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Exploring Pathways for Digital Technologies to Advance Sichuan Province's Modern Energy System Towards Achieving Dual Carbon Goals

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Abstract

Against the backdrop of global energy transformation and the deepening advancement of the dual carbon goals, digital technologies have emerged as a pivotal force driving the energy system towards cleaner and smarter transformation. This paper systematically elucidates the defining characteristics of a modern energy system – namely, 'secure and efficient, clean and low-carbon, diverse and synergistic, intelligent and inclusive' – based on the current development status of Sichuan Province's modern energy system. It further delves into the intrinsic mechanisms through which digital technologies empower the low-carbon transition of modern energy systems. Research findings indicate that digital technologies exert synergistic effects across the supply, demand, and management sides of the energy system through three mechanisms: optimising energy structures, fostering technological convergence and innovation, and driving industrial integration and upgrading. This propels the energy system from a physics-dominated paradigm towards information-physical synergy, and from chain-based innovation towards networked symbiosis. Building upon this foundation, the paper constructs an implementation pathway centred on 'optimising smart energy systems, deepening technological convergence applications, and establishing a modern industrial digital ecosystem.' Drawing upon Chengdu's practical experience in virtual power plants, smart energy management, and data platform development, it summarizes transformation insights driven by the synergistic advancement of 'technology-institutional-market' dimensions. This research not only provides theoretical foundations and practical references for accelerating modern energy system development and achieving carbon peaking and carbon neutrality goals in Sichuan Province, but also offers a systematic framework for other regions across China to advance the digitalisation of modern energy systems alongside coordinated green and low-carbon development.

Keywords

Digital Technology; Modern Energy System; Dual Carbon Goals; Pathway Exploration; Sichuan Province.

1. Introduction

Energy serves as the fundamental pillar underpinning national economic development and constitutes a strategic safeguard for enduring national stability. Presently, the global energy landscape is undergoing a profound transformation, with the new wave of technological revolution deeply intertwined with energy transition, propelling the modern energy system towards accelerated evolution towards greener and more digitalised approaches. In March 2022, the National Development and Reform Commission issued the '14th Five-Year Plan for the Modern Energy System', emphasising the promotion of digital upgrading within the energy

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sector and fostering innovative applications of next-generation information technologies such as artificial intelligence, big data, and blockchain within the energy domain[1]. In March 2023, the National Energy Administration's Several Opinions on Accelerating the Digital and Intelligent Development of Energy explicitly outlined the direction, objectives, and key tasks for energy digitalisation and intelligent development. It stressed the need to effectively enhance energy digitalization and intelligent development, promote the growth of the digital and green, low-carbon circular economies in the energy sector, and build a modern energy system that is clean, low-carbon, secure, and efficient. The modern energy system refers to a new paradigm of energy systems emerging against the backdrop of the global energy revolution. It aims to address climate change, ensure energy security, and advance sustainable development by establishing sustainable energy supply and consumption patterns through structural optimisation, efficiency enhancement, and system intelligence. By deeply integrating digital technologies such as big data and artificial intelligence with green and low-carbon practices-including renewable energy development and utilisation, energy efficiency enhancement, and smart grid management-it is possible to effectively break down barriers in traditional energy supply, transmission, and consumption models. This will drive the formation of a new paradigm for the modern energy system characterised by intelligent coordination and effective carbon reduction.

A review of existing research reveals widespread academic consensus on the positive role of digital technologies in achieving the dual carbon goals of modern energy systems[2][3][4]. However, literature systematically elucidating their underlying mechanisms and implementation pathways remains insufficient. Most studies either concentrate on macro-level strategic discussions or remain confined to the application of specific technologies, lacking an integrated analytical framework encompassing ‘technological empowerment-pathway construction-systemic synergy’. Particularly, a comprehensive theoretical analysis and practical pathway construction are required to elucidate the complete logical chain through which digital technologies synergistically influence the modern energy system via three key effects-energy structure optimisation, technological convergence and innovation, and industrial integration and upgrading-ultimately contributing to the realisation of the dual carbon goals. Against this backdrop, this paper deconstructs the intrinsic mechanisms through which digital technologies empower Sichuan Province's modern energy system to achieve its dual carbon goals. It explores the core implementation pathways comprising energy structure optimisation, technological convergence and innovation, and industrial integration and upgrading. By analysing the practical case of Chengdu City in Sichuan Province, this study aims to provide a reference for advancing modern energy system development and implementing 'dual carbon' goals across Sichuan Province and the nation as a whole.

2. The Essence and Characteristics of the Modern Energy System

The modern energy system represents a comprehensive upgrade and restructuring of the traditional energy framework. It transcends the mere physical network of ‘production-transmission-consumption’ to embody a profound revolution: shifting from resource dependency to technology-driven advancement, from monopolistic monopolies to diverse openness, and from fragmented supply and demand to integrated production and consumption. The essence of the modern energy system lies in its strategic top-level design and value orientation, which articulates the four-pronged objective of ‘security and efficiency, clean and low-carbon, diversity and synergy, intelligence and inclusiveness’[5]. Its characteristics, meanwhile, represent the concrete unfolding and phased achievements of this blueprint in practice, collectively sketching a vivid picture of China's energy system modernisation. Overall, the modern energy system exhibits the following four distinct features.

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2.1. Safety and Efficiency Form the Fundamental Premise of the System

The resilience, self-reliance and emergency preparedness of the energy system have been elevated to the foremost priority. 'Efficiency' permeates the entire chain of energy development, conversion, transmission and utilisation, signifying that maximum economic and social benefits must be attained with minimal resource and environmental costs. This ensures the energy system maintains economic viability and competitiveness while upholding safety standards.

2.2. Clean and Low-carbon Development Represents an Inevitable Trajectory

Clean and low-carbon approaches address both global climate change challenges and domestic ecological civilisation imperatives. This necessitates a fundamental restructuring of the energy system away from its current reliance on high-carbon fossil fuels. By controlling pollution emissions and reducing carbon footprints throughout the entire energy lifecycle, the system must advance towards a greener, lower-carbon energy mix.

2.3. Diverse and Synergistic Collaboration Defines the Operational Paradigm

Under the dual objectives of energy security and low-carbon transition, reliance on any single energy source has become untenable. 'Diverse Synergy' emphasises the necessity of establishing a multi-pronged energy supply system. This requires dismantling barriers between different energy sources, regions, and operational segments, fostering integration and complementarity between fossil and non-fossil fuels, promoting coordinated development of centralised and distributed systems, and interconnecting regional energy networks. Ultimately, this forms an organically unified, flexible, and reliable complex system, employing systemic thinking to address uncertainty.

2.4. Smart and Inclusive Energy: The Future Form

'Smart' signifies the deep integration of energy systems with digital technologies, empowering energy infrastructure through information technology to achieve precise forecasting, intelligent dispatch, optimised allocation, and efficient management. 'Inclusive' embodies the social value of energy systems, aiming to ensure affordable energy prices, sustainable supply, and universal access to high-quality energy services. This approach ensures that the benefits of energy development reach all citizens, underpinning social equity and improving people's livelihoods.

3. Current Development Status of Sichuan Province's Modern Energy System

3.1. Energy Resource Endowment of Sichuan Province

As a major energy-producing province in China, Sichuan possesses distinctive energy resource endowments characterised by 'clean energy dominance, hydropower as the core, abundant gas resources, coordinated wind and solar power, and coal as a supplement'. This endowment lays a solid foundation for building a clean, low-carbon, safe, and efficient modern energy system. Sichuan possesses abundant clean energy reserves. The province boasts a comprehensive range of clean energy sources, with its hydropower, natural gas, wind power, and solar energy reserves all ranking among the highest nationally, thereby establishing a solid foundation for constructing a green, low-carbon energy system.

(1) Sichuan's hydropower resources lead the nation. To date, its technically exploitable hydropower capacity reaches 148 gigawatts, ranking first nationwide. The Jinsha, Yalong, and Dadu rivers host clusters of world-class hydropower stations, establishing Sichuan as the core base for the "West-East Power Transmission" strategy.

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(2) Sichuan possesses substantial natural gas and shale gas reserves. Estimated natural gas resources total 5.1 trillion cubic metres, accounting for approximately 23.6% of the national total, while shale gas production constitutes around 60% of the national output. Large-scale development of the southern Sichuan shale gas fields has yielded significant results, with accelerated construction underway for the Sichuan-Chongqing natural gas production base targeting 100 billion cubic metres.

(3) Sichuan possesses immense potential in wind and solar resources. The technically exploitable wind energy capacity on the western Sichuan plateau is approximately 18 million kilowatts, while solar energy exceeds 100 million kilowatts. The commissioning of the Kela Photovoltaic Power Station-the world's first million-kilowatt-scale hydro-solar complementary project-demonstrates an innovative pathway for multi-energy coordinated development.

(4) Supplementary Safeguarding of Coal Resources in Sichuan Province. With relatively limited coal reserves, the province is transitioning from relying on coal as a primary energy source to utilising it as a supplementary energy source, placing greater emphasis on clean and efficient utilisation alongside ecological restoration.

3.2. Current Development Status of Sichuan's Modern Energy System

Presently, Sichuan's modern energy system has established a clean energy supply structure centred on hydropower, with rapid development of new energy sources, accelerating its transition towards a new power system dominated by renewable energy. Its core task is to resolve seasonal supply-demand imbalances by constructing a robust grid, developing diversified energy storage, and deepening market reforms, ultimately establishing a national-level clean energy strategic base and an efficient hub for the 'West-East Power Transmission' initiative.

(1) Strengths (S): Resource Abundance, Innovation-Driven Development and Cluster Formation

Sichuan Province demonstrates significant comprehensive advantages in modern energy system development. Leveraging its unique clean energy endowment, Sichuan not only possesses the nation's largest hydropower resources and accounts for 60% of China's shale gas production, but also hosts vast wind and solar resources on the western Sichuan plateau. Furthermore, it achieved a breakthrough in multi-energy coordinated development through the world's first million-kilowatt-scale hydro-solar complementary project. Building upon this foundation, the province has established a comprehensive technological innovation system. Over 150 national-level energy innovation platforms, combined with abundant talent resources from higher education institutions, have fostered a deeply integrated technology innovation ecosystem encompassing industry, academia, research, and application. Simultaneously, benefiting from its strategic positioning as a National Clean Energy Demonstration Zone, Sichuan has implemented targeted industrial policies and innovative green financial instruments. This has successfully cultivated world-class industrial clusters in power batteries and photovoltaics, attracting nearly 60,000 new energy enterprises to cluster and develop.

(2) Weaknesses (W): Structural Imbalances, Facility Constraints and Insufficient Support from

The development of Sichuan's modern energy system faces three primary disadvantages. Firstly, structural imbalances are pronounced, with new energy development lagging significantly. Combined wind and photovoltaic installed capacity accounts for only 10% of the province's total installed capacity, far below the national average. New energy vehicle production constitutes merely 7.2% of the national total, reflecting a relatively small industrial scale with shortcomings in key segments of the industrial chain. Secondly, infrastructure bottlenecks impose significant constraints. Lagging grid development hinders new energy integration, particularly in remote areas. An underdeveloped transport and logistics system elevates project operational costs, while progress on new infrastructure, such as smart grids,

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remains sluggish. Finally, insufficient innovation support constrains development prospects. Despite Sichuan's abundant higher education resources, there is a severe shortage of high-end R&D and management talent in the energy sector. Unattractive talent recruitment policies contribute to brain drain. Weak indigenous innovation capabilities in frontier technologies like hydrogen energy and energy storage persist, with continued reliance on external imports for core technologies. This hampers the enhancement of Sichuan's modern energy system competitiveness.

(3) Opportunities (O): Technological Breakthroughs, Institutional Safeguards, and Low-Carbon Transition

The development of Sichuan's modern energy system is poised to capitalise on three strategic opportunities. Technological innovation is emerging as a core driver, with the deep integration of digital technologies into energy systems providing the technical foundation for constructing smart energy systems. Particularly promising applications are evident in virtual power plants and multi-energy coordination. Concurrently, breakthroughs in critical equipment and technologies-including heavy-duty gas turbines, megawatt-class hydropower units, and shale gas development-have laid a robust foundation for high-quality energy sector advancement. Refined institutional safeguards provide robust support. At the national level, the renewable energy policy framework continues to strengthen. Sichuan Province, through supporting policies such as its 14th Five-Year Plan for Renewable Energy Development, has established a clear development pathway and target system, offering a stable institutional environment for industrial investment and technological innovation. Moreover, the deepening low-carbon transition has created vast development opportunities. The global energy revolution and the advancement of China's 'dual carbon' strategy have accelerated the clean energy transition, presenting Sichuan with a significant opportunity to leverage its comparative advantage in clean energy and participate in global climate governance.

(4) Threats (T): Pressure to Control Emissions, Integration Challenges and Innovation Bottlenecks

Currently, the development of Sichuan Province's modern energy system faces three primary threats. Firstly, the contradiction between energy consumption and the dual carbon goals is acute. With accelerated industrialisation and urbanisation, energy consumption will continue to rise during the 14th Five-Year Plan period. Significant pressure to control fossil fuel consumption poses a severe challenge to achieving the carbon peak target. Secondly, insufficient grid integration and system flexibility for new energy sources persist. The planned addition of 6 million kilowatts of wind power and 10 million kilowatts of photovoltaic capacity faces inadequate coordination with grid infrastructure development. The random and fluctuating nature of renewable energy intensifies peak-shaving pressures on the grid, while weak grid frameworks in certain regions constrain transmission capacity. Finally, technological bottlenecks constrain industrial upgrading. Significant technical shortcomings persist in key areas such as refined wind power design, photovoltaic system efficiency enhancement, hydrogen energy, energy storage, and smart grids. Critical technological challenges in oil and gas exploration and development, as well as clean coal utilisation, demand urgent breakthroughs. Innovation-driven capabilities require further strengthening.

4. The Underlying Mechanism of Digital Technology Empowering Sichuan Province's Modern Energy System to Achieve Dual Carbon Goals

Digital technology refers to a technical framework that employs tools such as computers, communication equipment, and software systems to collect, process, store, transmit, and apply diverse forms of information. This technology transforms complex physical-world data into quantifiable digital signals, enabling deep data mining and intelligent analysis through

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algorithms and computational power, ultimately serving to optimise decision-making and enhance efficiency. Against the backdrop of a burgeoning digital economy, the empowerment of modern energy systems through digital technology has become a pivotal mechanism for achieving the dual carbon goals. Its core lies in leveraging data as a key factor to drive the systematic reshaping of modern energy systems through technological application. This provides novel theoretical perspectives and practical pathways for reducing regional carbon emission intensity and realising the dual carbon goals.

4.1. Energy Structure Optimisation Effects

The rise of digital technology presents fresh opportunities to address the challenges of energy structure. By introducing data elements and intelligent algorithms, it reconfigures the traditional operational paradigms of the supply, demand, and management sides of energy systems. This transforms their relationship from one of independent, sequential linkage into a deeply interactive, synergistically evolving organic whole, thereby laying the theoretical foundation for system stability and efficiency enhancement under high-penetration renewable energy integration.

Traditionally, energy supply-particularly renewable sources-has been regarded as an uncontrollable power source characterised by strong randomness and volatility, with output dependent on natural endowments, forcing systems into passive adaptation. The integration of digital technology fundamentally alters this logic. Leveraging big data and machine learning algorithms, digital technologies enable sophisticated modelling and ultra-short-term forecasting of natural conditions such as meteorology, hydrology, and irradiance. This transforms the output of renewable sources like wind, solar, and hydro from random variables into predictable trends, significantly reducing their inherent uncertainty. Consequently, it provides the informational foundation for planning of operational modes and optimisation of reserve capacity within the system.

On the demand side, digital technologies activate the regulatory potential of demand-side resources through information exchange and price signals, theoretically reconfiguring their role from a system burden to a system resource. Smart meters and IoT sensors form the demand side's 'nerve endings', enabling granular perception and high-frequency data collection of vast numbers of users' electricity consumption patterns. This transforms the load curve from a coarse aggregate line into a resource pool composed of countless identifiable, quantifiable, flexible units. Concurrently, digital platforms establish bidirectional information channels from system operators to end users. Price signals, such as real-time electricity tariffs and demand response directives, can be efficiently and accurately transmitted to the consumer side. This mechanism transforms the previously fixed load curve into adjustable demand elasticity, providing the system with a zero-carbon, low-cost peak-shaving resource. This dynamically complements the fluctuations of renewable energy on the supply side, thereby enhancing the energy system's absorption capacity.

The management side serves as the central hub connecting the supply and demand sides. Conventional management models, constrained by incomplete information and insufficient computational capacity, often pursue localised or static optimisation. Digital technologies, however, foster system-level collaborative optimisation mechanisms through holistic data integration and intelligent decision-making. Energy Internet of Things and cloud computing technologies aggregate real-time status data from all segments of modern energy systems into unified data pools. This provides system administrators with a holistic, dynamic operational panorama of the energy system, establishing a comprehensive information foundation for global optimisation. Furthermore, advanced optimisation algorithms can solve joint optimisation scheduling models encompassing multiple energy sources and bilateral resources at second or minute-level time scales based on this holistic data. This mechanism no longer

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manages the supply and demand sides in isolation but treats them as an integrated whole. By leveraging computational power to identify the globally optimal solution, minimising total system costs while maximising renewable energy integration, it ensures the stability, economic viability, and feasibility of transitioning to a clean, low-carbon energy structure at the operational level.

4.2. Technological Convergence and Innovation Effects

Digital technologies, underpinned by information networks and intelligent algorithms, provide the core driving force for modern energy systems to achieve the dual carbon goals through deep integration and cross-fertilisation with energy technologies. This convergence is not merely a superimposition of technologies but a reconfiguration of the technical pathways and operational logic of modern energy systems through the seamless integration of data elements and the empowerment of intelligent models.

Firstly, the technical pathway undergoes reconstruction from experience-dependent to model-driven approaches. Traditional energy technologies heavily relied on physical laws and historical experience. Digital technologies, however, construct precise digital twins to achieve holographic mapping and dynamic simulation of physical systems within virtual spaces. This enables the transition from experience-based approximate judgements to data-model-driven, precise decision-making and forward-looking optimisation in energy system planning, design, and operation. Secondly, operational logic transforms physics-dominated to cyber-physical synergy. Information networks dismantle barriers across energy system segments, enabling real-time perception and interaction of data throughout the entire 'generation-grid-load-storage' chain. This shifts system operation from rigid control solely governed by physical laws to collaborative control characterised by global computation within the information domain and precise execution within the physical domain. Finally, the innovation model evolves from a linear chain to a networked structure. Digital platforms accelerate the diffusion and reconfiguration of technical knowledge, dissolving boundaries between energy and other industries. Cross-sectoral technology modules freely combine via standardised interfaces on these platforms, catalysing convergent innovations such as energy-transportation integration. This networked symbiotic mechanism significantly accelerates the formation and iteration of low-carbon technology systems, providing sustained technological supply and innovative momentum for achieving the dual carbon goals.

4.3. Industrial Integration and Upgrading Effects

Industry integration and upgrading driven by digital technologies serve as the pivotal link between the technological revolution and energy transition. This process transcends the mere application of individual technologies, fundamentally reshaping both internal industrial mechanisms and inter-sectoral relationships and value chains[6]. Consequently, it elevates the energy efficiency and low-carbon resilience of economic systems.

During the integration and upgrading process, digital technologies first drive the intelligent transformation of traditional industries, achieving intensive energy consumption through 'enhancing quality and efficiency'. By deploying industrial internet platforms and constructing digital twin systems, real-time perception and dynamic optimisation of energy and material flows are realised. This shifts production processes from 'experience-driven' to 'data-driven', significantly improving the utilisation efficiency of energy and raw materials, thereby achieving energy conservation and carbon reduction at source. Secondly, digital technologies foster industrial synergy, achieving optimal energy allocation through 'system coupling'. By leveraging industrial internet and big data platforms, they dissolve traditional industrial boundaries, facilitating cross-sectoral flow and efficient matching of energy, materials, information and other factors[7]. This substantially elevates the comprehensive utilisation efficiency of societal energy resources, reducing fossil fuel consumption and carbon emissions

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at the systemic level. Moreover, the development of the digital economy has spawned new business models centred on digital industries, such as information transmission, software technology services, smart logistics, and platform economies[8]. These drive the overall transformation of industrial structures from resource-dependent and labour-intensive models towards technology-intensive and knowledge-intensive ones[9]. These industries exhibit distinct characteristics of low material dependency and high value-added output, propelling the socio-economic structure towards a low-energy, low-emission 'lightweight' model from the high-energy consumption, high-emission 'heavy industrialisation' paradigm[10].

5. Innovative Pathways for Digital Technologies to Advance Sichuan Province's Modern Energy System Towards 'Dual Carbon' Goals

5.1. Optimising the Modernised Development System for Smart Energy to Enhance Overall Operational Efficiency

On the supply side, digital technologies drive structural transformation in energy provision, establishing a clean and low-carbon supply system. Within the fossil fuel sector, industrial internet platforms and big data analytics enable real-time monitoring and parameter optimisation of power generation units and chemical processes, significantly enhancing energy conversion efficiency[11]. In the renewable energy sector, Sichuan Province can leverage its abundant hydropower resources. Through digital technologies enabling high-precision power forecasting, intelligent operation and maintenance, and distributed control, it can effectively address the intermittency and grid integration challenges of new energy sources like wind and solar power[12]. This accelerates their large-scale substitution, driving a fundamental shift towards a cleaner, zero-carbon energy structure from the supply side.

On the demand side, digital technologies are spearheading a systemic transformation of energy consumption patterns, driving the evolution of end-use practices towards lighter, smarter approaches. The flourishing of emerging sectors such as the platform economy, remote working, and digital content industries has significantly reduced reliance on high-energy-consuming physical products. Sichuan Province should actively foster the growth of these emerging sectors to achieve a decoupling of economic growth from energy consumption. The proliferation of digital energy applications in smart buildings and intelligent transport systems, through energy consumption monitoring, demand response, and system optimisation, can substantially enhance end-use energy efficiency. Leveraging its strengths in the digital economy, Sichuan Province could pioneer the establishment of near-zero carbon emission demonstration zones in key areas such as the Chengdu Plain Economic Zone, reshaping energy consumption patterns through digital technologies.

On the management front, digital technologies optimise the operational logic of energy management systems, fostering a new paradigm of modern energy governance characterised by 'data-driven, intelligent decision-making' . Smart energy management platforms built upon cloud computing, the Internet of Things, and blockchain technologies can break down data silos across generation, transmission, consumption, and storage segments, enabling dynamic perception and coordinated dispatch of energy elements across the entire domain. Concurrently, the carbon footprint tracking and MRV (Monitoring, Reporting, Verification) systems enabled by digital technology provide comprehensive data support for Sichuan's participation in national carbon market development and policy oversight. This significantly enhances the effectiveness of carbon pricing mechanisms and the precision of policy implementation, systematically improving the efficiency of energy resource allocation from a management perspective.

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5.2. Deepening the Integration of Digital Technology with Energy Systems to Elevate the Intelligence Level Across the Entire Chain

Technological convergence is first manifested in the intelligent retrofitting and efficiency enhancement of existing energy infrastructure. By embedding the Internet of Things, digital twins, and AI predictive algorithms into energy production and transmission/distribution processes, the system achieves real-time monitoring and dynamic optimisation of unit performance, pipeline network loads, and renewable energy output. For instance, the digital twin system deployed at Yibin Thermal Power Plant utilises model predictive control to reduce coal consumption for power generation below 270 grams per kilowatt-hour, achieving annual carbon dioxide emissions reductions exceeding 100,000 tonnes per unit. Furthermore, this technological convergence fosters entirely new energy business models and integrated system solutions. Digital applications dismantle technical barriers between multiple energy subsystems-including electricity, thermal power, and chemical processing-driving their interconnection and collaborative optimisation. At the Yalongjiang integrated wind-solar-hydro-storage base, a cloud-edge collaborative energy management system built on a cloud computing platform coordinates regional generation, grid, load, and storage resources to achieve multi-energy complementarity and overall efficiency optimisation. Consequently, Sichuan Province has established a provincial carbon asset trading platform using blockchain technology, combined with an IoT monitoring system, to provide enterprises with end-to-end digital management solutions for carbon assets. Finally, the convergence of artificial intelligence and high-performance computing is accelerating the development of frontier technologies such as novel energy storage materials and compact nuclear systems, opening new technical avenues for deep decarbonisation of energy systems. Sichuan Province can leverage universities, including Sichuan University and Southwest Petroleum University, alongside research institutions like Mianyang Science and Technology City, to establish an energy digital technology innovation platform. This platform should focus on digital simulation and intelligent R&D of energy materials, prioritising breakthroughs in key technologies such as advanced energy storage materials and compact nuclear systems.

5.3. Building a Modern Industrial Digital Development System to Empower Industrial Chain Integration and Upgrading

Digital technologies are driving profound adjustments and upgrades within industrial structures, thereby establishing a modern industrial system at the macro level that underpins the dual carbon goals. Industrial consolidation and upgrading constitute an interlinked, incrementally progressive process, commencing with the digital transformation of traditional industries. The judicious application of digital technologies can comprehensively empower high-energy-consuming sectors such as steel, building materials, and chemicals, enabling refined management of production processes. Within Sichuan Province, priority should be given to steel and building materials enterprises such as Pangang Group and Chuanwei Group, alongside chemical enterprises including Sichuan Petrochemical and Luhua Chemical. Initiatives such as establishing smart factories, deploying Energy Management Systems (EMS), and implementing digital twins can achieve refined resource utilisation. Secondly, an industrial synergy ecosystem must be constructed. Digital platforms can transcend sectoral boundaries, facilitating cross-industry flow and optimised allocation of factors such as energy, materials, and information. Sichuan Province should encourage regional integration of digital technologies with local industries based on provincial conditions to optimise resource allocation. For instance: In industrial clusters like Chengdu, establish smart energy management platforms to facilitate cross-sectoral flow and optimisation of energy and materials; At Deyang's equipment manufacturing industrial park, utilise digital platforms to repurpose industrial waste heat for district heating, enabling resource reuse; In Yibin,

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converting waste biomass such as distillery residues into clean energy establishes a circular economy model featuring cascading energy utilisation. Finally, nurturing emerging industrial ecosystems is crucial. New business models catalysed by digital technology, such as platform economies and sharing economies, exhibit pronounced low-carbon characteristics.

The widespread adoption of remote working reduced commuting-related carbon emissions in China by approximately 30 million tonnes in 2022. E-commerce platforms optimised logistics routes, lowering carbon emissions per parcel by 20%. Online meetings replaced some business travel, cutting aviation carbon emissions by over one million tonnes annually. The growth of these emerging industries is driving the economic structure's shift from energy-intensive to knowledge-intensive sectors, providing the industrial foundation for decoupling economic growth from carbon emissions. Building upon this, Sichuan Province can leverage Chengdu's strengths in digital economic development to cultivate new business models with low-carbon characteristics, such as platform-based and sharing economies. This approach will support the province's modern energy system in achieving its 'dual carbon' goals.

6. Analysis of Chengdu's Modern Energy System Development Practices

As a national central city and the core area for the Chengdu-Chongqing region's 'dual carbon' goals, Chengdu faces dual challenges of economic growth and carbon reduction. By 2024, coal consumption in Chengdu's total energy mix had fallen to 25.8%, a reduction of 12.5 percentage points from 2020. Clean energy consumption rose to 68.5%, with natural gas accounting for 28.3% and non-fossil energy exceeding 40%. Regarding digital infrastructure, Chengdu has established 42,000 5G base stations, achieving continuous coverage across townships and above. It has constructed a national-level internet backbone direct connection point, with data centres housing a total of 80,000 standard racks. The city-level energy big data centre has been preliminarily established, aggregating over 200TB of multi-category energy data, including electricity, gas, and heating.

In leveraging digital technologies to advance Sichuan Province's modern energy system, Chengdu pioneered the establishment of Southwest China's first city-level virtual power plant operation management platform on the energy production side. Leveraging 5G communications and smart metering technology, this platform aggregates 850 MW of controllable resources, including distributed photovoltaic systems, energy storage plants, and commercial building air conditioning systems. During the 2024 summer peak period, it achieved precise peak shaving of 320 MW, equivalent to eliminating the need to construct a 300 MW traditional coal-fired power plant. On the energy consumption side, Chengdu's Tianfu Central Business District deployed a 'digital twin + smart energy' system to enable real-time monitoring and coordinated optimisation of energy usage across 128 large buildings within the area. This achieved annual electricity savings of 120 million kilowatt-hours and reduced carbon dioxide emissions by 75,000 tonnes. On the energy management side, Chengdu's New Energy Vehicle and Charging Intelligent Service Platform connects 38,000 public charging points. Through intelligent dispatch and orderly charging technology, it has elevated charging facility utilisation rates to over 45%, effectively stabilising grid load fluctuations. Through the systematic advancement of digital energy infrastructure, Chengdu achieved significant outcomes in 2024. Unit GDP energy consumption decreased by 16.2% compared to 2020, the added value of core digital economy industries accounted for 14.8% of GDP, and carbon intensity fell by 20.5% relative to 2020.

Moving forward, Chengdu should deepen the integration of digital technologies with its modern energy system, employing a systemic approach to advance the transformation towards higher standards and support Sichuan Province's 'dual carbon' goals. On the energy production side, efforts must focus on enhancing the intelligent aggregation and market trading capabilities of

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distributed resources such as virtual power plants. Building upon existing aggregated controllable resources, further exploration should be undertaken to achieve deeper integration with electricity spot markets and ancillary service markets. By optimising dispatch strategies through artificial intelligence algorithms, the economic viability and reliability of vast dispersed resources participating in real-time system balancing can be enhanced, establishing them as indispensable flexible regulation pillars within the regional new power system. On the energy consumption side, emphasis should be placed on expanding the coverage breadth and analytical depth of the 'digital twin + smart energy' system. Replicate and extend building energy optimisation models to key sectors such as industry and transport, integrating multi-dimensional data to establish city-level smart energy management platforms capable of predictive control and personalised energy-saving services, thereby unlocking society-wide energy conservation and carbon reduction potential. On the energy management side, actively build cross-category, cross-stakeholder urban energy data hubs and collaborative ecosystems. Building upon existing energy big data centres, break down data silos to deepen the integrated analysis and value extraction of multi-system data encompassing electricity, gas, heating, and transport. Encourage participation from diverse stakeholders to ultimately forge a sustainable development framework characterised by 'data empowerment, market-driven approaches, and ecosystem-wide mutual benefit'.

Notably, Chengdu's advancement of the digital transformation of its modern energy system has yielded practical experiences of significant reference value. These practices profoundly demonstrate that advancing energy digitalisation requires upholding a systemic approach, establishing a coordinated advancement framework integrating technology, institutions, and markets. This entails deepening the integration of digital and energy technologies, establishing robust market-oriented operational mechanisms, and fostering an industrial ecosystem where diverse stakeholders jointly build and share benefits. Chengdu's successful experience offers other regions a replicable 'technology-institutional-market' coordinated transformation pathway, possessing significant demonstrative value and replicability.

7. Conclusion

This paper focuses on researching the mechanisms and pathways through which digital technologies empower modern energy systems to achieve the dual carbon goals. First, it systematically outlines the current development status of Sichuan Province's modern energy system. Sichuan possesses a clean energy endowment centered on hydropower, complemented by abundant natural gas and wind/solar resources, laying a solid foundation for building a clean and low-carbon modern energy system. The current system has developed significant advantages in clean energy supply, technological innovation, and industrial clustering. However, it also faces challenges such as an unbalanced energy structure, infrastructure constraints like power grids, technological bottlenecks, and talent shortages. Against the backdrop of the “dual carbon” goals and the energy revolution, Sichuan Province is presented with strategic opportunities arising from technological breakthroughs, policy refinement, and low-carbon transformation. Simultaneously, it must address practical pressures, including rising energy consumption, grid integration, and the consumption of new energy, as well as innovation in key technologies.

Second, digital technologies empower the construction of Sichuan's modern energy system through three synergistic effects: energy structure optimization, technological convergence innovation, and industrial integration and upgrading. In optimizing the energy structure, digital technologies leverage big data, the Internet of Things, and intelligent algorithms to achieve precise forecasting and dynamic coordination across both supply and demand sides. This transforms the intermittency of renewable energy into dispatchable resources, providing the

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technological foundation for demand-side response and advancing the clean and low-carbon transformation of energy supply while ensuring system security. Regarding technological convergence and innovation, the deep integration of digital and energy technologies has given rise to new paradigms characterized by data-driven approaches, model simulations, and networked collaboration. This accelerates the R&D and application of smart energy systems and cutting-edge low-carbon technologies. Concerning industrial convergence and upgrading, digital technologies provide industrial support for overall economic decarbonization by driving the intelligent transformation of traditional high-energy-consuming industries, promoting cross-sectoral coordination of energy resources, and fostering new, low-energy-consumption, high-value-added digital economy models.

Finally, taking Chengdu City in Sichuan Province as a representative case, this study analyzes the effectiveness and implementation pathways of digital technology in empowering modern energy systems. Through initiatives such as establishing a city-level virtual power plant, deploying a 'digital twin + smart energy' system, and building an intelligent service platform for new energy vehicles, Chengdu has achieved substantial progress in enhancing energy system operational efficiency, promoting clean energy consumption, and reducing societal energy costs and carbon emissions. This provides a viable paradigm for digitally driven green energy system transformation for similar regions in Sichuan Province and across China.

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References

[1] Modern Energy System Plan for the 14th Five-Year Plan Period. [EB/OL]. [2022-03-22]. National Development and Reform Commission, https://www.ndrcgovcn/xxgk/zcfb/ghwb/202203/P020220322582066837126.pdf

[2] Huang Xiaohui, Nie Fengying. Research on the Mechanism of Digitalisation-Driven Green and Low-Carbon Transformation in Farmhouse Agriculture [J]. Journal of Northwest A&F University (Social Sciences Edition), 2023, 23(01): 30-37

[3] Wang Xuhui, Xie Xun. Mechanisms and Pathways for Digital Innovation to Lead Green and Low-Carbon Transformation in Logistics: A Case Study of JD Logistics [J]. Research in Economics and Management, 2024, 45(05): 21-40.

[4] Feng Ziyang, Song Donglin, Xie Wenshuai. The Digital Economy in Support of Achieving the 'Dual Carbon' Goals: Fundamental Approaches, Underlying Mechanisms and Action Strategies [J]. Journal of Beijing Normal University (Social Sciences Edition), 2023, (01): 52-61.

[5] Xie Kechang. Reflections and Recommendations on Developing a New Energy System [J]. Chinese Journal of Engineering Science, 2024, 26(04): 1-8.

[6] Liu Qiang, Ma Yanrui, Xu Shengxia. Has the Development of the Digital Economy Enhanced China's Green Economic Efficiency? [J]. China Population, Resources and Environment, 2022, 32(03): 72-85.

[7] Chang Haoliang. Digital Economy, Green Technological Innovation and Carbon Emission Intensity: An Empirical Study Based on Chinese Urban Panel Data [J]. Business Research, 2023, 34(02): 73-80.

ISSN: 2692-7608 DOI: 10.6981/FEM.202512_6(12).0010

[8] Shang Juan, Wang Zhenmeng. The Effects of the Digital Economy on Empowering Green Economic Development [J]. Ecological Economics, 2023, 39(03): 47-56.

[9] Li Xiaohua. New Characteristics of the Digital Economy and the Formation Mechanism of New Momentum in the Digital Economy [J]. Reform, 2019(11):40-51.

[10] Li Sanxi, Wu Yufan, Li Jiaqi. The Digital Economy and Chinese-Style Modernisation: Contemporary Significance, Opportunities, Challenges and Pathways for Exploration [J]. Economic Review, 2023, 12(02): 3-14.

[11] Wu Caixia, Gao Yuan. Research on the Mechanisms and Effects of the Digital Economy Driving Low-Carbon Industrial Development [J]. Guizhou Social Sciences, 2020, 23(11): 155-161.

[12] Xie Yunfei. Impact Effects and Mechanisms of the Digital Economy on Regional Carbon Emission Intensity [J]. Contemporary Economic Management, 2022, 44(02): 68-78.