efforts elsewhere.

The renaturation of the Emscher is one of the key achievements of the efforts to neutralize the negative legacy of heavy industrial expansion and put the region back on the path to sustainable development. The ecological conversion of the Emscher system (drainage area: 865 km2) took three decades from 1992 to 2022 and was carried out without the substantial use of digital or AI models. The total costs amounted to around 5.4 billion euros. The work focused on three major sub-projects: the construction of a central wastewater treatment system for the Ruhr region, the construction of underground sewers and the renaturation of the Emscher and its tributaries.

The work only became possible following the - by and large - end of the spontaneous occurrence of sinkholes that had shook the region in the 1970s and 1980s. Only now was it possible to discharge wastewater in closed underground sewers running at a depth of 10-40m. The main artery of the new drainage system is the Emscher wastewater canal between the Dortmund-Deusen sewage treatment plant and the Emscher-estuary sewage treatment plant in the Dinslaken-Oberhausen-Duisburg city triangle. Over a length of 51 kilometres, it receives the wastewater from around 2.3 million inhabitants and large quantities of wastewater from industry and commerce. The wastewater is fed into the main canal via a system of underground channels that were built at the same time alongside the tributaries of the Emscher. This measure laid the foundation for the renaturation of the Emscher, which is now free of wastewater. The Emscher now serves as a green corridor through the (former) industrial landscape of the Ruhr area, providing space for ecological habitats and a close-to-nature habitat for its citizens.

The conversion of 200 km of former industrial roads on the banks of the Emscher for public use has also opened up the possibility of designing new sustainable mobility concepts. The "NEMO - Smart Mobility for Sustainable Future" project concept, for example, aims to integrate these old industrial roads into the overall regional transportation network and facilitate multimodal access (bicycle, public transport, electric vehicles, autonomous driving, etc.). The realization of these projects, however, is still ongoing.

Efforts to establish a network of highly digitized and AI-enabled smart cities in the Ruhr region were significantly less successful. The city of Duisburg, which – by means of an intensive partnership with the Chinese technology giant Huawei – was to be developed into a reference model for medium-sized smart cities in Europe, has gained particular prominence among these initiatives. In January 2018 the city of Duisburg signed a memorandum of understanding (MoU) with Huawei. This step was followed by the signing of a framework agreement between Huawei and the Duisburger Versorgungs- und Verkehrsgesellschaft mbH in June 2018, supposed to set up “Rhine Cloud” (a cloud platform supporting local smart city development) and the provision of Smart City services. Three months later, a delegation from Duisburg visited the Huawei global headquarters in Shenzhen. The site of Huawei reads that their collaboration was supposed to “focus on transforming Duisburg from a traditional industrial city into a service-oriented smart city through smart government, smart port logistics, smart education, smart infrastructure, 5G and broadband, smart homes, and urban IoT”. It was intended to promote the “smart” digitalization of Duisburg with Huawei technologies and experience, finally transforming it into “an innovative and digital benchmark city in Western Europe”. However, the initiative was never implemented and came to a formal conclusion when the MoU expired in 2022 without a single concrete project having been executed.

The reasons for this failure are complex: On the one hand, the necessary technical absorption capacity first had to be created in Duisburg in order to be able to take up Huawei's input. On the other hand, the (urban planning as well as commercial) objectives of the cooperation venture between Duisburg and Huawei were not congruent in all areas, which led to misunderstandings and planning errors. These problems were further aggravated by rising political headwinds. Strong political and public opposition against the usage of Chinese technologies (and Huawei in particular) in German critical infrastructure projects eventually put an end to the collaboration.

But these developments did not bury the idea of turning Duisburg into a smart city. As a matter of fact, in 2020 the city government opened a “Smart City Duisburg Innovation Center”, which promotes digitalization in a wide range of activities. Moreover, it set up a smart city test field in the port. The German government and the Land of NRW are supporting the initiative, to which the city of Duisburg, the Harbor of Duisburg (duisport), Deutsche Telekom and the University of Duisburg-Essen are also collaborating. Instead of the intended quantum leap, the city is now pursuing a low-profile approach focusing on the gradual implementation of specific digital/AI building blocks. A combined approach to the dual goals of digitalization and green transformation is being implemented via sub-projects such as sustainable thermal supply, smart meter implementation, EV charging infrastructure, decentralized drainage systems, etc.

With this approach, which relies more on a network of individual projects instead of a large master plan, Duisburg is now following a path that since the end of the Covid pandemic has also been emphatically pursued in other cities in the Ruhr region. The five largest cities in the Ruhr region (Bochum, Dortmund, Duisburg, Essen and Gelsenkirchen) are each pursuing their own digitalization strategies in an approach that is only partially integrated. Digital solutions are to be established in the respective municipalities via a bundle of numerous individual projects, most of which do not communicate with each other, and are governed and executed by different entities. As such, the potential of digital infrastructure and AI solutions for the development of smart cities is to be tapped step by step. In this context, digital solutions are to some degree also being used to achieve "green goals". The city of Bochum, for example, has defined five key topics: "Sustainable infrastructure", "Intelligent city management", "Digital society", "Sustainable mobility & environment" and "Innovative business & science". At least 20 projects in the areas of "Energy and Resource Efficiency" (7 projects), "Climate Protection and Climate Impact Adaptation" (6) and "Sustainable and Integrated Mobility" (7) contribute to the implementation of a green transformation. A comparison of Bochum's range of initiatives with those of other cities reveals just how independent the initiatives of the Ruhr region cities are. In the area of green transformation, for example, the city of Dortmund only focuses on the three fields of "EV charging infrastructure", "smart waste management" and an "environmental dashboard". The city of Essen, on the other hand, is focusing on a smart municipal heat supply coupled with the expansion of photovoltaic systems and the construction of a biomass heating plant. Compared to these individual initiatives, cross-city project initiatives are rare. One example is the innovative processing of satellite data used in Bochum, Dortmund and Essen for municipal green space planning and corresponding micro-climate control. In this project "Urban Green View", the cities in the Ruhr region are working together with the European Space Agency (ESA), among others.

In 2020 a new major initiative has been started with the vision to transform the Ruhr area into the “greenest industrial region in the world”. This Green Infrastructure strategy is based on the concept to create a strategically planned network of natural or semi-natural green and open spaces that connect the various industrial and residential districts of the Ruhr area. Under the leadership of the government of North Rhine-Westphalia the project is to be developed in a flexible participatory development process. About 100 individual projects are to be set up and implemented in a step-by-step process. Central fields of action are defined as: "Networked mobility - short distances", "Successful economy - good work", "Living diversity - strong cohesion", "Secure Energy – Healthy Environment" and "Best Education - Excellent Research". It must be noted that digitalization is not earmarked as a separate field of action, but only has a supportive function for other specific goals.

Seen in perspective, the implementation of strategies for a digital-green dual transformation and sustainable development in the German Ruhr Area reveals a mixed record of success. The Ruhr area has achieved great success in the re-naturalization of a region that has been brought to the brink of ecological collapse in the past. The green transformation and the establishment of new, sustainable development structures for the region have made considerable progress in recent years. In contrast, the Ruhr region is lagging behind in terms of the development of digital and smart city structures. With the failure of Duisburg's highly ambitious, integrated smart city strategy, the Ruhr region has returned to a gradual, step-by-step development concept that takes into account the diverse needs of different population groups. Instead of a comprehensive master plan, a model is now being pursued that aims to build an integrated smart city ecosystem via a decentralized, patchwork-like construction process. The overall picture also makes it clear that the idea of digital-green dual transformation in the Ruhr region has hardly been conceived and implemented as an integrated concept to date. Instead, approaches that drive either the green or the digital transformation dominate. Integrated approaches in which the development of innovative digital structures promotes the green transformation are still underrepresented.

Annex 4. Digital-Green Dual Transformation and Sustainable Development in Vienna, Austria

The city of Vienna is a leader for a principles-driven, human-centric development, oriented towards quality of life for all. This ambition is visible across strategies and programs, for example both climate program and digitalization agenda include firm principles and are strategically integrated e.g. in 2022 the city created a ‘Smart Climate City Strategy’ instead of having a smart city strategy and a climate action plan in parallel. The city of Vienna aims to reach net-zero carbon emissions by 2040 [1] and implements climate action following a set of intergenerational solidarity principles [2], collaborative climate governance (e.g. Climate City Council) and with a focus on both protection and adaptation. Digitalization is practiced as a tool to achieve the sustainability agenda, including climate goals.

Based on the city’s carbon budget, Vienna has about 60million t CO2 equivalents left, signaling urgency for effective action. Guided by prioritizing big levers before smaller ones, the city is focusing on phasing out fossil fuels in transport and building sectors. Combined, both sectors produce around ¾ of the cities GHG emissions [2]. As such the city is implementing actions to switch to EVs, public transport and biking; and moving away from gas used in building sector as well as to decarbonize electricity in district heating and cooling networks.

Whilst many other city administrations struggle to scale up climate action in building sector due to private ownership, Vienna historically owns a significant of buildings in the city i.e. about 220.000 buildings. This gives the city an advantage for implementing large scale decarbonization programs in the building stock independent from the private market, such as the ‘Raus aus Gas’ program (phase out of fossil fuels in building heating by 2040).

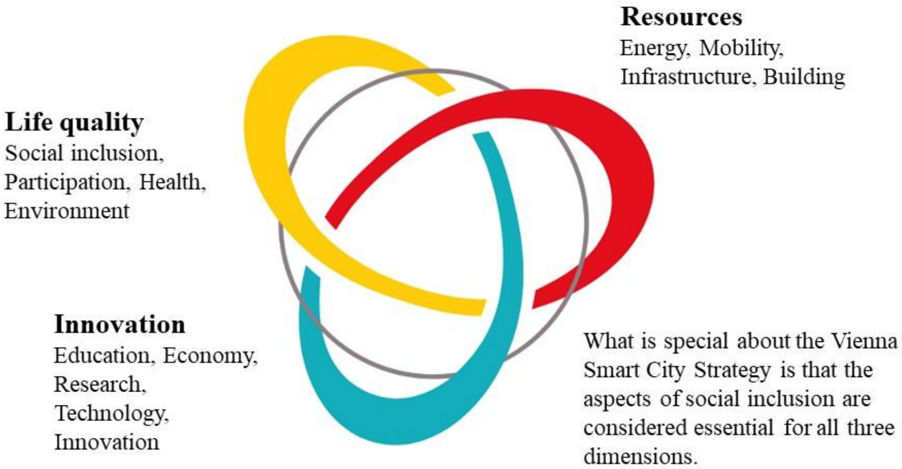
With the ambition to be an open, digital city, Vienna incrementally digitalizes all its procedures. When deciding which procedures to prioritize over another, impact on climate change and needs of citizens are two critical factors. More specifically, the city agreed on 12 digital principles, such as gender equity or environmental sustainability. These principles are put into practice across various digital strategies and projects, such as ‘Digital health’ or the digital platform ‘Sag’s Wien’ (tell Vienna), where citizens can report any infrastructure faults or issues that will then be taken care of by the city.

The city holds digital capacity and continues to advance and adapt it, i.e. the city has a Chief Technology Officer, a Chief Innovation Officer, fosters collaborations between departments, closely works with Urban Innovation Vienna (innovation company), and companies. For example, in collaboration with the innovation company, the city uses satellite data to monitor green space, land cover changes or car park utilization as well as machine learning to detect patterns in usage of public spaces.

The latest example showcasing Vienna’s continuous digital capacity development is the recently published ‘Compass for the use of generative AI in a work context’ [3], guiding staff toward responsible and purposeful use of generative AI tools.

Vienna’s smart city indicators:

The city of Vienna showcases the practical use of smart city indices in monitoring progress towards strategic objectives. The city established a sophisticated indicator concept for its Smart City Vienna Framework Strategy, matching European standards and developed in cooperation with main stakeholders based on the city's data and reports. The figure below shows the structure and target dimensions of the “indicator set”. Vienna formulated a total of 51 goals – input for the indicators is collected, among other things, through surveys or similar.



▲ Target dimension and target areas of the Smart City Vienna framework strategy[7]

Regarding the digital-green dual transformation and the sustainable development of smart cities, indicators are relevant in each of the areas:

Target dimension and target areas	Examples of indicators
Life Quality	
Social Inclusion	Distribution of household and childcare work Percentage of people who are satisfied with the squares and other public open spaces in their residential area
Health	Statistical excess mortality due to heat Average length of stay at home from the start of care
Environment	Total green space share Noise and light pollution
Innovation	
Education	Number of schools with comprehensive wireless access to the Internet Number of open child and youth work offers
Economy	Gender pay gap Energy consumption of manufacturing companies
Research, technology, innovation	Number of large mission-oriented research and innovation projects Number of cooperation projects between city administration, universities, research institutions, companies and users
Resources	
Energy	Number of renewable energy systems in the city Emissions for heating, cooling and hot water of buildings per capita
Mobility	CO_2 emissions from the transport sector per capita Share of the expanded environmental network in the modal split
Infrastructure	Area coverage with current digital network infrastructure Number of IoT sensors in the city
Buildings	Total output of the photovoltaic systems in relation to the gross floor area Proportion of green roof areas in total roof areas

[7] Source: Smart City Wien Rahmenstrategie, 2019–2050, Die Wiener Strategie für eine nachhaltige Entwicklung. https://smartcity.wien.gv.at/wp-content/uploads/sites/3/2019/10/Smart-City-Wien-Rahmenstrategie-2019-2050.pdf

Sources: Nachhaltig wirtschaften 2017; Smart city Wien 2022.

Lessons learned:

- There are many opportunities to leverage smart city development to contribute to the implementation of the climate action strategy.
- Establishing climate governance and strong principles around quality of life for all are key to the success of Vienna's sustainable and smart development.
- Digital technologies can be part of climate action, and climate impact a factor in decision-making in digitalization agenda.
- Important to be deliberate about using indicators for measuring progress.

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Annex 5. Digital-Green Dual Transformation and Sustainable Development in Helsinki, Finland

Helsinki is the capital of Finland, with 1.6 million inhabitants living in the metropolitan area. The city must cope with extreme conditions throughout the year, such as a varying temperature between -30 °C to 30 °C [4] as well as days with 6 hours of sunlight and 18 hours of darkness. The city's economy is thriving with the port being one of the busiest passenger ports in Europe. Helsinki is a hotspot for start-up tech companies, for example in the gaming industry, bringing jobs and investment opportunities to the capital. Helsinki is an attractive city due to its high quality of life, for instance through active use of waterways, and sustainable urban design, i.e. using wood as key building material.

The city is considered a leader on sustainable development, which includes a commitment to reach carbon neutrality by 2030, to implement the UN 2030 Sustainable Development Goals at local level, and to promote non-discrimination and gender equality [1]. Central sustainability challenges for Helsinki include navigating the growth of the city while protecting green spaces, accelerating reduction of greenhouse gas emissions, specifically in transport and building sectors, while keeping resident satisfaction high [2], adapting the city to more frequent and severe flooding. Helsinki aims to be 'Climate Proof by 2050', meaning to implement adaptation measures in land use planning, preparation and preparedness planning, stormwater management, the development of green areas and structures [7].

In Helsinki, smart means to make the sustainable option the easy option. Helsinki Smart Region initiative [3] strategically placed sustainable development objectives at the heart of its links the smart city agenda. Urban innovation means to take a people-centred approach, that prioritizes what works well long-term in the local context. As such, the city starts urban development projects by asking 'who to design for?' and 'how to make this liveable long term?'. That way accessibility needs can be met, transport options and communal spaces tailored to a neighborhoods' needs.

In Helsinki implementing this smart sustainable city approach in the two new districts Jätkäsaari and Kalasatama. Jätkäsaari district is being built on the south-west tip of Helsinki as an extension of the inner city by the sea. Jätkäsaari is a district characterized by a wide range of services, extensive trInam connections and functional cycling and pedestrian routes. As the landowner, the city cleaned up the previously polluted industrial land, auctioned the right to develop plots, strategically steering land use towards diversity, sense of community, accessibility, and quality of life. Once completed in 2030, Jätkäsaari will have homes for 18,000 residents and business space for 6,000 office workers. When developing the design of the buildings social and generational inclusion was a priority. For example, the city was adamant that there mustn't be discrimination between rich and poor with regards to the quality of housing. The districts' waste and transport infrastructure are designed to make the sustainable option the easy option, i.e. correct sorting of waste and cycling instead of taking the private car.

Similarly, Kalasatama district was built on a former harbour and industrial area, is becoming a district for 25,000 inhabitants and 10,000 jobs. Overall, the jointly developed vision of Smart Kalasatama is for everyone to gain an extra hour of free time every day through smart and clean services [5]. To reach this goal, the area serves as a testing ground for experiments and co-creation between the city, companies, researchers and residents in smart sustainable urban development. For example, the district includes a carbon-neutral smart grid that enables users of electricity to also become its producer. The development of Kalasatama is also based on collaborative use of digital technologies enabling quality of life. For example, a Green Kalasatama pilot project tested how an augmented reality (AR) application could be used to help residents commit to and learn about the design of green spaces. Residents across generations could use the application to see and change what a planned green space would look like. The pilot was carried out in Sompasaari, one of the neighbourhoods of Kalasatama, which is located by the sea and is very densely built. The pupils of the local school and the area's residents were invited to discover the future of the built area with the help of the Green Kalasatama application and share their thoughts on what the planned green space should look like [8]. Such integration of digital technologies into participatory planning processes can enable planners to test, iterate, and tailor ideas for sustainable urban development to a local context.

Amongst European cities, Helsinki is also a leader in digitalization. Together with its innovation company 'Forum Virium Helsinki', the city pilots and co-creates innovation that algins with the ambition of the sustainable development agenda. For decades, the city has collected data and drives the development of digital infrastructure and digital capacity enabling digital services and testing of innovative technologies such as artificial intelligence.

The Helsinki Region Infoshare [6] is a key example to how the city shares its datasets and APIs publicly, with the aim to enable private sector innovation for the benefit of all inhabitants. In addition, the city offers various upskilling programs to its employees, for instance, in the field of data engineering.

Lessons learned:

- Smart means to make the sustainable option the easy option.
- Helsinki is using digitalization for innovation to realize a sustainable city which equally includes economic development and well-being for a diverse urban population.
- Collaboration between the city and research institutions, companies, other cities, and inhabitants is key to implementing a smart sustainable city.

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Annex 6. Role of Artificial Intelligence in Waste Management

Single-use plastic waste represents a major environmental challenge, significantly impacting both marine and freshwater ecosystems. In response, governments across the globe are increasingly implementing policies aimed at mitigating this issue, with a particular focus on reducing single-use plastics. According to Xanthos and Walker (2017), policy instruments in the plastic waste sector encompass regulatory measures such as bans, alongside informational and economic tools. These policy interventions aim to address the pervasive problem of plastic pollution through various approaches, demonstrating differing levels of effectiveness and public acceptance.

6.1 Shanghai's smart waste management system

China has taken significant steps to address its plastic waste problem, with a comprehensive plan to ban or restrict single-use plastic products by 2025. This policy includes eliminating non-degradable plastic bags in major cities by 2020 and expanding the ban nationwide by 2022. By 2025, China aims to reduce plastic use intensity in key industries by 30%. Major cities like Beijing, Shanghai, and Shenzhen have reported up to a 50% reduction in plastic bag usage as of 2021 (Ministry of Ecology and Environment, 2021).

Shanghai has been a leading city in implementing smart waste management systems, integrating AI technologies to tackle plastic waste. The city enforced the Domestic Waste Management Law in 2019, mandating the recycling of waste into four categories and imposing fines for non-compliance. This initiative led to a significant increase in sorted kitchen waste, exceeding government targets (Shanghai Municipal Government, 2020).

Key Features:

- **AI-Powered Monitoring.** Smart bins equipped with facial recognition technology weigh rubbish and assign social credits or cash rebates for compliance.
- **Public Engagement.** Innovative methods, such as video games, smartphone APPs, and songs, educate and engage the public in proper waste sorting.
- **Investment.** Over $3 billion invested in the recycling system, showing early signs of success with increased compliance and reduced waste (Ministry of Housing and Urban-Rural Development, 2021).

The successful implementation of a single-use plastic ban in China faces challenges related to public compliance, availability of alternatives, and enforcement. AI technologies offer innovative solutions, enhancing monitoring, optimizing waste management, and supporting data-driven policymaking. Shanghai's example demonstrates how AI can be central to achieving sustainability goals and reducing plastic pollution.

6.2 Policy interventions and effectiveness

The implementation of bans on single-use plastics is a prominent strategy employed by numerous governments. These bans are seen as top-down, command-and-control policy tools that directly eliminate the availability of single-use plastics, thereby forcing a shift in consumer behavior. For instance, policies in the Caribbean have focused on banning single-use plastics and polystyrene, which constitute a significant portion of marine litter in the region (Clayton et al., 2021). In the USA, local governments have adopted a variety of measures, including bans, fees, and educational campaigns, to reduce the consumption of single-use plastic bags. These measures have proven effective in places like San Francisco and Seattle, where significant reductions in plastic bag usage were observed following the implementation of such policies (Wagner, 2017).

Economic instruments, such as levies and taxes, have also been effective in reducing plastic waste. The introduction of a levy on plastic bags in Ireland led to an immediate and substantial reduction in their use, showcasing the potential of economic tools to influence consumer behavior positively (Xanthos & Walker, 2017) Similarly, Wales experienced a dramatic decrease in single-use plastic bag consumption following the introduction of a levy, highlighting the success of such economic interventions (Wagner, 2017).

6.3 Role of artificial intelligence in plastic waste management

Artificial Intelligence (AI) has emerged as a powerful tool in enhancing the effectiveness of sustainable policies for managing plastic waste. AI technologies can assist in various stages of waste management, from monitoring and data collection to optimizing recycling processes and predicting pollution trends. For example, AI can improve waste sorting efficiency by using machine learning algorithms to identify and separate different types of plastics, thereby increasing the rate of recycling and reducing contamination in recycling streams (Xanthos & Walker, 2017).

Moreover, AI-driven data analytics can provide valuable insights into consumption patterns and the effectiveness of policy interventions. By analyzing large datasets, AI can help policymakers understand the impact of bans and levies on plastic use and identify areas where additional measures may be needed. Predictive modeling can also forecast the potential outcomes of proposed policies, enabling governments to design more effective and targeted interventions (Wagner, 2017).

The integration of AI in waste management systems represents a significant advancement in the fight against plastic pollution. By leveraging AI's capabilities, governments can enhance their policy frameworks, ensuring more efficient and sustainable management of plastic waste. This technological approach not only supports the enforcement of existing regulations but also facilitates the development of innovative solutions to address the complex challenge of plastic pollution (Clayton et al., 2021).

In conclusion, the adoption of sustainable policies, including bans and economic instruments, has proven effective in reducing single-use plastic waste. The incorporation of AI technologies further amplifies these efforts, offering new avenues for optimizing waste management and strengthening environmental protection. As governments continue to refine their strategies, the synergy between policy interventions and AI will be crucial in achieving long-term sustainability goals.

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Annex 7. European and Chinese Smart City Indicators

The European Union's assessment criteria for smart cities include several indicators: for example Smart Economy (i.e. innovative economy), Smart Mobility (not only smart transport, but also education, shopping and other important areas), Smart Environment (i.e. focusing on the ecological environment of the city) and Smart Governance (i.e. adapting and improving government management models). Examples include “Sustainable Development in Municipalities - Indicators for Smart Cities" by the International Organization for Standardization (ISO) [1], the Key Performance Indicators (KPIs) for Smart Sustainable Cities (SSC) by United for Smart Sustainable Cities (U4SSC) [2] or the IMD Smart City Index [3].

In 2013, Wang Guangbin summarized national evaluation indicators, among others. He pointed out that there are various evaluation indicator systems for China. [4] These include evaluation index systems by Chen Ming et al. (2011) [5] or the Chinese researchers Lu Cui and Kairui Yang (2018) [6]. Wang Guangbin pointed out that due to the significant differences between cities in terms of government policies, economic fundamentals, infrastructure, laws and regulations, and talent reserves, the indicator settings vary greatly. Most of these systems are government initiatives that focus more on the construction of ICT and other infrastructure, as well as on informatization, and emphasize investment value. They are highly targeted but lack guidance.

On May 1, 2024, Guangdong Province launched pilot studies on the smart city standardization system in cities such as Shenzhen and Zhuhai. These studies aim to establish a smart city standardization system that leverages the construction of smart and digital cities to build an innovative service platform for smart city standardization. The focus covers various aspects including sensing, identification collection, network transmission, computer storage, data services, general engineering services, intelligent applications, and security guarantee. Efforts are being made to explore and formulate local and group standards in areas such as infrastructure, information collection, data exchange, data elements, business applications, operation management, service specifications, intelligent transportation, digital homes, and security guarantee. This resulted in a "Smart City Standardization White Paper 2022".

The “Evaluation Indicators for New Types of Smart Cities” (GB/T33356-2022), which came into force on May 1, 2023, proposes an index system for the construction of new types of smart cities at the prefectural and county levels.

The China Academy of Information and Communications Technology (CAICT) has also reviewed the seven key aspects of smart cities from an industrial perspective, including top-level design, standards and specifications, infrastructure, intelligent hubs, intelligent applications, operational services and cybersecurity.

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Annex 8. Benchmark and KPIs to monitor progress on cities performance towards more sustainable societies

The adoption of digitalization strategies by cities is adding an additional layer to an urban system that is already extremely complicated. An efficient way to guarantee that this new layer delivers its promises of streamlining the adaptation towards a more sustainable urban environment is to monitor the progress and development of the process. Examples of a such a practice are abundant in Sweden. As far as KPIs are concerned, the Swedish public has access to a comparison service, Kolada, which ranks Swedish municipalities according to some variables. On the sustainability-side, Kolada offers overviews on the results that the municipality, as an organizational body, is achieving and on the results that the municipality, as a geographical definition, is obtaining. The former, for instance, offers the possibility to explore the dimensions of operations, for instance, that support green procurement, enhance the use of public transport among the municipal staff or actions that guarantee an efficient use of waste that is produced in premises owned by the municipal government. The latter comprises the results that the collective, including private citizens and businesses, is achieving in terms of sustainability. The use of rankings may, however, provide distorted incentives for the cities to focus on short-term goals and miss the long-term perspective.

Rivalry and competition between the cities may also hinder the willingness to collaborate (Giffinger et al., 2010). The definition of the KPI will likely present a reason for debate given the interests that cities have in picturing themselves as leaders in the greening and digitalizing race. One relevant aspect may be the definition of sustainability. On the one hand, service-oriented cities may be willing to push for a territorial-based emissions approach, while production-oriented cities may push for a fairer account, such as a consumption-based approach, that would attribute emissions to the demand generated in larger and richer cities. Individual cities are extremely complex environment and, on top of that, they are also part of an extensive network of trade of goods and services (Athanassiadis et al., 2018). Attributing responsibilities to one or the other cities for its emissions will result in a long debate.

Cities are home to reduced green environment but they can play a major role in guaranteeing that the urban setting benefits biodiversity too. While the measurement of biodiversity aspects has proven itself to be particularly challenging in the last decade, substantial improvements are being made in urban settings through the use of AI, machine learning and smart cities applications. Nitoslawski et al. (2019) offers a review of what technologies can be used in urban contexts to help monitor and enhance the quality of biodiversity: augmented reality (AR) and virtual reality (VR) for the assessment and the measurement of urban forests; open and big data for real time applications, image classification automation for species identification and disease diagnostics, etc.

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Annex 9. Use "Artificial Intelligence +" to Explore "Digital Intelligence" Mode for Ecological Environment Governance in Yizhuang, Beijing

With the core of continuously improving the quality of ecological environment under its jurisdiction, Beijing Yizhuang continuously enriches the application scenarios of artificial intelligence in ecological environmental protection, expands and improves the ability to analyse and predict environmental problems, explores new paths of precise pollution control and intelligent management, and contributes Yizhuang's power to enhance the ability of modern environmental governance, promote the development of new quality productivity, and build a green and intelligent digital ecological civilization.

The "new artifact" of intelligent networked vehicles to help improve the quality and efficiency of ecological environmental protection. 16 January 2024, the country's first batch of unmanned patrol cars approved for road testing began to be on duty 24 hours a day in Beijing Yizhuang's many parks, underground stations, commercial plazas and other densely populated and key places, becoming the country's first batch of mobile intelligent vehicles to monitor the quality of the air environment. The unmanned vehicle for monitoring the quality of the atmospheric environment, with radar and multi-parameter sensors for monitoring the quality of the atmospheric environment installed on the body, has the dual identity of "security guard" and "air pollution scout". The unmanned patrol car complements the existing satellite remote sensing monitoring and aerial monitoring, and operates 24 hours a day, realising real-time monitoring of respirable particulate matter (PM2.5), fine particulate matter (PM10), nitrogen oxides, ozone and other gaseous pollutants with a total of eight parameters, which helps to accurately monitor the quality of the atmospheric environment and formulate measures to deal with it.

"One network to manage the whole city", press the "fast-forward button" for ecological environmental protection. As a common shared, intensive and efficient city operation integrated perception system, "city operation brain" according to the "positioning of governance priorities, diagnosis of the causes of the problem, event disposal scheduling, governance effect evaluation" management ideas, overview of the air quality situation, support the analysis of pollution trends, closed-loop disposal of events, ecological environmental management like a tiger. It provides an overview of air quality trends, supports the analysis of pollution trends, and realises closed-loop disposal of events, adding wings to ecological environment management. Through continuous self-service monitoring equipment, vibration sensors, etc., Beijing Yizhuang has achieved intensive, real-time monitoring of key industries, key enterprises, motor vehicle telemetry points, etc., and guided enterprises to regulate production and green production. At the same time, the video captures the road with or without slag spillage, whether the slag transport is thatched or not, whether the site is in the stage of earthwork operation, timely and proper dust control, to achieve reliable traceability and accurate pollution control. Through precise and scientific measures, Beijing Yizhuang synergistically promotes high-level protection of the ecological environment and high-quality economic development, and the quality of the ecological environment continues to improve.In the first half of 2024, the cumulative concentration of PM2.5 dropped by 9.5% year-on-year, the road dust load dropped by 53% year-on-year, and the rate of meeting the standard for the river cross-section was 100%, with the proportion of good water bodies reaching 50% steadily.

In order to better understand the biodiversity of the region, most of the bird monitoring previously used the "artificial + observation equipment" method, but the investment in manpower and material resources is large, and the requirements of the personnel are high, it is difficult to ensure the accuracy, continuity and integrity of the bird monitoring. However, the investment in manpower and material resources is large, and the requirements for monitoring personnel are high, making it difficult to ensure the accuracy, continuity and completeness of bird monitoring. 2022 July, Beijing Elk Ecological Experimental Centre and the Institute of Semiconductor Research of the Chinese Academy of Sciences cooperated to set up a set of "audio-video intelligent perception" based on the AI bird identification system, which provides an innovative means of investigation and dynamic monitoring of avian biodiversity. At the beginning of 2023, the Elk Park was the first time to monitor the white-tailed sea eagle, a national-level protected animal, by artificial intelligence, which was also the first time to monitor a rare raptor after the adoption of "bird" face recognition in this area. This white-tailed sea eagle in the Elk Park stayed nearly 3 months, spent a full winter. With the "reminder" of the intelligent monitoring system, it is also very helpful for the monitoring staff to understand the habits of the birds.