Research on the Assistance and Countermeasures of Digital Empowerment in the Environment of Carbon Emission Reduction

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Abstract: In the current global context, what carbon reduction challenges do other nations face, and how are they leveraging digital technologies to facilitate carbon emission mitigation? Under the circumstances where China currently ranks first in the world in terms of total carbon emissions, how can the country, in light of its unique situation, employ digitalization more effectively to aid in realizing efficient carbon reduction measures? Within this framework, starting from the critical and challenging aspects of domestic carbon emissions, this paper contemplates the ways in which contemporary digital tools can be harnessed to implement high-efficiency carbon reduction strategies tailored to the national context. In the acceleration of the development of the digital economy, the role of digital technology in reducing CO2 emissions is becoming increasingly apparent. The traditional energy interconnection network has long been integrated with the traditional energy industry, but how to apply the advantages of network technology to the energy industry, so that energy has new digital characteristics and network thinking has become the energy industry urgently. To this end, this paper mainly focuses on the project research on digital empowerment in the environment of carbon emission reduction, and will mainly consider the key aspects of domestic carbon emission accounting for a large proportion based on the current situation at home and abroad and the research and development status of digital combined carbon emission reduction. In view of these aspects, the feasibility of implementing the digital assistance scheme was discussed, such as focusing on the domestic power system and aiming at the interaction and mutual drive relationship between the power system and the economic and social system; Factory operation planning, transportation industry, with data sharing open system and new format and new model innovation as the guarantee, overall promotion of comprehensive transportation digital transformation and intelligent upgrading; The building materials industry and the discussion of digitalization help build smart parks and improve the level of park informatization. Reduce carbon emissions and create favorable conditions for the subsequent domestic "zero carbon" and "carbon neutral" goals.

Keywords: Carbon Neutrality; Digital Empowerment; Carbon Emission Environment

1. Introduction

Scholarly research has irrefutably demonstrated that excessive carbon emissions led to global warming, greenhouse effect, and the emergence of extreme weather events, with the greenhouse effect being the most immediate and severe issue. According to data released by the International Energy Agency (IEA), in 2022, the global carbon dioxide emissions related to energy surpassed 36.8 billion metric tons, increasing by 321 million metric tons compared to the previous year, reflecting a growth rate of 0.9%. The data indicates that during 2022, droughts, heatwaves, and other extreme weather phenomena, coupled with the shutdown of several nuclear power plants, contributed to a rise in CO2 emissions. However, the deployment of more renewable energy technologies mitigated these increases, averting an estimated 550 million metric tons of emissions. Hence, controlling carbon emissions holds profound and long-term significance for sustainable development.

Currently, China is rapidly advancing towards becoming a powerhouse in the digital economy, and the digital technology revolution is pivotal to driving the country's economic transformation, low-carbon development, and the attainment of peak carbon dioxide emissions and carbon neutrality targets[1]. As per reports from the Global e-Sustainability Initiative (GeSI), over the next decade, digital technologies could potentially reduce carbon dioxide emissions across various industries by 20 percent. The national government has enacted a series of governcies aimed at promoting energy conservation in the information and communication sectors, as well as enhancing energy efficiency, providing robust support for the realization of the objectives of reaching peak carbon dioxide emissions and achieving carbon neutrality.[2] Therefore, in the contemporary context of carbon dioxide emission reduction, delving into the profound implications of digital empowerment is essential and indispensable.

2. Digital Empowerment Promotes Context of Carbon Emission Reduction

Under the mounting ecological challenges facing our planet Earth, harmonious coexistence between human society and the natural environment has emerged as one of the paramount questions of our time. Over the past century, a defining characteristic of global climate change has been the trend of warming. The discovery and utilization of fossil fuels such as coal and oil have propelled humanity into the era of industrial civilization, which, while greatly enhancing labor productivity, has simultaneously given rise to significant environmental and climatic concerns. Widespread use of fossil fuels has led to a surge in carbon dioxide emissions, causing atmospheric concentrations of CO2 to rise and contributing to global warming(Figure 1 shows the carbon emissions in various regions of the world since 1750). A multitude of scientific theories and simulation experiments continue to substantiate the validity of the greenhouse effect theory, with an accumulating body of research indicating that the growth in greenhouse gas emissions driven by human activities is the principal cause of global climate change [3]. According to the World Meteorological Organization's (WMO) '2020 State of the Global Climate' report, the global average temperature was 1.2°C higher than the pre-industrial level (the average between 1850 and 1900), and the period from 2011 to 2020 marked the warmest decade since records began in 1850. Currently, more than 130 countries and regions worldwide have pledged to achieve "zero carbon" or "carbon neutral" goals [4].

Global warming poses severe threats to both the natural ecosystems worldwide and human livelihoods, resulting in increased temperatures on land and sea, rising sea levels, melting glaciers, and extreme weather events, among others [5]. In recent years, climate-related natural disasters have become increasingly severe and frequent. The Intergovernmental Panel on Climate Change's (IPCC) Special Report on Global Warming of 1.5°C published in 2018 highlighted that a global temperature increases of 1.5°C would entail numerous risks to terrestrial and marine ecosystems, human health, food security, and socio-economic development. Furthermore, the report underscored that these risks escalate significantly if the global temperature rise reaches 2°C [6].

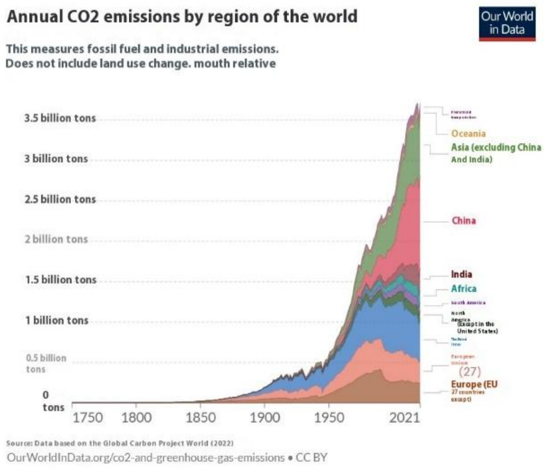

Figure 1. Global CO2 Emissions in 2022

2.1 The Current Status of International Research on Digital Empowerment for Carbon Emission Reduction

Data from PBL Netherlands Environmental Assessment Agency and the World Resources Institute reveal that, in the global carbon emission structure, the leading industries in terms of contribution are electricity generation (approximately 30%), industry (approximately 18%), transportation (around 16%), and buildings (approximately 6%). The three economies with the highest carbon emissions are China (approximately 26%), the United States (approximately 13%), and the European Union (around 8%). Presently, green development has become a global trend, with countries enacting various initiatives. However, considerable controversy surrounds the carbon reduction policies implemented by the US and Europe in recent years [7].

As early as the beginning of the 21st century, many international research institutions had already embarked on applications and studies concerning the use of digital technologies to enable carbon emission reductions. European nations, among others, began strategic planning and actively promoted the development of digital technologies associated with carbon sinks to catalyze decarbonization and sustainable development across industries. They introduced policies to incentivize companies to enhance their capacity to address climate change through digital transformation. For instance, the UK established a £20 million Industrial Strategy Challenge Fund (ISCF) in 2017, aimed at fostering the adoption of artificial intelligence (AI) and robotics in industrial sectors [8], thereby improving industrial productivity, reducing energy consumption, and lowering carbon emissions. Furthermore, the renowned EU initiative, Horizon Europe, announced that it will provide €724 million in grants over the next two years to support the digitalization of manufacturing and construction sectors and shrink their carbon footprints [9]. The program aims to deploy smart mobility, green building, and intelligent energy solutions within innovative projects, aligning with the overarching goal of transitioning toward a greener and more sustainable economy.

Digital technologies have created novel business models, enhanced industrial productivity, and facilitated the low-carbon transition of economic development, gradually reshaping the face of industrial growth. The European Union has devised a strategy to shape Europe's digital future, with industrial digitalization focusing on several key areas. Firstly, there is a concerted push to accelerate investments in technological R&D, particularly in the realms of artificial intelligence, data analytics, and metaverse data analysis. Secondly, the establishment of a governance framework that enables enterprises to produce, collect, and leverage data is prioritized. This framework not only enhances products and services, fortifying competitive advantage, but also embodies European values regarding rights and privacy. Thirdly, there is a drive to bolster industrial capabilities in critical digital infrastructure. Fifth-generation (5G) networks are set to become the cornerstone of industrial big data, and as such, Europe is intensifying investment in the construction of 5G networks [10].

Taking the example of the widespread power outages experienced in Texas during the early spring of 2021 due to an extreme cold snap, this event exposed a primary challenge faced by American society: a continued heavy reliance on fossil fuels that cannot be swiftly altered. In the context of global collaboration on climate governance, wind power generation in Texas has rapidly expanded in recent years, accounting for approximately 23% of the state's power supply structure. However, under extremely cold conditions, the infrastructures supporting wind power generation struggled to function normally. At the technical development level, thermal power generation maintains an absolute advantage due to its stable and continuous output, an edge that remains difficult to surmount in the short term. Currently, the majority of renewable energy sources, due to technological limitations, suffer from significant variability in power generation reliability, influenced by a multitude of factors such as weather patterns and the costs of energy storage facilities. In contrast to the stability offered by thermal power, renewable energy often plays a supplementary rather than a dominant role in power generation [11].

In September 2020, the US Department of Energy (DOE) announced a $16 million funding initiative for fundamental research aimed at advancing digitalization in various sectors to promote energy efficiency and carbon reduction. The focus includes advancing foundational research and simulation applications in areas such as machine learning, artificial intelligence, and other related fields[12].

In 2021, the United States reentered the Paris Agreement, setting forth ambitious greenhouse gas reduction targets of a 50% to 52% decrease by 2030 relative to 2005 levels and achieving net-zero carbon emissions by 2050. Continuous technological innovation is pivotal to expediting progress toward these decarbonization goals and promoting green and low-carbon transitions, with digital technologies emerging as a potent and scalable instrument among these tools. At the forefront of this domain lies 5G technology. Recently, the CTIA (Cellular Telecommunications and Internet Association) in the US commissioned Accenture, a consulting firm, to conduct research which concluded that 5G is poised to be the most environmentally friendly generation of network technology, playing a critical role in the nation's pursuit of its carbon reduction commitments. The study further forecasted that by 2025, 5G would contribute significantly towards realizing 20% of the United States' carbon reduction target [13].

Japan has always attached great importance to resource recycling due to its island country's resource constraints. In December 2020, the Japanese government released the "2050 Carbon Neutrality and Green Growth Strategy", proposing the development and integration of carbon reduction and emission reduction technologies in 14 fields through digital empowerment, and the deployment of advanced smart energy management systems using digital technology [14]

In contemporary times, the thematic undercurrents of global economic recovery have coalesced around "digitalization" and "greenification." Economic revival strategies in countries and regions such as Europe, the United States, and Japan all converge on the crucial role digital technologies play in facilitating worldwide green economic growth and addressing the pressing challenges posed by climate change.

2.2 The Current Status of Domestic Research on Digital Empowerment for Carbon Emission Reduction

According to IEA research references, since 2007, China has surpassed the United States to become the world's largest carbon emitter. When viewed in an international context, the situation regarding China's low-carbon and energy-saving development is highly challenging [15]. According to Figure 2, China's carbon emissions accounted for about one-third of the world' s in 2020, which means that China's low-carbon and energy-saving development is facing huge challenges. In 2021, Zhong Ping and Li Wenshen conducted a study on China's current carbon emission status, revealing that existing mature technologies can only meet 25% of the future carbon neutrality and reduction demands. A further 40% of the required reductions will need to be realized through technologies currently in their early stages of application, while another 35% of the emissions cuts are expected to come from technologies that are still in their prototype or initial demonstration phases [16].

On May 18, 2021, the "5G+ Energy Internet Technology Conference" was convened in Zhengzhou, Henan Province, primarily organized by the China Electric Power Research Institute. The conference revolved around the theme of "New Power Systems Catalyzing the Dual-Carbon Strategy," outlining the envisioned technical framework and innovative trends for future Energy Internet from multiple perspectives, including communication networks, information security, and digital twin applications. It provided solutions for constructing a novel power system, offering significant reference and inspiration for the development of China's Energy Internet [17]. Starting from September 2020, Xu Chuanzi and her team completed a pilot renovation project at the Hangzhou Artificial Intelligence Industrial Park within a two-week period. This included implementing wireless IoT network coverage, integrating IoT into air conditioning and public lighting equipment, conducting intelligent transformations such as dynamic environmental sensing within the buildings, upgrading water, electricity, and gas meters, and developing a smart, low-carbon digital operational platform [18].

In 2022, Sany Heavy Industry Co., Ltd. in China proposed a practical scheme for energy conservation and carbon emission reduction in smart factories. By establishing standard networks, a sophisticated measurement system, and an interconnected equipment platform, the company aimed to construct an intelligent energy management system that facilitated digital control to enhance energy transportation efficiency and significantly reduce unit output energy consumption [19]. Luo et al., through case analyses of Sany Heavy Industry and Zoomlion Heavy Industry Science & Technology Co., Ltd., found that the adoption of digital methods to elevate product intelligence led to improvements in the efficiency of intelligent product development. They also highlighted the establishment of a collaborative innovation platform for digitalized R&D and manufacturing, which boosted the efficiency of developing intelligent products. Furthermore, they emphasized the deepened implementation of factory production line digitization, exemplified by the construction of a tower crane intelligent factory and intelligent production lines for aerial work machinery. These advancements incorporated the use of sensing devices to collect, analyze, and apply big data during the production process, thus strengthening the monitoring of component reliability in manufactured products [20].

According to research led by a team from Peking University, the optimization of China's transportation structure is poised to lead to a substantial increase in the potential for carbon emission reductions in the transport sector [21]. As demonstrated by Jia Feng and colleagues using Didi Chuxing as a case study, recent years have seen rapid growth in low-carbon and green mobility options in China driven by digital platforms, resulting in pronounced carbon reduction effects. The development of intelligent digital platforms has played a proactive role in promoting the construction of green transportation infrastructure and encouraging the public to adopt greener modes of travel [22].

Zhang Kai in their research have found that green buildings serve as a key force in achieving the dual carbon targets. The construction industry, as a foundational sector supporting the high-quality development of China's infrastructure construction and urbanization advancement, is also one of the major consumers of energy and emitters of carbon dioxide. The energy consumption and carbon emissions within the construction industry far exceed those of many other industries.China explicitly highlights the necessity to deepen the low-carbon transformation across sectors such as industry, construction, and transportation [23].

Shi et al. discovered that the development of smart cities leverages modern information technology to drive innovations in urban development models, generating technology effects, configuration effects, and structural effects. Through these three core effects, there is a subsequent reduction in industrial sulfur dioxide (air pollutant) emissions, industrial wastewater discharge, and industrial solid waste generation [24]. Ge and Yu, based on panel data from 223 Chinese cities between 2006 and 2019, meticulously analyzed the theoretical mechanisms underlying how smart city construction impacts urban carbon emissions. Their findings revealed that digital technological innovation is a significant factor affecting urban carbon emissions through smart city development. Smart cities influence urban carbon emissions through both direct pathways of digital technological innovation and indirect paths involving "digital technological innovation → industrial structure upgrading" [25].

Thus, it is evident that digital technologies will increasingly assume a paramount role in the endeavor to facilitate the attainment of dual carbon reduction goals.

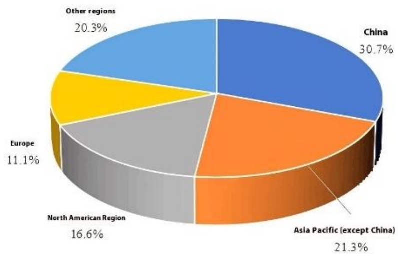

Figure 2. Regional Distribution of Total Carbon Emissions in 2020 (%)

3. Analysis of Digital Empowerment Strategies for Carbon Emission Reduction Solutions

At the general debate of the United Nations General Assembly in September 2020, THE President formally announced China's commitment to peak carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060, commonly referred to as the “30-60 Target”. This paper aims to examine the practical context of China against the backdrop of this timeline, grounded in guiding policy documents such as the "Opinions on Comprehensively, Accurately, and Fully Implementing New Development Concepts for Work Pertaining to Peaking Carbon Dioxide

Emissions and Achieving Carbon Neutrality". It explores the pathways and strategies enabled by digitalization to realize the dual carbon goals.

Achieving the dual carbon goals represents a formidable challenge and test for China, which is still in the midst of its industrialization process. Currently, China accounts for approximately 30% of global carbon dioxide emissions. When you look at Figure 3, you will find that, upon disaggregating China's carbon emissions by specific sectors, it becomes apparent that the power and industrial sectors, both notorious for high emissions, collectively contribute over 70% of the total share, whereas the transportation sector constitutes about 11%, and the building sector accounts for roughly 7%. Notably, industrial parks, as pivotal entities in socioeconomic development, are poised to become major consumers of energy and emitters of carbon in the future. Clearly, the imperative of propelling reforms in energy structure optimization stands out as a critical measure for short-to-medium-term decarbonization in high-emission industries. Moreover, the pathways and modalities adopted by different sectors to attain carbon neutrality vary significantly.

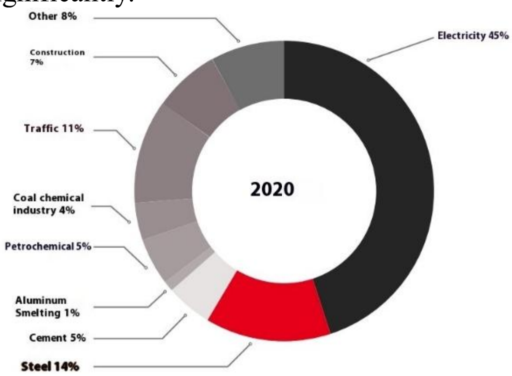

Figure 3. Carbon Emissions Proportion of Different Industries in China

Therefore, the content of this article is divided into five aspects, focusing on the future development of digital carbon reduction and empowerment technology in five fields: 1) Digital empowerment helps to build a new type of power system; 2) Digitalization empowers future factory development; 3) Digitalization empowers the construction of a green and intelligent transportation system; 4) Digitalization empowers carbon reduction throughout the lifecycle of green buildings; 5) Digitalization empowers smart parks to reduce carbon emissions throughout the entire cycle. Figure 4 is Digital Empowerment Helps Carbon Reduction Flowchart, fully demonstrating how to achieve emission reduction in the five areas with high carbon emissions.

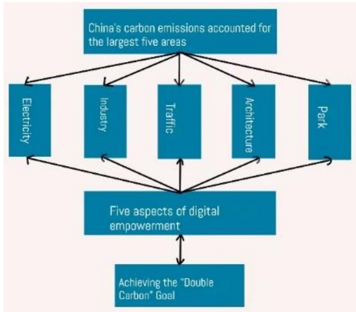

Figure 4. Digital Empowerment Helps Carbon Reduction Flowchart

3.1 Digitalization Empowers the Construction of New Power Systems

According to figure 5, the traditional power sector accounts for 45% of China's total carbon dioxide emissions, ranking first among all industries. In 2020, thermal power plants continued to occupy a significant share of 68% in China's overall power generation mix. Presently, the electric power system is undergoing a transformative shift from a predominantly high-carbon emitting conventional model to a low-carbon emitting, new-type power system centered on renewable energy sources. During the process of establishing a clean, low-carbon, safe, and efficient new energy system and a holistic, source-grid-load-storage integrated modern power system, digital technologies are poised to play a proactive role, enabling novel functionalities such as extensive interconnection, intelligent regulation, and flexible energy-saving measures.

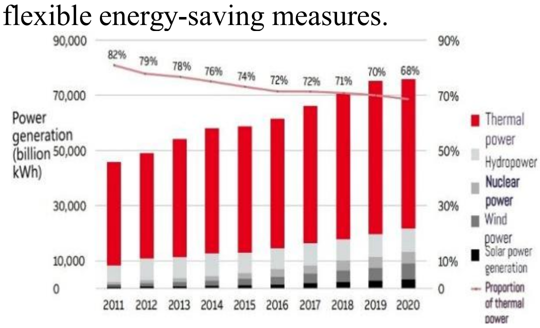

Figure 5. Ten-Year Trend of China's Power Generation Structure and Share of Thermal Power

In the context of digital empowerment, this study focuses on investigating future energy storage methods and green grid operation modes. On the one hand, the accelerated development of renewable energy generation necessitates large-scale deployment of energy storage solutions, which not only addresses fluctuations in daily and seasonal power demand but also caters to emergency situations. Currently, pumped hydroelectric storage and grid-scale battery storage technologies have made notable advances. By 2025, the total scale of go into production will exceed 62 million kilowatts [26], and the installed capacity of new energy storage will reach over 30 million kilowatts [27]

On the other hand, power grids generate massive amounts of data during operation, and through data mining, valuable insights can be extracted from the copious real-time operating data. This research delves into the methodologies concerning the collection, aggregation, intelligent analysis, and edge computing collaboration of state big data, aiming to align with diverse demand scenarios. It organizes and compares the means to achieve state awareness of power equipment and precise fault localization, centering on the upgrade of traditional grids and the enhancement of grid resource allocation capabilities. The study explores the future applications of various artificial intelligence technologies in the realm of power grids, the direction of digital-smart grid development, and the prospective enhancement of intelligent dispatching and smart maintenance operations across the grid infrastructure.

3.2 Digital Empowerment Helps Future Factory Development

The industrial sector serves as a critical source of energy consumption and CO2 emissions. Over half of the industrial carbon emissions derive from industrial combustion, industrial processes, and waste discharge, especially in heavy industries such as steel and cement production. The application of digital technologies can promote energy optimization and cost-effectiveness enhancements in traditional industries, enabling predictive risk assessments and decision control, thereby holistically achieving energy conservation, cost reduction, and improved efficiency. Digitization represents a pivotal pathway for China's industrial green transformation, catalyzing technological innovation in traditional manufacturing and fostering the development of environmentally sustainable production practices. It empowers a comprehensive green transition across the entire value chain of the manufacturing sector. For example, new network technologies represented by Internet of Things technology empower each production unit to be perceptible, communicable, connectable, and computable. Overall, digital technology-enabled industrial carbon emission reduction mainly includes product process research and development, production process control, operation and management mode, operation and maintenance and service, multi-link collaborative optimization, and building industry chain supply chain collaboration. This study will focus on investigating and analyzing three aspects:

1) The development direction of digitally empowered effective petrochemical combustion technologies. Given that traditional industrial combustion heating currently accounts for over 60% of industrial emissions in China [28]and electrification cannot entirely supplant coal and oil as fossil fuels for driving industrial production processes at present. Therefore, through digital simulation and analysis, the establishment of diversified energy fuel alternatives is essential. For instance, electrification can be applied to low- and medium-temperature production processes, while cleaner hydrogen can serve as a substitute fuel for high-temperature processes, demonstrating higher economic feasibility and technical viability.

2) Digital empowerment to enhance energy efficiency and advance the technology roadmap for circular economy. The overarching approach is to devise digital solutions tailored for the adjustment and optimization of technologies and processes in heavy carbon-emitting sectors such as steel and chemical industries. For instance, this entails exploring how digital technologies can be harnessed to improve systemic energy utilization efficiency and foster the research and development of innovative low-carbon products.

Research on the Development of Digital Carbon Accounting and Carbon Capture Technologies. This entails not only scientifically calculating carbon footprints of industrial processes for use in carbon trading markets but also employing sequestration technologies that involve capturing emitted carbon dioxide during production, purifying it, and reintroducing it back into the production cycle, thereby realizing a closed-loop reutilization of carbon. While numerous carbon capture technologies remain in the laboratory phase, they are envisaged as potentially becoming one of the key technologies in humanity's response to global climate change in the long run. If carbon capture technologies prove to be economically viable, technologically mature, and safe following rigorous testing and validation at industrial scales, they could be effectively integrated with power generation, refining, coal chemical processing, and other industries, providing a potential 15% to 20% reduction in emissions within future industrial sectors.

3.3 Digitalization Empowers the Construction of a Green and Intelligent Transportation System

In 2020, the transportation sector accounted for 11% of China's total carbon dioxide emissions. Looking ahead, China's overall transportation demands are expected to maintain an upward trend, suggesting that carbon emissions from the transportation industry will continue to grow, posing a significant challenge to reaching the peak carbon emissions target by 2030. However, decarbonizing the transportation sector is particularly arduous compared to other sectors. Unlike power generation, transportation resides in the 'high-cost' zone of the decarbonization cost curve. The complexity of the transportation industry stems from its multifaceted carbon emission sources, intricate structures, and challenging statistical quantification, necessitating the identification of segments with considerable emission reduction potential and targeted interventions. According to figure 6, road transportation consumes seven times more energy and emits thirteen times more pollutants than rail transportation. Additionally, the average fuel consumption of passenger cars in China exceeds European standards by 1.0 to 2.0 liters per 100 kilometers and Japanese standards by 2.0 to 3.0 liters per 100 kilometers. Thus, optimizing road freight transport and urban traffic management emerges as the crux for achieving peak carbon emissions in the transportation domain.

This study includes two aspects:

1) This study will concentrate on investigating the focal points where digital technology promotes carbon emission reduction in the transportation sector Through big data analysis, the technical analysis of the system's self-construction of a more flexible, efficient, economical, and environmentally friendly smart green transportation system. This includes examining how digital technology supports changes in travel habits, optimizes the travel structure, builds a green mobility framework, and achieves comprehensive carbon reduction.

2) This study will also explore the role of digital technology in empowering the future governance of transportation through the research of digital solutions. Leveraging big data and artificial intelligence technologies, we aim to enhance transportation efficiency, where the Internet of Vehicles (IoV) can facilitate holistic optimization of regional traffic flow, thereby increasing the transportation capacity per unit time and area, as well as improving the traffic flow efficiency within the region.

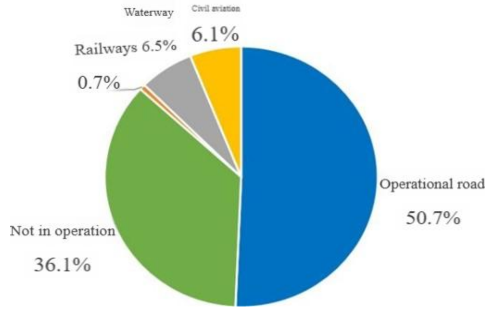

Figure 6. Carbon Emissions Proportion of Transportation Sub Sectors in 2019

3.4 Digitalization Empowers Carbon Reduction throughout the Lifecycle of Green Buildings

In 2018, the operational energy consumption of buildings had reached 1000 million tons of standard coal, accounting for approximately 21% of China's total energy consumption [29], with direct carbon emissions from the construction industry comprising 7% of the annual national carbon emissions total. The lifecycle carbon emissions of the construction industry consist of three components: direct, indirect, and embodied carbon emissions. Direct carbon emissions from buildings refer to those arising from the direct consumption of fossil fuels during the operational phase of buildings. Indirect carbon emissions relate to the emissions caused by the consumption of secondary energy sources – electricity and heat – during the operational phase of buildings, which represent the primary source of carbon emissions for buildings. Embodied carbon emissions in construction encompass those generated by the production and transportation of building materials and the actual construction process itself. From a life-cycle perspective and according to figure 7, the production and transportation of building materials account for 55% of the total carbon emissions, operational phase emissions make up 43%, and emissions from the construction phase constitute 2%.

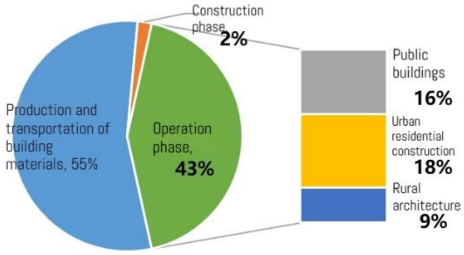

Figure 7. Carbon Emission Proportion at Each Stage of Construction

This research centers on a comprehensive exploration and analysis of how digital technologies can be harnessed to empower the operational management of buildings, positioning green and intelligent buildings as efficacious conduits for achieving peak carbon emissions and carbon neutrality within the built environment. The study delves into strategies to lower building energy consumption, elevate energy efficiency, adhere to green building standards, and thus accomplish the low-carbon objectives inherent to the construction sector. this includes:

1) Digital technologies are being employed to facilitate energy-efficient design, enhance energy efficiency during the operational phase, and construct "photovoltaic-storage-direct current-flexible" (PV-Storage-DC-Flex) buildings. While digital technologies have already permeated every stage of a building project's lifecycle, ranging from planning, design, procurement, production, construction, to operation, the systematic integration of green architecture and intelligent building concepts remains an underdeveloped core component. This goes beyond merely installing various sensors and metering devices for energy management and online monitoring; instead, there is a need to embed the concept of managing the full lifecycle carbon emissions from a green perspective right from the design stage. In the realms of energy-efficient architectural design and construction practices, leveraging big data and artificial intelligence technologies enables designers to select low-energy materials and techniques. Through meticulous design and precision construction, these technologies can guide architects and engineers to create structures that significantly reduce energy consumption throughout their lifecycles.

2) Technological Analysis and Compilation of Digital Technologies Enhancing Energy Efficiency in Building Operation Phase, Including Comparative Analyses of Automated Building Systems, Intelligent Heating, Ventilation, and Air Conditioning (HVAC), Lighting Systems, and “Photovoltaic-Storage-Direct Current-Flexible” Solutions.

3) The development of digital technologies drives the evolution of digital supply chains. To overcome persistent issues such as lengthy procurement cycles and lack of transparency, major general contracting enterprises have progressively transformed their procurement platforms into industry e-commerce platforms. Through the employment of digital means, they achieve interconnectedness among upstream and downstream entities within the supply chain, thereby enhancing the level of supply chain collaboration, boosting resource allocation capabilities, and raising operational efficiency.

Under the impetus of carbon peak and carbon neutrality policies, the development of green buildings is expected to shift into high gear, with an anticipated annual addition of 400 to 600 million square meters of new green building space in the future. The market for retrofitting existing buildings to meet green standards is forecasted to reach a trillion-yuan scale, indicating immense market potential. It is crucial to seize this historic opportunity by nurturing a cohort of leading and benchmark enterprises and establishing a series of demonstration projects and exemplary cases.

3.5 Digitalization Empowers Smart Parks to Reduce Carbon Emissions throughout the Entire Cycle

In 2021, the government vigorously advanced the "Dual Carbon" strategy and the "3060" target, signifying that the nation was entering a critical juncture in its energy transition. Achieving the goals of carbon peaking and carbon neutrality presents both challenges and opportunities. Throughout this process, reforms in the energy structure leaning towards decentralization, the proliferation of distributed power generation, and the extensive deployment of microgrids within parks will play a significant role. Activities related to carbon emissions, carbon reduction, and carbon investment are all taking place within these park settings.

In carbon emissions, industrial energy consumption accounts for the largest proportion, and 80% of GDP is generated within parks, where the combined carbon emissions from building energy use and industrial energy use exceed 41%. In the future, the elements of "source, grid, load, and storage" will all be situated within parks, necessitating unified management and scheduling of these components for effective carbon reduction. By 2030, China's carbon investments are expected to reach 8 trillion yuan, with key focus areas such as energy supply and storage predominantly located within these parks.

The main issues center around:1)Incomplete Energy Usage Data: Disconnected operation of the energy system results in "three barriers": the lack of communication between energy supply and demand information, non-integration between electricity, heat, and gas, and disconnected energy flows and financial flows; 2)Emphasis on Construction Over Operation: There is a heavy emphasis on projects and energy-saving construction, while lacking a comprehensive operational framework, organizational structures, and professional management personnel;3)Passive User Engagement: Policies, technologies, and services tend to neglect active user interaction, with user needs remaining unaddressed or "silent";4) Multiple scenarios and complex access: Multiple media access scenarios, multiple protocols, and complex on-site environment;

Figure 8. Difficulties and Challenges of Integrated Energy Management in Future Parks

This study will delve into seven key scenarios within the park setting to investigate the feasibility and methodology for achieving a holistic zero-carbon footprint within the park, encompassing

1) The substitution of clean energy within the park, exemplified by the paradigm of utilizing diversified photovoltaic power generation and containerized energy storage systems.

2) The synergy of efficient multi-energy complementarity, incorporating ground-source heat pumps, air-source heat pumps, and the integration mechanisms of ice storage cooling/heating systems.

3) Green transportation within the park, including smart street lighting and solar-powered direct current charging for electric vehicles.

4) Smart office practices within the park, featuring digital adaptive control of lighting and air conditioning loads for energy conservation based on direct current technology.

5) Comprehensive energy performance services, including park-wide energy efficiency management, carbon management, and building-level energy efficiency optimization.

6) Park operations, involving the digitalization of operational aspects such as charging stations, virtual power plants, and real-time carbon emission management.

7)Maintenance and operation of park infrastructure, covering maintenance of distribution networks, charging facilities, as well as operation and maintenance of renewable energy sites, including photovoltaic installations, energy storage systems, and cold/heat storage units.

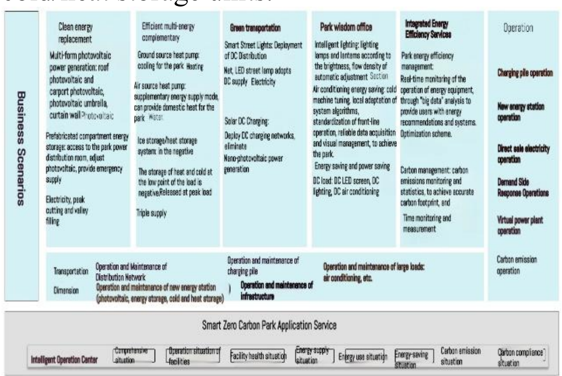

Figure 9. Seven Key Scenarios for Zero-Carbon Parks

The research focal points for developing a Smart Zero-Carbon Campus involve:

1)Intelligent Applications: Augmenting the campus with energy management and operational support platforms, offering a one-stop suite of smart applications for low-carbon campuses that streamline service delivery.2)Intelligent Core: Incorporating essential services such as energy efficiency management engines, fault diagnosis engines, and energy dispatch engines to facilitate rapid development of low-carbon applications, thereby reducing the cost of application development.3)Intelligent Connectivity: Expanding device compatibility with protocols like Modbus and RS485 to enable plug-and-play functionality for power equipment, ensuring seamless integration into the energy ecosystem.4)Intelligent Interaction: Integrating photovoltaic, energy storage, and power supply and distribution equipment, allowing for uniform operation and maintenance management across all types of terminals within the campus, thus creating a holistic approach to managing and optimizing energy resources throughout the facility.

Figure 10 Schematic Diagram of the Three Central Operational Components of a Zero-Carbon Campus

4. Epilogue

Overall, this project centers around the "Dual Carbon" agenda, with the core technologies being the Internet of Things, Big Data, and Artificial Intelligence. Departing from five high-energy-consuming and high-carbon-emitting industries, it seeks to digitally empower the energy, electricity, industrial, transportation, construction, and zero-carbon sectors. Multiple solutions are proposed to achieve the targeted outcomes by focusing on energy conservation management, technological innovation, increasing the share of renewable energy usage, promoting renewable energy procurement, and exploring new pathways for carbon sink utilization. In the domain of electrical power, the implementation of digital enablement technologies has facilitated the establishment of a novel renewable energy system characterized by cleanliness, low carbon emissions, safety, and high efficiency, alongside an integrated power network infrastructure that harmoniously combines power generation, transmission, consumption, and storage elements. This innovative transformation has resulted in the realization of intelligent regulation and flexible energy conservation capabilities. In the context of addressing the challenges posed by fluctuating day-to-day and seasonal electricity demand patterns and emergency situations, the deployment of these digitalized solutions facilitates enhanced responsiveness and expeditious handling of these issues. Within the scope of this project, digital technologies are poised to significantly transform energy storage methodologies in the power sector, empowering the grid to facilitate the integration and application of green energy while enhancing power supply efficiency and fostering the growth of new renewable energy resources. In the industrial context, through digital simulation analyses, diversified energy fuels are being developed, exemplified by the substitution of cleaner energy alternatives for conventional fuels in high-temperature industries. The employment of digital technologies promotes energy optimization and cost-effectiveness within traditional industries. Leveraging digital empowerment techniques, innovative low-carbon products are being researched and developed, thereby improving the overall energy utilization efficiency of systems. The project plays a decisive role in the establishment of zero-carbon factories and green manufacturing facilities, as well as in the development of eco-innovative products and green design, which profoundly impacts the carbon reduction initiatives within factory settings. This effort greatly facilitates the attainment of end-to-end supply chain carbon neutrality across industries, thereby propelling the practical implementation of sustainable development strategies. In the realm of transportation, digital technologies have proven instrumental in alleviating traffic congestion and optimizing transport services.

Digitization has emerged as a central driving force in the evolution of digital transportation and constitutes a vital component of China's future transportation development trajectory. This project catalyzes the progress of transportation by enabling a robust, stable, and expedited advancement of digitalized transportation systems. It thereby improves travel efficiency and contributes significantly to carbon reduction efforts. Digital empowerment in the construction industry leverages digital technologies to simulate and orchestrate construction processes, utilizing digital computation for predictive analysis and optimization of building operations. This application minimizes unnecessary resource depletion throughout various stages of the industry, including design engineering, material planning, transportation of materials, and project execution, striving to attain the rational and maximized use of resources. Ultimately, this serves to reduce avoidable carbon consumption, aligning with the digital empowerment-driven carbon reduction objectives in the construction sector. Integrating digital empowerment into the development of modern smart campuses allows for the establishment of intelligent, digitally-managed communities. By employing digital management, these campuses can meet their energy-saving targets; for instance, water and electricity resources are optimized through digital computations to ensure their most efficient use. Furthermore, digital calculations refine the management of property resources within the campus and ensure the rational operation and maintenance of different zones. This concerted effort not only maximizes the convenience and quality of life for residents but also promotes the efficient organization and utilization of equipment and resources, thereby achieving a reduction in carbon emissions from the entire campus.

5. Conclusion

In the post-pandemic era, the recovery trend of the global economy is characterized by "digitalization" and "greenification," providing a theoretical foundation and data support for China's endeavor to build demonstration provinces of clean energy at a high standard and construct a modern energy system that is clean, low-carbon, safe, and efficient. This paper conducts research on digital empowerment under the context of carbon reduction, aiming to create favorable conditions for the subsequent domestic goals of achieving "zero carbon" status and "carbon neutral".

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