China Council for International Cooperation on Environment and Development (CCICED)

Promoting Digitalization and Green Technologies for Sustainable Development

CCICED Special Policy Study Report

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Contents

Executive Summary

The Chinese economy has undergone a phenomenal process of digital transformation over the past decades, which has significantly contributed to China's economic development and extended its influence beyond the national border. This Special Policy Study Report of the China Council for International Cooperation on Environment and Development (CCICED) explores the link between digitalization and sustainability within a clear mission: digitalization as a major transformative force of the 21st century must be put at the service of sustainable development. Based on theoretical and empirical studies conducted by the project team, comprising Chinese and international members, the report aims to provide policy recommendations on promoting digitalization and green technologies for sustainable development in the Chinese context. Special thanks are given to Mr. Scott Vaughan, International Chief Advisor of the CCICED, and Prof. Shijin Liu, Chinese Chief Advisor of the CCICED, for their valuable guidance throughout the project cycle.

Achieving sustainable development at the global level is a historically unprecedented task. Efficient strategies to address the sustainability challenge should examine the complicated socio-techno-economic transformation process with a comprehensive system perspective covering several areas, such as agriculture and food, consumption, energy, manufacturing, and mobility, and consider their interdependencies and synergies. In practice, strong capabilities shall be in place to initiate, drive, and scale up the multiple transition processes toward sustainability. Representing the next level of General Purpose Technologies (GPT), digitalization offers a powerful solution space of digital capabilities to match the urgently required transformation capabilities. To better realize this potential, digital transformation needs to be guided at the national policy framework level to provide directions and purposes to technological innovation and deployment, and a holistic policy approach is needed to tackle the strategic gaps between digital technology and sustainability transformation.

China has made breakthroughs in the development of its digital sector, which is already the second largest in the world. The fast development of the Chinese digital economy has been associated with rapidly rising energy consumption and carbon emissions, as well as other environmental issues, such as e-waste. Currently, digital infrastructure, companies, and services in China are facing high pressures on green upgrades. To achieve such upgrades, proactive policy measures are needed to promote energy conservation, enhance energy efficiency and foster the decarbonization of digital infrastructure, in particular data centres. Furthermore, policies shall actively promote the low-carbon development of digital companies, encourage green social responsibility and sustainability reporting, and improve the supportive capabilities of digital technologies to empower industries to reduce carbon emissions.

At the city level, digitalization contributes to several urban problems but offers sustainable solutions in areas like transport, buildings, and urban planning. For example, digitalization can replace resource-demanding offline activities with online services, optimize existing activities, and enhance resource circularity and efficiency. However, digitalization and the associated efficiency gains can also lead to increased consumption—the so-called rebound effects—that may overcompensate efficiency effects. Conceptually, transitions in urban mobility and buildings toward sustainability are distinguished as "avoid, shift, and improve." Digitalization supports the transition in all three areas and provides opportunities for emerging new technologies and business models. In spatial planning, artificial intelligence (AI) and machine learning can help promote energy-conserving urban form and inclusiveness. Building smart, sustainable cities can create win-win-win opportunities, as they support economic growth, advance the quality of life, and reduce the local and global environmental burden. Realizing these goals requires substantial policy efforts, including, for instance, implementing a "Smart Sustainable Cities Audit" system, advancing urban digital governance, promoting special sustainability zones, and implementing sustainable urban planning with the support of AI.

In the fight against climate change, digital technologies contribute to both mitigation actions and adaptation efforts. China's National Climate Change Adaptation Strategy 2035 emphasizes the role of technical support and research and development, and, in this context, deploying relevant advanced digital technologies, such as AI, for high-accuracy meteorological forecasting, an important area of action. In this regard, the government shall strengthen support for scientific and technological research in the field, improve multi-source data integration and multi-institutional coordination, and accelerate related legislative efforts.

As GPTs, digital devices and applications reflect and (re-)produce social relations and understandings of the world. Therefore, it is vital to understand the costs and benefits of promoting digital technologies, especially for those who stand to benefit and who do not. The gender dimension is crucial, and it is necessary to make gender analyses part of policy planning and monitoring. To deal with gender-related biases, the government can consider the following policy actions: raising awareness, detecting biases in datasets, reducing existing biases, and enhancing transparency. This requires keeping gender-conscious humans in the loop of AI development.

Key Policy Recommendations

- The government must establish clear standards, timelines, and credible pathways to decarbonize the digital sector and meet carbon-peaking and carbon neutrality targets. A crucial step is to facilitate the green transformation of digital infrastructure and reduce its carbon emissions by promoting energy conservation and enhancing energy efficiency, with a particular focus on data centres. Additionally, it is crucial to effectively manage the carbon emission data generated throughout the entire life cycle of electronic equipment. At the corporate level, it is imperative to promote and incentivize green social responsibility and sustainability reporting. Regarding digital technologies, both hardware and software should be consistently optimized to play an increasingly important role in empowering other industries in managing and minimizing carbon emissions. In this context, digital technologies are the key enabler of the green transition, both in planning processes and consumer choices.

- China has made significant progress in developing smart cities, but there is a need for further alignment with the green transition. To address this, the government could explore the implementation of a "Smart Sustainable Cities Audit" system, which would evaluate the extent to which digital technologies are effectively employed to promote sustainable development in crucial areas such as mobility, buildings, and spatial planning. It is also necessary to advance urban digital governance in accordance with climate goals to improve sustainable urban planning with the support of artificial intelligence and to promote highly efficient pooled mobility.

- Harnessing digital technologies is crucial in establishing climate resilience and enhancing early warning systems for extreme events. To achieve this, the government should prioritize bolstering support for research and innovation in targeted digital adaptation solutions. It is equally important to establish data standards, data-sharing mechanisms, and coordination policies in the realm of climate change adaptation, including fostering information exchange and cooperation between various agencies. Legislative measures should also be taken to incentivize the development of digital climate change adaptation solutions.

- Gender mainstreaming in digitalization is of utmost importance. It is crucial to integrate gender analyses and encourage woman's participation as integral components of policy-making and implementation processes. To achieve this, collecting gender-disaggregated data and promoting data-based research on gender is essential. Furthermore, there is a pressing need to detect and mitigate gender bias in risk assessments for emerging digital technologies and solutions, including within the field of artificial intelligence.

1. Theoretical Basis and Conceptual Framework

1.1 Introduction

The overarching topic of this study links two of the most relevant development trends of our time within a clear mission: digitalization as the dominating transformative force of the 21st century must be put at the service of sustainable development, as the most pressing transformation challenge of the 21st century.

Chapter 1 establishes a conceptual framework to research digital technology opportunities and related policy implications for leveraging digital technologies for sustainable development. Based on these initial considerations, the subsequent chapters in this report will investigate selected use cases in greater detail and elaborate in a four-step approach the theoretical basis and the conceptual framework.

Chapter 1 addresses the following questions. First, what is the nature of the sustainability challenges ahead of us, and what transformation capabilities are required for entering successful transition pathways in complex technological, economic, and social systems (Section 1.1.)? Second, what is the key mechanism and the potential contribution of digital technologies and solutions to the sustainability transformation challenge, given their character as GPTs (Section 1.2)? Third, what are development patterns for digital technologies, related capabilities, and platform economies in China, and what is the state of the digital business ecosystem (Section 1.3)? Fourth, what are the strategic gaps to be tackled in order to fully benefit from the digital opportunity space, what are the characteristics of a sustainable development of digital economies and societies that require new policy thinking, and what are the generic categories of policy approaches to leverage the digital solution space for sustainability that should be investigated in the case studies (Section 1.4)?

1.2 Embracing the Sustainability Transformation Challenge

1.2.1 Problem Statement: What is the nature of the sustainable development challenge?

Entering the 21st century, humanity is confronted with severe and aggravating risks to the global Earth system and its ecological balance. Illustrated by the concept of planetary boundaries (Rockström et al., 2009), there is growing scientific evidence that human activities are overstretching the ecological limits of our planet, e.g., with regard to an accelerating loss of biodiversity or increasing pressure on freshwater resources. Most prominently, climate change impacts are affecting societies around the globe, calling for a rigorous reduction in GHG emissions and—ultimately—aiming at climate neutrality around the middle of the century.[1] Digitalization itself is a major force of the Anthropocene Era, with direct and indirect implications for planetary boundaries (Creutzig et al., 2022).

Hence, all countries worldwide are facing a joint challenge to setting the course for achieving the sustainable development of societies and economies while safeguarding the ecological foundations of our well-being and prosperity. From the broader perspective of the 17 sustainable development goals put forward in the United Nation’s "Transforming Our World – 2030 Agenda for Sustainable Development," [2] the essence of the sustainability challenge is the need to coordinate and reconcile the development dynamics between the various dimensions of economy, society, and the ecological environment. While jointly experiencing numerous aggravating ecological crises, the world still faces divergent perspectives and trade-offs when entering zero-growth pathways of population and achieving equal economic prosperity on a global scale.

One holistic approach to this challenge is China's Ecological Civilization strategy. Facing the resource and environmental problems that occurred during the process of accelerating industrialization and urbanization, the Report of the 18th Communist Party of China (CPC) National Congress in 2012 proposed the strategy of Ecological Civilization Construction, believing that ecological civilization is the sum of material, spiritual, and institutional achievements made by human beings to protect and build a beautiful ecological environment. Also, it runs through the whole process of economic, political, cultural, and social construction. On March 24, 2015,

[1] Intergovernmental Panel on Climate Change IPCC (2023): Synthesis Report of the sixth IPCC Assessment Report (AR6), https://www.ipcc.ch/report/ar6/syr/, access 29.3.2023.
[2] United Nations (2015): Transforming our world: the 2030 Agenda for Sustainable Development, Resolution adopted by the General Assembly on 25 September 2015 (A/RES/70/1), access 29.3.2023.

the Political Bureau of the CPC Central Committee deliberated and adopted the Opinions on Accelerating the Construction of Ecological Civilization (hereinafter referred to as the Opinions). In October 2015, strengthening the construction of ecological civilization was included in the national "Five-Year Plan" for the first time. On March 11, 2018, the sixth item, "leading and managing economic work and urban and rural construction," in Article 89 of the Constitution "The State Council exercises the following functions and powers," was revised to "leading and managing economic work, urban and rural construction, and ecological civilization construction" through the amendment to the Constitution adopted at the first session of the 13th National People's Congress revised. The construction of ecological civilization is considered a fundamental change in China's development notion and mode, involving various aspects of economic, political, cultural, and social construction. Closely related to the layout of productive forces, spatial pattern, industrial structure, production mode, and living styles, as well as the value concept and institutional system, ecological civilization construction is a comprehensive and systematic project.

In this context, achieving sustainable development at a global scale is a historically unprecedented task, characterized by the following features:

- The increasing urgency to act as current trends and projections of ecological tipping points (e.g., in global climate systems) indicate that the room to manoeuvre is shrinking, and the time window for achieving sustainable system changes is closing.
- The complexity of reconciling and coordinating social and economic development processes in balance with ecological and environmental boundaries. These dimensions are intertwined, calling for holistic approaches to enhance human well-being and quality of life within a healthy natural environment. Importantly, this also requires global cooperation on climate change, biodiversity, artificial intelligence and other threats to human survival.
- The need for aspiring at bold ambitions, one of them being the decarbonizing of our societies within a few decades, calling for far-reaching system changes in the economy and society, such as the transition to a fully renewable energy supply and drastic reductions in global resource consumption patterns.
- The need for a system-thinking mindset at all levels. Individuals as well as institutions or societies must embrace, understand, and manage the multi-faceted interrelations, interdependencies, and dynamics of acting in complex systems. It is important to look for tangible action points and insights that are action relevant in this regard.

Therefore, there are some key implications for designing and implementing strategies for sustainable development.

1.2.2 How to Get It Solved: Cultivating the core transformation abilities to achieve sustainable development

Effective strategies to address the sustainability challenge aim at driving socio-techno-economic transformation processes. This requires the following key elements:

- A comprehensive system perspective covering the full range of sustainability transformation areas, such as energy, mobility, agriculture and food, manufacturing, consumption, cities, and urban transitions. Fighting climate change, for example, depends on GHG emission abatement in all sectors. Moreover, interdependencies and synergies need to be taken into account, for example, in the introduction of e-mobility and the expansion of renewable energy sources or the linkage between urban planning and mobility demand patterns.
- Fundamental structural changes (system changes) that redefine the physical and institutional boundary conditions for individual and collective action, such as a shift toward decentralized renewable energy systems, enhancement of public transport infrastructure, transforming the built environment of cities, (re)designing markets and economic rules, reform of institutional settings, mandates, and capabilities, etc.
- A process of understanding and acknowledging the dynamic nature of the problem as well as the growing evidence and knowledge on cause-impact relations and solutions. There is no simple solution,

and the whole world needs to advance step by step, taking the benefits from quick wins while investing in long-term solutions, continuously learning, and improving our capabilities.

- Collaboration and international cooperation as the system changes at the scale and impact needed cannot be achieved in isolation but require global effort, joined forces, and coordinated governance.

At the operational level, these requirements can be translated into core capabilities needed to initiate, drive, manage, and scale the multiple transition processes toward societal, economic, and environmental sustainability on all levels. Such a set of generic sustainability transformation capabilities could provide conceptual framing for exploring, assessing, and enforcing the potential contribution of digital solutions to sustainability. Tackling the sustainability challenge requires the ability to realize multiple objectives related to a very high level of required changes (Table 1.1).

Table 1.1 Transformation abilities to achieve sustainable development

Monitor the Earth system	Monitor and analyze the state of the environmental space, specify and measure KPI trends and quantify impacts of private initiatives and public policies for decoupling human activity from environmental impact
Manage complex technical systems	Control, optimize, and (re)design technical infrastructures and equipment, especially for achieving decarbonized energy provision and sustainable resource use
Guide research and innovation	Enhance scientific research, development, and innovation and leverage the emerging technology capabilities for solving sustainability challenges (*directionality of innovation*)
Reform economic value creation	Manage economic transactions, shape governance frameworks of (international) value networks and markets for spurring business model innovation and leveraging entrepreneurial dynamics
Enhance human engagement	Trigger individual and collective commitment (readiness to act) and strengthen their competencies (ability to act) through value orientation, information, education, and empowerment of individuals as well as triggering social innovations in communities, organizations, and society
Adaptable institutions and policies	Modify governance systems, establish effective institutions, and foster policy innovation via new modes of collaboration and enhanced regulatory learning

1.3 Digital Capabilities and Sustainable Development: The opportunity space

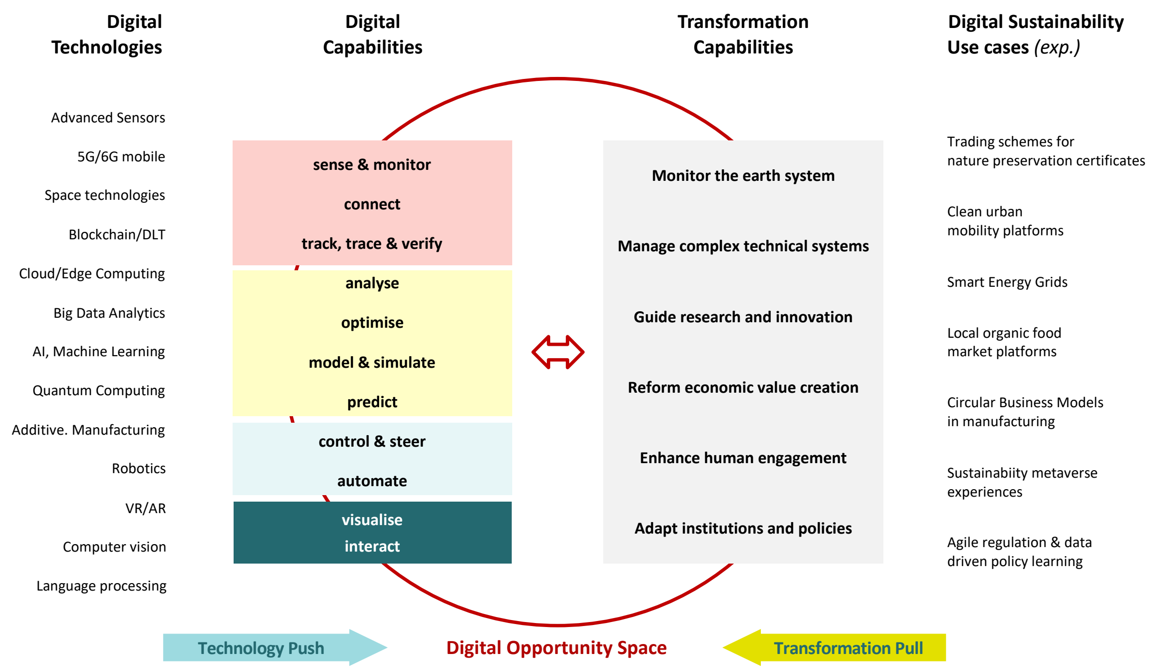
Distinct from the previous three industrial revolutions, the ongoing digital transformation fundamentally changes the complex system interrelations between technology, economy, and society on an informational level. Whereas in former times those interrelations have been formed mainly by physical and monetary interactions, digital societies and digital economies are based on the emergence of cyberspace and the underlying data relations between objects, people, and activities—both in the physical space of manufacturing, infrastructures, and the built environment as well as in the economic and socio-cultural space. This offers new opportunities to create new technological economic and social systems oriented to sustainable development and, at the same time, requires new political and institutional regulatory capabilities (cf. Section 1.4).

This process is driven by the outstanding development dynamics of digital technologies, which are a new generation of information technologies, including the Internet, the Internet of Things (IoT), 5G/6G mobile communication, cloud or edge computing, big data analytics and artificial intelligence, etc. In most use cases, several of these technologies interact and reinforce themselves as digital solutions, i.e., in the case of self-driving cars that build on advanced sensors, 5G/6G telecommunication, high-performant edge computing, and AI. In addition, versatile digital platforms allow us to connect and integrate multiple digital services, thus accumulating digital capabilities, use cases, and user communities. This is of special relevance with regard to the interactions with startups. Whereas startup companies often succeed by solving specific "pain points" in economic, social, and ecological areas, the overarching platforms play a critical role in the selection and allocation of opportunities, technologies, human capital, and sources of financing for entrepreneurship.

Digital platforms, therefore, play a pivotal role in shaping the digital space by introducing new economic playgrounds and market coordination mechanisms. In this sense, digital transformation is a multi-dimensional phenomenon, combining physical hardware with virtual software and services.

This offers great opportunities for sustainability. Through sensing, data collection, connection, and sharing, data analysis driven by growing computing power and performant algorithms and the data-based interference into the physical world by controls, data-driven operation regimes, and ultimately even automated devices such as robots, human beings can continuously monitor, evaluate, reorganize, and optimize economic and social activities. Digital transformation offers a powerful solution space of digital capabilities that now need to be matched with the urgently required transformation capabilities introduced in the previous Section 1.1 (Figure 1.1).

Figure 1.1 Illustrative mapping of the digital opportunity space for sustainability



The key question is now: how to leverage the digital opportunity space for the sustainability challenge? Digital transformation and its technologies are not limited to specific use cases or sectors. In line with historical precursors such as the introduction of electricity at the end of the 19th century, digital transformation represents the next level of GPTs that lay the foundation for a broad boost of technological innovation and socio-economic development across civilizations. Digital technologies are versatile and ubiquitous, their impact diffuses into almost every aspect of human life. The emergence of such cyberspace and its interaction with the physical and social spaces turns the core elements of "data" and "computing" into strategic assets for creating and managing complex technological, economic, and social systems.

Moreover, digital transformation is characterized by unique patterns of economic cost degression. Technical progress is continuously squeezing the cost of hardware, illustrated by the famous Moore's Law for computation performance. Once the physical basis of infrastructure and devices is established and the initial costs of software development are covered, any further expansion of digital functionality and outreach can be realized at very low or even close to zero marginal costs. This is a fundamental difference from traditional manufacturing paradigms, and it opens up so-far unseen opportunities for scaling digital services within user groups and application areas as well as for the transfer between application areas and sectors.

With these aspects in mind, the implications for sustainability policy-making are straightforward. The availability and accessibility of green digital technologies need to be expanded to strengthen the digital capabilities and put them into service for growing our transformation capabilities through spreading and scaling digital solution use cases for sustainability.

Hence, the task is twofold:

- **Technology push**. Ongoing technical progress and innovation are boosting the performance of digital technologies and, hence, are expanding the versatility and functionality of the digital toolbox. This potential needs to be leveraged and directed toward the pressing sustainability challenges. Part of this task is to reduce the environmental footprint of digital technologies themselves regarding energy demand, GHG emissions, and e-waste (Chapter 2). Nonetheless, to avoid the risk posed by artificial intelligence to humanity, it's also important to restrain technology development in certain areas, e.g., in terms of multi-modality capability.[3]
- **Transformation pull**. From the transition perspective, the single-use cases need to be scaled, disseminated, and transferred, aiming at growing critical momentum and self-sustaining demand for system change. Hence, the notion of the sustainability transformation capabilities helps to systematically search, scan and investigate the opportunities to benefit from the digital capabilities—and hence spurring the sustainable deployment and commercialization of technologies and solutions.

This section provides a generic framework for describing the functional relations between digital technologies and the sustainability transformation capabilities introduced above in Section 1.1. (e.g., better decision making under conditions of uncertainty and complexity). It sheds light on general aspects of how to shape the complex socio-technical innovation system required for sustainability in technologies, economy, and society. This provides the basis for sketching the overarching framework for policy-making in the next section and discussing in greater detail the case studies of Sustainable Cities and Climate Change Adaptation in the following chapters.

1.4 Sustainable Development Driven by Digital Technology: China's practices and prospects

After 2015, it has become a strategic choice of China to achieve sustainable development through the development of the digital economy. This section illustrates innovative applications of digital technology driving the achievement of economic, ecological, and social goals of sustainable development through the building of core competencies. The section refers to quantitative data analysis of technology partnerships among 2,200 Chinese digital backbone enterprises.

1.4.1 Characterization of China's Digital Economy

By classifying the core business of 2,200 digital key enterprises, these enterprises are distributed in 20 business areas. Among these, two business areas, enterprise technology integration and solutions together with smart business and retail, account for the highest proportion of the total number of enterprises, which are 17.20% and 10.31% respectively. Intelligent robots, intelligent hardware, technological finance, smart health care, and intelligent manufacturing account for a relatively high proportion of the total, which are 8.39%, 8.06%, 7.39%, 7.27%, and 6.26% respectively.[4]

[3] See e.g.: https://europepmc.org/article/med/26185241; https://dl.acm.org/doi/abs/10.1145/3514094.3534146.

[4] Data source: China Intelligence (Digital) Economy Database of Chinese Institute of New Generation Artificial Intelligence Development

These enterprises are centred around a few dominant platform nodes. In 2021, in the value network of China's digital economy (Figure 1.2), the 10% nodes with the highest degree of centrality accounted for about 70% of the links in the network.[5] Innovative platform enterprises, including Huawei, Baidu, Alibaba, Tencent, JD, iFLYTEK, and SenseTime, and industrial innovative ecology guided by them are playing leading roles in the development of China's digital economy. The platform, together with research universities, research institutions, technology-based SMEs and startups, governments, and other organizations, form an innovation ecosystem and are carriers of digital technologies and capabilities.

Figure 1.2 Value network diagram of China's digital economy in 2021

1.4.2 Technology System and Application Areas

Digital technology is a complex technology system, including 17 key technologies, which are big data and cloud computing, the Internet of Things, intelligent robots, intelligent recommendation, 5G, blockchain, speech recognition, virtual/augmented reality, AI chips, computer vision, natural language processing, biological recognition, space technology, photoelectric technology, automatic driving, human-computer interaction, and knowledge map.

Digital technologies are widely applied to 19 applied fields in China, which are intelligent management of enterprises, intelligent marketing and new retail, scientific finance, smart city, smart medical treatment, new media and digital content, intelligent manufacturing, smart education, intelligent transportation, network security, intelligent logistics, intelligent cultural tourism, smart governance, smart energy, intelligent hardware, intelligent connected vehicle, smart home, smart agriculture, and intelligent security.

Viewing from the results of the analysis of application complexity of China's digital technology in 2021 (Appendix 1), knowledge map, blockchain, human-computer interaction, natural language processing, and intelligent recommendation systems are the top five complex key digital technology for technology application. The results of the calculation of the complexity of a technical system of the application field showed that intelligent manufacturing, smart home, intelligent marketing, new retail, intelligent hardware, and intelligent management of enterprises are the top six technically complicated applied fields. There is little difference in technical complexity between either the 17 technologies or the 19 application areas, indicating that digital technologies have similar general-purpose technical characteristics.

1.4.3 Innovative Applications of Digital Technology in the Economy

The application of digital technology in the economy first became large-scale in the Consumer Internet and then extended to the Industrial Internet. Since 2016, the upgrading of the Consumer Internet and the diffusion of industrial ecosystem in cyberspace to small- and medium-sized cities and rural areas have not only driven the

Strategies, Chinese Academy of Engineering, 2022.

[5] Ibid.

development of tertiary industry but also radiated the transformation and upgrading of secondary industry.

In the field of the Consumer Internet, the innovative application of the new generation of information technology has given rise to the dominance of trading platforms. The development of trading platforms has produced vast amounts of data that are online, shared, and traded in real time. The formation of the digital ecosystem further leads to the innovation and application of algorithms, computing power, and blockchain technology, including the development of data technology systems and the expansion of application fields.

China's Consumer Internet sector is mature in metropolitan areas, including Beijing, Shanghai, Hangzhou, Chongqing, and Shenzhen. Since 2016, the trend has moved down to small- and medium-sized cities and rural areas. Furthermore, new platforms have promoted the development of e-commerce in many verticals, including clothing, food, housing, and transportation. It not only allows consumers to enjoy more convenient services but also creates a lot of employment and entrepreneurial opportunities for low- and middle-income people, especially rural residents.

The Industrial Internet is a new type of infrastructure deeply integrated with the new generation of information technology and the industrial economy. Through the interconnection of equipment, material flows, and parts in the value chain, new value systems, including flexible manufacturing, service, and services, emerge. For the development of the Industrial Internet, AI plays a pivotal role. Production intelligence includes the development and production of intelligent factories, intelligent production lines, and intelligent equipment. From the current situation of integrated development of AI and the manufacturing industry, in 2021, among 32 AI technology cooperation between core industry sectors and the manufacturing industry, the top five are all related to the equipment manufacturing industry. Intelligent equipment is at the forefront of deep integration of artificial intelligence and manufacturing. As of January 2023, there are 50 lighthouse factories in China among the 132 lighthouse factories in the whole world selected by the World Economic Forum.[6] From the practice of enterprise digitalization and intelligent transformation, the deeply integrated development of artificial intelligence and the manufacturing industry can continuously improve the total factor productivity, making China's economy enter the development stage of high economic growth.

1.4.4 Application of Digital Technology in Social Fields

The application of digital technology in the social sector is mainly to solve the "social pain points" that emerged during the industrialization and urbanization of China. Among these applications, deploying digital technologies to solve urban problems and achieve poverty eradication are successful examples.

Smart Cities

China's urbanization entered a rapid development stage in the 21st century. The rapid development of cities has also brought about social pain points such as traffic, safety concerns, pollution, and access to education and medical care. Smart Security and Smart Cities have become the major playing fields for digital technologies. Since 2009, the combination of edge computing and cloud computing systems has given birth to the city brain concept, which laid the digital capability in the construction and development of smart cities. Chapter 3 will elaborate on the topic of cities.

Digital Poverty Alleviation

In 2016, the Chinese government released the Online Poverty Alleviation Action Plan, which calls for the implementation of five major online poverty alleviation projects: network coverage, rural e-commerce, online intellectual support, information services, and online public welfare, giving full play to the role of digital technology in boosting poverty alleviation and achieving targeted poverty alleviation and eradication objectives. The plan aimed to lift more than 70 million people out of poverty, where the innovative application of digital technologies was expected to play a significant role.[7]

By 2020, China has made some main achievements in network poverty alleviation: The network in poor areas in China has been 100% covered, and the proportion of optical fibre in poor villages has increased from less than 70% before the implementation of universal telecommunications services to 98% now; E-commerce now covers all 832 impoverished counties in rural areas; Online retail sales in rural areas increased by 8.4 times from

[6] https://initiatives.weforum.org/global-lighthouse-network/home

[7] http://www.xinhuanet.com/politics/2015-12/03/c_128494323.htm

RMB180 billion in 2014 to RMB1.7 trillion in 2019; The Internet access rate in primary and secondary schools increased from 79.2% at the end of 2016 to 98.7% by August 2020 which has enhanced distance education and enabled the most remote rural areas to access high-quality urban education virtually; Telemedicine has covered all poverty-stricken counties and county-level hospitals, and the basic financial services in administrative villages reached 99.2%.[8]

1.5 Leveraging the Digital Transformation Opportunity Space – Closing the strategic gap between digital technology and the sustainability transformation

The previous section revealed the great opportunities to foster sustainable development by deploying digital technologies and leveraging digital capabilities for manyfold transformation purposes in our economies and societies. To fully benefit from this potential, mechanisms of how to implement digital solutions and explore the diversity of channels for dissemination must be better understood.

The starting point is promising in that a lot of digital capabilities are present. Digital technologies and solutions are already omnipresent in everyone's lives, offering versatile applications, and increasingly shaping the world. Many players are already engaged in moving technology borderlines through R&D, driving business innovation, and creating new markets. It will be vital to successfully harness the entrepreneurial creativity of these actors and related market dynamics. At the same time, however, digital transformation is still far from being a self-fulfilling sustainability promise.

Technology innovations, business models, and use cases too often still serve short-sighted patterns of profit maximization at the price of resource consumption and environmental damages or even perpetuate prevailing unsustainable fossil path dependencies. There are strategic gaps between the digital technology potential and the actual—often non-beneficial—contributions to the sustainability transformation. Recalling the nature of digitalization as a GPT, any detrimental impact is not related to the intrinsic nature of digital technologies per se but depends solely on the socio-economic-political framework of application areas and use cases. This holds not only for the ecological effects of digitalization, but ambivalent impacts can be found with regard to the social aspects of sustainability such as gender issues. Whereas digitalization can improve the lives of women, e.g., through e-commerce in rural areas, there is an increasing risk of distorted and gender-biased data foundations of AI modelling resulting in flawed results, discrimination, inequalities, etc. of such solutions (Box 1.1). To ensure that data is used appropriately, the governments need to gain knowledge of data biases, study them systematically, and adhere to international guidelines (Berkley Haas Center for Equity, Gender and Leadership, 2020).

Box 1.1 Artificial intelligence and biases

AI is "a machine-based system that is capable of influencing the environment by producing an output … for a given set of objectives" (UNESCO, OECD, and IDB, 2022). This definition demonstrates the power and, at the same time, the weakness of AI. Algorithms use data to make reliable predictions and seemingly neutral decisions. However, datasets that algorithms draw from use existing data. More often than not, this data is therefore not neutral and is characterized by biases. Biases are unjustified preferences for or against something and often happen unconsciously. From data collection, through data labelling, to the analysis, evaluation, and interpretation—biases can be found at every stage of the data processing cycle (World Economic Forum, 2022). For example, gender biases can be found in countless examples and different application areas, which becomes particularly relevant for AI and machine learning when they find themselves in training data fed to algorithms. Here, the "garbage in, garbage out" principle takes effect, i.e., the quality and values conveyed by the input data are reproduced in the output, which can cause harm through direct and indirect discrimination, e.g., in the context of health, hiring processes, or translation software (McKinsey, 2021). A global analysis of 133 AI systems across industries found that 44.2 % demonstrate gender bias (UN Women, 2023). The increasingly ubiquitous use of AI systems, such as ChatGPT, is threatening to make bias reproduction an increasingly

[8] https://www.gov.cn/xinwen/2020-11/06/content_5558468.htm

prevalent problem.

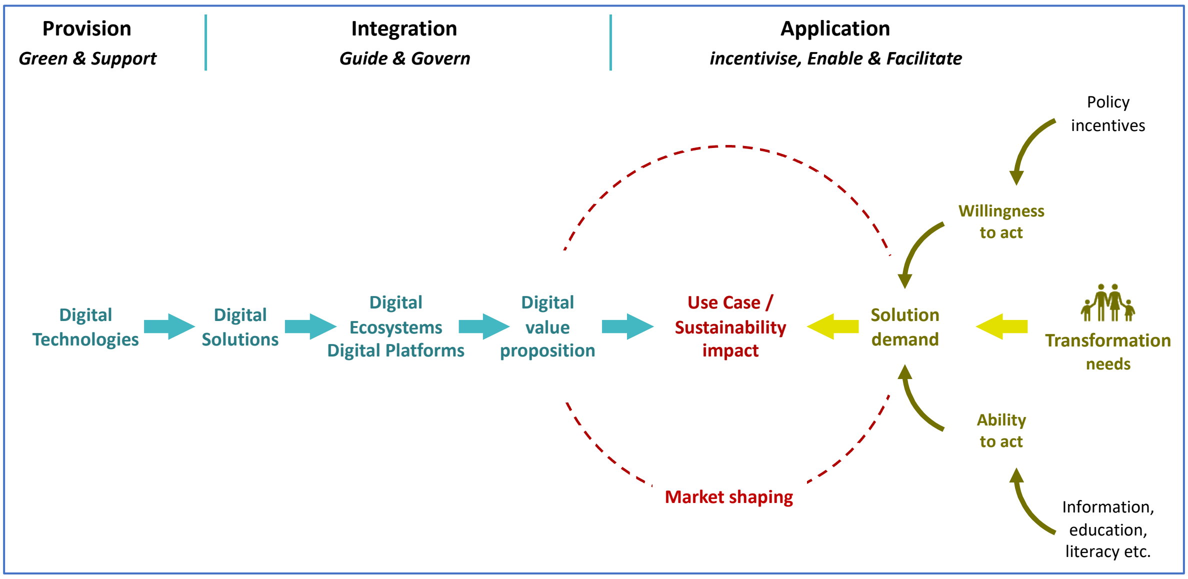
A major challenge in making AI systems gender-responsive is the existing gender data gap. UN Women stated in 2022 that only 42% of the gender data for monitoring the gender-specific dimensions of the SDGs exist or are accessible. The gender data gap would need 22 years to close (Encarnacion et al., 2022). To make girls and women in all their diversity visible and represented in data—and by that address essential biases in training data—it is inevitable to collect gender-disaggregated data. Also, it is advisable to think of new forms of data sources, to enable diverse and multidisciplinary teams and to include gender equality advocates and other civil society groups in the development processes (UN Women, 2018).

Therefore, digital transformation needs to be politically framed and guided in order to provide directions and purposes to technological innovation and deployment, which includes both the trigger for exploiting currently untapped benefits and limiting adverse effects of today.

Hence, a holistic policy approach is needed to tackle the strategic gaps across the various stages of the technology implementation and deployment cycle. Such an approach needs to consider stakeholders' divergent roles and responsibilities within the complex socio-technical systems. Aiming at innovation and business-friendly frameworks to leverage private enterprises and market dynamics, clear guidance on overarching ecological and social values and practical incentives for directing economic activities toward decarbonization and resource efficiency are in demand, which sheds light on the role and effectiveness of (public) institutions and highlights the responsibility of politics to enforce adequate coordination mechanisms.

The following three core building blocks will be essential for policy initiatives striving for a digital-driven sustainability transformation (Figure 1.3):

Figure 1.3 Illustrative mapping of the strategic policy space for digital sustainability



Fostering a Green Technology Push

Given the increasing availability of digital technologies and, thus, growing technological innovation momentum (cf. Section 1.3), the main task is to diminish the environmental footprint of digital technologies. Therefore, "greening" and decarbonizing the digital sector must become a policy priority in the early stages of technology provision, including less resource use and enhanced circularity of digital devices.

Accordingly, academic, public, and private R&D funding will be beneficial but not sufficient without enforcing ecological quality requirements. In this context, early-stage technology development will benefit from proper incentives for sustainability during the commercialization phase, such as regulation on the clean energy supply for data centres and telecommunication infrastructure, as well as the proper reuse and recycling of devices (Chapter 2).

Guiding and Governing Sustainable Digital Value Propositions

Enterprises, private actors, and platform players play a vital role in integrating digital technologies and accumulating digital capabilities, e.g., within digital ecosystems. They set the rules and boundaries for access to solutions and define the conditions for enjoying the digital value propositions offered.

Usually, the commercial interests of those players and prevailing market characteristics determine the outcome, again, too often not yet oriented toward sustainability goals. Hence, in this stage, policy and effective institutions for market surveillance can play an important role in guiding and governing the scope and rules for offerings, e.g., in terms of ecological standards, fairness, gender equality, level playing fields in competition, interoperability, inclusivity, privacy protection, and consumer protection, etc. This requires a holistic approach to institutional design as well as policy coordination among various government agencies.

Growing Market Momentum and Strengthening the Sustainability Transformation Pull

At the same time, private engagement and market forces represent powerful drivers for sustainability transformation. Hence, all kinds of private and public stakeholders need to articulate their increasing demand for realizing digital use cases with sustainability impact, which triggers technology innovation, solution development, and the commercial engagement of players aiming at capturing the growing green solution markets.

Accordingly, policy should address the stakeholders' willingness to act by providing economic and regulatory incentives for sustainable use cases. In addition, policies should enhance the stakeholders' ability to act, e.g., through improving individual literacy, education, removal or mitigation of barriers, facilitation of self-organization, networking, etc.

Moreover, a very important role for policy-making is to provide complementing market frameworks and market incentives for establishing and growing a self-sustaining commercial dynamic in deploying sustainable digital solutions (e.g., with generic strategies of emissions regulation, GHG trading schemes, or resource pricing). It is equally important to break the supply pull for digital value propositions that are associated with unsustainable outcomes, such as the fostering of GHG-intensive consumption or fossil fuel exploration.

The following chapters will discuss the strategic gaps and relevant policy requirements in greening the digital sector, sustainable cities, and climate change adaptation in detail. Therein, a specific focus will be given to the following aspects: 1) the opportunity for governance innovation and related growth of policy capacities through digital solutions, i.e., digitalization as enabler and driver for policy reforms; 2) the pivotal role of politics in creating and shaping markets and, hence, preparing the seed ground for private business model innovation and entrepreneurship; 3) the importance of overarching environmental policy frameworks of climate change mitigation, resource management, nature preservation etc., such as enforcing the growth of renewable energy sources (RES) as key to achieve decarbonized energy supply to data centres or implementing adequate CO_2 and resource pricing for better integrating harmful environmental externalities into private commercial rationalities; and 4) the contributions of government-led digital projects aiming at environmental protection that serve as drivers for digital capability accumulation and, thus, can ignite multiplication and growth effects in adjacent digital solution arenas (see Box 1.2 for the case study on the pollution control of Taihui Lake).

Box 1.2 Taihu Lake pollution control and Wuxi IoT cluster

The Taihu Lake Economic Zone is one of the most economically developed regions in China. Since 2005, it became obvious that industrialization and a continuous increase in population density are putting pressure on the Taihu Lake ecosystem. On May 29, 2007, a cyanobacteria contamination incident caused by water pollution in Taihu Lake resulted in tap water pollution in Wuxi and a severe shortage of domestic and drinking water. The key to solving pollution problems in Taihu Lake was adopting the Internet of Things (IoT) technology to develop a multi-source data-based cyanobacteria monitoring and early warning system, which had shown an important opportunity for developing the IoT-based digital economy in Wuxi.

In 2009, relying on the National Sensor Network Engineering and Technology Research Center, Shanghai Institute of Microsystems and Information Technology, the Chinese Academy of Sciences and the Wuxi Municipal Government jointly established the Wuxi Institute of Internet of Things Industry and the Research and Development Center of Micro-Nano Sensor Network Engineering and Technology of the Wuxi High-tech Zone to support the research and development of IoT technology for Taihu Lake pollution control. With the successful implementation of the pollution control, in 2012, the number of employees of the IoT in Wuxi exceeded 100,000; in 2018, Wuxi officially dominated the Chinese IoT standard; in 2021, Wuxi Internet of Things cluster was selected and approved as a national advanced manufacturing cluster; in December 2022, the total number of IoT enterprises in Wuxi exceeded 4,000.[9]

1.6 Conclusion

Chapter 1 provides the conceptual framework to map the strategic gaps, related policy approaches, and selected major policy options for leveraging the transformative power of digitalization for the sustainability challenge. The digitalization process offers new capabilities for understanding, monitoring, and managing our socio-economic systems and, thus, enlarges the capabilities for the urgently required sustainability transformation in society and the economy. Based on data-related and increasingly virtual interactions between individuals, companies, and institutions, a new kind of so-called socio-economic cyberspace is emerging that defines specific conditions for both commercial and political actions. As one prominent feature, cyberspace serves as a dynamic economic innovation ecosystem centred around platforms with growing technology performance, which is boosting business model innovation and entrepreneurial momentum. At the same time, these dynamics must be aligned with overarching goals of sustainable development, calling for effective policy-making both with regard to forward-looking guardrails and guiding market frameworks (ex-ante or pre-regulation) as well as to mitigating responses to undesirable developments (ex-post or post-regulation).

The following chapters will elaborate on this interplay between the digital opportunity space for sustainability and the related strategic gaps and policy requirements to achieve such a transition. This report will focus on fighting climate change and the urgent need to reduce GHG emissions. As the world's second-largest economy, the largest GHG emitter, and the nearly largest population, China has both a global responsibility and a national need to redirect its economy toward carbon-free renewable resources and, ultimately, decarbonize the entire society and economy.

In this context, the report will highlight two prominent use cases of Sustainable Cities (Chapter 3) and Climate Change Adaptation (Chapter 4), representing the complex and challenging transformation arenas of global relevance that will extensively benefit from the contribution of innovative digital solutions. As a fundamental prerequisite, however, the environmental footprints of any digital solution and infrastructure must be minimized to prevent detrimental rebound effects and to safeguard the ecological benefits of deploying digital technologies. As a baseline for the subsequent discussions, Chapter 2 will provide insights and recommendations for ensuring a sustainable and climate-friendly digitalization.

[9] https://www.xinhuanet.com/tech/20230111/a748fa0331b6455baee6ff84daa44c83/c.html

2. Green the Digital Sector and Accelerate Digitalization for Green Transformation

2.1 Introduction

As the international communities initiated the sustainable development concept, low-carbon-oriented economic and social transformations surged. Guided by the *United Nations 2030 Sustainable Development Agenda*, more than 130 countries and regions have committed to carbon peaking or carbon neutrality, sending a strong signal of green and low-carbon transformation.

The initiation of the digital era results in extensive and profound revolutions in both economy and society, triggering new modes of thinking, production, and life. The digital sector plays an active role in nearly all fields and sectors by promoting green technology innovation, improving economic efficiency, enhancing energy conservation, emission reduction, and carbon reduction, and is one of the drivers for the green transition. At the same time, the raw materials and rare earth mining used to manufacture information and communication technology (ICT) equipment have dramatic consequences for humans, animals, and the environment. Air pollution with toxic exhaust gases (SO2, heavy metals) from metallurgical processes, treatment residues in wastewater from the production of rare earth elements, radioactive contamination, and desertification are the result of rare earth mining, which is the consequence of the production of the technical infrastructure for the digitalization. Furthermore, the fast development of the digital sector accelerates energy consumption, the curve of which will continue to rise steeply.

The digital sector links with the green transformation of the economy through three channels: 1) the digital industry directly reduces the carbon emission throughout the entire value chain; 2) the digital industry indirectly benefits the greening process (green development) by driving technical and social innovation; and 3) the greening of the digital sector has a rebound effect, which means that the energy savings achieved by improving energy efficiency are partially or completely offset by expansionary energy consumption. However, the hope that digitalization will reduce overall energy consumption and resource use may not be fulfilled, as digitalization not only improves efficiency but also increases the options and activities of consumption that cancel out any efficiency gains. The international community has detected new opportunities for digitalization to accelerate the greening process. For instance, the European Commission launched the “European Green Deal," where the dual-track transformation of "greening" and "digitalization" is highlighted in the EU’s work in the next 5 years, and some practice cases have emerged in European countries such as Germany (Appendix 2). According to reports released by Deloitte and the Global Enabling Sustainability Initiative (GeSI), digital technology has a direct impact on 60% of the 169 sub-goals of the UN Sustainable Development Goals—digital technology will reduce global carbon emissions by 20% by empowering other industries over the next decade. [10] The *Exponential Climate Action Roadmap* (the Global Climate Action Summit) shows that deploying digital technologies in every field will contribute to global carbon emission reductions of between 15% and 20% (Rockström & Figueres, 2018).

The lack of standardized definitions for the terms “digital economy,” “digital sector,” and “digital infrastructure” continues to pose significant challenges to statisticians worldwide, hindering accurate measurement and analysis. According to the U.S. Bureau of Economic Analysis, digital economy activities are organized by digital infrastructure (hardware and software), e-commerce (B to B and B to C), and priced digital services, including telecom services, Internet and data services, cloud services, etc. The SDIA (Sustainable Digital Infrastructure Alliance) defines digital infrastructures as follows: “The total physical and software-based infrastructure necessary to deliver digital goods, products & services. This includes data centres, fibre infrastructure, server hardware, personnel, IT virtualization & infrastructure software, operating systems, etc.” However, it is crucial to recognize that digital infrastructures encompass not only the data centres where data is processed but also the networks through which it flows. These networks play a vital role in the overall framework of digital infrastructure. In this chapter, the term “digital sector” is used interchangeably with “ICT industry” in the Chinese context, which includes the subsectors of "C39 Manufacturing of computers,

[10] The Global Enabling Sustainability Initiative (GeSI), Deloitte. Digital with Purpose: Delivering a SMARTer 2030 Agenda [EB/OL]. [2023-02-02]. https://gesi.org.

communication devices, and other electronic devices," "I64 Internet and related services," and "I65 Software and IT services" according to *China's National Economic Industry Classification and Code* (GB/T 4754-2021) issued by the National Bureau of Statistics of China. The digital sector encompasses various elements, including intelligent and efficient computing centres that serve as digital facilities. Digital companies prioritize green development as a fundamental aspect of their operations, while digital services contribute to energy consumption reduction through algorithm optimization. By offering data analysis and digital transformation services to industries and sectors, the digital sector plays a vital role in empowering the greening transition. This chapter focuses on the greening strategies within the ICT fields, the ways in which the digital sector promotes sustainability, and provides relevant policy recommendations.

2.2 Present Development and Problems

2.2.1 Present GREEN DEVELOPMENT of the DIGITAL SECTOR

China has made breakthroughs in the development of the digital economy. According to the prediction by the China Academy of Information and Communications Technology (CAICT), in 2021, the scale of the digital economy reached CNY45.5 trillion, with a nominal growth rate of 16.2% year-on-year, 3.4 percentage points higher than that of GDP in the same period. The digital economy contributed to 39.8% of GDP. The added value of the digitization industry reached CNY 8.4 trillion, with an increase of 11.9% year-on-year, contributing to 7.3% of GDP.[11]

As the rapid development of the digital economy leads to the rise of additional demands and business, the carbon emissions of the digital sector also increase rapidly. According to official statistics, from 2012 to 2017, the total carbon emissions of the digital sector, including the above-mentioned subsectors, increased by 61% in China, ranking first among all economic subsectors. The significant development of digital services, including the Internet, software, and telecommunications, contributed mainly to the growth of carbon emissions in the digital sector. In 2017, ICT manufacturing released about 81.66 million tons of carbon dioxide, marking an increase of 40.6% based on the 2012 data, accounting for 59% of the total carbon emission of the digital sector. In 2017, digital services produced about 55.95 million tons of carbon dioxide, marking an increase of 106.0% based on the 2012 data, far higher than that of the ICT manufacturing field, accounting for 41% of the total carbon emission of the digital sector.[12] Overall, as the digital sector boosts support to social and economic development, its carbon emission tends to increase in the short term. Nevertheless, carbon emissions can potentially decline in the medium to long term due to the following factors: 1) advancements in energy conservation and carbon reduction technologies within the digital sector; 2) adjustments and optimizations in China's energy mix; and 3) a growing proportion of non-fossil energy sources.

2.2.2 Integration of the Digital Sector and Green Development

Digital Infrastructure: High pressure on green upgrading

According to the *Energy and Environmental Efficiency Framework Initiative* issued by the ICT sector of the EU, the information and communication industry uses almost 10% of energy and releases 4% of carbon dioxide. China's digital industry, especially digital infrastructure construction, is at the initial stage of green transformation. Digital facilities such as data centres and 5G base stations face increasing pressure in energy conservation and carbon emission reductions. At present, countries worldwide have not yet developed a unified standard for monitoring and measuring the energy conservation and carbon emission reduction effects caused by digital technologies. The high cost associated with carbon emissions reduction accounting poses a challenge in objectively and effectively measuring the energy conservation and carbon emission reduction benefits resulting from the construction and transformation of digital infrastructure. Consequently, it becomes difficult to directly apply the accounting results to assess and incentivize such construction and transformation projects.

A significant issue in the realm of digital infrastructure is the lack of transparency in both the public and private

[11] CAICT. China Digital Economy Development Report (2022) [EB/OL]. [2023-02-02]. http://www.caict.ac.cn/kxyj/qwfb/bps/202207/P020220729609949023295.pdf.

[12] CAITI. White Paper on Digital Carbon Neutrality [EB/OL]. [2023-02-02]. http://www.caict.ac.cn/kxyj/qwfb/bps/202112/P020211220632111694171.pdf.

sectors. This lack of transparency permeates all aspects, including data centres and software, making it difficult to ascertain their energy consumption levels. To efficiently implement targeted and meaningful sustainable measures in digitalization, it becomes essential to establish transparency across these domains. One potential approach is to systematically categorize different types of digital infrastructures, such as data centres, networks, and software applications, and define specific action areas that require transparency and key performance indicators to access their sustainability.

Digital Companies: Facing higher costs and stronger regulation

Digital companies currently face a challenging operating environment characterized by two major factors. Firstly, they encounter significant costs associated with green upgrading, research and development of green ICT products and services, implementing low-carbon operations, as well as marketing and promotion efforts; Secondly, they must navigate international carbon tax policies, green trade barriers, and other regulatory measures.[13] These companies must swiftly adapt to stricter import/export standards and production/operation requirements in the context of carbon peaking and carbon neutrality. Furthermore, the absence of standardized green product certification and labelling weakens regulation within the market for green products. Consequently, digital companies face difficulties in managing their green products, and even the environmental impact figures published by major Internet giants lack verifiability. In such a chaotic landscape, consumers are unable to discern which digital products or services are environmentally friendly.

Digital Services: Strengthening social consensus to empower green transformation

The public sector plays a crucial role in regulating and supporting environmental pollution control and other aspects. However, the difficulty lies in accurately measuring the green GDP contribution enabled by digital services, which hinders effective investment in research and development and social support promoting green ICT products and services (Box 2.1). This, in turn, presents challenges in terms of R&D and financing. Consequently, green ICT products and services tend to have relatively higher pricing compared to conventional products. However, due to the limited promotion of the green consumption concept in society, public awareness regarding green ICT products and services remains low. As a result, consumers find it challenging to make informed decisions and actively choose green ICT products and services, considering factors such as price, quality, and other reasons.

Furthermore, software plays a significant role in determining the environmental friendliness of the deployed information and communication technology. It directly impacts energy consumption and can contribute to the premature replacement of hardware. Therefore, it is crucial to acknowledge the issue of software-related obsolescence and its environmental implications.

Box 2.1 Definition of terms

There are no universally agreed-upon definitions for terms such as “green ICT,” “green products,” “low-carbon,” “green products,” “green data centre,” “green power,” and “clean energy.” In this report, the terms green/sustainable ICT and green products refer to consumer goods, digital services, and IT solutions designed to reduce environmental impact across their life cycle, including production, use, and disposal. The aim is to minimize energy and resource consumption.

The term “clean energy” or “green power” refers to energy that does not emit (or emits very few) pollutants, thus contributing to energy conservation, reducing environmental pollution, and minimizing ecological damage. Clean energy, as jointly defined by experts, mainly includes solar energy, bioenergy, hydrogen energy, wind energy, marine energy, bioenergy, hydrogen energy, wind energy, geothermal energy, and hydropower. In principle, sustainable digitalization endeavours to minimize the environmental impact and energy consumption associated with the digital sector. Efforts are focused on maximizing the efficiency of digital infrastructure and reducing its overall environmental footprint as much as possible.

[13] Green trade barriers are also known as ecological barriers. They refer to measures introduced by importing countries to protect natural resources, ecological environment, and human and animal health.

At the global level, the rapid growth of digital infrastructure and data traffic poses challenges in regulating their environmental impacts. It is crucial to explore new technical solutions and adopt a holistic perspective of the digital economy by examining a wide range of environmental indicators. The production cycles of hardware devices should be intelligently and environmentally designed, considering product longevity and recyclability from the initial stages, while software applications should operate in energy-efficient ways. The digital economy is interconnected with numerous other sectors and lies at the heart of the ecological transformation of the economy and society. To effectively address sustainability concerns in digitalization, transparency across various aspects of digital infrastructure must be enhanced. Holding digital companies accountable and requiring them to assess and report their environmental impacts in a timely and comprehensive manner is essential. In order to understand and mitigate the environmental impacts associated with the digital economy, it is essential to have knowledge of the specific electricity consumption, greenhouse gas emissions, and other environmental effects that stem from it.

2.3 Green Development Path in the Digital Fields

2.3.1 Digital Infrastructure and Facilities

Present Development

In 2022, China's telecommunications sector witnessed significant growth, with its business revenue reaching CNY1.58 trillion, marking an impressive 8% increase compared to the previous year. Notably, emerging sectors like data centres, cloud computing, big data, and the Internet of Things (IoT) experienced rapid development, contributing to a total business revenue of CNY307.2 billion in 2022. This figure represents a substantial growth rate of 32.4% compared to the previous year.[14] Furthermore, China’s mobile communication infrastructure also witnessed substantial expansion. By the end of 2022, the country had a total of 10.83 million mobile communication base stations, of which 2.312 million were 5G base stations. These 5G base stations accounted for 21.3% of the total, indicating a notable increase of 7 percentage points from the end of the previous year. Additionally, the electronic information manufacturing industry in China exhibited remarkable performance. From January to November 2022, the industry’s added value above the designed size increased by 8.3% year-on-year, surpassing both the industrial and high-tech manufacturing sectors by 4.5 and 0.3 percentage points, respectively.

With the rapid expansion of digital infrastructure and facilities, there is a corresponding increase in the pressure to reduce carbon emission reduction. Improper disposal of materials from decommissioned digital infrastructure and facilities can have detrimental effects on soil and the surrounding environment. Moreover, it is projected that by 2035, the combined electricity consumption of China's data centres and 5G base stations will amount to 5%–7% of the country’s total electricity consumption, while their total carbon emissions will contribute to 2%–4% of China’s overall carbon emissions. Considering the average service life of data centres and 5G base stations, which is approximately 10 years, and taking into account other factors, the "lag effect" in carbon reduction within digital infrastructure poses a significant challenge for China in achieving carbon-peaking targets.

- **5G base station.** As of September 2022, global 5G subscribers had reached 853 million, marking a remarkable year-on-year increase of 113.5%. This achievement corresponds to a 10.5% penetration rate among mobile subscribers. In China alone, by the end of November 2022, over 2.287 million 5G base stations had been deployed, accounting for more than 60% of the global total.[15] Compared to 4G base stations, 5G base stations offer significant improvement. The bandwidth of the 5G base station increases by over five times, the number of channels increases by eight times, and the transmit power increases by more than six times. Consequently, the peak power consumption of 5G base stations is

[14] MIIT. The 2022 Statistical Bulletin of Telecommunication Industry [EB/OL]. [2023-02-02]. http://www.gov.cn/xinwen/2023-02/02/content_5739680.htm.

[15] CAICT. White Paper on China's 5G Development and Economic and Social Impact (2022) [EB/OL]. [2023-02-02]. http://www.caict.ac.cn/kxyj/qwfb/bps/202301/t20230107_413792.htm.

approximately 3 to 4 times that of 4G base stations. Currently, the energy consumption of the 5G network remains high. In 2021, the total energy consumption of three major communication operators in China amounted to 13.69 million tons of standard coal, including 105.3 billion kWh of power consumption. For example, China Mobile's base stations' power consumption accounted for roughly 65% of its total power consumption, with 5G base stations constituting approximately 12% of its overall base station count. Furthermore, as the deployment of 5G base stations continues to expand rapidly, and with the initiation of 6G construction anticipated by 2030, energy consumption is expected to rise for an extended period.

- **Data centres.** In 2018, data centres accounted for approximately 1% of global energy consumption.[16] However, by 2021, the total computing power of computing devices worldwide had surged to 615EFlops, experiencing a substantial growth rate of 44%. It is projected that global computing power will reach 56ZFlops by 2030, with an average annual growth rate of 65%. In 2021, China's computing devices contributed significantly to the total computing power, reaching 202EFlops, which accounted for approximately 33% of the global share. Notably, China's computing power demonstrated a remarkable growth rate of over 50%, surpassing the global growth rate. In terms of energy consumption, China's data centres consumed 93.9 billion kWh in 2020, resulting in carbon emissions of 64.64 million tons. It is expected that the total energy consumption of data centres in China will reach 380 billion kWh by 2030, accompanied by a carbon emission growth rate exceeding 300%.[17] The utilization rate of renewable energy in domestic data centres remains relatively low, generally below 30%. This falls significantly short of the ambitious targets set by the *European Convention on Climate Neutral Data Centres*, which aims for a 75% renewable energy utilization rate by 2025 and 100% by 2030. In addition to energy consumption and carbon emissions, it is crucial to address other issues, such as the use of halogenated cooling liquids, e-waste management, and other related environmental concerns.
- **Chip manufacturing.** Based on the statistics provided by the China Semiconductor Industry Association, the sales of China's integrated circuit (IC) industry reached CNY1,054.83 billion in 2021, showing a year-on-year growth of 18.2%. Specifically, the manufacturing sales accounted for CNY317.63 billion, experiencing a significant year-on-year growth rate of 24.1%. In the future, the chip market size in China is expected to continue expanding, driven by the ongoing wave of intelligent upgrading within the manufacturing industry. In the IC manufacturing sector, stringent production and environmental requirements are imposed due to the diverse range of raw and auxiliary materials used, as well as the extensive array of equipment involved. The production processes in IC manufacturing generate wastewater, exhaust gas, noise, and solid waste, which can have adverse environmental impacts. It is important to address the concerns and adopt appropriate measures to mitigate the negative environmental effects associated with IC production.
- **Photovoltaic device manufacturing.** The newly installed solar power capacity is estimated to be 87.41GW in 2022, an increase of 60.3% year-on-year. Based on the standard 25-year service life in the market, the number of discarded PV modules will be huge in a few years. The PV device manufacturing process generates negative environmental impacts, including environmental hazards due to the toxic liquid $SiCl_4$ produced in the production process of silicon raw materials, the indiscriminate discharge of exhaust gas and wastewater from companies, the disposal of discarded components, and light pollution. Production technology, regulatory efforts, economic benefits, and other relevant factors determine the degree of the negative impacts.

Future Path

Promote the application of green energy-conservation technologies. To enhance resource efficiency and reduce energy consumption in communication network facilities, it is imperative to drive innovation in 5G network technology solutions. This includes advancements in networking technology, intelligent systems, network energy efficiency evaluation, and product life-cycle assessment tools. Green data centres have successfully embraced cutting-edge liquid cooling technologies, such as all-in liquid cooling, cold-plate liquid

[16] See e.g., "Recalibrating global data center energy-use estimates" (https://www.science.org).
[17] CAICT. White Paper on China's Computing Power Development Index (2022) [EB/OL]. [2023-02-02]. http://www.caict.ac.cn/kxyj/qwfb/bps/202109/t20210918_390058.htm.

cooling, heat-pipe liquid cooling, and liquid immersion cooling. These technologies enable the implementation of comprehensive liquid cooling solutions in data centres, incorporating liquid cooling cycles on the primary and secondary sides, along with coolant distribution units. In the realm of electronic equipment manufacturing, companies are strongly encouraged to explore breakthroughs in lightweight, modular, and intelligent design technologies. Moreover, the utilization of new materials that are non-toxic, harmless, energy-conserving, and easy to recycle should be prioritized. Box 2.2 highlights some application examples of green energy-conservation technologies.

Box 2.2 Selected cases of green energy-conservation technologies

Energy-conservation transformation of communication base stations

Taking the three major operators in communication network development as an example, China Mobile launched a green action plan in 2007, promoted the energy-conservation transformation of communication base stations in an orderly manner, and actively carried out green 5G, home green Internet access, and other actions. China Mobile has proposed to drive green network development with green network architecture and energy-conservation network technology to achieve "carbon peaking and carbon neutrality" goals. China Telecom has been carrying out energy conservation and emission reduction work since 2007 and completed the transformation and upgrading of the FTTH optical access network during the 13th Five-Year Plan period, achieving a 60% reduction in energy consumption per unit information flow; reduced the average daily energy consumption in the pilot areas by 17% through jointly developing a comprehensive energy-conservation solution for 5G base stations with ZTE; reduced the annual energy consumption by nearly 15% by applying self-developed energy-conservation technology in more than 95% of self-built base stations. By promoting the minimalist station construction and tidal energy conservation, China Unicom has focused on increasing the proportion of clean energy consumption and built a 4G/5G collaborative intelligent energy-conservation management platform, providing accurate energy consumption judgment and diversified energy-conservation scheme services, effectively realizing multi-standard intelligent network collaboration and personalized and differentiated energy-conservation scheduling. (The exact utilization and recovery data are temporarily unavailable, which is worth continuing to track in the future.)

Green development of data centres

Pioneering green data centres provide diversified solutions through model innovation and technological innovation. For example, China Unicom Deqing Data Center in Zhejiang has adopted distributed natural gas energy mode, which has reduced power consumption, with comprehensive energy utilization efficiency as high as 86%. Tencent Shanghai Qingpu Caoying Data Center has applied micro-module technology to realize accurate refrigeration management. By making the Power Usage Effectiveness (PUE) of a single micro-module reach about 1.08 and the annual PUE of the data centre reduced to 1.28, it was selected for inclusion on the list of "National Green Data Centers in 2020." By deploying the world's largest liquid cooling cluster and using the insulation coolant, Alibaba Zhejiang Cloud Computing Renhe Data Center has reduced its PUE to 1.09;[18] by equipping the Panjiu server with Yitian 710 and adopting the most advanced 5nm technology, the centre has made its single chip accommodate up to 60 billion transistors, with performance exceeding the industry benchmark by 20% and energy efficiency ratio increased by more than 50%. Looking into the future, data centres need to further tap their greening potential through the improved management of the whole life cycle of design, construction, operation, and maintenance, as well as innovation and the use of advanced technologies.[19]

[18] At present, the most commonly used refrigerant for air-conditioning units is R22, and the more environmentally friendly refrigerant that can replace R22 in the refrigeration system is R407C. R407C has no detrimental effect on the ozone layer, but is still a greenhouse gas. At present, there is no perfect refrigerant to replace R22 (http://www.ke-hai.com/upfile/201405071006133496.pdf).

[19] As an international reference, Microsoft has committed to be carbon negative by 2030, including through scaling carbon removal from operations (https://blogs.microsoft.com/blog/2020/01/16/microsoft-will-be-carbon-negative-by-2030).

Regulations on green data centres

To support the principles of green development and achieve the objectives of carbon peaking and carbon neutrality, the Ministry of Industry and Information Technology (MIIT) of China released the "Three-Year Action Plan for the Development of New Data Centers (2021-2023)" in July 2021,[20] which outlines specific targets to promote environmentally sustainable practices within the data centre industry. One of the primary goals set by the plan is to increase the national average utilization rate of data centres to above 55% by the end of 2021. Additionally, the plan aims to reduce the Power Usage Effectiveness (PUE) of newly constructed, large-scale data centres to below 1.35. By the end of 2023, the plan further envisions maintaining an average annual growth rate of approximately 20% for the national data centre rack size. This growth will be accompanied by an increased average utilization rate of over 60%. To optimize energy efficiency, the PUE of newly built, large-scale data centres is targeted to be less than 1.3 nationwide, and below 1.25 in severely cold regions. Through these measures, China aims to enhance the sustainability and energy efficiency of its data centre infrastructure, aligning with its green development objectives on carbon neutrality.

However, it is important to note that the PUE should not be evaluated in isolation when accessing the overall optimization and efficiency of data centres. The PUE values can vary significantly depending on the time of measurement and other factors. To obtain a comprehensive understanding of a data centre's infrastructure efficiency, it is crucial to consider additional indicators, such as the Renewable Energy Factor (REF), Cooling Efficiency Ratio (CER), and Water Usage Effectiveness (WUE). Only when analyzed collectively do these indicators provide a comprehensive assessment of a data centre's efficiency. Relying solely on PUE as a measure of efficiency does not provide a complete and accurate depiction of the data centre's infrastructure efficiency. For more detailed information on important indicators related to data centres, including case studies from Europe, please refer to Appendix 2 – Typical Practical Cases in Europe. This resource offers further insights into evaluating and improving the efficiency of data centre operations.

Increase the proportion of green energy applications. In regions with favourable climatic conditions, it is encouraged to implement locally generated renewable energy sources, such as small-scale wind power and rooftop photovoltaic (PV) systems. Additionally, exploring low-cost green power options through power transactions, such as direct purchases by large-scale users in areas with competitive green power prices, is also encouraged.[21] For smaller data centres, optimizing the energy supply pattern can be achieved through the utilization of modular hydrogen fuel cells, solar panel houses, and other relevant technologies. In an effort to reduce energy consumption in 5G base station construction, China has actively promoted the co-construction and sharing of 5G base stations. Furthermore, the country has facilitated green electricity transactions related to 5G infrastructure (Box 2.3), ensuring a more sustainable approach to powering these base stations and associated facilities.

Box 2.3 Co-construction and sharing of communication base stations and green electricity transactions

In 2020, based on sharing tower resources, 330,000 5G base stations were shared and co-constructed in China, accounting for more than 45% of the total base station numbers. Co-construction and sharing reduce the energy consumption of base stations by 20-30%, save resources such as land, poles and towers, pipelines, and equipment, help the entire society to save energy, and reduce emissions. In January 2021, Xinjiang completed the first all-green electricity transaction of 5G base stations. Based on the power trading platform of Xinjiang Electric Power Trading Centre, 490 5G base stations operated by the Urumqi Branch of China Unicom completed the monthly contract power transfer transaction in January through three power sales companies, with all-green electricity transaction power reaching a total of 4.5 million kWh, opening up space for clean energy consumption.

Strengthen the role of industry standards and the supervision of green production. Industry standards,

[20] http://www.gov.cn/zhengce/zhengceku/2021-07/14/content_5624964.htm.

[21] Large-scale power purchase agreements are used by digital companies, such as Apple, Google and Microsoft.

technical support, industrial incentives, etc., can be leveraged to promote the integration and innovation of information and energy, implement the manageability and controllability of energy terminals, and enhance product carbon footprint management. Other actions include, such as formulating relevant management measures for green production and operation, improving the rules and regulations for monitoring, statistical work, supervision, review, reporting, and disclosure of energy consumption and carbon emissions, forming a green and low-carbon development management system throughout the whole value chain, strengthening the efforts on the supervision of green production of ICT products, and punishing the companies that randomly discharge pollutants.

Promote the recycling of discarded electronic equipment products. In addition to the establishment of a compulsory recycling list and associated management measures for waste electronic products and packages (Box 2.4), there is a need to further focus on research and application of recycling technologies. Specifically, advancements are required in the disassembly, transportation, recycling, and reuse of retired electronic equipment, which can be effectively carried out by third-party professional organizations. The formulation of standards and technical specifications, process environment management, intelligent and refined disassembly, etc., shall be implemented more strictly. It shall be ensured that the standard requirements for component recycling are met.

Box 2.4 Sharing, Utilization, and Recycling of Electronic Equipment: Role of Platforms

The platforms such as Idle Fish, Aihuishou, and Zhuanzhuan are effective tools for promoting resource sharing and second-hand trading, which results in more efficient use of resources, reduced excessive consumption, and a sustainable development model. For instance, Idle Fish has demonstrated its impact by supporting more than 20 business categories in reducing over 1.74 million tons of carbon emissions in 2021.[22] With the growing number of discarded electronic products, Idle Fish and similar platforms provide a space for second-hand transactions, which can significantly reduce carbon emissions and alleviate environmental burdens. According to the calculation conducted by ATRENEW, the parent company of Aihuishou, Paijitang, and Paipai, the sales of second-hand mobile phones on these platforms contributed 30.41kg in carbon emission reduction in 2021, which was 72.6% of the contribution by the sales of new mobile phones of the same brands; the sales of second-hand mobile phones on the whole platform contributed 463,692 tons in carbon emission reduction, equivalent to the carbon sink effect of 2.3 million mu (15 mu = 1 ha) of urban forests for one year; a total of 223,000 sets of discarded electronic equipment were recycled and treated green in 2021, reducing the pollution of electronic products by about 35.7 tons.

Carry out carbon footprint accounting for electronic equipment products. In managing carbon assets, the electronic equipment industry must consider several factors, such as resource consumption, efficiency, life cycle, repairability, and recyclability of the electronic equipment through integrating data from the entire production process of the electronic equipment and the evaluation of carbon emissions generated by electronic equipment products throughout their life cycle. Promoting product carbon labels requires quantitative evaluation of carbon emissions generated throughout the material consumption, manufacturing, transportation, usage, and waste disposal involved in products and services. This evaluation shall be displayed on product carbon labels along with information about the carbon-reduction measures taken by companies and their carbon neutrality actions.

2.3.2 Green Digital Services

Present Development

In the context of the digital economy's development, the demand for algorithm model training to support the development and application of AI technologies has grown significantly. However, this growth has also resulted in increased energy consumption and carbon emissions within the digital sector. In recent years, the emergence

[22] "Idle Fish Carbon Emission Reduction Report: In 2021, more than 20 business categories will achieve a carbon emission reduction of over 1.74 million tons" (https://www.dsb.cn/177084.html).

of the super-large-scale AI model industry has opened up a new development path of AI with "high computing power + big data + large parameter quantity" and further promoted the rapid growth of the model training scale and computing volume required. A study at the University of Massachusetts Amherst showed that the training process of popular deep neural network models such as Transformer and GPT-2 could emit more than 626,000 pounds of carbon dioxide equivalent, which is five times the carbon emission of the average U.S. car over its lifetime (Strubell et al., 2019). A study conducted by Google indicated that as models become larger and more accurate, the computation demand surges, leading to a subsequent increase in carbon emissions. Therefore, algorithm researchers should carefully select algorithm models and take the energy efficiency of these models as an index to evaluate compute-intensive models (Patterson et al., 2021).

At the same time, China's ultra-large-scale AI model industry is experiencing rapid growth. In April 2021 Alibaba DAMO Academy introduced PLUG, a Chinese pre-trained language model boasting 27 billion parameters and 1TB of training data. In April 2021, Huawei, Recurrent AI, and other institutions jointly unveiled "Pangu NLP," a Chinese pre-trained language model equipped with 110 billion parameters and 40TB data during the pre-training stage. In July 2021, Baidu launched ERNIE 3.0, a large-scale knowledge-enhanced model with tens of billions of parameters and 4TB data trained.

Future Path

The carbon emission problems resulting from the growth of the ultra-large-scale AI model industry and the expansion of data training scale pose a significant challenge for the digital sector within the context of green development.

Explore and optimize the operational energy efficiency of large models. In June 2021, the Alibaba DAMO Academy released M6, a Chinese multimodal pre-training model with trillions of parameters. During the R&D process, the model was trained with 480 V100 GPUs. Compared with Google, NVIDIA, and other institutions, it saved computing power resources by over 80% and improved training efficiency by nearly 11 times.[23]

Use "Tiny AI" to reduce power consumption. For example, the Nanjing Institute of Artificial Intelligence Chip Innovation, and the Institute of Automation of the Chinese Academy of Sciences (CASIA), focused on "Tiny AI" to solve the problems of soaring storage, data congestion, privacy leakage, and high energy consumption faced by the applications of artificial intelligence in the industry. Through tiny technologies, tiny AI platforms can train and run AI algorithms with lower energy consumption, thus maximizing hardware capacities. Tiny AI improves the efficiency of chips, platforms, and algorithms, enables low-power AI training and application deployment, and allows intelligent operation without interacting with the cloud.

However, it is important to note that solely focusing on the efficiency and optimization of AI algorithms is not the sole solution to address the environmental challenges arising from the digital sector. While improving efficiency is crucial, it is equally essential to aim for a general reduction in overall consumption and promote sufficiency to prevent potential rebound effects.

2.3.3 Green Development of Digital Companies

Present Development

In addition to fostering green development in the electronic equipment manufacturing industry, communication industry, and software and information service industry, it is crucial to prioritize the green development of digital companies as well. Digital companies play a pivotal role as the comprehensive carriers of the digital sector. However, as digital businesses continue to rapidly grow and industrial ecological complexity increases, there has been a concerning upward trend in carbon emissions resulting from these companies' operations and supply chains. The primary sources of carbon emissions generated from digital companies encompass both direct emissions and fugitive emissions from their greenhouse gas emission sources (Scope 1), as well as indirect emissions arising from purchased energy such as electricity and heat (Scope 2). Additionally, emissions from office spaces, employee commuting, business travel, and other related factors within the supply chain contribute to the overall carbon footprint (Scope 3). Recent data indicate that Scopes 2 and 3 account for the majority of greenhouse gas emissions produced by leading digital companies, as elaborated below.

[23] Beijing Academy of Artificial Intelligence. Development Report of Ultra-large-scale AI Model Industry [EB/OL]. [2023-02-02]. https://hub.baai.ac.cn/view/10236.

In the fiscal year 2022, Alibaba's total greenhouse gas emissions amounted to 13.25 million tons. These emissions can be categorized into different scopes based on their sources and impacts. The direct greenhouse gas emissions by Alibaba entities (Scope 1) accounted for 927,000 tons. This includes emissions from the combustion of stationary sources (such as natural gas), fugitive emissions (such as refrigerant escape), and emissions from mobile sources (such as company-owned vehicles in retail business). The greenhouse gas emissions from electricity and heat purchased by Alibaba (Scope 2) were approximately 4.445 million tons. This electricity and heat primarily served the operational needs of cloud computing data centres, retail stores, warehouses, and offices. Indirectly, the greenhouse gas emissions generated from the upstream and downstream within the value chain (Scope 3) that can be accurately measured were around 7.877 million tons, which were mainly generated from the fuel consumption in the transportation and distribution services purchased by e-commerce operators, purchased electricity for company-leased data centres, packaging materials and consumables, and staff travel.[24]

In 2021, the direct carbon emissions from the greenhouse gas emission sources owned or controlled by Tencent (Scope 1) amounted to 19,000 tons, representing approximately 0.4% of the total emissions. These emissions primarily originated from company-owned vehicles, diesel generators, and refrigerants. The indirect emissions of greenhouse gases resulting from the generation of power and other energy purchased for Tencent's operations (Scope 2) reached 2.349 million tons, constituting about 45.9% of the total emissions. These include emissions arising from electricity consumption in company-owned or jointly constructed data centres and office buildings. Furthermore, all other indirect carbon emissions generated in Tencent's supply chain (Scope 3) accounted for 2.743 million tons, representing around 53.7% of the total emissions. These emissions primarily stem from capital goods (such as infrastructure consumables, and data centre equipment), company-leased assets (such as electricity for company-leased data centres), and staff travel.[25]

Baidu's carbon dioxide emission equivalent amounted to 490,841.4 tons in 2020 and 1,791,607.8 tons in 2021. The direct emissions (Scope 1) accounted for 16,407 tons, including combustion emissions from stationary sources and fugitive emissions involving boiler equipment, restaurant equipment, refrigerators, and other similar sources. The indirect emissions (Scope 2) were 601,740.2 tons and primarily resulted from the consumption of purchased electricity, steam, and heat. Other indirect emissions (Scope 3) totalled 1,173,460.6 tons, including emissions from electricity consumption of employees commuting and emissions associated with company-leased data centres (Digital Water, 2023).

Future Path

Emphasize the social responsibility of green development and encourage sustainability reporting. Since 2020, prominent Internet platforms companies such as Tencent, Ant Group, Alibaba, Baidu, Huawei, and others have initiated carbon neutrality action plans. These companies have demonstrated a commitment to transparency by disclosing their green development initiatives, pathways, and targets. They have utilized various means, such as releasing roadmaps, environmental information disclosure (ESG) reports, and corporate social responsibility (CSR) reports to communicate their progress. To align their strategies with sustainability goals, it is essential for companies to enhance the integration of digital and green development strategies. Large-scale digital companies are taking the lead in moving rapidly toward sustainable development, setting an inspiring example for others to emulate (Box 2.5).[26]

Box 2.5 The announced Carbon Neutrality Roadmap of digital companies

In April 2021, Ant Group announced its *Carbon Neutrality Roadmap,* outlining three primary objectives. Firstly, the company committed to enhancing energy efficiency and reducing emissions in its office buildings and transportation by leveraging renewable energy sources. Secondly, Ant Group pledged to collaborate with data

[24] Alibaba. Environmental Social and Governance (ESG) Report 2022 [EB/OL]. [2023-02-02]. https://data.alibabagroup.com/ecms-files/1452422558/7a2bf413-5b3d-4042-a42d-1f88199917b5.pdf.

[25] Tencent. Carbon Neutrality Target and Roadmap Report 2021 [EB/OL]. [2023-02-02]. https://www.tencent.com/attachments/carbon-neutrality/tencent-carbon-neutrality-report.pdf.

[26] A useful benchmark for net zero plans has been referenced by various UN bodies, and one has been developed for the ICT sector (https://sciencebasedtargets.org/sectors/ict).

service providers that prioritize low energy consumption or renewable energy usage, to achieve a 30% renewable energy power consumption rate by 2025. Furthermore, the company aimed to encourage its suppliers to establish and implement their carbon neutrality targets. Lastly, in cases where emissions reduction measures are insufficient, Ant Group committed to offsetting the remaining emissions by either establishing carbon sink forests or directly purchasing carbon credit products.

In December 2021, Alibaba released the *Alibaba Carbon Neutrality Action Report* and put forward three major targets: to achieve carbon neutrality in its operations no later than 2030; to halve the carbon emission intensity of upstream and downstream value chains no later than 2030 and take the lead in achieving carbon neutrality in cloud computing and promoting the green development of this sector; to achieve 1.5 billion tons of carbon reduction through the platform economy ecosystem in 15 years. Energy transformation, scientific and technological innovation, and fostering a stakeholder economy will become the core factors in achieving carbon neutrality in the future.

In February 2022, Tencent released the *Tencent Carbon Neutrality Target and Roadmap Report*, unveiling its carbon neutrality action plan (Appendix 3). Tencent pledged to achieve comprehensive carbon neutrality not only within its operations but also across its supply chain. By 2030, the company aims to ensure that 100% of its electricity is sourced from renewable and green power. The realization roadmap encompasses three dimensions: energy-conservation and efficiency improvement, increased utilization of renewable energy, and carbon offsetting initiatives. At the same time, Tencent also aims to lead by example in promoting green lifestyles among consumers, digitizing low-carbon transformation in industries, and promoting sustainable social value innovation. Through these efforts, Tencent hopes to accelerate the process of achieving neutrality at national and societal levels.

Shift to renewable energy to promote the private sector's action to reduce carbon emissions. Carbon emissions reductions at the internal operation level are crucial for the green development of digital companies (Box 2.6). Companies can drive innovation and implement energy conservation and emissions reductions measures across management and technology domains to reduce their carbon footprints. On the one hand, companies can achieve low-carbon emissions at the source by introducing green energy, such as photovoltaic power generation, wind-solar hybrid systems, and solar heating, within their self-built office parks. Additionally, companies can actively participate in green electricity transactions and explore technological innovation in carbon sinks to achieve carbon elimination and offsetting. On the other hand, companies can promote green office practices by leveraging digital technologies, such as intelligent sensors and the Internet of Things, to realize the intellectualization of office parks and buildings. By building a visual and intelligent energy-management and control centre, companies can refine energy consumption management and achieve green office practices.

Box 2.6 Cases of companies' practices in reducing carbon emissions

Use clean energy to help companies reduce carbon emissions

During the first half of 2022, Alibaba's trading volume of clean and renewable energy exceeded 800 million kWh, making a 150% increase compared to the entirety of 2021. In the same year, Alibaba achieved a total carbon emission reduction of 619,944 tons through its green mix transformation efforts, where 21.6% of the electricity used by Alibaba Cloud was generated from clean and renewable sources. Cainiao Logistics designed the logistics park according to the highest international sustainability standards for logistics sites, and actively laid distributed photovoltaic power generation equipment, with a cumulative installed capacity of 24.9MW and a carbon reduction of 16,000 tons in the fiscal year 2022.

In 2021, Baidu installed photovoltaic power generation equipment in the spare roof area, and photovoltaic power generation systems installed on the roofs of Baidu Edifice and Penghuan Building generate 1 million kWh of electricity every year, which can reduce carbon emissions by about 600 tons.[27]

In the warehousing industry, Jingdong Logistics laid out a rooftop distributed photovoltaic power generation system in a park connected to the grid. In 2020, the power generation of this system reached 2.538 million kWh, reducing carbon emissions by about 2,000 tons.

However, it is crucial to closely track and monitor the practices of large companies, particularly regarding how they calculate emissions, energy, and other resource savings. This includes keeping a close eye on information provided in corporate social responsibility (CSR) reports. The terms “clean energy” and “low-carbon” can be susceptible to misuse, potentially leading to greenwashing, where companies may misrepresent their environmental impact and sustainability efforts.

Smart parks and smart buildings help companies reduce carbon emissions

Alibaba Xixi Park extensively utilizes the Intelligent Internet of Things and sensors, enabling the adjustment of air conditioning and lighting based on the flow of people. Between 2020 to 2021, Alibaba achieved a reduction of over 10% in per capita energy consumption by its employees. Alibaba has set a goal to replace all short-distance fuel vehicles with electric vehicles by 2030 while also pushing for implementation of an intelligent logistics transportation system, including expanding the coverage of the electric unmanned logistics vehicle “Little Man Donkey” and accelerating the R&D progress of its self-driving truck “Big Man Donkey.”

Baidu has consistently prioritized obtaining certification for international standardized energy-management and environmental management systems. As of December 31, 2021, Baidu successfully obtained ISO 50001 energy-management system certification for its office buildings, while Anxinxing Property Management Co., Ltd., which manages Baidu buildings, had obtained ISO 14001 environmental management system certification.

Presently, numerous buildings owned by Tencent have obtained LEED gold certification for their design or have met China's green building standards. In 2020, the Shenzhen Tencent Binhai Building saved 5.98 million kWh of electricity and reduced emissions by approximately 2,690 tons of carbon dioxide year-on-year by implementing technical optimization and managing air-conditioning terminal controls.

Promote the green transformation of the supply chain and industrial ecosystem. Digital companies play a significant role in shaping the industrial supply chain and have the potential to collaborate with upstream and downstream partners to drive low-carbon transformations of relevant products and supply chains. Through these efforts, digital companies can contribute to creating a more environmentally friendly and sustainable business ecosystem. To achieve this, digital companies can make efforts in two aspects: On the one hand, they can leverage their digital technology expertise to build and optimize a comprehensive green supply chain, including solutions such as green product packaging, environmentally conscious logistics and transportation, energy-efficient warehousing, and paperless e-procurement to achieve energy conservation and emission reductions. On the other hand, digital companies can promote the circular economy by optimizing the production, sale, use, recovery, and reuse of ICT equipment and terminal facilities, and maximizing the reuse of components (such as obsolete server racks) to reduce the carbon emissions of ICT equipment waste.

Guide the formation of green habits on the consumer side. Digital companies pose a unique opportunity to utilize their influence on users and promote environmental awareness through their widely accessible digital services. By guiding consumers toward adopting a green lifestyle and fostering a positive social environment that supports carbon neutrality (Box 2.7), these companies can make a significant contribution to advancing environmental protection. The ongoing efforts of digital companies have already led to significant carbon-reduction effects and have successfully cultivated green consumption habits in various domains, such as travel, home, office, study, catering, shopping, and electronic product recycling. Their contributions toward embracing green value have been noteworthy.

Support consumers to reduce their data and hardware consumption. Additional measures can be taken to promote environmentally friendly behaviour, such as minimizing the use of digital resources. Optimizing video content to match the display size of end devices is one way to ensure that the default resolution aligns with the device’s capabilities. Additionally, disabling the automatic playback of video content on web pages by default

[27] Baidu. Environmental Social and Governance (ESG) Report 2021 [EB/OL]. [2023-02-02]. https://esg.baidu.com/resource.

can help reduce unnecessary data consumption. To prevent false incentives that may encourage excessive data usage, flat rates for large data volumes should be avoided.

Box 2.7 Digital companies guiding green lifestyle

In 2022, Alibaba introduced the "Carbon88" system, which encompasses platforms such as Taobao, eHungry, Idlefish, Amap, and Cainiao Logistics, as well as other application scenarios and industrial ecosystems. As of July 2022, under Alibaba's industrial ecosystem, over 20 million users have actively participated in carbon-reduction programs and embraced green lifestyles as part of their daily routines.

Meituan platform launched the "Qingshan Plan" in 2017 to promote green consumption within the food and beverage take-out industry. The initiative aims to guide platform merchants in providing eco-friendly services by implementing measures such as deploying environmentally friendly bags, utilizing recycled packaging, and offering the option of no tableware. Simultaneously, it encourages consumers to reduce consumption at the source. Over the past 5 years, more than 200 million Meituan take-out users have chosen the “no tableware” function, contributing to a nearly 40-fold increase in the proportion of “environmental protection orders.” The online promotion of environmental protection concepts has reached over 3 billion people. In addition, over 330,000 merchants have been recognized with the "helping low-carbon consumption" badge, indicating the initial success of efforts to raise awareness of green consumption.[28]

Baidu has introduced a "green module" to its APPs, aiming to enhance the public's awareness of environmental protection in various everyday scenarios. The "AI garbage sorting" applet assists users in effectively classifying waste materials.

Tencent promotes its green development concept to users and consumers through a range of initiatives. For example, Tencent Games’ TiMi Studio Group, which has partnered with the United Nations Environment Programme (UNEP) by joining the "Playing for the Planet Alliance.” Through this collaboration, TiMi Studio Group aims to raise public awareness of environmental protection and contribute to carbon neutrality by leveraging the influence of gaming. Additionally, Tencent's public welfare platform has witnessed remarkable engagement, with over 24.58 million people contributing more than CNY 460 million to support 2,583 nature conservation projects.

It is important to acknowledge that the terms “Green Consumption” or “Green Lifestyle” can have varying interpretations. To avoid greenwashing, it is advisable to refer to CSR reports to gain a clear understanding of what is meant by these terms. For instance, if video games are being produced that consume substantial amounts of energy, it should not be assumed that such activities are environmentally friendly. Moreover, it is essential to recognize that merely having “environmental awareness” does not necessarily translate into genuinely environmentally friendly behaviour.

2.4 Mode of Digital Technology-Based Greening

Use digital services to promote green development. Companies operating in the software and information technology services industry can provide a wide array of solutions, including software development, data analysis, and intelligent transformation, to assist businesses in different sectors in managing and optimizing their environmental impacts on production and business activities (Box 2.8). Large-scale digital service companies and leading firms across industries can also provide information technology consulting services or integrated solutions to small and medium-sized companies in traditional industries, such as manufacturing, to facilitate the coordinated digital and green transformation and bring technology into the green development of industrial companies.

Apply key clean technologies to promote green development. Digital technology holds significant potential to enhance efficiency and optimize resource allocation within traditional industries. It drives innovation in

[28] Meituan. Progress Report on the Fifth Anniversary of Meituan Castle Peak Project [EB/OL]. [2023-02-02]. http://finance.people.com.cn/n1/2022/0831/c1004-32516282.html.

processes and services while facilitating intelligent and green development, particularly in areas such as energy optimization and decision control. The emergence of new network technologies, such as 5G, enables every production unit to be perceivable, communicable, connectable, and computable. AI-powered analysis technologies transform decision-making processes and empower intelligent decision-making capabilities. Cloud computing and big data technologies have enabled new applications across various fields. Leveraging the massive data collected by sensors, these technologies enable the effective utilization of data resources and unlock their full value. According to IDC research, the continued adoption of cloud computing between 2021 to 2024 has the potential to reduce carbon dioxide emissions by over 1 billion tons. To achieve carbon neutrality by 2060, the contribution of AI-related technologies to carbon reduction will increase year by year, with a minimum target of 70% by 2060.[29]

Apply software and information technology services in industries. Software and information technology services play a crucial role in promoting green economic and social development by providing networked, digitized, and intelligent technology solutions. These solutions empower industrial transformation and upgrading, optimize structures, modernize government supervision and social services, accelerate the adoption of green production methods and lifestyles, and contribute to the overall reduction of social energy consumption. The next-generation information technology can effectively be applied in energy-intensive sectors to drive the clean transformation of energy structures. It enhances energy efficiency, reduces environmental impact, and promotes resource recycling, thereby directly contributing to the reduction of carbon emissions and the achievement of carbon-peaking and carbon neutrality goals. This is particularly important in critical carbon-emitting sectors such as energy and electricity, industry, construction, and transportation. By strengthening the deep integration of digital technology applications in these sectors, energy and resource consumption can be reduced, leading to simultaneous improvements in production and carbon efficiency. Clarity is needed in both the key components and the path ahead. For example, the World Economic Forum has developed a framework with the key transformational stages of the software-defined vehicle, including the main strategic decisions required and the related impact that can be achieved in each stage.[30]

Box 2.8 Intelligent technology optimized industry environmental footprint

In the field of express delivery and logistics, Cainiao Logistics, a subsidiary of Alibaba, took the lead in launching a digital package management tool based on electronic express sheets in the entire industry to replace traditional paper sheets and reduce carbon emissions. The digital package management tool based on electronic express sheets has been applied to more than 100 billion express packages, helping save 400 billion sheets of paper in the entire industry. Combined with the big data algorithm model, by further optimizing and designing the carton model and recommending the most suitable packing scheme by the algorithm, Alibaba reduced the packaging materials used by 15% on average, further promoting low-carbon and green development in the express delivery industry.

In the realm of warehousing and logistics, Huawei has implemented measures to enhance the storage efficiency of its warehouse. This includes adopting more intensive storage methods and transitioning toward "dark warehouses" by employing automation equipment instead of manual labour. Furthermore, Huawei has made efforts to minimize over-packaging and the use of fillers by optimizing the selection of logistics packaging boxes. It has also implemented carton recycling through customized turnover containers and utilized old packaging materials for new packaging purposes. In 2020, Huawei reduced its carbon emissions by more than 114,000 tons in logistics transportation, which represents an average reduction of 15% per product, the equivalent of planting 65,000 trees.[31]

Baidu has played a pivotal role in enhancing transportation services through various initiatives. One notable contribution is the deployment of intelligent traffic signal controllers that adjust the duration of traffic lights

[29] https://www.tsinghua.edu.cn/info/1182/98386.htm.
[30] https://www.weforum.org/agenda/2023/04/3-ways-intelligent-cars-positively-impact-daily-mobility.
[31] Watch: Digital technologies continue to enable low-carbon transformation [EB/OL]. [2023-03-28]. http://finance.people.com.cn/n1/2022/0925/c1004-32533527.html.

based on the real-time traffic flow. This intelligent system helps reduce road congestion and minimizes carbon emissions resulting from vehicle idling. [32] The company also developed sixth-generation high-tilt video technology for smart parking, featuring parking space guidance, unmanned charging, and efficient parking lot management. By streamlining parking space operations, Baidu's innovation significantly reduces carbon emissions caused by vehicles searching for parking, paying fees, and idling unnecessarily. Baidu further developed the ACE intelligent transportation system engine and established a comprehensive intelligent transportation system to meet the intelligent transportation needs of various scenarios, enabling low-carbon travel.[33]

[32] Assessing the systemic effects needs to consider the induced demand.
[33] Huawei Investment & Holding Co., Ltd. 2021 Sustainability Report [EB/OL]. [2023-03-28]. https://www-file.huawei.com/-/media/corp2020/pdf/sustainability/sustainability-report-2021-en.pdf.

3. Digital Technology and Sustainable Development of Cities

3.1 Introduction

Digitalization contributes to several urban “pain points” and offers sustainable solutions. Ongoing urbanization drives planetary change and shapes economic and social development. Capturing their dynamics is demanding, as cities are complex systems. Digital technology offers the opportunity to manage complexity, adding a new layer of governance. While unchecked digitalization is an acceleration force of unsustainable outcomes, digitalization can also become an enabler to accelerate the systemic transformation in cities for carbon neutrality and inclusiveness through circularity and sufficiency.

Cities are places characterized by exchange and communication among a vast multitude of individuals. A central theory of the emergence of the first cities suggests that cities were firstly trade hubs, in which further functions were increasingly built. This penultimate social role is realized by a physical infrastructure offering shelter for many in limited space and mobility, enabling people to meet and deliver goods. Cities are attractive precisely for the opportunities of exchange that often translate into economic, social, and cultural opportunities and diverse ways of living. However, this glorious role of cities is compromised by its success, at least when implemented the way it currently is. Large cities suffer from congestion, and the physical infrastructure and transport systems support unsustainable outcomes, from air pollution to climate change, traffic congestion, housing shortages, inadequate water supply, and energy shortages. Generalized congestion results in a “pain point” of cities, where the environment degrades and livelihoods are compromised (increasing the suffering of many struggling to afford high living costs), limiting the potential for economic development.

The role of cities matters from a global sustainability perspective (Skea et al., 2022). Direct and indirect energy use and consumption are the main drivers of anthropogenic climate change (Lwasa et al., 2022). Urbanization contributes to land loss and, thus, marginally also to food insecurity and biodiversity loss, notably in the Pearl River Delta (Bren d’Amour, 2016). Inside cities, air pollution, noise, and unsafe traffic conditions compromise well-being and place quality.

Digitalization can support sustainability transitions, and it can do so in three urban sectors: transport, buildings, and urban planning. First, digitalization can replace resource-demanding activities with services, e.g., when trips replace video meetings. Second, digitalization can support the optimization of activities, e.g., through smart homes with optimized HVAC or pooling trips in shared taxis. Third, it can intensify the use of resources, thus creating a lower resource demand per service, e.g., supporting the high use of flexible spaces and avoiding resource use for both construction and operations. Fourth, digitalization can communicate sustainability implications, initiating more sustainable decisions, e.g., by agile and AI-assisted urban planning for sustainability.

With all that potential, a note of caution: digitalization and associated efficiency gains lead to increased consumption levels, so-called rebound effects, that may even overcompensate for the efficiency effects. A risk is misunderstanding “Smart” as being equal to “sustainable” when, in many cases, it is not (Höjer and Wangel, 2015). Information and communications technologies also have a significant and rapidly growing environmental footprint. This observation indicates the importance of proper evaluation of systemic effects, a focus on options that promise high sustainability wins, and the avoidance of digitalization associated with a high environmental burden.

The population gathers with the economic and social development of cities, which also gives birth to innovation and thus to new ways of service provisioning that ameliorate undesired outcomes and offer pathways to sustainability. Digitalization and artificial intelligence are general-purpose technologies that can find applications in all domains of life. In some cases, digital increases the pain, for example, when fostering increasing consumption and clogging streets with delivery vans or requiring increasing energy demand for data centres, often supplied by coal power plants. However, digital and green technologies have also created conditions for solving urban development problems. Central to this is the potential to focus digital applications on increasing quality but avoiding quantity—additional material turnover. For mobility, options include electrifying the vehicle fleet, replacing private vehicles with public transport and shared pooled mobility, providing safe cycling infrastructure, and limiting total transport volumes through, for example, enabling home offices. For shelter, options include limiting total space demand through, e.g., luxury taxes on high per capita floor space, passive house standards, retrofitting, replacing gas heating with heat pumps, and implementing top runner programs for efficient appliances. For spatial planning, options include promoting compact development along public transit and agile digital tools that optimize urban settings for sustainability. The industry offers an additional layer with considerable resource savings realized by circular design. All those examples require that the positive effects are not outnumbered by indirect effects, such as more traffic when there is more space on the roads, more lighting when light is cheaper, or more leisure travel when saving time on commuting.

3.2 State of Smart Cities in China

China's 12th Five-Year Plan from 2011 covers digital/smart cities. In 2011, China's 12th Five-Year Plan promoted infrastructure construction, urban informatization, and refined management to improve urban digital capabilities.[34] China has been advancing smart city construction since 2012.[35] The Ministry of Housing and Urban-Rural Development of China selected 290 cities, districts, and towns as smart city construction pilots between 2013 and 2015 and has established an indicator system (focusing on safety and infrastructure, smart building and livability, city function enhancement, smart management, and services) to guide the smooth implementation of the pilot areas[5]. To ensure the healthy and sustainable development of smart cities, the General Office of the China State Council has proposed guidelines and objectives, which include promoting the development and upgrading of the information industry and infrastructure (2013),[36] increasing the development and sharing of information resources and scientifically formulating the top-level design of the smart city construction (2014),[37] and building a geospatial framework for digital cities (2015).[38]

China's 13th Five-Year Plan from 2016 further promotes digital/smart cities. During China's 13th Five-Year Plan, China focused on providing intelligent technologies related to smart cities and industries to enhance productivity and resource efficiency.[39] The main goal was to integrate intelligent technologies with urban planning and industry and to achieve highly-visible results in Digital China by 2020, such as forming distinctive smart cities.[40] Core technologies include cloud computing, big data, 5G, and Internet of Things. The innovative projects were developed in the areas of smart agriculture (e.g., smart granaries, 2016), smart energy systems (forming a coordinated development of "source-grid-load-storage," 2016), smart oceans (aiming to make full use of marine resources, 2016), smart transport (e.g., passenger transport information services, 2017; integrated road-vehicle management, 2018), and geospatial information systems (e.g., construction of spatio-temporal big data platforms, 2019).[41]

China's 14th Five-Year Plan from 2021 continues and amplifies a focus on digital/smart cities. The 14th Five-Year Plan continues building digital China and smart cities, realizing the dual path of technology development and online applications. Technology development includes cloud computing, big data, the Internet of Things, Industrial Internet, blockchain, artificial intelligence, virtual reality, and augmented reality. To promote the digitization of management services, China has proposed the construction of a digital village to digitize China's rural areas, break down data barriers, and improve collaborative processing capabilities and operational efficiency. At the same time, China continues to build smart cities and realize the intelligent transformation of lifestyle services, including property, elderly care, childcare, tourism, health care, logistics,

[34] General Office of the State Council of the People's Republic of China. (2011) China's 12th Five-Year Plan. http://www.gov.cn/2011lh/content_1825838.htm.
[35] Ministry of Housing and Urban-Rural Development of the People's Republic of China. (2012) Notice on launching national smart city pilot work. https://www.gov.cn/zwgk/2012-12/05/content_2282674.htm.
[36] General Office of the State Council of the People's Republic of China. (2013) Promoting Information Consumption Several Opinions on Expanding Domestic Demand. http://www.gov.cn/zwgk/2013-08/14/content_2466856.htm.
[37] National Development and Reform Commission of the People's Republic of China. (2014) Promoting Smart Cities Guidance on the Healthy Development of Smart Cities. http://www.gov.cn/govweb/gongbao/content/2015/content_2806019.htm.
[38] National Geomatics Center of China. (2015) Notice on Promoting the Transformation and Upgrading of Digital City to Smart City. http://www.glac.org.cn.
[39] General Office of the State Council of the People's Republic of China. (2016) China's 13th Five-Year Plan. http://www.gov.cn/zhengce/content/2016-12/19/content_5150090.htm.
[40] General Office of the State Council of the People's Republic of China. (2016) Several Opinions on Further Strengthening Urban Planning and Construction Management. https://www.gov.cn/zhengce/content/2016-12/19/content_5150090.htm.
[41] Ministry of Natural Resources, PRC. (2019) Technical outline for the construction of a spatio-temporal big data platform for smart cities. http://gi.mnr.gov.cn/201902/t20190218_2395831.html.

and transportation, to build a convenient environment for digital living and innovate service models and products.[42]

"Guiding opinions on promoting the healthy development of smart cities" – the basic Chinese smart city construction principles. The basic principles are fourfold. First, with human needs at the core, smart cities innovate urban management models and public services to provide a wide-coverage, multi-level, personalized, and high-quality public service system to urban residents. Second, smart cities apply advanced technologies based on regional characteristics, such as geographic location, history and culture, resources and industries, and socio-economic settings. Smart cities can be tested first in regions or districts with better comprehensive conditions and gradually roll out nationally while avoiding large-scale and redundant construction. Third, smart cities focus on stimulating market vitality and encouraging social capital to participate in investment, construction, and operation to leverage the sustainable development path of smart cities. Fourth, smart cities should follow secured information management principles to avoid data leaks and protect privacy.

China's New Urbanization Policy is achieving remarkable progress. The urbanization rate of permanent residency is 65% and continues to grow, requiring further reform of the household registration system. Urban clusters serve as centres of spatial patterns of urbanization, linked by the world-leading high-speed railway network that is rapidly expanding. Cities are increasingly designed around high-tech manufacturing and information technologies and improved public services and infrastructures while renovating old communities (52,500 units, 2022) and shanty towns (1.81 million units, 2022). Development is similarly advanced in rural areas, with a focus on water, electricity, roads, and the Internet, and the income gap between rural and urban settings is getting smaller.

These developments encounter several challenges. Environment, transportation, urban planning and construction, and land use are areas of increasing pain points, exacerbated by unbalanced development and utilization of resources (Jiang et al., 2021). The biggest challenge of new urbanization is promoting balanced development and reducing the pressure on big cities. The measures currently proposed by China are rural revitalization and green development of urban agglomerations through technological efficiency (Liu and Li, 2021). Challenges also include changing the traditional Chinese thinking that personal development opportunities in big cities are more promising than in small cities or villages and identifying economic instruments to increase the attractiveness of rural areas to young talent and business.

Shenzhen and Hangzhou are two examples of digital cities in China. Shenzhen's smart city development model is called "1+4,"[43] supported by new infrastructure construction in four areas: public services, urban governance, digital economy, and security prevention and control. As a national pilot for high-quality infrastructure development, Shenzhen has built 70,000 5G base stations and achieved city-wide coverage of 5G networks to support smart city development.[44] Shenzhen Tong, an APP, provides the basis for residents' daily life and government affairs. The so-called One City Map envisages the integrated supervision of the city. Shenzhen has established a 5G industry cluster to promote the development of the digital economy and implemented Shenzhen Special Economic Zone Data Ordinance to protect data security.

The structure of Hangzhou smart city is core system + sub-platform (district, county, and city) + data system + application scenario.[45] The core system connects all sub-platforms and databases to realize multi-platform data and business interoperability. Application scenarios are built around the core system and sub-platforms to achieve intelligence in health care, transportation, housing management, industrial development, and other areas. In large cities in the central and western regions, such as Chengdu, innovative measures have also been taken to promote digitalization and green development (Appendix 4).

Chinese smart cities offer opportunities for efficient system management of GHG emission reduction.

[42] General Office of the State Council of the People's Republic of China. (2021) China's 14th Five-Year Plan and Outline of Vision 2035. http://www.gov.cn/xinwen/2021-03/13.
[43] Huawei. (2021) The Shenzhen Model of a New Smart City. huawei https://www.huawei.com/cn/huaweitech/publication/88/smart-city-shenzhen.
[44] National Development and Reform Commission of the People's Republic of China. (2022) Shenzhen pilots high-quality infrastructure development. https://www.ndrc.gov.cn/xwdt/ztzl/ygadwqjs1/202203/t20220319_1319689.html.
[45] Hangzhou City Brain Empowers Urban Governance to Promote Regulations. (2021) The people's Government of Hangzhou City. https://www.hangzhou.gov.cn/art/2021/1/21/art_1229063379_1717741.html.

Carbon neutrality goals also require the replacement of fossil fuel hardware. Digital and AI-based applications can support residents, city managers, and industry in reducing their GHG emissions. Digital monitoring of water quality, air pollution, traffic flows, and online services for citizens forms the backbone for digital applications, many of which are AI-based. For residents, AI-based improvements in logistics, if supported by real incentives, such as CO_2 pricing in transport, can reduce packaging and return rates and improve consumer satisfaction. AI-based services, especially in shared mobility, offer substantial improvements in mobility, especially if accompanied by higher occupancy per vehicle (Guo et al., 2020; Creutzig, 2021). For city managers, AI enables real-time adjustment of operational plans and fast implementation of city-level climate goals and emergency measures, thus reducing waste of resources and CO_2 emissions caused by disasters, operation errors, and poor scheduling methods. For industries, AI enables real-time supervision of all production processes, including the selection of raw materials for products, production, transportation, and sales, to maximize the use of production resources and reduce production costs and CO_2 emissions. AI calculates and predicts market demand in real time, adjusts production volumes with production and sales plans in real time, and prevents CO_2 emissions from overproduction (Johnson et al., 2021). However, efficiency gains are often overcompensated by accelerated consumption and GHG emissions, requiring systematic measures in addition to AI-based efficiency to achieve climate goals (Creutzig et al., 2022).

The following session focuses on three sectors: transport, buildings, and urban planning. Chapter 3 focuses on options for how digital solutions offer the potential for sustainability and a healthy economy, with three policy recommendations.

3.3 Mobility: Avoid-shift-improve approaches

Transitions in urban mobility toward sustainability can be categorized into “avoid, shift, and improve” (Bongardt et al., 2013). Digitalization can support the transition in all three areas and can, in addition, provide opportunities for new business models. The three categories are characterized as follows:

- **Avoid.** This action area focuses on avoiding travel altogether by providing high-level services with reduced need for travel and transport. Key options include home office policies, digital work environments, and urban planning that provide high accessibility but low levels of inefficient motorized transport.
- **Shift.** It focuses on switching from polluting to fewer polluting modes of transport, which often translates into a change from private motorized modes to environmentally friendly modes, such as public transport or active modes (cycling and walking). Digital is central in new modes that can provide the flexibility and accessibility of individual transport while keeping some of the efficiency of public transit—shared pooled mobility and multimodal routing.
- **Improve.** It focuses on technological efficiency, both in terms of the efficiency of vehicles and traffic flows. Especially for the latter, digital options can provide crucial support.

Three options were detailed where digitalization can leverage substantial potential for sustainability transitions. The first is shared or pooled mobility. There are many smart mobility options, all of which are present in Chinese cities. However, it is beneficial to understand their differential environmental footprints. Some smart mobility options belong to those with the worst environmental footprint, especially ride-hailing. Ride-hailing includes rides without passengers (so-called deadheading), which makes ride-hailing highly emission-intensive and adds to congestion. In contrast, bike and e-scooter sharing demonstrates environmental benefits.[19] Also, ride-pooling services, such as Didi’s carpooling option, offer substantial benefits. The International Transport Forum demonstrated in a modeling study of Helsinki that replacing commuter trips with shared pooled mobility (prohibiting city entry by private vehicles) enables a 37% reduction in congestion and a 33% reduction in GHG emissions—even before electrifying car fleets. Shared pooled mobility not only relies on digital smartphone services but also optimal routing algorithms and thus necessitates advanced digitalization business models. The World Economic Forum-hosted Global New Mobility Coalition seeks to accelerate a synced transition to shared, electric, connected, and autonomous mobility (SEAM) solutions to provide for greener cities while creating new business opportunities (World Economic Forum, 2023).

The second is online work and education. The home office prevents travel trips and saves time for employees. Accordingly, a study of Chinese employees during the pandemic lockdown finds that the quality of jobs is experienced higher in working from home (Qu and Yan, 2023). Online education, forced upon China and most other countries globally by the pandemic, leads to a drastically reduced carbon footprint from students (Yin et al., 2022). However, to reach the full educational potential of students and meet their social needs, online education must be complemented with in-person seminars.

The third is efficient management of traffic flow. Hangzhou's Urban Brain, a collection and combination of available urban data processes with artificial intelligence, had urban traffic flow as its first showcase. Even though Hangzhou's population grew by about 1.5 million between 2010 and 2020, about 30%, average travel speeds increased by 15.3%, and the peak hour congestion rate was reduced by 9.2% (Caprotti and Liu, 2022). As a result, Hangzhou's traffic congestion ranking dropped from 2nd to 57th place in China (Yan and Li, 2022) (Box 3.1). Public transport can also be operated more efficiently. With a combination of Radio Frequency Identification (RFID), GPS, and video analytic technologies, light-rail speed and position monitoring systems can improve railway operational safety as demonstrated in Hong Kong (MTR Lab, 2023).

Box 3.1 Hangzhou's Urban Brain

Hangzhou's comprehensive application of digital technology in urban transportation, smart city, and smart government is a model and reference for China's urban development. The city has become a centre of online trading by developing cross-border e-commerce platforms, such as Alibaba and its financial spin-off Ant Financial. These platforms attracted millions of customers and merchants from China and abroad, creating huge demand and complexity for online transactions, logistics, and services. To meet this demand, Hangzhou developed advanced computational infrastructures, such as cloud computing (Alibaba Cloud) and artificial intelligence (DAMO Academy).

Hangzhou has also become a leader in the world surveillance market by producing intelligent security products such as cameras, sensors, and video analytics systems. Companies such as Hikvision and Dahua Technology pioneered applying the AI Cloud framework "Cloud-Edge Convergence" to provide a converged computing architecture that covers both complete cloud computing and edge computing, which supports various purposes, such as traffic management, public safety, disaster prevention, and urban governance. Hangzhou also hosted major events, such as the G20 Summit in 2016, which showcased its smart city capabilities.

Hangzhou's digital/smart city development benefits from an active municipal governance that embeds data infrastructure into urban planning and management. The city established a comprehensive pilot zone for smart city projects in 2017, covering 11 major systems and 48 application scenarios. The city also collaborated with academic institutions such as Alibaba DAMO Academy to foster innovation and research fields, such as quantum computing, machine learning, natural language processing, and computer vision.

Hangzhou City Brain is a smart city platform that uses cloud computing and artificial intelligence technologies to collect, analyze, and apply city data. Led by the Hangzhou Municipal Government and Alibaba Cloud, supported by Hikvision, Dahua Technology, Zhejiang Zhongkong, and other enterprises, Hangzhou City Brain was initially designed in April 2016 for traffic congestion control as the first application scenario. It effectively alleviated Hangzhou's traffic problems by processing traffic data with big data and controlling traffic lights automatically. In 2017, Hangzhou City Brain 1.0 was officially released, achieving a 15.3% reduction in travel time by intelligently adjusting traffic lights in the pilot area and reducing the police response time in case of traffic accidents. In 2018, Hangzhou City Brain was upgraded from "traffic congestion management" to "city management," covering 11 major systems and 48 application scenarios, including police, traffic, city management, cultural tourism, health care, housing management, disaster prevention, agriculture, environmental protection, market supervision, and grassroots management. Through cross-departmental collaborative innovation, it achieved an efficient allocation of public resources, accurate and scientific decision making, and significant improvement in urban management efficiency. The urban brain supported the design of effective measures, such as providing dedicated bus lines (fewer vehicles on the road), building a shared parking information platform (fewer vehicles on the road), and building a polycentric city (fewer vehicles on the road).

The purpose of creating Hangzhou City Brain is to improve urban governance and service qualities and improve urban operation efficiency and security. Among them, traffic management is important as traffic congestion affects people's travel convenience and quality of life, consumes energy and emits greenhouse gas. Using City Brain to monitor and optimize traffic data in real time can reduce vehicle waiting time, increase road capacity, and reduce gasoline consumption and carbon emissions. However, systemic effects (such as induced demand) may compromise GHG emission savings considerably. The Urban Brain will need to address privacy, a major concern of many Chinese citizens.

In general, all three measures—shared transport, teleworking, and traffic flow management—allow for better traffic flows. Unless combined with complementary measures to limit private car traffic, such as an inner-city toll, there is a high risk the benefits are eaten by the latent demand that exists in cities with congestion.

3.4 Buildings: Avoid-shift-improve approaches

Sustainability in the building sector involves consideration of indoor air quality, avoiding the high material and GHG emission footprints of construction, and energy-efficient use, as part of overall urban infrastructure. Relying inter alia on a study on the more efficient use of buildings (Höjer and Mjörnell, 2018), this includes:

- **Avoid.** Reduce the need for space and use space more efficiently (shared desks and space). Use modular design to adapt space for new purposes. Renovate old buildings instead of replacing them with new construction. Apply digital sufficiency to ICT use in households.
- **Shift.** Provide heating service via private heat pumps, rooftop solar heating, geothermal energy, and large-scale heat pumps for district heating. Decentralize energy supply with solar PV on rooftops, and install more double-glazed windows, better insulation, and LED lighting, etc.
- **Improve.** Make use of more efficient energy. Create virtual load management with smart meters in coal and gas power plants to reduce air pollution and GHG emissions. Optimize energy use through intelligent buildings. Retrofit existing buildings, optimize material-saving construction for passive housing, e.g., based on 3-D printing; make use of the digital economy and home office to optimize existing building use.

Three digital case studies were selected, including the big data-based management of building stock, digital sufficiency, and smart metering and feedback. First, big data-based approaches can optimize the use and modification of existing building stock for sustainability. A key application is data sourcing of thermal properties of existing building stock to allocate optimal strategies for retrofitting, saving precious energy and gas. A data-based strategy could include scanning building stock with thermal cameras in winter. Merging with climate data and climate projection could then enable the computation of prioritization in building stock retrofitting. Another strategy involves reallocating floor space, inter alia as demanded by the digital economy. A reduction of bank offices and retail is accompanied by an increase in demand for logistical warehousing. Big data tools could help optimally redistribute and reduce the need for floor space.

Second, digital sufficiency can support the sustainable lifestyles of households and building users (Santarius et al., 2022). Digital sufficiency includes hardware, software, user, and economic sufficiency.[46] A central motivation is that increasing energy use and GHG emissions are more and more attributed to digitalization and the abundant purchase and use of digital devices. In addition, mining rare minerals leaves scars on the Earth and is a key concern of unsustainability related to digitalization. Strategies to implement user sufficiency in cities include education campaigns and information disclosure on energy and GHG emission footprint from streaming services. More radical measures include limiting or banning online advertisements.

Third, smart metering and feedback can create virtual power plants, creating a sustainable and economically advantageous instead of new constructions of gas and coal power plants. Smart metering allows for dynamic pricing and load reduction in times of high electricity prices. It can save household budgets and release utilities from the burden of constructing economically non-viable power plants, releasing the rarely used capacity. For

[46] Santarius and Lange were the first to coin the term "digital sufficiency", which includes three dimensions: technical sufficiency, data sufficiency, and user sufficiency.

high-consuming households, smart metering, and information feedback (e.g., on prices and on opportunities to save energy) can reduce energy bills by 16%, even if current implementations usually do not reach that high numbers. Still, smart metering and information feedback, combined with price signals, can reduce at least a gigaton of GHG emissions if persistently applied over several years globally (Khanna et al., 2021).

3.5 Spatial Planning: Use AI for sustainable urban design

Spatial planning refers to the advanced long-term management of cities. Spatial layout predetermines accessibility, housing affordability, job market opportunities, air pollution, noise nuisance, and GHG emissions from transport and building use. Spatial planning is a forward-looking strategy to realize vast sustainability gains. The main dimensions for sustainability evaluation include the energy use and GHG emissions committed by urban form, local air quality and ambience, water absorption capacity (sponge city), and quality of place, including the enjoyment of street life for seniors and children.

Digitalization and machine learning can support urban planning for sustainability (Milojevic-Dupont and Creutzig, 2021). Computing energy use and GHG emissions as a function of spatial layout and street networks enables planners to estimate the relevance of urban form in driving air pollution and GHG emissions (Silva et al., 2017). A case study of Berlin reveals that centrality, and the presence of sub-centres are key predictors in predicting GHG emissions induced by urban form, enabling estimates at street, and building scale (Wagner et al., 2022). In a further step, this advanced pattern recognition can be used to plan the urban form and transport-oriented development at high spatial accuracy and in accordance with desired sustainability metrics, relying on predictive learning (Milojevic-Dupont and Creutzig, 2021; Silva et al., 2018). High-resolution maps can also visualize the contribution of the built environment in amplifying heat waves and associated heat stress, thus enabling targeted urban resilience plans and urban greening strategies.[47]

Spatial and transport planning are also areas where technical solutions intertwine with gender equity and inclusion. Spatial planning and smart mobility solutions must be designed in an inclusive manner to avoid repeating past mistakes that sideline women, children, and the elderly (Box 3.2).

Box 3.2 The avoid-shift-improve framework for gender-inclusive smart cities

Given a "default-male" approach in urban design and decision making in the 20th century, the perspectives and needs of women, children, and persons with different impairments have been systematically excluded. Women are disadvantaged by the male-centric design of public infrastructures, including means of transport. Yet, it is well documented that women follow different travel patterns, linked to frequent chaining of trips and higher reliance on public transport (Ramboll, 2021). Accordingly, women's representation in decision-making and technology-related careers must be strengthened to unlock the full potential of inclusive smart city design.

While many present urban policies and their underlying datasets are insufficiently considering heterogeneous use cases, AI trained with historical patterns risks perpetuating existing gender biases and deepening inequalities. Cities worldwide are recognizing these risks and have started taking respective measures. By using the example of gender-disaggregated data, the following recommendations aim to inform inclusive smart city governance:

-- **Avoid.** This approach relies on gender-blind data sources that perpetuate gender stereotypes and discriminate against age and ability, which applies, for example, to the accessibility of public charging stations for electric mobility, for which significant barriers for people with wheelchairs or other mobility needs persist (Falchetta and Noussan, 2021).

– **Shift.** This approach emphasizes the shift toward gender-disaggregated data and incorporating perspectives from diverse stakeholders. Gender-disaggregated data should feed into all realms of digital applications, smart infrastructures, and related policy-making. Gender-sensitive surveys, research

[47] See e.g.: https://www.sciencedirect.com/science/article/pii/S2210670722003687; https://www.sciencedirect.com/science/article/abs/pii/S2212095523000615.

dedicated to gender equity in smart cities, and mixed-method approaches are needed to better understand the needs and concerns of all citizens, regardless of gender, age, or other parameters. The European DIAMOND project is a good practice example. It is a joint initiative by research institutes from several EU countries, engaged in microdata collection via surveys, literature review, focus group discussions, and social media data analysis to filter the most promising policies for a more inclusive mobility landscape (Santarremigia et al., 2022).

– **Improve.** This approach aims to improve and humanize smart city design to ensure inclusive and safe public spaces. The recalibration of safe, accessible, and inclusive spaces and itineraries in smart cities is particularly relevant for women, who are disproportionately affected by persistent harassment and gender-based violence (UN Women, 2022). Relevant measures include, for example, adequate lighting, surveillance cameras, and trained staff to improve safety perceptions in public spaces. New technologies can leverage such efforts: In the United Kingdom, the Path Community App provides users with information on the safest route home.[48]

[48] See e.g. Path Community App.

4. Digital Technology and Climate Change Adaptation

The effects of climate change are increasingly transforming human living environments. While mitigation action remains a priority, government efforts must also focus on helping people adapt to today's climate impacts. Emerging digital technologies, which provide more efficient, rapid, and reliable risk monitoring and forecasting, enable better decision making based on quantitative, actionable indicators (Argyroudis et al., 2022) and can play an essential role. In 2013, the Chinese government released the climate change adaptation strategy for the first time. The National Climate Change Adaptation Strategy 2035, released in May 2022, put forward the basic principles and main objectives of China's adaptation to climate change in the new era. The strategy emphasizes strengthening scientific and technological support, accelerating research and development, and adopting relevant technologies. In this context, deploying digital technologies to promote climate change adaptation capabilities in China is necessary, well-founded, and has great potential.

This chapter aims to provide policy recommendations for deploying digital tools to promote climate change adaptation in China. It first identifies the major climate change adaptation challenges in China and then discusses the high-performing digital solutions developed and deployed in countries outside of China. Afterward, the chapter analyzes these solutions in the Chinese context and formulates policy recommendations for advancing similar approaches. In keeping with the overall theme of the report, the chapter focuses its discussion on adaptation in urban areas, with a broader discussion of digital adaptation solutions and policies to be developed in future research.

4.1 Major Climate Change Adaptation Challenges in China

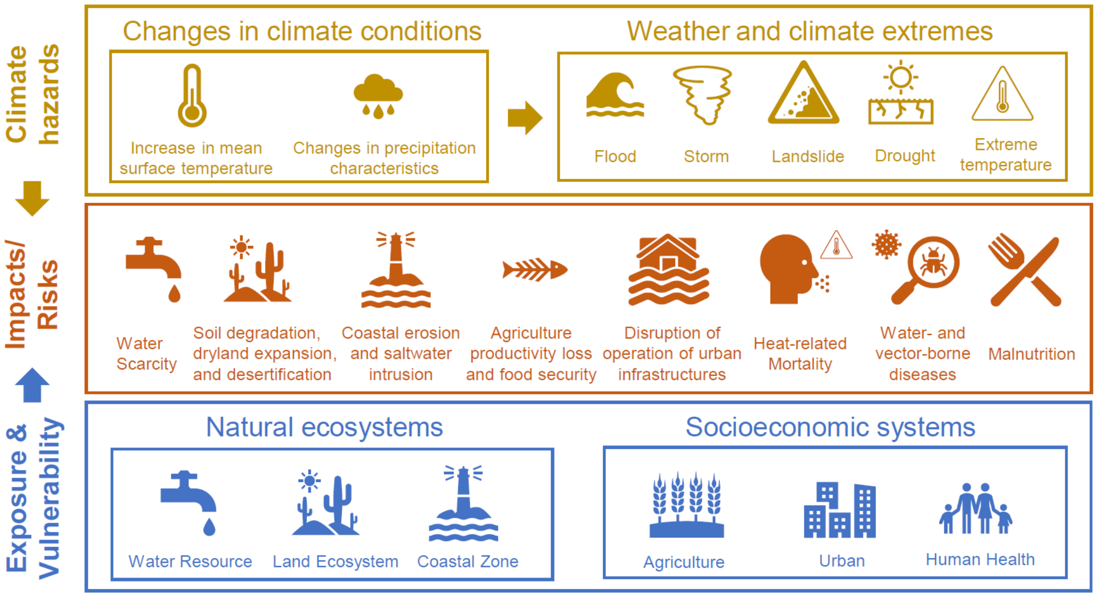
An analysis of climate change risk and adaptation challenges must begin with a typology against the situation in China that can be assessed. Following the risk framing in IPCC AR6 (Masson-Delmotte et al., 2021), the analysis in Chapter 4 defines risks as the potential for adverse consequences for ecological or human systems[49] and impacts as the consequences of realized risks on natural and human systems. Climate change risks and impacts result from dynamic interactions between climate-related hazards and the level of exposure and vulnerability of the ecological or human system.[50] Under this framework, Figure 4.1 presents the major climate change risks facing China.[51]

[49] In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. Related concepts to these two types of risk are "physical risk" and "transition risk." The risks (include its components: hazards, exposure, and vulnerability) discussed in this chapter only refer to the former.

[50] Climate-related hazard: the potential occurrence of a natural trend or event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. Exposure: the presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected. Vulnerability: the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

[51] See: 1) The People's Republic of China Third National Communication on Climate Change[Z/OL]. (2018). https://unfccc.int/sites/default/files/resource/China%203NC_English_0.pdf. 2) Climate Risk Country Profile: China[Z/OL]. (2021). https://www.adb.org/sites/default/files/publication/703641/climate-risk-country-profile-china.pdf. 3) National Climate Change Adaptation Strategy 2035[Z/OL]. (2022). https://www.mee.gov.cn/xxgk2018/xxgk/xxgk03/202206/W020220613636562919192.pdf.

Figure 4.1 Major climate change risks facing China



The main climate-related hazards in China are increase in climate-related extreme weather events on the one hand and increased vulnerability because of more exposure, etc. on the other. Significant changes in China's annual mean temperature and precipitation characteristics over the past century have been observed:[52] The average surface air temperature increased by 0.98°C between 1901 and 2010, with a particular acceleration in warming since 1980; Mean temperature changes are projected to be higher than the global average, at an estimated of 5°C increase by the end of the century. Although the annual average precipitation did not exhibit any significant changes, notable shifts were observed in the spatial and temporal distribution of precipitation. Changes in climate conditions also alter the severity of weather and climate extremes in China. According to the EM-DAT, [53] there have been 482 weather and climate extremes recorded in China since 2001. The five most frequent extremes include flood (202 times), storm (192 times), landslide (53 times), drought (22 times), and extreme temperature (9 times). [54]

The main exposures include two categories, namely natural ecosystems and socio-economic systems. In China, the vulnerability of natural ecosystems lies mainly in the fact that socio-economic development creates strains on water resources, terrestrial ecosystems, and coastal ecosystems. The insufficient agricultural irrigation facilities, lack of risk-oriented planning of urban infrastructure, and the insufficient supply of medical resources reflect the vulnerability of the socio-economic system, while the changing hydropower output due to lowering water levels from drought is another potential risk.

Although China has taken some adaptation actions to reduce the above-mentioned hazards, exposure, or vulnerability, there are still many residual risks that have not been coped with and adapted (see Figure 4.1). According to the Climate Risk Country Profile of China,[55] the major impacts (realized risks) include water scarcity; soil degradation, dryland expansion, and desertification; coastal erosion rates and saltwater intrusion; productivity loss of the agriculture sector and food security; disruption of the operation of urban infrastructures and broader economies; increase in heat-related mortality; increase in water- and vector-borne diseases; and malnutrition. These are the main risks that China needs to adapt to.

China has always attached equal importance to mitigation and adaptation and implemented a national strategy

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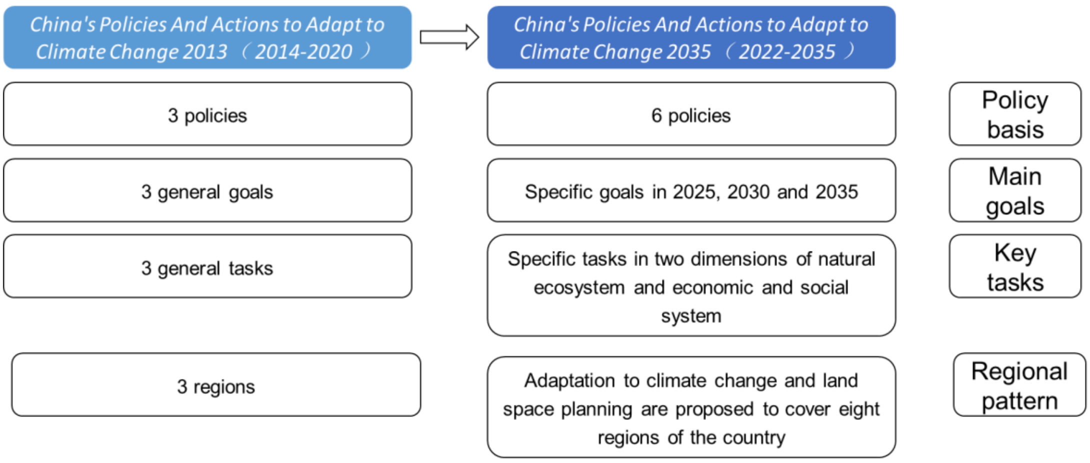
[52] World Bank Climate Change Knowledge Portal[EB/OL]. [2023-03-15]. https://climateknowledgeportal.worldbank.org.
[53] EM-DAT stands for Emergency Events Database. It is an international database that contains comprehensive information on natural and technological disasters that have occurred around the world since 1900.
[54] Flood includes riverine, flash, and coastal flooding; storm includes tropical cyclones and convective storms; extreme temperature includes heat and cold extremes and severe winter conditions.
[55] Ibid.

to promote adaptation to climate change (Box 4.1). The Chinese National Climate Change Adaptation Strategy 2035 defines three adaptation priorities to mitigate climate change risks in China: 1) strengthening climate change monitoring, early warning, and risk management; 2) improving the climate change adaptation ability of natural ecosystems, including water resources, terrestrial ecosystems, and coastal zones; and 3) improving the climate change adaptation ability of socio-economic systems, including agriculture, urban systems, and human health.

Box 4.1 China's policies and actions to adapt to climate change

Since 2013, China has released two versions of *China's Policies and Actions to Adapt to Climate Change*. The latest version (2022–2035) focuses on strengthening climate change monitoring, early warning, and risk management, including improving the climate change observation network, strengthening climate change monitoring, prediction, and early warning, strengthening climate change impact and risk assessment, strengthening comprehensive disaster prevention and mitigation.

Box Figure 4.3.1 Chinese climate change adaptation strategy



4.2 Potential Digital Solutions for Climate Change Adaptation

Given the major climate change adaptation challenges and priorities in China discussed above, this section explores international cases and best practices, keeping the Chinese needs in mind. Extensive literature reviews focus on the potential role that digital technologies and tools can play in promoting climate change adaptation. Some of these tools can assist in long-term planning for adapting to climate change, while others can aid in forecasting and reacting to immediate climate change hazards. As shown in Chapter 3, spatial planning can help cities build resilience to climate change challenges. This section explores two other main areas: climate change monitoring and early warning; urban water management in response to flooding—the most frequent immediate climate hazards China is facing.

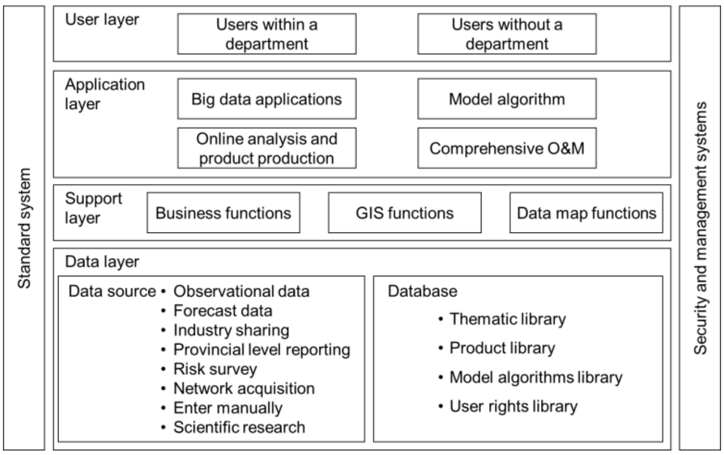
4.2.1 AI Techniques for High-Accuracy Precipitation Forecasting

Climate change monitoring and hazard early warning rely on precise climate and weather extremes forecasting. China has made substantial efforts and progress in developing and implementing extreme weather forecasting and risk management systems (Box 4.2). Current weather forecasting approaches rely on physics-based techniques. Such methods are sensitive to approximations of the physical laws on which they are based and are constrained by their high computational requirements (Kalchbrenner and Espeholt, 2021). Therefore, the weather forecasting systems could further improve efficiency and accuracy. For instance, the China Meteorological Administration has issued the Meteorological Technology Development Leading Program 2020-2035 for promoting meteorological modernization through the development and deployment of smart technologies, such as multi-dimensional stereo observation technology for specific targets, intelligent collaborative observation technology, and multi-source observation data fusion application technology.[56]

Box 4.2 China's Meteorological Disaster Risk Management System[57]

To improve the capacity of disaster risk management, China has formed a technological system consisting of a meteorological hazards survey, disaster-causing threshold identification, an early warning system based on the disaster-causing threshold, quantitative disaster risk assessment, refined disaster risk zoning, business inspection, and benefits evaluation. The risk management system has clarified the risk management responsibilities of the local governments (province, city, and county) and the central government. (Box Figure 4.2.1).

Box Figure 4.2.1 Framework of Meteorological Disaster Risk Management System



Digital technologies help realize the system functions, including the real-time release of disaster monitoring, disaster event identification, impact assessment, risk assessment, risk estimation, risk zoning, and other types of business products. The application in national meteorological business departments shows that the system has good capabilities and development prospects. Further improving its accuracy and geographical coverage, for instance, by including more remote, less-populated areas, is expected.

A promising new approach for precise precipitation forecasting is currently in development, utilizing AI techniques (Espeholt et al., 2022). Unlike traditional methods that rely on explicit physical laws, AI weather forecast models learn to predict weather patterns directly from observed data, resulting in faster and more accurate predictions (Kalchbrenner and Espeholt, 2021). By incorporating AI techniques for precipitation forecasting, scientists can achieve a new modeling paradigm for weather prediction that boosts accuracy. This approach eliminates the need for manual coding of weather physics and instead utilizes end-to-end learning from observations to weather targets. Additionally, AI technology allows for parallel forecasting on low-precision hardware, representing a significant advance in weather-prediction methodology.

These approaches, which include Google's MetNet2, Pangu-weather, and others, could potentially improve the

[56] Meteorological Technology Development Leading Program 2020-2035[Z/OL]. (2019). http://www.gov.cn/zhengce/zhengceku/2019-11/04/5456909/files/c7c2e1cfb36d4817ba6f6d8fd293f7f7.pdf.

[57] Li Ying, Wang Guofu. Design and implementation of Meteorological Disaster Risk Management System. J Appl Meteor Sci, 2022, 33(5): 628-640. DOI: 10.11898/1001-7313.20220510.

scope and resolution of the predicted forecasts (Bi et al., 2022). Although it is still in the laboratory stage, MetNet-2 has shown its potential for accurate and efficient precipitation forecasting (Espeholt et al., 2022). The prediction performance and speed of MetNet-2 exceed those of traditional physics-based models, especially for nowcasting (i.e., predicting weather between 2-6 hours ahead). Compared to physics-based models, MetNet-2 outperforms the state-of-the-art High-Resolution Ensemble Forecast model for weather forecasts up to 12 hours in advance. [58] Meanwhile, the computational requirements of an AI-based approach are lower, and the speed is faster. Comparing the time needed for prediction, physics-based models take about an hour, whereas MetNet-2 takes only a second (Kalchbrenner and Espeholt, 2021).

These models have only recently been published in journals such as *Nature Communications* and have not yet been implemented. Several obstacles hinder the implementation of such approaches. The first is that the technologies need to be further developed to expand the scope of weather phenomena considered and extend the forecasting horizon to days and weeks, while there are no mechanisms and incentives for multiple participation of universities and corporate research institutes in China. For instance, according to China's Meteorological Law, some weather detection data are confidential,[59] which may affect the data availability for research on new technologies from private institutions. In addition, while there are incentives for innovation within the meteorological department, there are no channels and incentives for external participation in innovation. The second is that they are more data-intensive, which creates issues in data collection, integration, and governance (Kalchbrenner and Espeholt, 2021).

4.2.2 Operational Digital Twins in the Urban Water Sector

Changes in the spatio-temporal distribution of precipitation driven by climate change create challenges for water management in Chinese urban areas. The substantial uncertainty associated with precipitation events results in an increased frequency of high flows within sewer systems, causing a significant number of sewer overflows. These overflows discharge untreated wastewater into the environment, posing serious threats (Digital Water, 2023) and exacerbating water pollution, water scarcity risk, and water-borne disease.[60] The Swedish cities of Gothenburg and Helsingborg have implemented a digital twin approach to water resource management, which has great potential to reduce the vulnerability of the Chinese urban water sector to climate change.

The digital twin approach implements a decision support system with online flow prediction and suggestions for control strategies. Utilizing the digital twin approach provides greater confidence in decision making by enabling quick visualization of the effects of changes in control strategy (Digital Water, 2023). Simulation results indicate that implementing real-time control strategies can significantly reduce sewer overflow events in the Gothenburg case, with potential benefits, including more stable water treatment processes, lower risk of critical load situations, and increased flexibility for handling issues with the accumulation of material. Sewer overflows are common in Chinese cities after heavy rainfall (Talamini et al., 2016). The untreated wastewater, possibly carrying pollutants from the ground, enters the urban environment, causing serious water pollution, freshwater shortages, and an increase in water-borne diseases. [61] Such a climate change vulnerability, which has not been well addressed in China, will be magnified by rapid urbanization and increasing climate hazards. Therefore, scaling up digital twin solutions will generate great impacts on urban water management in China.

While drawing on experiences from the Gothenburg and Helsingborg cases, implementing the digital twin presents several challenges (Digital Water, 2023). One major challenge is integrating data reflecting water flow fluctuations from multiple sources, including weather forecasting, water-intensive entities, sewage treatment sector. The insufficiency of high-quality data collection and management, lack of inter-institutional data transfer coordination mechanisms, or absence of privacy protection laws could prevent a smooth integration of multiple source data. Another challenge is establishing trust and confidence in the digital twin system among control room operators.

[58] HREF Model [EB/OL]. [2023-03-16]. https://nomads.ncep.noaa.gov/txt_descriptions/HREF_doc.shtml.
[59] Meteorological Law of the People's Republic of China [EB/OL]. [2023-03-16]. http://www.gov.cn/ziliao/flfg/2005-09/27/content_70627.htm.
[60] Combined sewer systems lead to risk of illness after heavy rains [EB/OL]. [2023-03-16]. https://today.uic.edu/combined-sewer-systems-lead-to-risk-of-illness-after-heavy-rains/.
[61] Ibid.

4.3 Governance Innovation for Leveraging Digital Adaptation

As demonstrated in the case studies earlier, digitalization plays a significant role in promoting climate change adaptation. Meanwhile, there are many challenges in developing and deploying such digital solutions, which can be grouped into four categories: 1) the development of digital technologies, especially research that promotes techniques from labs to practical application; 2) data collection, management, and integration; 3) coordination issues between multiple institutions, and 4) legal issues on the permissibility of sharing data or developing novel approaches. In addition, adaptation planning needs to examine the longer-term risks, for example from changing patterns of extreme events over time—multiple floods, heat waves, drought, wildfires, etc. AI shall play an important role in this regard by helping identify these long-term risks and support decisions on how to build resilience.

China has initiated a series of research and development programs to foster the creation of digital solutions for climate change adaptation. For instance, the Ministry of Science and Technology is backing studies on extreme weather and forecasting technologies and research on digital adaptation decision support systems. However, funding in this area is relatively limited, resulting in such research typically being conducted on a small scale at universities and other public research institutions, and the findings often remain in the laboratory stage. The "last-mile problem" of practical applications remains unresolved. Moreover, there is a deficiency in comprehensive incentive policies that encourage participation from various sectors to develop digital solutions for climate adaptation. Private sector research institutions also possess robust capabilities in this aspect. Given that adaptation efforts are long-term in nature and often have positive externalities, appropriate incentive policies are required to address market failures and promote private sector involvement.

Deploying digital technologies for climate change adaptation requires support from multiple data sources, including data from individuals, businesses, governments, and non-profit organizations. These multi-sources of data are not easily put together, from either a technical, legal, or management perspective. First, the different statistical standards and the varying quality of data from different departments result in data islands and poor information sharing in China. Second, privacy and data security cannot be guaranteed, which undermines the willingness of individuals and businesses to share data. Third, there is a lack of standardized sharing methods and policies. The Chinese government has also made many attempts in this regard. For instance, the government released the technical specifications of the "one map" implementation supervision information system for land and space planning. This technical specification systematically describes the collection standards, data management, and data supervision strategies of national land planning data.

Deploying digital technology for climate change adaptation requires coordinated efforts from multiple institutions across sectors. For example, agriculture, urban planning, emergency management, and meteorological departments need to exchange information on digital solutions for climate change adaptation. China is actively establishing cross-sectoral coordination mechanisms for climate change adaptation, promoting the coordinated advancement of policies and technologies. For example, 17 departments jointly released the National Climate Change Adaptation Strategy for 2035. However, the substantive coordination mechanism is still in its early development stages and is not yet fully established.

Legal issues related to liability and accountability may arise when deploying novel digital approaches for climate change adaptation. Determining who is responsible for potential uncertainties and harm caused by digital adaptation technology is essential to address these concerns. Since deploying digital solutions are still in the initial stages, relevant government policy support is needed, as presented in Section 6.3.

5. The Gender Perspective

The last 50 years of record-breaking economic growth that benefited large parts of Chinese society have not yet been able to sufficiently improve women's status relative to their male counterparts. In most countries that move from an industrial to a service economy, the equality of women follows a U-shaped path, from higher-level of equality in pre-industrial society to lower equality in industrial society to, again, higher equality in the service economy. In China, where services already account for more than half of GDP, this pattern does not hold, and the equality of women follows an L-shaped path (Brussevich et al., 2021). Women's labour force participation rate declined from 73% in 1990 to 61% in 2021, compared to that of men which declined from 86% in 1990 to 78% in 2021.[62] Thus, even though China has made huge strides in economic growth and general welfare to its population, some tendencies point to growing inequalities between men and women.

According to a study by McKinsey, Industry 4.0 has the potential to improve the current labour market situation by opening new opportunities, especially for women. Tasks that previously had to be done by humans can be outsourced or automated and thus change the way of working. McKinsey estimates that women will be slightly more affected by (partial) automation of their jobs, which would result in more flexibility but also a necessary shift of activities and the increasing importance of specific skills. In China, about 4 million to 36 million women (1% to 10% of 2017 employment) may face a need to transition across occupations and skill sets by 2030 to remain employed (Madgavkar et al., 2019).

Artificial intelligence (AI) and digital infrastructures more generally are not only technologies. "At a fundamental level, AI is technical and social practices, institutions and infrastructures, politics, and culture. Computational reason and embodied work are deeply interlinked: AI systems reflect and produce social relations and understandings of the world" (Crawford, 2021). Today, women make up only 22% of AI workers globally (UN Women, 2023). This picture is also evident in science, technology, engineering, and mathematics (STEM) fields in general, where women are in the vast minority. Women are underrepresented in the STEM field throughout the world, be it in higher education, tertiary education, or the workforce (Ortiz-Martinez et al., 2023). They make up roughly 29% of scientific research positions globally, and 23% in East Asia and the Pacific (UNESCO, 2020a). Tech companies in Silicon Valley estimate that only 1% of their applicants for technical jobs are women (UNESCO, 2020b). UNESCO reported that women make up 31% of the research and development positions globally and that women are 25% less likely than men to operate basic digital technology.[63]

In China, less than 30% of the students in STEM fields are female, less than 20% of acclaimed tech positions are held by women, and the Chinese Academy of Science counts only 6% of women in STEM faculties (UNDP, 2021). The UNDP Resident Representative estimates that 80% of high-paying STEM jobs in the green economy in China will be held by men (UNDP, 2022). The AI Index Annual Report 2021 estimated that only 16% of the computer science tenure track faculty is female (Zhang D. et al., 2021). While the percentage of women as publishers of articles on AI ranges around 10% to 30% in many G20 countries, in China, it has stayed consistently at about 4% throughout the last decade (OECD, 2022). However, these numbers are to be understood as a baseline indicating that there are more gender inequities not visible in the existing data. A study of the gender gap in STEM revealed that the lack of gender-disaggregated data prevents policy-makers from understanding the true depth of the problem (Vargas-Solar, 2022).

Although disruptive technologies bring new jobs and potential if handled correctly, they also harbour many risks for social inequalities: The people who benefit most from the effects of Industry 4.0 are those who are able to take advantage of digital solutions and services. Those who may be left behind are those who are digitally disconnected, those who cannot afford digital solutions or who do not have or are not granted access, those who lack basic knowledge and educational options, and those who don't trust their digital skills. The largest marginalized group affected by these barriers and the resulting digital divide is women (GAMA, 2022). Disadvantages can increase if discrimination is compounded by other factors, which are referred to as intersectionality. This means that discrimination against one group, for example, based on gender identity,

[62] The World Bank 2023 Data (Labor force participation rate, total (% of total population ages 15+) (modeled ILO estimate) - China | Data (worldbank.org), access 3/7/2023).
[63] UNESCO, UIS Data Center (UIS Statistics (unesco.org), access 3/17/2023).

sexual orientation, age, origin, disabilities, or socio-economic status cannot be viewed in isolation or simply added up, but rather new forms of discrimination emerge at the intersections. Consequently, women living in remote and rural areas, Indigenous women, women with disabilities, or young or elderly women face additional and probably different forms of barriers and marginalization (UNESCO, 2020c).

To exclude women from design, policies, and social interventions based on digital technologies has harmful consequences for effective climate change mitigation and prevention. First, women are more vulnerable to climate change. Climate change is expected to increase gender-based violence, child marriage, and school dropout rates of girls, and force women to travel longer distances to fulfill daily tasks (UNFCCC, 2022). If digital solutions do not take women's needs into account properly, they risk exacerbating existing inequalities and limiting the effectiveness of those solutions.

Second, women are effective agents, arguably more effective than men, of climate change adaptation and prevention measures. However, women are underrepresented in "green jobs" and the STEM fields, which are crucial to successfully applying digital tools for sustainable development goals. Furthermore, women in decision-making positions shift the companies they lead decisively in the direction of sustainable growth (Deininger and Gren, 2022). Women have also been found to be more efficient drivers of ESG programs and to improve sustainable business practices.[64] If women remain rare in the STEM fields, which are crucial to developing digital solutions, chances are that these industries will not tap into the full pool of talents to find efficient solutions for a green transition of the digital sector that works for all (Giner-Reichl, 2023).

Box 5.1 General Purpose AI: Gender Bias in Matching

Advancing human-centred AI with a special focus on mitigating gender and other biases is beneficial to the climate and social equity. AI is a disruptive technology that will transform the way people work. Gartner predicts that 50% of knowledge workers will use AI on a daily basis by 2025, up from 2% in 2019 (Bradley, 2020). A telling example of a potential impact of AI is that it could significantly reduce the 25% of time knowledge workers spend, on average, to find data (Patenall, 2022).

Matching, the process of matching workers with jobs, is a particularly promising field in which AI may help to reduce the burden on knowledge workers. However, algorithmic bias might lead to unequal treatment of different genders. For instance, setting one's gender to female leads to less high-paying jobs appearing in a search query (Collett et al., 2022). Furthermore, LinkedIn found that men were more often shown open positions than women simply because men tended to search more often for jobs (Wall and Schellmann, 2021). Openings for positions in STEM fields are 20% more likely to be shown to men than women, compounding inequalities already dominating that field (Lambrecht and Tucker, 2019).

AI might also be part of the solution because it can adjust the language of job descriptions and make it more equal as, for instance, in the company Textio (Black and van Esch, 2020). Another silver lining might be active labour market policies that are supported by AI. AI might help governments to improve the matchmaking between vacancies and job seekers. Big data analysis might identify the most important interventions for up- or re-skilling. If these measures were, at least in part, specifically tailored to women's needs or if the relevant AI was programmed in a way to address women candidates specifically, this could have a beneficial impact on the job market (Collette et al., 2022).

Bringing women into influential green jobs that are often based on STEM expertise improves climate change mitigation measures. Recently, the World Bank concluded that women are underrepresented in these high-paying green jobs. They make up as little as 8% of students enrolled in the STEM field, 15% of board positions, 4% of CEOs globally, 23% of managers in water utilities, and 32% in renewable energy. Only 62 women to 100 men are ascribed "green talent."[65] However, since the Paris Agreement, companies with higher gender diversity reduced their CO_2 emissions by 5% more than less-diverse companies. A

[64] Forbes, "Five Reasons to develop Women to lead and influence your corporate ESG operating models" (Five Reasons To Develop Women To Lead And Influence Your Corporate ESG Operating Models (forbes.com), access 3/14/2023).

[65] LinkedIn, 2022. Global Green Skills Report (li-green-economy-report-2022-annex.pdf (linkedin.com), access 3/16/2023).

higher percentage of women on company boards helped to reduce energy consumption, water use, and GHG emissions. Finally, women in STEM have been found to promote climate mitigation more strongly than their male counterparts (Deininger and Gren, 2022). Improving AI matching algorithms, in particular for "green jobs," may thus have immediate benefits for a just sustainable transition.

6. Policy Recommendations

The Chinese economy has undergone a rapid process of digitalization over the past decades, significantly contributing to China's economic development and extending its influence beyond the national border. Against this background, this study aims to explore the link between digitalization and sustainability with a clear mission: digitalization as a dominating transformative force of the 21st century must be put at the service of sustainable development. The study assesses the relationship between digitalization and sustainability in the Chinese context, reviews global best practices, and provides policy recommendations concerning four major areas of action: greening the digital sector, building smart sustainable cities, leveraging digitalization for climate change adaptation, and mainstreaming gender in digital transformation.

6.1 Greening the Digital Sector

- **Promote the green transformation of digital infrastructure and facilities to reduce carbon emissions**

First, promote energy conservation, energy efficiency, and low carbonization of digital infrastructures. Specifically, policy actions should start from two aspects: to keep the construction of new digital infrastructures under strict, sustainability-oriented supervision and promote the energy conservation and low-carbon transformation of existing new infrastructure. They need to focus on key areas such as 5G, data centres, software design and development, and Industrial Internet, and accelerate the R&D of green and low-carbon technologies in data centres with support from various organizations, including industry standardization organizations, scientific research institutes, and leading companies. It is important to encourage companies to speed up the application of energy-conservation technologies such as liquid cooling, natural cooling, high-voltage DC, and waste heat recovery, extend the eco-friendly products' useful life cycle, reuse ICT equipment and eliminate high-energy equipment gradually, advance the formulation of energy-conservation grade and carbon grade standards for ICT equipment in data centres, and orderly decommission facilities with high energy consumption and low efficiency. However, there is a concern regarding the potential for greenwashing, where terms such as "clean energy" or "green infrastructure" can become subjective and open to interpretation, which is sometimes observed in the practices of digital companies. To ensure genuine progress toward sustainability in digital infrastructures, transparency is an essential prerequisite.

Second, optimize the energy mix of existing data centres through green power trading, improve the efficiency of wind, solar, and other new energy, and reduce the carbon emissions of these data centres. Building on the self-commitments of Alibaba, Ant Group and Baidu, a binding 100% renewable energy target for all data centres and digital companies above a certain size is suggested. While the target is clear, flexibility is needed in terms of timeframe and mechanism. It is necessary to evaluate the annual energy consumption of national computing hubs and data centres and publish the evaluation results, as well as to support large-scale data centres to carry out energy efficiency evaluation where conditions permit, using metrics such as Power Usage Effectiveness, Cooling Efficiency Ratio, Energy Reuse Factor and Water usage effectiveness. In addition, cloud services should be labelled with a carbon footprint per service unit. It is also useful to promote the graded construction of zero-carbon data centres, regularly evaluate them and publicize the evaluation results. Information regarding energy consumption, as well as indicators like PUE and other metrics discussed in earlier chapters, should be made publicly accessible. Digital companies should demonstrate transparency by openly showcasing how they have achieved these metrics.

Third, manage the carbon emission data of electronic equipment in their full life cycle. Manufacturing companies should be encouraged to establish a "carbon asset management system" to monitor the carbon emission data of different links and products, standardize carbon data management and accurately identify the actual situation by accounting. Upstream companies engaged in raw materials, components, and parts should be encouraged to transmit carbon emission data to the downstream, through the green supply chain management, to provide high-quality databases for downstream companies to track their product carbon footprint and carbon emission, using indicators such as Carbon Productivity and Carbon Production to evaluate green production.

- **Actively promote the low-carbon development of digital companies and encourage green social responsibility**

First, advocate digital companies to shoulder social responsibility, establish corresponding incentive mechanisms, encourage large digital companies to track, measure, and publish their energy consumption and carbon emissions, and pay attention to the positive and negative impacts of digital technology on the environment.

Second, build an ESG evaluation system with Chinese characteristics, promote the establishment of a scientific and standardized index system with Chinese characteristics on the basis of realizing the unification of international and domestic standards, and effectively guide digital companies to pay more attention to environmental and social responsibilities during investment. Company ESG reporting standards should be set up to strengthen the evaluation of government regulators on the company's ESG compliance.

Third, explore the application of digital tools such as "green passport for digital products" to record the carbon emission footprint based on the supply chain, and design incentive measures and price mechanisms under the guidance of government procurement to promote consumers to purchase more eco-friendly products and services.

Fourth, use digital platform services to leverage green consumption, and cultivate public green living habits, for example, supporting consumers to reduce their data and hardware consumption. Algorithms may prefer consumption of high-quality and long-livability products but demote the consumption of high-turnover, high material-intensity products. Improve the policy environment conducive to shared economic services modes, such as shared travel, online office, and transactions of idle items.

- **Improve the support service capabilities of digital technologies to empower industries to manage and reduce carbon emissions**

Policy-makers should adapt to the development needs of various industries for accurate carbon emission management and green production with lower carbon emission levels, accelerate the R&D and promotion of basic, cutting-edge, and applicable software and information technology services, and enhance the support of digital carbon management and reduction innovation capability.

In terms of carbon reduction via digital technology deployment, it is essential to keep optimizing algorithms because more efficient machine learning algorithms (such as sparse models) can improve the efficiency and reduce the energy consumption of model operation, as well as use special chips for machine learning for large model training. Compared with general-purpose processors, special chips and systems optimized for machine learning training, if used, can significantly improve the performance and energy efficiency of large models. In addition, cloud computing should be used instead of internal computing resources to reduce energy consumption.

To empower other industries through the application of digital technology to reduce carbon, it is important to enhance the research on sensing technologies such as real-time data exchange and information processing and integration, improve the comprehensive performance of carbon sensors, drive breakthroughs in big data technologies such as data mining, machine learning, and modeling analysis, and promote carbon-efficient data management, analysis, and prediction. It is also necessary to strengthen the carbon efficiency-oriented R&D of various technologies and facilitate the application of blockchain in carbon asset management and carbon trading platforms. Furthermore, specific policy actions are needed to support the construction of promotion centres targeting systematically integrated digital and green transformations.

In areas such as smart energy and intelligent manufacturing, digital companies and relevant agencies can carry out demonstration applications of digital carbon management and reduction, provide digital services or solutions for green upgrading and transformation for industrial companies, and advance the digitalization, intelligence, networking, and low-carbon development of traditional industries to better promote digital carbon reduction in various fields.

6.2 Building Smart Sustainable Cities

Smart sustainable solutions can create win-win-win opportunities at the city level: they can promote a modern economic sector; they make cities more livable and advance the quality of life; and they help reduce the local and global environmental burden. However, realizing these goals requires substantial policy and technological efforts and expertise in both digital infrastructure provision and sustainability goals. A central risk is misunderstanding "smart" as being equal to "sustainable." Digital solutions are general-purpose technologies making applications, technologies, and business activities more efficient, but environmental consequences also depend on rebound effects and area of application. It is hence paramount to double down on efforts in sectors and applications that promise the highest sustainability gains, particularly in reducing GHG emissions, improving air quality, encouraging sustainable lifestyle, and achieving a high quality of life. The following policies can help achieve win-win-win situations in Chinese cities.

- **Develop a "Smart Sustainable Cities Audit" System**

The role of audits is to evaluate the performance outcomes, to ensure, in this case, that opportunities created by digitalization are fully utilized to support sustainable development within mobility, buildings, and spatial planning. In cases when weaknesses are found, suggestions in terms of such things as incentives, regulations, and further research should be presented. The "Smart Sustainable Cities Audit" could be generalized to a "Sustainable Digitalization Audit," covering all parts of society.

- **Advance Urban Digital Governance in the Context of Climate Solutions**

Cities like Hangzhou and Shenzhen are world-leading in digital infrastructure and offer the potential for highly adaptive urban governance. It is suggested that the cities' urban climate management makes the best use of these infrastructures to promote climate neutrality. This requires coordinated plans, evaluation of the most effective options in reducing GHG emissions, and the development of digital applications in mobility, building, and urban planning areas consistent with climate goals. Digital innovations have the potential to improve sustainable infrastructures as well as urban governance practices.

- **Promote Special Economic Sustainability Zones Experimenting With Highly Efficient Shared Pooled Mobility**

Provide carpooling and similar services that transport several people in one vehicle (minibus) with tax credits and preferred access to urban street networks. At the same time, limit and regulate on-street parking and introduce inner-city tolls for private vehicles. The expected result is a much more efficient door-to-door mobility system without congestion, better air quality, and smoother economic functioning of cities. With the support of digital platforms, cities such as Hangzhou would be in an excellent position to advance this policy and become a global pioneer in this regard.

- **Advance Sustainable Urban Planning With Artificial Intelligence**

Map building stock and its energy-relevant features and street networks and compute sustainability metrics of urban form. Apply results to sustainable urban planning to make urban use more accessible, less energy- and resource-intensive, healthier, and resilient to high precipitation and extreme heat and cold events. Build a scalable service for all Chinese municipalities.

6.3 Leveraging Digitalization for Climate Change Adaptation

- **Strengthen Support for Scientific and Technological Innovation and Formulate More Resilient and Targeted Digital Adaptation Solutions**

Comprehensively evaluate the scientific, technological, economic, and social research results related to China's adaptation to climate change, starting with digital adaptation in agriculture, cities, and ecosystem management, and systematically strengthen the application of digital technologies in agricultural production, urban disaster prevention and mitigation, and ecological protection. What needs special attention is that the government should provide support for research on the implementation of digital adaptation solutions, which includes providing support for universities and research institutions and promoting the connection between research activities and practical applications.

- **Improve Multi-Source Data Integration and Management and Multi-Institutional Coordination and Cooperation Mechanism**

Developing data standards, data-sharing mechanisms, and coordination policies in the field of climate change adaptation, including especially 1) creating data-sharing centres (data marketplace) that bridge the data gap between different digital projects; 2) developing appropriate data regulation policies to remove disincentives for data sharing (e.g., privacy policies, justice); and 3) establishing information exchange and cooperation mechanisms between agriculture, urban planning, emergency management, and meteorological departments. Digital technology for climate change adaptation requires the support of a large amount of multi-source data. The technical specifications of the “one map” implementation supervision information system for land and space planning are a good reference.

- **Accelerate Legislation to Encourage the Digital Climate Change Adaptation Solutions**

Accelerate the construction of supporting laws for developing and deploying digital climate change adaptation solutions, including especially (a) establishing laws to protect trial-and-error activities, which is essential for the deployment of new technologies; and (b) improving laws on data sharing and privacy protection to remove disincentives for data sharing and multistakeholder participation.

6.4 Mainstreaming Gender in Digitalization

As a typical general-purpose technology, AI both reflects and produces social relations and understandings of the world. Therefore, certain questions must be asked when promoting AI and digital infrastructure for general use in society, such as which resources are necessary, how they are extracted, and who stands to benefit and who does not. To address these questions, the report makes the following recommendations: first, make gender analyses part of policy planning and monitoring; second, empower women and diversity experts in planning, implementation, and monitoring processes; third, make gender-disaggregated data part of every data collection activity and promote data-based research on gender; fourth, include bias detection in risk assessments for new digital technologies and solutions and implement measures to mitigate biases. To deal with gender-related biases related to AI, the government can consider the following policy actions:

- **Raise Awareness.** Gain knowledge of biases, study them systematically, and adhere to international guidelines. The implementation of policies to address gender bias in data and AI systems, e.g., regulations that encourage companies to conduct gender impact assessments or the promotion of algorithmic transparency, can accelerate the process.
- **Detect biases in datasets**. Risk analyses help to identify weaknesses and threats in datasets. Biases can be made visible with the help of software, by using explainable AI techniques contrary to black-box models and to help understand and identify any gender bias, through evaluating bias with disaggregated analyses and by drawing on scientific studies.
- **Reduce existing biases**. Existing weaknesses in datasets can be fixed by improving the process of data collection or combining data sources together with debiasing, e.g., balancing data and removing stereotypical features.
- **Communicate**. It is important to be transparent about methods and data models. The disclosure of results and the project design helps to enable others to understand and improve the model.

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Appendix 1 – Technology Complexity Measurement Index of China's Digital Technology Application and Application Area in 2021

No	Technology	Complexity Index of Technology Application	Application Area	Complexity Index of Application Area Technology
1	Knowledge Map	16.5685	Intelligent Manufacturing	18.8338
2	Block Chain	16.2024	Smart Home	18.766
3	Human-Computer Interaction	16.0711	Intelligent Marketing and New Retail	18.677
4	Natural Language Processing	16.0669	Intelligent Hardware	18.5538
5	Intelligent Recommen-dation	15.9579	Corporation Intelligent Management	18.5489
6	Big Data and Cloud Computing	15.9505	Smart Agriculture	18.5262
7	Speech Recognition	15.8385	New Media and Digital Content	18.4512
8	Smart Chip	15.8158	Intelligent Culture and Tourism	18.3505
9	Computer Vision	15.8113	Intelligent Security	18.3421
10	Space Technology	15.7028	Smart Medical Treatment	18.0937
11	Automatic Drive	15.6962	Intelligent Logistics	18.0227
12	Biological Recognition	15.6318	Intelligent Transportation	17.6297
13	5G	15.6195	Smart City	17.547
14	Virtual/ Augmented Reality	15.6053	Smart Energy	17.2894
15	Intelligent Robot	15.5315	Intelligent Connected Vehicle	17.2766
16	Internet of Things	15.5029	Smart Education	16.8158
17	Photoelectric Technology	15.1286	Smart Governance	16.2989
18			Network Security	15.4846
19			Smart Finance	14.6639

Appendix 2 – Typical Practice Cases in Europe

- ***The KPI4DCE Indicator system for data center***

There are excellent examples of the green digital economy, including some from Germany, that can be highlighted. One example is the KPI4DCE indicator system for Data Centers, created by the German Environment Agency (UBA). This calculation method (KPI4DCE) enables the determination of energy and resource efficiency of data centers, taking into account the entire life cycle of ICT products and supply structure. The KPI4DCE method calculates not only energy efficiency indicators like Power Usage Effectiveness (PUE) and Global Warming Potential (GWP) but also raw materials requirement, Cumulative Energy Demand (CED), and Abiotic Depletion Potential (ADP). Therefore, this indicator system serves as a valuable best-practice guide for data centers seeking to enhance their efficiency.

- ***The public energy efficiency register for data centers***

Another solution to reduce the environmental impact of data centers is to establish a public energy efficiency register for data centers. Currently, there is no statistical record or database that summarizes the energy consumption of data centers based on measured or reported figures by companies. This makes it difficult to obtain an overall picture of their energy efficiency and evaluate the development of their energy consumption in Germany, set minimum requirements, and check their compliance. The energy efficiency register will create transparency about energy consumption and efficiency, providing a basis for legislation and a market dynamic. Data centers are important contributors to digitalization and efficiency improvements in other sectors. However, transparency about their energy efficiency and energy consumption is needed to incentivize and compete for a transition to sustainable and energy-efficient digital infrastructures. The research project "Establishment of a Register for data centers in Germany and Development of an evaluation system for energy-efficient data centers" (short title: Peer DC) aims to establish a secure database and create the prerequisite for increasing energy efficiency in data centers. Its three main goals are 1) establishing a register for data centers and visualizing its contents; 2) developing an evaluation system and software for energy-efficient data centers; and 3) examining the transferability and feasibility of an evaluation system for data centers at the European level.

The register will provide reliable information on the energy consumption and energy efficiency of data centers in Germany, which allows the public and the federal government better assess the impact of digitization on the future energy consumption of data centers and more realistically estimate the efficiency potential. At the same time, by highlighting data centers as usable sources of waste heat, the register can contribute to the heat transition. As a web-based geographical information portal, the register contains data on energy efficiency and other relevant information about the data centers, which are publicly available in a suitable form. The expansion of the register for other EU member states is being considered conceptually.

- ***Green ICT procurement***

ICT devices have high environmental impacts in terms of energy and resource requirements, and the shorter the time they are used, the higher the environmental impact. There is great potential to reduce the environmental impact of ICT use by considering sustainability criteria in the procurement process and extending the useful life/reuse of the equipment. Private and public institutions should adopt a strategic, sustainable ICT procurement strategy to reduce e-waste and other environmental impacts. Eco-labels, such as the Blue Angel in Germany can contribute to this effort by providing high-quality criteria for environmentally friendly ICT products and digital services. The Blue Angel includes a comprehensive catalogue of ecological criteria and health aspects, such as the use of non-carcinogenic materials and low noise levels. It is an important label for green procurement and provides guidelines for consumers. The 40-year-old governmental label ensures transparency and orientation for consumers while creating a market dynamic. The Blue Angel is available for a wide range of ICT products, including software, which plays a major role in determining how environmentally friendly information and communication technology is used. Software influences energy consumption and can contribute to premature hardware replacement (i.e., “software-related obsolescence”).

- ***Energy- and resource-efficient software programming***

The disciplines of software development and data processing have not been limited by technology so far. Inefficient programming is often compensated for by faster processors and more main memory, which leads to larger amounts of data that need to be transmitted and stored. However, the high use of hardware due to inefficient or bloated software has a direct impact on energy consumption and the hardware renewal cycle. The "SoftAWERE - Software architecture tools for energy-efficient and resource-saving development" project aims to address the following tasks: 1) access the energy efficiency and hardware requirements of software development components and tools; 2) develop tools that support software developers in creating energy-efficient and hardware-saving software; 3) investigate the feasibility of labelling energy-efficient software and develop a concept for assessing energy efficiency; 4) increase awareness of energy and resource consumption of software through various communication channels; and 5) enhance the transparency of software energy consumption for third parties.

Furthermore, the SoftAWERE project aims to contribute to the German government's climate protection goals by promoting sustainable digitalization. By developing energy-efficient and resource-saving software, the project creates a solid foundation for achieving this goal.

- ***Transparency of the environmental impacts of digital infrastructures***

The transparency of digital infrastructures must be improved. This can be achieved through the implementation of a binding energy certificate for data centers, which will enable better planning and promotion of future expansion. Cloud services should also be labelled with a carbon footprint per service unit (e.g., per hour, per year). This will create market transparency, incentivizing cloud providers to offer climate-friendly services. Additionally, telecommunication network operators (broadband, telephone, mobile) should label their services with a carbon footprint per transmission unit. This will empower customers to choose more climate-friendly transmission paths.

- ***Energy efficiency and resource protection in the expansion of broadband and mobile networks***

In terms of broadband expansion, priority should be given to the expansion of energy-efficient fiber-optic networks and 5G infrastructures to the end user over other transmission technologies. The expansion of mobile networks should be carried out in a lean and resource-efficient manner by reducing multiple radio coverage of the same regions by different providers.

- ***Environmentally friendly planning, operation and disposal of data centers***

When selecting the location for new data centers, waste heat utilization should be taken into account. Often, data centers are oversized and operate at low capacity, so future planning should be more aligned with actual demand. Modular concepts should be used to improve data center efficiency in partial load ranges. These centers also hold significant amounts of hardware and valuable raw materials; thus, monitoring instruments must be developed to recycle electronic waste. Reusable technology should be identified and repurposed, while monitoring mechanisms for e-waste should be developed to enhance the recycling process.

- ***Support consumers to reduce their data and hardware consumption***

Video content should be optimized to match the display size of the end devices, to ensure that the default resolution aligns with the device's capability. Additionally, the automatic playback of video content on web pages should be disabled by default. In order to prevent false incentives that may encourage excessive data usage, flat rates for large data volumes should be avoided.

Appendix 3 – Practice Case in China: Tencent's Carbon Neutrality Target and Roadmap

In February 2022, Tencent announced its carbon neutrality target and roadmap. Tencent pledges to achieve carbon neutrality in its own operations and supply chain and to use green power for 100% of all electricity consumed by 2030. In the roadmap, Tencent announced three initiatives to achieve self-zero:

Renewable Energy (RE) – Tencent has actively participated in the green electricity market transaction to secure RE supply. In the 2023 trading market, Tencent has signed sustainable power trading contracts for a total of 534 GWh, through which four data centers have achieved 100% RE coverage. Tencent has also invested in distributed solar power and on-site energy storage to create a microgrid on the campus, which allows Tencent to take advantage of its digital power, such as the smart energy-management platforms to increase its RE usage and participate in the electricity market trading in the future.

Energy Efficiency – Tencent has adopted energy-efficient design in its 4th generation "T-block" data center, with an average Power Usage Effectiveness (PUE) of less than 1.3 achieved across all Tencent data centers. Efforts include modularization, power supply optimization, cooling optimization, load optimization, site selection, etc. To complement the hardware design, Tencent deploys a data center intelligence platform that applies automated management, monitoring and analysis, and AI-based intelligent recommendations to help make data centers more efficient and eco-friendlier.

Low-Carbon supply chain and offset – As part of the effort to reduce Scope Three emissions, Tencent is actively advocating for a low-carbon supply chain by partnering with suppliers on low-carbon server procurement and rented data centers. In addition to active emission reduction, carbon offset serves as a supplementary method for Tencent to achieve the final net zero. Tencent supports emerging carbon-offset technologies, such as developing quantitative methodologies, and digital tools for carbon credit measurement.

In addition to its own carbon neutrality goal, Tencent aspires to be a leader in encouraging society to embrace sustainable and lower-carbon consumption, facilitating a low-carbon transformation across industries, and promoting sustainable economic and social development, which is in line with its strategic goal to promote sustainable innovation for social value.

Facilitate a low-carbon transformation for the industrial sector - Tencent actively applies digital technologies to help optimize energy efficiency to achieve zero-carbon buildings and parks. For example, Tencent Cloud offers 'Enerlink' and 'Enertwin' to connect energy data and Carbon Engine to tally GHG inventory. Tencent also offers specific digital solutions to improve carbon-related performance, such as digitalization in forestry carbon credit verification, visualization in CO_2 underground storage, and virtual power plant solutions for the steel industry.

Promote low-carbon lifestyle – Tencent offers a series of Internet products to promote a low-carbon lifestyle. Specifically, Tencent has launched a Carbon Neutrality Quiz mini app to raise awareness and launched a Carbon Island game for players to build a sustainable island. Tencent has also launched a Blue Planet Mini Program to encourage consumers to take public transportation. In office collaboration software, Tencent offers Tencent Meeting, Tencent Doc, and Corporate WeChat to facilitate online, paperless workstyles.

Appendix 4 – Chengdu's Innovative Practices in Digitalization and Green Development

Chengdu, located at the western edge of the Sichuan Basin and sitting on the Chengdu Plain, is a hub in southwest China. The city has a monsoon-influenced humid subtropical climate. With a total area of 14,335 square kilometers, Chengdu is known as the 'Country of Heaven'. Chengdu is a megacity and the National Central City of China, which serves as the capital of the Chinese province of Sichuan. The city is also a significant driving force in Chengdu-Chongqing Economic Circle. With a population of 21.192 million inhabitants and an urbanization ratio of 79.48% in 2021, it is China's fourth most populous city. With a regional GDP of 199.17 billion yuan ($293.6 billion), Chengdu was the 7th largest city in China, higher than cities such as Berlin (Germany), Seoul (South Korea), and Toronto (Canada) during the same period, ranking within the top 30 cities in the world.

Chengdu is the core city in Chengdu-Chongqing Economic Circle (Chengdu-Chongqing city cluster development plan). In 2018, the Chengdu Sustainable Development Guidelines were issued. Furthermore, the SDGs-oriented diagnosis of urban sustainable development was conducted to address the core questions related to the SDGs, the Chengdu Sustainable Development Plan, and the Chengdu National Sustainable Development Agenda Innovation Demonstration Zone Construction Program. Over the years, Chengdu has seized the development opportunities of constructing the National Data Center Node City and the National Sustainable Development Agenda Innovation Demonstration Zone, transforming the eco-environmental construction actions into local socio-economic development with digital efforts. New economic sectors centered on the digital economy have been developing rapidly. As a result, while maintaining rapid and steady economic growth, Chengdu has seen a continuous reduction in total emissions of major pollutants and a gradual improvement in ecological and environmental quality. (Since 2015, Chengdu's GDP has grown from 108.12 billion yuan to 199.17 billion yuan. However, its energy consumption per unit of GDP has decreased from 0.369 tce/yuan to 0.313 over the same period; PM_{10} concentration from 108 to 61μg/m^3; $PM_{2.5}$ from 64 to 40μg/m^3; nitrogen dioxide from 53 to 35μg/m^3; And Forest coverage rate increased from 38.4% to 40.8%; the water quality compliance rate of important water function areas in rivers and lakes increased from 35% to 100%). As a result, the green digital transformation of the economy has been promoted.

Having long been acclaimed as the 'Country of Heaven', Chengdu boasts the unique landscape of the plain in West Sichuan, a more-than-2000-year history of city establishment, and a rich cultural heritage. The city, thriving from its history and transforming through inheritance, turned into a cultural and historical hub of abundance, rich heritage, peace, and charm. It has formed a diverse and inclusive cultural system with 'accent Shu Kingdom' culture as the core, and water culture, Three Kingdoms culture, commercial culture, folk culture, and poetry culture incorporated. Its geography characterizes that two mountains face each other, and the mountains and cities blend; Rivers cross the city and hundreds of waterways moisten the city, which have created the grand scenery of Sichuan and its name card.