



Accelerating Decarbonization in Data Center Infrastructure in Smart Cities With Digitalization: Insights From Shenzhen (China) and Cyberjaya (Malaysia) for Promoting Net-Zero Emissions

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Abstract

Digitalization is a key driver of decarbonization in data centers, as demonstrated by the strategic initiatives in Shenzhen, China, and Cyberjaya, Malaysia. This work presents the key findings and insights from a comparative analysis of their digitalization strategies and impact on data center sustainability. China's digital economy, which accounted for 39.8% of its GDP by 2021, reached CNY 45.5 trillion by 2021, and its data center market reached revenues of USD 95.74 billion by 2024, with a CAGR of 8.97%. The country aims to increase non-fossil energy consumption to 20% by 2025 and 25% by 2030, aligning with its goal of carbon neutrality by 2060. Malaysia, on the other hand, focuses on renewable energy integration, aiming for 31% renewable energy in its installed capacity by 2025. However, the opportunities for energy savings and reduced carbon emissions are significant. The experiences of China and Malaysia highlight the importance of strategic planning and policy support. Both countries face significant structural challenges; while the initial financial investment in digital infrastructure is substantial, the more critical hurdle is the gap in intellectual capital. To achieve sustainable operations, data centers must serve as more than just hardware hubs; they must become repositories of human intellectual capital while encompassing technical, behavioral, and managerial competencies that allow for the navigation of complex technological and sustainability transitions. Support and investment in digital infrastructure to leverage digitalization for the purpose of decarbonization is crucial. China and Malaysia are well-positioned to lead in sustainable data center operations, setting a precedent for global sustainability initiatives.

Keywords Digitalization · Decarbonization · Data Center · Renewable Energy Integration · Smart cities

Extended author information available on the last page of the article

Introduction

With the increasing global need for carbon reduction and sustainable development, the focus on managing data center infrastructure has become more pronounced (Channi and Kumar, 2024). The use of digitalization plays a crucial role in speeding up decarbonization efforts in smart cities (Zheng, 2023). China stands as the world's largest carbon emitter, with a significant increase in emissions over the past decade, highlighting the urgency for action (Wu and Li, 2024, Iea, 2023). The integration of data as a fundamental factor in production has sparked debates on its role in the low-carbon development of the manufacturing industry; it has the potential to optimize processes and reduce emissions (Zheng, 2023). Global data centers contribute to a substantial percentage of electricity usage, with Bitcoin mining alone consuming a notable share, emphasizing the need for sustainable energy practices (Thangam et al., 2024).

Smart cities and the connection between safety and sustainability are closely intertwined. Creating a sustainable future for smart cities is a multifaceted endeavor that involves integrating advanced technology and innovative urban planning to address environmental, social, and economic challenges. Smart cities require the safeguarding of critical infrastructures such as energy grids, water supply systems, transportation networks, and communication systems. Ensuring the resilience and security of these systems is vital for the city's sustainability in terms of reducing energy consumption and greenhouse gas emissions and the well-being of its inhabitants. Moreover, developing and maintaining robust and efficient infrastructure is critical for cities to be resilient to climate change and natural disasters. This includes flood protection measures, disaster preparedness plans, and resilient building codes. Sustainability practices can improve overall safety and enhance the resilience of urban infrastructure (Masanet et al., 2020).

This work argues that the transition to net-zero emissions is fundamentally a knowledge-driven process. Beyond the technical reduction of CO₂, decarbonization in this sector is driven by the mobilization of relational and structural capital within smart city frameworks. We address three core research questions: (RQ1) How do decarbonization strategies transform regional intellectual capital? (RQ2) How do these strategies generate innovation spillovers across digital ecosystems? (RQ3) How does this transition reshape economic value capture and governance?

In China, cities are responsible for a significant proportion of natural resource consumption and greenhouse gas emissions, making the role of electrolytic hydrogen in decarbonization efforts crucial (Wu and Li, 2024). Digitalization is a pivotal force in achieving specific United Nations Sustainable Development Goals (SDGs), particularly those concerning clean energy and sustainable infrastructure. In nations like Malaysia and China, the focus is on utilizing the Internet of Things (IoT) and smart systems to bridge the gap between burgeoning digital growth and carbon reduction targets (Mondejar et al., 2021). The Smart Cities Research Center is at the forefront of this movement, focusing on enhancing urban mobility and quality of life through data-driven decision-making (Li et al., 2015).

Emerging digital technologies are vital for energy efficiency and integration in smart cities, with applications ranging from data collection to AI-driven predictions and optimizations. The rise of digital infrastructure, including data centers, is critical for the efficient transmission, storage, and processing of data, underpinning the digi-

tal economy (Wu and Li, 2024). As global CO₂ emissions continue to rise, there is a pressing need for a roadmap towards a net-zero future, with milestones to decarbonize the global economy within three decades.

The synergy between digitalization and industrialization in Chinese cities has been recognized as a new driving force for energy conservation and emission reduction (Ma and Lin, 2023). Digital technologies are being leveraged to break away from extensive economic growth models, exploring innovative paths for urban development (Liao, 2023). This transition is supported by China's burgeoning digital economy, which is a significant contributor to its GDP. The role of digitalization in empowering energy-saving and emission reduction in cities is a universal issue, with valuable implications for other emerging economies aiming for sustainable development through digital and intelligent means (Feroz et al., 2021).

Digitalization is a pivotal force in achieving carbon reduction targets, particularly within the framework of smart city development in nations like Malaysia and China. China's digital economy has burgeoned into a global leader, reaching a staggering \$7.5 trillion in 2022, as noted in the 'Global Digital Economy White Paper (2023)' (Iea, 2022; Zhang & Chen, 2019; United Nations, 2024). This expansion is not merely a reflection of increased energy demand or economic output; it represents the creation of dense knowledge clusters where data centers act as the central nodes. Within these clusters, digital innovation ecosystems are comprising tech giants, startups, and research centers that facilitate innovation spillovers that optimize energy use and accelerate the development of green technologies. Similarly, Malaysia has set forth ambitious goals to decrease its carbon emission intensity by 40% from 2005 levels by the year 2020, and by 45% by 2030, despite the challenges of population growth and poverty (Susskind et al., 2020).

The integration of sustainability and digitalization within the context of data center infrastructure management highlights the critical need for human capital development. Both transitions demand a workforce equipped with interdisciplinary skills to navigate the complexities of technological innovation and sustainability. As nations aim to decarbonize and digitalize their economies, the role of skilled professionals becomes central in implementing, maintaining, and advancing these transformations. Developing human intellectual capital from technical expertise to behavioral and managerial competencies is essential for meeting individual and systemic needs. This manuscript recognizes the interplay between human capital development and the twin transitions, emphasizing its significance in ensuring a sustainable, resilient, and human-centric future (Zahid et al., 2023).

The connection between urbanization, digitalization, and carbon emissions is undeniable. Cities, despite covering a mere fraction of the Earth's surface, are responsible for over 70% of global CO₂ emissions, with projections indicating a rise to nearly 78% by 2030 (Churkina, 2016). This reality has galvanized a global consensus on the pursuit of low-carbon development strategies. The role of digitalization in this context extends beyond economic activities; it is also a key driver for environmental management. The proliferation of digital technologies like the Internet of Things (IoT), advanced sensors, and data analytics is enabling more efficient energy use, promoting the development of electric vehicles, and facilitating remote work, thereby contributing to reduced carbon emissions (Javaid et al., 2022).

Moreover, digitalization is a catalyst for technological innovation and a means to address income inequality, both of which are instrumental in enhancing carbon productivity (Yu and Liu, 2024). Innovations in renewable energy technologies and the democratization of knowledge through digital platforms are key to this endeavor. Policymakers are encouraged to formulate visions and strategies that leverage digital technologies to transition towards renewable energy, improve energy efficiency, and minimize emissions from industrial and transportation sectors (Subramanian, 2023, Nguyen et al., 2024, Hoz et al., 2023). Initiatives like the Green Technology Financing Scheme (GTFS) in Malaysia exemplify government efforts to incentivize renewable energy investments and practices (Ezuma et al., 2022).

Digitalization is a multifaceted tool for achieving carbon reduction targets that not only optimizes economic activities and energy consumption but also fosters innovation, equality, and sustainable development (Yu and Liu, 2024, Mondejar et al., 2021, Huang et al., 2024). As cities continue to be hubs of socio-economic activities, the integration of digital technologies becomes increasingly vital for the realization of smart, low-carbon urban environments (Li, 2024). The global community must support and learn from the efforts of nations like Malaysia and China, which are actively pursuing digitalization as a pathway to a greener and more sustainable future (Yu and Liu, 2024, Huang et al., 2024).

Data centers are pivotal in modern infrastructure, significantly influencing energy consumption and carbon emissions (Thangam et al., 2024). South Korea announced its plan to buy 10 thousand high-end GPUs during 2025 to remain competitive in the AI realm globally. As the competition to dominate the AI industry intensifies, the competitive landscape is changing from competition between companies to full-scale rivalry between the country's innovation ecosystems.

To understand the environmental footprint, one must distinguish between the IT load (compute activity) and the facility load (cooling and power distribution). While data centers globally consume approximately 3% of total electricity, the efficiency of the facility load is captured by the Power Usage Effectiveness (PUE) metric (Fig. 1). In China, current facility load inefficiencies result in PUE scores of 1.6–1.7, which the government aims to reduce to below 1.3 by 2025. This reduction targets the facility's overhead, allowing for greater IT load capacity within the same energy budget (Ni et al., 2024).

This work argues that the transition to net-zero emissions is fundamentally a knowledge-driven process, where the mobilization of relational and structural capital within smart city frameworks determines the success of decarbonization strategies.

In the realm of smart cities, data centers are the backbone, supporting the management and digitization of industries (Lam et al., 2020). Malaysia's strategic location has positioned it as a burgeoning hub for data centers in Southeast Asia, attracting substantial investments from major tech corporations. The impact on energy demand is undeniable, with global internet users doubling and internet traffic increasing by 20-fold since 2010, driving up energy use for these centers (Thangam et al., 2024). Efficiency improvements in data center operations are framed here as the manifestation of dynamic capabilities, the ability of firms to integrate, build, and reconfigure internal and external competencies to address the urgent demands of the green transition.

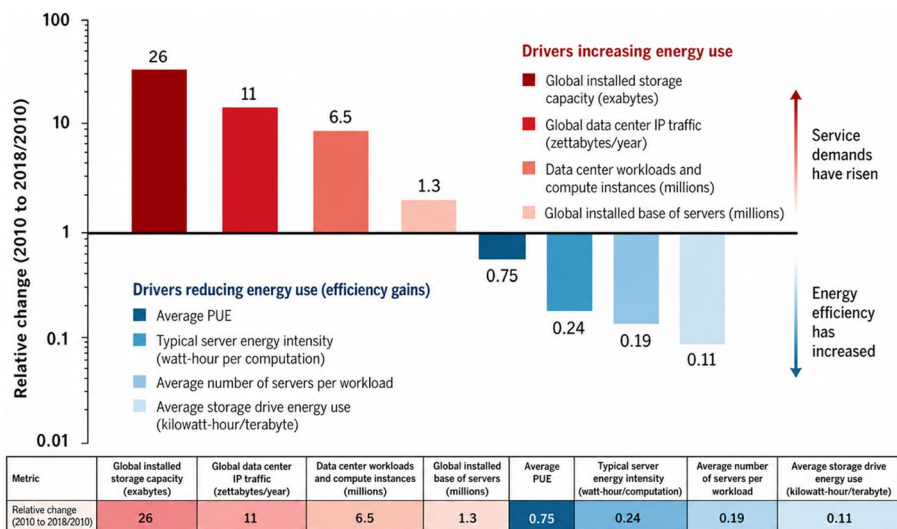


Fig. 1 Trends in global data center energy-use drivers

Resource allocation within data centers is a key area for optimization. Implementing fast reinforcement learning algorithms can lead to more efficient energy use, improving performance and reducing waste (Perera and Kamalaruban, 2021). Additionally, data centers' water consumption is a growing concern, particularly in the United States where they rank among the top ten water-consuming industries, yet there is a lack of transparency in reporting water usage (Mytton, 2021). By examining the Regional Innovation Systems of Shenzhen and Cyberjaya, the review explains why certain urban ecosystems adapt faster than others. These systems facilitate innovation spillovers and inter-firm learning, allowing city planners and operators to leverage digitalization as a catalyst for long-term sustainable urban development.

The lifecycle costs and benefits of data centers are complex, involving high construction and operational costs, and the need for careful site selection due to stability and security concerns (Lam et al., 2020). The return on investment for these mission-critical facilities is intricate, as any disruption could lead to significant losses. As the world increasingly relies on data centers, ensuring their sustainable development and operation is essential for meeting global energy and environmental goals (Thangam et al., 2024).

Relevance to Smart Cities

Data Centers as Knowledge-Intensive Infrastructure

Digitalization is a cornerstone in the evolution of smart cities, leveraging data and digital technologies to enhance decision-making processes and elevate the quality of life for residents (Gracias et al., 2023). The integration of digital solutions in smart cities allows for real-time data analysis, enabling authorities to respond promptly

to citizen needs and service demands (Okonta and Vukovic, 2024). In the context of smart cities, digitalization acts as the cornerstone for decision-making, with the potential to improve urban standards by 10 to 30%. However, rather than focusing on broad social indicators like crime or health, this study emphasizes the data center as a knowledge-intensive asset within the city. These centers support the digital fabric of urban environments, transforming traditional infrastructure into dynamic systems capable of meeting specific climate and energy goals (Sánchez-Corcuera et al., 2019, Buttazzoni et al., 2020, Qian et al., 2023).

The energy efficiency of data centers is a critical aspect of smart cities, as these centers consume a notable portion of the world's electricity (Thangam et al., 2024). Despite the growth in data center workloads, advancements in energy efficiency have helped to limit the overall increase in energy usage. However, the carbon footprint of these centers remains a concern, with factors such as electricity and water consumption and server lifespans contributing to their environmental impact. The Power Usage Effectiveness (PUE) metric is a key indicator of data center energy efficiency, with an ideal PUE of 1.0 signifying that all energy is directed towards IT equipment (Seymour and Herrlin, 2015). Nonetheless, most data centers operate with a PUE between 1.2 and 1.4 due to inefficiencies in equipment, cooling systems, and power distribution (Shao et al., 2022).

A comprehensive study has provided a detailed dataset of city-level final energy consumption in China, encompassing a variety of energy resources across numerous cities, offering valuable insights into energy usage patterns and potential areas for improvement (Yang et al., 2024). Additionally, the International Renewable Energy Agency (IRENA) contributes to the global understanding of renewable energy by providing extensive datasets on capacity, generation, and energy balances, highlighting the progress and potential of clean energy sources worldwide (Hassan et al., 2024).

The decarbonization of data center infrastructure is not merely a technical adjustment but an interaction between Structural Capital (the physical facility, cooling systems, and power distribution) and Digital/Algorithmic Capital (AI-driven models and real-time automation). This synergy allows for predictive maintenance and energy-efficient resource allocation, transforming static infrastructure into a dynamic, knowledge-intensive asset capable of optimizing energy use (Engel-Cox & Broughel, 2026).

This transformation requires a robust foundation of Human Capital as the technical and managerial competencies necessary to navigate complex sustainability transitions. Human capital acts as a vital bridge, translating algorithmic insights into structural improvements (Delgado-Verde et al., 2025). Through the mobilization of Relational Capital, these individual competencies generate innovation spillovers across the regional ecosystem. A prime example is the collaboration between China and Malaysia through Alibaba's 'City Brain' program in Kuala Lumpur. This partnership facilitates inter-firm learning and the exchange of structural knowledge, allowing Malaysia to leverage China's digital leadership to accelerate its own renewable energy targets.

By positioning data centers at the intersection of these four capitals, they transition from energy consumers to knowledge-intensive assets that anchor regional innovation

ecosystems and drive the global shift toward a green digital economy. Digitalization in smart cities is a multifaceted approach that not only incorporates technology into traditional infrastructure but also employs it to make strategic, data-driven decisions that enhance urban living (Herath and Mittal, 2022). As cities continue to adopt and integrate digital solutions, the potential for significant advancements in efficiency, sustainability, and overall quality of life becomes increasingly tangible.

Digital Decarbonization Through the Knowledge-Economy Lens

The rapid expansion of the digital economy in China and Malaysia represents a fundamental shift in how national productivity and sustainability are conceptualized. By 2021, China's digital economy reached CNY 45.5 trillion, accounting for 39.8% of its national GDP. Similarly, the digital sector contributed 22.6% to Malaysia's GDP as of 2019. Within the knowledge-economy paradigm, this growth is not merely a reflection of increased energy demand or infrastructure footprint; it signifies the emergence of dense knowledge clusters where data centers function as central, intelligent nodes. These facilities anchor digital innovation ecosystems comprising tech giants, startups, and research institutions, all of which facilitate innovation spillovers that optimize energy use and accelerate the development of green technologies (Aisha & Swamy, 2024).

However, the transition to a sustainable digital future faces a significant hurdle often characterized as a “skilled labor” shortage, which this study frames as a systemic gap in intellectual capital. For data centers to achieve true sustainability, they must evolve from passive hardware hubs into repositories of human intellectual capital, encompassing the technical, behavioral, and managerial competencies required to navigate the “twin transitions” of digitalization and decarbonization (Asiaei et al., 2022). This perspective shifts the focus from mechanical upgrades to a human-centric knowledge evolution, recognizing that technological innovations remain static without a workforce capable of managing complex, knowledge-intensive assets.

The proposed conceptual framework positions data centers at the intersection of four critical domains: Structural, Digital/Algorithmic, Human, and Relational Capital. Under this lens, observed energy efficiency improvements are interpreted as the manifestation of a firm's Dynamic Capabilities, the ability to reconfigure internal and external competencies to address urgent green transition demands (Chu et al., 2025). This theoretical anchoring explains why Regional Innovation Systems (RIS) such as Shenzhen and Cyberjaya adapt more rapidly than other urban environments; these systems foster inter-firm learning and utilize digitalization as a long-term catalyst for sustainable growth.

A primary example of this is the collaboration between China and Malaysia through Alibaba's “City Brain” program, which facilitates the exchange of structural and relational knowledge to accelerate renewable energy targets. Evidence from the regional case studies further supports this theoretical alignment. In Malaysia, hubs such as Sedenak Tech Park serve as Regional Innovation Ecosystems designed to mobilize structural capital. The entry of global leaders like AWS, Google, and Microsoft into these parks generates critical learning spillovers that force a domestic elevation of green standards and ESG compliance (Kilinc-Ata & Rahman, 2024). In

parallel, China's East-West Computing Resources Transmission (EWCRT) Project exemplifies Macro-level Knowledge Governance. By deliberately mobilizing structural capital (computational power) into western regions that traditionally lack relational networks and innovation infrastructure, the project allows these provinces to capture economic value as central players in the green digital economy (Constantin et al. 2021; Papiashvili et al. 2025). Looking toward future trajectories, technologies such as AI and Blockchain are evolving from mere tools into drivers of knowledge creation. AI-driven models are now conceptualized as generators of algorithmic capital, capable of providing proactive energy management that can reduce operational costs by 15–25% (Gao et al., 2025). This shift empowers emerging economies to transition from being passive hosts for foreign technology to becoming active architects of Green Intellectual Capital. By establishing low-PUE standards and strategic governance frameworks like Malaysia's MyRER or China's EWCRT, these nations are redefining economic value capture and sustainable governance for the global digital age.

Focus on Malaysia and China as emerging leaders in digital infrastructure development

Malaysia and China are emerging as leaders in the digital infrastructure sphere, with robust support from various factors. The Malaysian digital infrastructure market is witnessing rapid growth, particularly in the Kulai district of Johor, which is strategically located near Singapore and is currently undergoing significant data center construction. This expansion is set to attract substantial investments, building on the momentum of investments made in previous years (Gong and Yeung, 2022, Hu, 2024).

The Malaysian government is actively supporting this ecosystem by developing industrial parks equipped with the necessary infrastructure, such as the Sedenak Tech Park and Nusajaya Tech Park (Fig. 2). Technological cooperation between China and Malaysia is also fostering progress, exemplified by Alibaba's implementation of its "City Brain" program in Kuala Lumpur, which complements its broader e-commerce and logistics initiatives in the region (Naughton, 2020, Triolo, 2020, Ordóñez De Pablos et al., 2024, UNESCO and ICEE, 2021).

The Malaysian Digital Economy Corporation (MDEC) is at the forefront of driving national digital transformation and adoption, with the Malaysia Digital initiative serving as a strategic plan to attract businesses, talent, and investments to the country. The World Bank reports that Malaysia's economic growth is set to expand, with digital technology playing a key role in enhancing productivity, employment, and poverty reduction (Aziz et al., 2021; Edrak et al., 2022; Mansor, 2022).

Rather than static outcomes, high-end projections serve as evidence of the rebound effect inherent in the digital transition. Projections suggesting data centers could reach a 13% share of global electricity by 2030 illustrate the 'induced demand' created by expanding AI workloads. In Malaysia, this manifests as a potential 5 gigawatts of demand by 2035 according to researchers at Kenanga Investment Bank Malaysia. This is more than half of Malaysia's entire renewable capacity in 2023. These figures are utilized here not as inevitable forecasts, but as the 'baseline risk' that Macro-level

Data Centers in Southern Johor, Malaysia

Key data center parks and operators supporting Johor's digital infrastructure and regional connectivity

DATA CENTER PARKS

- 1 Sedenak Tech Park (Kulai District)
Operators: Princeton Digital Group, Yondr Group, MN Holdings
- 2 YTL Green Data Centre Park (Kulai District)
Operators: Sea Limited, YTL Power
- 3 Nusajaya Tech Park (Iskandar Puteri, Johor Bahru District)
Operators: GDS Holdings, Equinix
- 4 Nusa Cemerlang Industrial Park (Johor Bahru District)
Operator: ST Telemedia Global Data Centres

CONNECTIVITY

- Singapore–Johor Bahru Causeway
- - - Second Link Expressway

SOUTHERN JOHOR DATA CENTER SNAPSHOT (2024)	
Operational Data Centers	>20 facilities
Total Capacity (IT Load)	>1,000 MW
Planned Capacity (by 2026)	>1,500 MW
Primary Operators	Hyperscale, Colocation, and Enterprise
Key Strengths	Power Availability, Land Availability, Connectivity to Singapore

Source: Company websites, press releases, industry reports (2024)



Fig. 2 Data centers in Southern Johor, Malaysia

Knowledge Governance and Algorithmic Capital (AI-driven optimization) are specifically designed to mitigate.

More than 95% of the energy available to Malaysia in 2022 came from fossil fuels, according to the International Energy Agency. The country is now the fifth-largest exporter of liquefied natural gas globally. Today, artificial intelligence is driving the desire to build more data centers. Moreover, tech companies are looking for larger, cheaper locations around the world as part of a ‘global strategy’.

Trade and investment between Malaysia and China are significant, with China being a major trade partner for Malaysia. Partnerships such as Tencent Cloud’s collaboration with Global Resources Management to launch a new Internet Data Center in Malaysia further underscore the commitment to digital advancement (Fig. 3). China’s plan for digital development aims to achieve significant progress in digital infrastructure and innovation by 2025, positioning the country as a global leader in digital development by 2035 (Yeoh et al., 2018, Zenglein and Holzmann, 2019, Shi, 2022, Hu, 2024).

In Malaysia, the digital economy is seen as a new driver for development, although the adoption of digital technologies by businesses has been slower compared to the government and the general population. Only a fraction of businesses have a web presence, and fixed broadband coverage, while growing, still presents challenges in terms of quality and accessibility (Edrak et al., 2022; Gong & Yeung, 2022).

Together, these developments signal a promising trajectory for Malaysia and China as they continue to strengthen their digital infrastructure and economy, positioning themselves as influential players on the global stage.

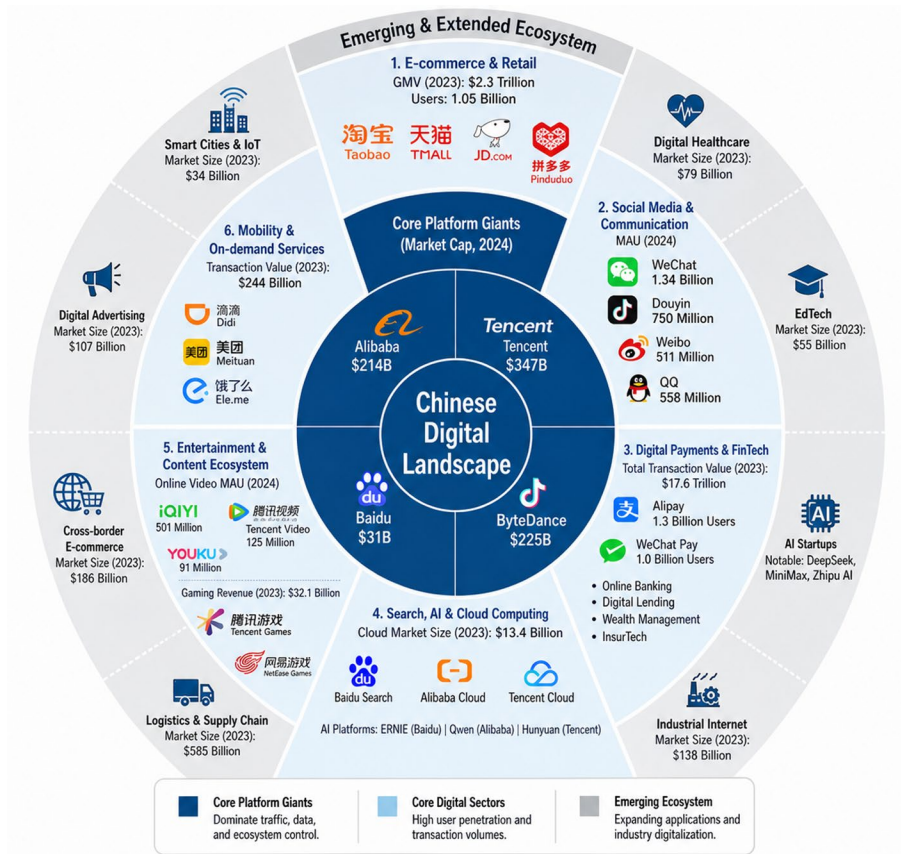


Fig. 3 Chinese Digital Landscape

The Role of Digitalization in Expediting Decarbonization of Data Centers Within Smart City Initiatives

This review aims to analyze the role of digitalization in accelerating the decarbonization of data centers within smart city initiatives, an increasingly important focus as urban areas seek to reduce their environmental impact. The objectives encompass a comprehensive analysis that begins with assessing the current energy consumption and carbon footprint of data centers, understanding how digital technologies can improve their efficiency, and identifying opportunities for decarbonization through digital means (Joshi et al., 2016; Sánchez-Corcuera et al., 2019; Gracias et al., 2023).

The review evaluates the latest technological advancements that contribute to more sustainable data center operations, such as IoT, AI, and cloud computing. This synthesis positions the green transition of data centers within the Knowledge Economy paradigm. Rather than viewing digitalization as a mere technical utility, this review conceptualizes emerging technologies such as IoT, AI, and cloud computing as knowledge-intensive assets. The value of these assets lies not in their hardware, but in the algorithmic capi-

tal and institutional support systems required to mobilize them for substantive carbon reduction. It will also examine the influence of policy and regulatory frameworks that encourage the adoption of these technologies. Through case studies of smart cities that have successfully integrated digital strategies, the review will synthesize best practices for data center design and operation (Al-Badi et al., 2020; Ullah et al., 2024).

Additionally, the review explores the challenges and barriers to adopting digitalization in data centers, including technical, financial, and regulatory hurdles. It proposes recommendations for stakeholders, offering a clear pathway to navigate these complexities. The scope of the review is all-encompassing, including peer-reviewed articles, case studies, policy documents, and industry reports, to provide a holistic view of the intersection between digitalization and decarbonization (Seymour & Herlin, 2015; Lam et al., 2020; Thangam et al., 2024).

The overarching aim of this work is to provide actionable insights and strategies that can guide city planners, data center operators, and policymakers in leveraging digitalization for a more sustainable urban future. By doing so, the review contributes to the broader understanding of how digital transformation can support environmental goals within the context of smart city development (Al-Badi et al., 2020; Qian et al., 2023; Huang et al., 2024).

Case Study Focus: Malaysia and China

Digital technology is proving instrumental in the reduction of carbon footprints within data center operations in Malaysia and China, setting a precedent for sustainable practices. The digital economy's growth in China is not just a technological leap but a strategic move towards high-quality economic development, with the potential to cut oil and gas production costs significantly, thereby promoting green development. This drive is mirrored in the focus on enhancing Carbon Total Factor Productivity (CTFP), which is a key performance indicator in the shift towards a low-carbon economy (Qian et al., 2023; Li, 2024; Ni et al., 2024).

In Malaysia, the government's commitment to renewable energy as part of its power generation plan reflects a regional effort to increase energy efficiency within the data center market. This market is expected to burgeon, with investments in cloud-based services, IoT, and big data analytics contributing to the demand for robust digital infrastructure. The global data center industry's energy consumption and carbon emissions are substantial, with estimates suggesting a 13% share of worldwide electricity use by 2030 (Fig. 4). This urgency is prompting a green transformation in data centers, with a focus on energy efficiency and the adoption of renewable energy (Gong & Yeung, 2022; Al-Wadi et al., 2023; Ullah et al., 2024).

China's response to this environmental challenge includes the implementation of policies that foster the development of energy-efficient data centers. The government aims to reduce primary energy consumption and improve the power usage effectiveness (PUE) of data centers, a metric that indicates the total energy needed for computing (Fig. 5). The digital economy's impact on carbon emissions is a subject of global interest, with studies suggesting that digital technologies could lead to a significant reduction in CO₂ emissions by 2030 (Li and Wang, 2022, Yi et al., 2022, Yu and Liu, 2024).

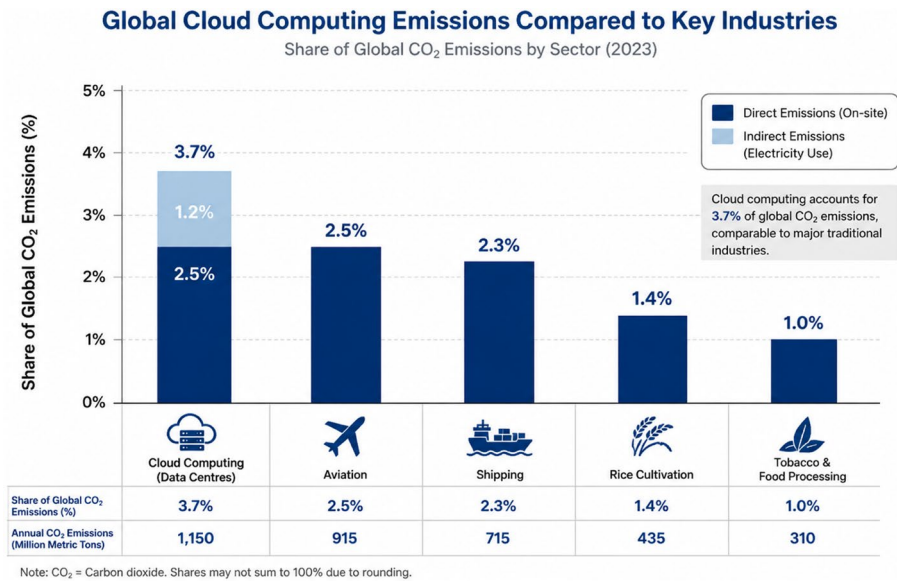


Fig. 4 Global cloud computing emissions compared to other industries

Malaysia, recognizing its potential as a data center hub, is actively pursuing decarbonization strategies that align with its national climate targets. The country's digitally savvy population and progressive economic policies are attracting global data center operators, who are increasingly investing in Malaysia's digital infrastructure (Susskind et al., 2020; Gong & Yeung, 2022).

In summary, the integration of digital technology in data center operations in Malaysia and China is a testament to the potential of digitalization in driving decarbonization efforts. With supportive policies, technological advancements, and a shared commitment to environmental sustainability, these nations are emerging as leaders in the global pursuit of a greener and more efficient digital future (Zeng & Yang, 2023).

Digitalization in Data Center Infrastructure Management

Understanding Digitalization in the Context of Data Centers

Digitalization in data center infrastructure management is a comprehensive strategy that involves the integration of advanced digital technologies to enhance operational efficiency, reduce energy consumption, and lower carbon emissions. It is defined by the application of software and automation to manage critical performance and reliability aspects of data centers, such as cooling, power distribution, and security. The scope of digitalization is extensive, encompassing energy-efficient cooling systems, advanced analytics for decision-making, connectivity for optimized performance, and AI for predictive maintenance and automated operations (Seymour & Herrlin, 2015; Huang et al., 2024).



Fig. 5 Data Centre Market in China

To further strengthen the physical and network security of a data center, controlling who can access the data center and its systems is vital for preventing unauthorized activity. The Role-Based Access Control (RBAC) is one of the best practices in establishing permission based on job roles to limit access. RBAC prevents insider attacks which is still the one of the most dangerous threats in data center and in an organization as a whole (Baracaldo and Joshi, 2013). Security is a vital boundary condition for decarbonization; a data center's physical and network integrity is prerequisite to its energy performance. While standard controls like Multi-Factor Authentication (MFA) and Role-Based Access Control (RBAC) are essential for preventing unauthorized activity, their primary role in this study is to ensure the resilience of Structural Capital (Almadani et al., 2023). An insecure system faces risks of 'insider attacks' or disruptions that would negate the energy gains achieved through AI-driven predictive maintenance and automated operations.

Energy efficiency is significantly improved through digitalization, as reported by the International Energy Agency (IEA), which highlights the potential of digital technologies to increase efficiency across various sectors. In data centers, this is achieved through the use of smart meters, sensors, and AI algorithms that collect and analyze data to optimize energy usage. Additionally, digitalization plays a pivotal role in integrating renewable energy sources into data center operations, as exemplified by China's action plan, which aims to increase the utilization of renewable energy by an average of 10% annually (Zeng & Yang, 2023; Yi et al., 2022).

The impact of digitalization on carbon emissions is notable, with technologies such as immersion cooling reducing energy consumption per server by at least 20% compared to traditional air-cooling systems (Hnayno et al., 2023). This not only brings economic benefits in terms of reduced operational costs but also contributes to

environmental sustainability. The shift towards green and low-carbon development in data centers aligns with global efforts to combat climate change (Thangam et al., 2024; Yu & Liu, 2024).

However, digitalization also presents challenges, including data sovereignty, the need to focus on critical infrastructure, and the necessity for robust data privacy and cybersecurity measures. Taxation across jurisdictions and financing structuring are important considerations for investors interested in this growing asset class. Despite these challenges, the future outlook for digitalization in data centers is promising, with the potential for even greater energy efficiency, further integration of renewable energy, and the development of innovative cooling concepts capable of handling higher heat densities while reducing energy consumption. As digital technologies continue to evolve, their integration into data center management will be essential for achieving sustainability goals and meeting the escalating demand for data services (Lam et al., 2020).

Digitalization in data center infrastructure management is a pivotal force in the evolution of smart cities, underpinned by key technologies such as Artificial Intelligence (AI), Internet of Things (IoT), Big Data Analytics, and Cloud Computing. AI, with its ability to simulate human intelligence, is instrumental in optimizing data center operations, enhancing security, and driving decision-making processes. The IDC forecasts a surge in global AI solution spending, anticipating a significant shift in enterprise technology investments towards AI implementations and services by 2027 (Nguyen et al., 2024; Al-Badi et al., 2020; Ullah et al., 2024).

The IoT extends connectivity to physical devices, allowing for the collection and exchange of data, which is vital for applications in smart cities like traffic management and environmental monitoring. Big Data Analytics complements IoT by processing vast datasets to uncover insights that can inform urban planning and service delivery. The National Engineering Laboratory for Big Data Analysis and Application at Peking University is at the forefront of this field, driving innovation in the digital ecosystem (Ullah et al., 2024; Kshetri, 2017).

Cloud Computing provides the flexibility and scalability required to manage data center resources efficiently. It supports the deployment of smart city services and is highlighted by Gartner as a critical component for local infrastructure to offer cloud-inspired and cloud-native capabilities, given that a substantial portion of workloads remain on-premises (Katal et al., 2023; Bharany et al., 2022; Rong et al., 2016).

Together, these technologies form the backbone of smart city initiatives, enabling the transformation of data centers into intelligent, efficient, and secure hubs that support the digital fabric of urban environments. As technology continues to advance, their role in shaping the future of smart cities and data centers becomes increasingly prominent, offering a robust foundation for sustainable and innovative urban development (Lam et al., 2020; Huang et al., 2024).

Digitalization Trends and innovations in Data Center Management

Digitalization in data centers is currently a driving force for innovation and sustainability, as evidenced by several key trends and innovations. Artificial Intelligence (AI) is becoming increasingly integrated into data center operations, with the market

expected to reach US\$407 billion by 2027, showcasing an impressive annual growth rate of 37.3% between 2023 and 2030. This growth is fueled by AI's role in optimizing data center processes and enhancing sustainability, as data centers are projected to increase their power consumption significantly by 2030 (Herath & Mittal, 2022; Kibria et al., 2018).

The Internet of Things (IoT) is also playing a pivotal role in data center management, with IoT devices set to automate routine tasks and improve energy monitoring. Globally, data center markets are experiencing robust demand, despite power shortages, with some markets like Singapore reporting near record-low vacancy rates. Artificial intelligence advancements are anticipated to further boost data center demand, necessitating rapid innovation in data center design to accommodate increasing power density (Mehta et al., 2018; Ramphela et al., 2020; Ansari & Memon, 2022).

To manage this density, data centers are adopting advanced cooling solutions such as liquid cooling, which are more efficient than traditional air-cooling systems. The advent of 5G and IoT is also pushing for decentralized edge data centers to handle surging data demands with minimal latency. Additionally, there is a notable increase in investment in renewable energy by data center companies to reduce their environmental impact (Liu et al., 2016; Ramphela et al., 2020; Ansari & Memon, 2022).

Data migration and management are becoming more challenging with the exponential growth of data, necessitating the development of best practices and tools to ensure data integrity and system compatibility during transitions. Generative AI models are influencing significant changes in computer architectures and data center design, potentially reshaping both the cloud industry and the traditional supercomputing sector (Wang et al., 2015; Todd et al., 2021).

The digitalization trends in data centers reflect a commitment to innovation, efficiency, and sustainability. As technology advances, data centers are not only adapting to meet the escalating demand for computational power but are also addressing environmental concerns, ensuring they remain at the forefront of the digital transformation (Seymour & Herrlin, 2015; Wang et al., 2015; Liu et al., 2016).

Digitalization in data center management is increasingly leveraging automation, real-time monitoring, and predictive maintenance to significantly reduce energy consumption and enhance operational sustainability. Automation streamlines processes, minimizing human error and optimizing tasks that were once manually intensive. Real-time monitoring provides actionable insights into energy usage patterns, enabling prompt adjustments to improve efficiency. Predictive maintenance, powered by machine learning and data analytics, preempts equipment failure, reducing downtime and cutting maintenance costs (Liu et al., 2016; Levy & Subburaj, 2021; Ansari & Memon, 2022).

The integration of energy efficiency technologies such as advanced cooling systems and virtualization has helped data centers to moderately increase their energy use despite a surge in demand for services. Renewable energy adoption is another key strategy, with data centers looking to wind, solar, and other clean sources to lessen their carbon footprint. The International Energy Agency emphasizes the need for strong government and industry initiatives to further curb energy demand and emissions from data centers, which currently account for 1–1.5% of global electricity use (Channi & Kumar, 2024; Huang et al., 2024).

Policies like the European Union's Energy Efficiency Directive are setting new standards for data center energy reporting, driving transparency and accountability. Innovations by companies such as Sustainable Metal Cloud, which uses synthetic oil for superior heat dissipation, exemplify the industry's push for more efficient cooling methods. These efforts, combined with a commitment to renewable energy and adherence to stringent energy efficiency policies, are steering data centers towards a greener and more sustainable future. As technology and policies continue to evolve, data centers are poised to play a leading role in global decarbonization efforts (Pereira & Da Silva, 2017; Veselova, 2023; Ohenhen et al., 2024).

Benefits of Digitalization for Decarbonization

Digitalization serves as a pivotal force in driving decarbonization through three distinct theoretical pathways: operational optimization, strategic energy sourcing, and governance-enabled accountability. Operational optimization, achieved via software and automation, streamlines cooling and power distribution. Strategic energy sourcing utilizes digital management to integrate variable renewable power. Governance is enabled through standardized metrics like PUE and energy reporting directives that foster institutional transparency. It enhances energy efficiency across sectors such as industry, buildings, and transport, with the IEA suggesting a potential global CO₂ emissions reduction of 15% through these digital technologies. Optimized resource allocation, made possible by predictive analytics, can significantly cut down energy waste, with the industrial sector alone projected to reduce emissions by up to 3.75 gigatons of CO₂ by 2030 through a 10% improvement in energy efficiency (Sánchez-Corcuera et al., 2019; Feroz et al., 2021; Al-Wadi et al., 2023; Huang et al., 2024).

The integration of renewable energy sources is facilitated by digitalization, which adeptly manages the variability of solar and wind power. The IEA anticipates a rise in the share of renewables in global power generation, supported by digital management systems. Smart grids represent another stride in energy system optimization, with the global market size expected to double from US\$32 billion in 2020 to US\$76 billion by 2025 (Sharvini et al., 2018).

In the transportation sector, digitalization aids logistics route optimization and electric vehicle charging infrastructure management, contributing to a reduction in fuel consumption and emissions. The EV charging station market is set to surge from US\$9.3 billion in 2020 to US\$58.7 billion by 2025, propelled by digital technologies (Song et al., 2022; Arévalo et al., 2024; Avesh et al., 2024).

Digital tools also empower businesses and consumers to monitor and mitigate their carbon footprints. The use of digital twins in buildings can simulate and fine-tune energy consumption, potentially decreasing emissions by 10–20% (Céspedes-Cubides and Jradi, 2024). Precision agriculture technologies are expected to reach a market value of US\$23.4 billion by 2025, up from US\$15.3 billion in 2019, showcasing the potential of digitalization to reduce the carbon footprint in farming (Balafoitis et al., 2017).

Decentralized energy systems, underpinned by digitalization, are carving a path for peer-to-peer energy trading platforms, further diminishing the carbon footprint of energy consumption. Corporate sustainability initiatives, such as Google's commit-

ment to carbon neutrality and 100% renewable energy for its operations, exemplify the impact of digitalization in corporate responsibility (Martínez-Peláez et al., 2023; Li & Wang, 2022; Huang et al., 2024).

Government policies and incentives, like those within the European Union's Horizon 2020 program, further underscore the global commitment to fostering digital solutions for energy efficiency. However, an objective assessment of the 'net effect' of digitalization requires addressing significant countervailing risks. While digital technologies can reduce global CO₂ emissions by up to 15%, they simultaneously induce a 'rebound effect' characterized by a surge in demand for compute and storage. Global internet traffic has increased 20-fold since 2010, and global data volume is projected to reach 175 zettabytes (ZB) by 2025 (Pereira & Da Silva, 2017; Huang et al., 2024).

The rapid growth of AI workloads represents a particularly acute challenge. AI-driven demand is projected to increase power consumption significantly by 2030, with some estimates suggesting that AI systems in Malaysia could demand more than 5 gigawatts of power by 2035 exceeding half of the nation's total 2023 renewable capacity. Consequently, the net environmental benefit of digitalization depends on whether the algorithmic capital created for optimization can outpace the structural demand created by expanding digital footprints (Chang et al., 2024).

Digitalization is a key driver for enhancing the efficiency and sustainability of data center operations, which is essential for reducing carbon emissions. The integration of digital technologies in data centers leads to significant improvements in energy efficiency, as exemplified by Meta's operational data centers, which had an average Power Usage Effectiveness (PUE) of 1.09 in 2023. With the global data volume projected to reach 175 ZB by 2025, there is a pressing need for sustainable energy solutions, including the integration of renewable energy sources in data center operations (Thangam et al., 2024).

Water stewardship is another critical aspect of data center sustainability, as demonstrated by Meta's Water Usage Effectiveness (WUE) of 0.20 in 2023. The development of smart cities worldwide is closely linked to data center sustainability, with cities like Bristol in the UK and Singapore leveraging data centers to create smart, low-carbon environments. Carbon emission reduction is a global concern, and data centers are taking steps to address this, with companies like Unilever setting ambitious carbon reduction goals for 2030 (Karimi et al., 2022; Ristic et al., 2015; Mytton, 2021).

Cooling systems in data centers are a significant focus for optimization, as they directly impact energy consumption. By optimizing the design of cooling systems, such as the use of immersion cooling and advanced airflow management, data centers can achieve better energy efficiency. The application of artificial intelligence (AI) and machine learning in data centers can further automate data collection and energy efficiency analysis, providing actionable insights for optimization (Ohenhen et al., 2024; Ullah et al., 2024; Chen & Wemhoff, 2022).

There is a growing call for the global standardization of energy efficiency metrics, which will facilitate the uniform measurement and comparison of data center performance. The integration of digitalization not only offers economic benefits in terms of reduced operational costs but also contributes to environmental sustainability.

Ongoing research and development in energy-conservation and emission-reduction technologies aim to enhance the resource utilization rate of data centers by lowering energy consumption, incorporating low-carbon energy, and optimizing load distribution (Shao et al., 2022; Levy & Subburaj, 2021; Ansari & Memon, 2022; Seymour & Herrlin, 2015).

In summary, digitalization in data center operations offers a comprehensive set of benefits that support decarbonization efforts, emphasizing the importance of continued innovation and adoption of sustainable practices in data center management worldwide.

Methodology

Explanation of the Systematic Review Approach

The research design methodology for exploring the role of digitalization in decarbonizing data centers within smart city initiatives is structured and evidence-based. It encompasses a systematic review of existing literature, which delves into peer-reviewed articles, white papers, and industry reports to identify trends, challenges, and opportunities in the digital transformation of data centers. Policy analysis is also integral, evaluating how government policies and regulations influence the adoption of sustainable practices and technologies in data center operations.

The systematic review approach is methodical, aiming to answer a clearly formulated research question with transparency and repeatability. It involves using the PICO framework to formulate a research question, developing a protocol with defined selection criteria and search strategies, conducting comprehensive searches, applying criteria to select studies, extracting and synthesizing data, and finally, writing and publishing a detailed report of the findings (Booth et al., 2016; Mengist et al., 2020).

Data support is foundational to this research methodology, offering quantitative insights into energy consumption and carbon emissions associated with data centers. For example, the projection that global data center energy consumption will double every four years underscores the urgency for decarbonization efforts. Moreover, the growing demand for data services and the expansion of renewable energy capacities provide critical data points that enrich the analysis (Snyder, 2019; Igwenagu, 2016).

This research design methodology, with its focus on systematic literature review, policy analysis, and empirical data, ensures a comprehensive examination of the potential for digitalization to accelerate decarbonization in data centers within smart city initiatives (Fig. 6). It provides a robust evidence base to inform strategies and practices that contribute to the sustainability goals of smart cities (Mengist et al., 2020; Snyder, 2019).

The research design for this study is rooted in a structured, evidence-based systematic review aimed at deciphering the complex role of digitalization in the decarbonization of data centers. To ensure the findings were both credible and reproducible, the process was anchored by the PICO (Population, Intervention, Comparison, Outcome) framework, which allowed for the formulation of precise research questions regarding the digital transformation of infrastructure within smart cities. This

methodological choice was foundational, as it allowed the study to move beyond a narrative overview and provide quantitative insights into the energy consumption trajectories and carbon emission footprints associated with modern data centers.

Selection Criteria for Case Studies and Literature

The selection of both literature and case studies followed a rigorous screening process to guarantee the quality and relevance of the synthesized data. We employed purposeful sampling to identify information-rich cases from the innovation ecosystems of Shenzhen, China, and Cyberjaya/Johor, Malaysia. To be eligible for inclusion, records had to meet specific operational criteria as they were required to be peer-reviewed academic articles, authoritative industry reports, or official government

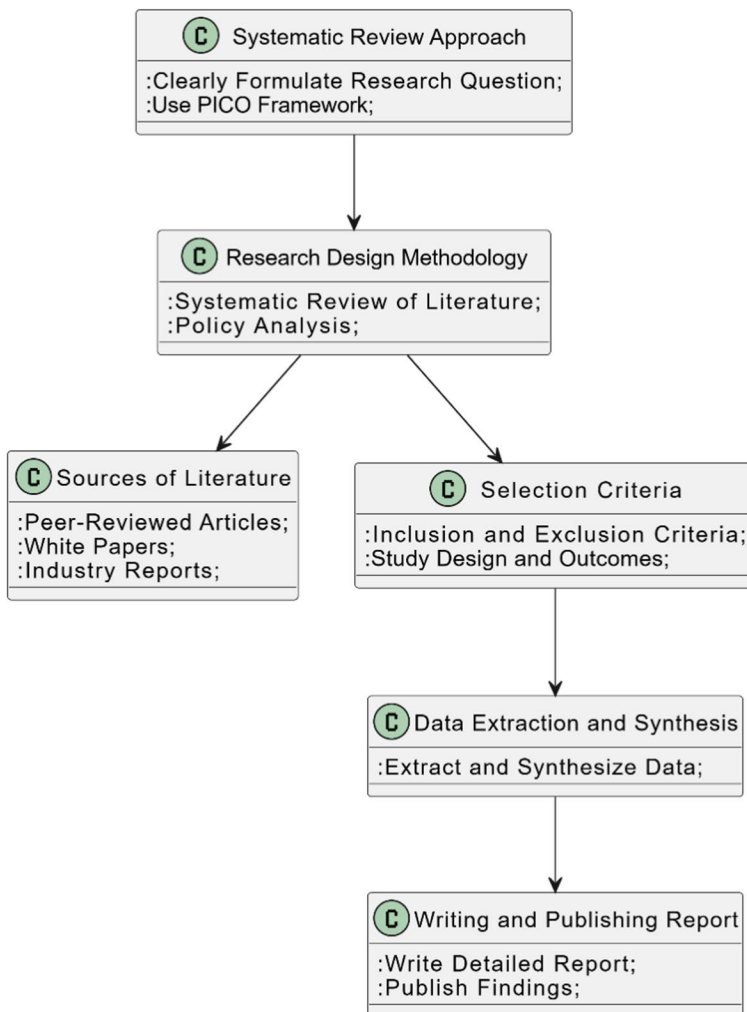


Fig. 6 Systematic Review Approach

publications that provided empirical evidence of data center efficiency or renewable energy integration.

Selecting case studies and literature in research is a meticulous process that ensures the data used is relevant and of high quality. Case studies are chosen based on their potential to offer deep insights into the critical issues under investigation, often employing purposeful sampling to select information-rich cases. This approach enhances the richness of the collected data and the likelihood of revealing multiple realities (Snyder, 2019).

In systematic literature reviews, we apply clear inclusion and exclusion criteria, focusing on aspects such as the research question, study design, and outcomes. This methodical process is essential for identifying existing gaps and challenges within the field. Empirical research, which relies on tangible evidence gathered through observation or scientific instruments, can be quantitatively or qualitatively analyzed, allowing researchers to answer well-defined questions supported by the collected data (Mengist et al., 2020; Snyder, 2019).

Numerical data plays a crucial role in providing specific insights into the research topic. For instance, in a study examining the impact of music on workplace creativity, numerical data from an experiment with different conditions can be analyzed to find empirical evidence supporting the hypothesis. Quality assessment tools like the Newcastle-Ottawa Scale (NOS) and the Cochrane Handbook ensure that the selected literature meets methodological standards, contributing to the validity of the research (Snyder, 2019; Igwenagu, 2016). To safeguard the validity of our conclusions, each selected source underwent a quality appraisal using the Newcastle-Ottawa Scale (NOS) and the standards set by the Cochrane Handbook. Quantitative analysis was facilitated by IBM SPSS Statistics, which was vital for managing the multivariate relationships between digitalization adoption rates and carbon mitigation outcomes.

Reporting standards, including the PRISMA statement, ensure transparency and reproducibility in research reporting. Following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, the study documented a clear “funneling” of records to maintain transparency. The initial identification phase yielded 350 records, which were then narrowed to 210 after duplicate removal and abstract screening. A final assessment of 120 full-text reports was conducted to ensure each source met the methodological standards of this study. Furthermore, qualitative research methods like thematic synthesis involve coding and thematic analysis to generate comprehensive insights from qualitative data (Clarke and Braun, 2017, Page et al., 2021, Rahman and MuktaDir, 2021).

By applying these criteria and utilizing the appropriate tools and standards, we can guarantee that our case studies and literature reviews are methodologically robust, thereby significantly contributing to the existing body of knowledge.

Data Collection: Academic Journals, Industry Reports, Government Publications, and Case Studies

Data collection is essential in research, providing empirical evidence that substantiates findings and conclusions. When examining the role of digitalization in decarbonizing data centers, a variety of data sources are pivotal. Academic journals offer

peer-reviewed research findings, theoretical developments, and methodological approaches, often including quantitative data that can be synthesized to identify trends. Industry reports from market research firms and associations provide valuable data on market trends and the adoption of sustainable practices in data center management (Taherdoost, 2021).

Government publications contribute crucial data on energy consumption, carbon emissions, and policies impacting digital infrastructure. These publications offer insights into regulatory landscapes and national commitments to decarbonization. Case studies provide in-depth qualitative and quantitative data, revealing the real-world applications and complexities of digital technologies in reducing data center carbon footprints (Snyder, 2019, Taherdoost, 2021).

Numerical data from these sources can offer specific insights. For example, the International Energy Agency (IEA) might report global data center energy consumption and projected increases in energy demand by 2030. Industry reports could highlight the percentage of data centers utilizing renewable energy sources and the expected growth of this trend. Government publications may outline national carbon emission reduction targets, including goals specific to the data center industry. Academic journal studies might present data on the economic impact of digitalization, such as cost savings or return of investment (ROI) from implementing digital technologies in data centers. Case studies could provide numerical data on efficiency improvements, such as reductions in Power Usage Effectiveness (PUE) scores (Igwenagu, 2016; Snyder, 2019). The analytical framework evaluated the effectiveness of digitalization through a suite of sustainability metrics. These included the Power Usage Effectiveness (PUE), where lower ratios signify optimized energy distribution to IT equipment; the Carbon Usage Effectiveness (CUE), which targets zero-emission energy profiles; and the Energy Reuse Factor (ERF), which assesses the proportion of repurposed energy, such as waste heat recovery for urban heating. By systematically applying these metrics, this study provides an evidence-based roadmap for stakeholders aiming to transition data centers from simple hardware nodes into sustainable, knowledge-intensive assets.

By integrating data from these sources, researchers can develop a comprehensive understanding of digitalization's role in decarbonizing data centers. The numerical data can be analyzed to assess the effectiveness of various strategies, identify best practices, and offer evidence-based recommendations for stakeholders in the field.

Description of Search Strategies and Keywords Used

Crafting a meticulous search strategy is vital for conducting a systematic review or any research that necessitates an exhaustive literature search. The process begins with a clear definition of the research question, which guides the selection of appropriate keywords such as “digitalization,” “data centers,” “energy efficiency,” and “sustainability.” Identifying key concepts from the research question is followed by the compilation of specific keywords and their synonyms to broaden the search scope (Mengist et al., 2020).

Boolean operators, AND, OR, and NOT, are utilized to combine keywords into search strings that precisely reflect the research focus. For instance, a search string

might look like this: (“digitalization” OR “digital technology”) AND (“data centers” OR “server farms”) AND (“energy efficiency” OR “sustainable practices”). To capture all variations of a word, truncation and wildcards are effectively employed.

We use the thesaurus and subject headings provided by databases to refine their search with index terms related to the research topic. Selecting the appropriate databases, such as IEEE Xplore, ScienceDirect, ACM Digital Library, and Google Scholar, is crucial for gathering literature relevant to the field of study. The search strategy should be continually refined based on initial search outcomes, and the process documented meticulously to ensure transparency and reproducibility (Snyder, 2019).

Recognizing that search strategy development is iterative, we test, refine, and adjust our approach to ensure comprehensive retrieval of the most pertinent literature. This thorough approach is essential for effective data collection in research concerning the impact of digitalization on decarbonization within data centers.

Framework for Analyzing Digitalization Strategies and Their Impact on Decarbonization

The analytical framework for examining the impact of digitalization strategies on decarbonization within data centers is a systematic approach that provides a comprehensive evaluation of these strategies’ effectiveness. It begins with setting clear objectives, such as assessing how digitalization reduces energy consumption and carbon emissions. Data is then collected from a variety of sources, including academic journals, industry reports, case studies, and government publications, to gain insights into digital practices and their outcomes (Goldstone, 2019; Taherdoost, 2021).

Key variables for analysis are identified, encompassing the types of digital technologies used, energy consumption metrics, carbon footprint measurements, and sustainability indicators. The selection of appropriate analytical methods follows, which may include both quantitative analyses like regression models to determine correlations and qualitative analyses to explore contextual nuances (Ngulube, 2015).

Performance indicators are developed to measure the effectiveness of digitalization strategies, such as Power Usage Effectiveness (PUE), carbon emission metrics, and cost-benefit ratios. These indicators are then used to assess the impact of the strategies on decarbonization by comparing them before and after the implementation of digital technologies. The perspectives of various stakeholders, including operators, technology providers, policymakers, and users, are considered to understand the broader implications of these strategies (Snyder, 2019).

The framework also evaluates potential risks and opportunities associated with digitalization strategies, such as technological challenges and market opportunities. Policy and regulatory influences on the adoption and effectiveness of these strategies are examined, along with industry benchmarks and best practices that serve as references for success evaluation (Goldstone, 2019).

Sustainability assessment of digitalization strategies considers their long-term viability, including scalability and adaptability to future advancements. Finally, the framework leads to the development of evidence-based recommendations for stake-

holders to enhance decarbonization efforts through digitalization. This structured approach allows for a thorough understanding of how digitalization can contribute to more sustainable data center operations (Veselova, 2023; Al Kez et al., 2022; Martínez-Peláez et al., 2023).

Metrics and Indicators for Assessing Decarbonization in Data Centers

Assessing the decarbonization efforts in data centers is facilitated by a suite of metrics and indicators that provide a comprehensive view of energy efficiency and carbon reduction. Power Usage Effectiveness (PUE) is a standard metric that measures the ratio of total energy consumed by a data center to the energy used to power its computing equipment, with lower values indicating better energy efficiency. The Carbon Usage Effectiveness (CUE) quantifies the carbon emissions related to energy consumption, aiming for a zero value in scenarios where renewable energy sources are exclusively used (Shao et al., 2022).

The Energy Reuse Factor (ERF) and Energy Reuse Effectiveness (ERE) focus on the proportion of energy losses that are repurposed, such as waste heat for district heating, highlighting the efficiency of energy reuse. The Renewable Energy Factor (REF) and Partial Renewable Energy Factor (pREF) encourage the use of renewable energy sources, reducing the carbon footprint by increasing the reliance on clean energy (Huang et al., 2019; Silva et al., 2024).

Cooling Efficiency Ratio (CER) and Partial Energy Reuse Factor (pERF) are indicators that target the cooling subsystem, promoting energy efficiency and waste heat recovery. Partial Carbon Usage Effectiveness (pCUE) emphasizes the carbon impact of cooling systems, incentivizing the use of decarbonized electricity and thermal storage investments. The Renewable Energy Reuse Efficiency (RERE) merges the REF and ERF, tracking the use of renewable energy in waste heat recovery for heating purposes (Shao et al., 2022; Huang et al., 2019; Silva et al., 2024).

These indicators are crucial for guiding data centers towards sustainability. For instance, studies on waste heat recovery systems have shown that innovative approaches can lead to significant energy and CO₂ emission reductions, with some schemes achieving rapid payback periods due to the elimination of heat pumps. In China, the push for green data centers has resulted in policies that have played a significant role in promoting energy-saving technologies and carbon reduction strategies, focusing on improving PUE and increasing renewable energy usage (Ni et al., 2024; Qian et al., 2023).

As data centers expand, these metrics will play a pivotal role in ensuring their operations become more sustainable and aligned with global decarbonization goals. The effective use of these metrics depends on the ability to access relevant data, connect it meaningfully, and support data centers in making sustainable operational choices. Policymakers and industry stakeholders must work together to ensure these metrics are not only well-defined but also systematically applied to drive the sector's transition towards carbon neutrality (Al Kez et al., 2022; Orikpete et al., 2023; Zhu et al., 2021).

Case Studies: Malaysia and China

Summary of National Policies and Strategies Promoting Digitalization and Decarbonization

Malaysia and China are showcasing their commitment to leveraging digitalization for decarbonization within data centers through targeted initiatives and strategic planning. Malaysia's push towards digital transformation is exemplified by the Malaysia Digital (MD) initiative, which aims to foster a robust digital economy ecosystem. This initiative is designed to create substantial digital economic spill-over effects by ensuring equitable access to digital tools, knowledge, and income opportunities. In line with this, Malaysia has set an ambitious target to achieve a 31% share of renewable energy in its national installed capacity mix by 2025, aligning with its broader goal of reducing economy-wide carbon intensity by 45% by 2030 compared to 2005 levels (Pandey, 2020, Tee et al., 2024). Local findings in Cyberjaya and Shenzhen are now analyzed through the lens of specialized workforce development. The "skilled labor" shortage is evaluated as a critical intellectual capital deficit. For example, data centers in Cyberjaya are shown to move past basic "hardware hosting" to become active repositories of human capability, transforming local tech competencies to manage the target 31% renewable energy installed capacity mix.

China, on the other hand, is actively pursuing energy conservation and carbon reduction through a strategic action plan for the period 2024–2025. The plan targets a reduction of about 2.5% in energy consumption and 3.9% in carbon dioxide emissions per unit of GDP. This aligns with China's overarching objective to peak its total CO₂ emissions before 2030 and achieve carbon neutrality by 2060 (Shao et al., 2024). The country is also focusing on the development of green and low-carbon data centers, with an emphasis on reducing primary energy consumption and improving energy efficiency (Qiu et al., 2021, Xie et al., 2024). As a global leader in digital innovation, Shenzhen's ecosystem is characterized by high-density computing needs, with a digital economy that contributes nearly 40% to the national GDP. However, the local grid faces extreme pressure, as data centers in the region consumed 150.7 billion kWh in 2020 alone, representing over 2% of total national electricity usage. Technical improvements, such as the target of reducing China's data center PUE from 1.6 to 1.7 down to below 1.3 by 2025, are explicitly framed as advancements in firm-level Structural Capital. Physical facility optimizations (immersion cooling reducing server energy consumption by 20%) are no longer treated as mere mechanical variables but as institutionalized, green corporate assets (Li et al., 2025).

Digitalization in data center operations is being enhanced through advanced automation solutions, predictive analytics, and the optimization of wireless instrument performance. A case in point is the collaboration between PETRONAS and Emerson, which aims to drive digital transformation and decarbonization initiatives, focusing on areas such as carbon capture, utilization, and storage (CCUS), hydrogen, and ammonia (Dziejarski et al., 2023). Positioned as the nucleus of Malaysia's ICT landscape, Cyberjaya serves as a burgeoning hub for Southeast Asian data center investments. Its baseline is defined by a strategic location and a digital economy that reached RM 205 billion by 2022, contributing roughly 23% to the national GDP.

Regional alliances and cross-border knowledge clusters are classified as relational assets. The partnership between China and Malaysia via Alibaba's 'City Brain' in Kuala Lumpur is evaluated as the strategic deployment of Relational Capital to drive inter-firm learning and cross-border tech adoption.

Both countries are integrating renewable energy into their energy mixes. Malaysia's MyRER roadmap outlines strategies to achieve the government's renewable energy target and further decarbonize the power generation sector by 2035. Meanwhile, China expects to source about 20% of its total energy consumption from non-fossil sources by 2025, indicating a significant shift towards renewable energy (Chen et al., 2019). Advanced software assets, such as fast reinforcement learning algorithms and AI-driven predictive modeling, are classified under this node (Yu et al. 2025). These digital assets are shown to reduce operational data center costs by 15–25% by converting raw operational metrics into actionable sustainability insights.

National policies and strategies, such as Malaysia's digital economy blueprint and the National 4IR Policy, as well as China's implementation plan for promoting green and low-carbon data center development, underscore the importance placed on digital competitiveness and sustainable growth (Suryadi et al., 2022). These initiatives collectively demonstrate the active role that both Malaysia and China are playing in using digitalization to drive decarbonization efforts in data center operations, moving towards a more sustainable future.

Case Study 1: Malaysia

Overview of Malaysia's Digital Economy and Data Center Landscape

Malaysia is emerging as a pivotal player in the digital economy, with a clear vision to become a regional leader by 2030. The country's digital economy is thriving, underpinned by strategic initiatives such as the Digital Malaysia and the National Fiberisation and Connectivity Plan, which are aimed at enhancing broadband quality and coverage. The Malaysia Digital Economy Corporation (MDEC) plays a significant role in advising on ICT and multimedia development, ensuring that the nation stays at the forefront of technological advancements (Susskind et al., 2020).

The data center landscape in Malaysia is robust, with an estimated market value of RM900 million, driven by the growing demand for AI and other technological innovations. Strategically located and offering business-friendly policies, Malaysia is becoming an attractive hub for data centers, with ambitious plans for further sectoral development (Fig. 7).

Malaysia's digital economy achievements: the digital economy contributed 22.6% to the nation's GDP in 2019 (Gong and Yeung, 2022). The country has set ambitious targets, including the digital transformation of 875,000 MSMEs through eCommerce, the attraction of two unicorns, and the creation of 500,000 new jobs in the digital sector (Table 1). By 2025, Malaysia anticipates a 30% uplift in productivity across all sectors (Raj et al., 2020).

These initiatives and targets underscore Malaysia's commitment to leveraging digitalization for economic growth and sustainability. With strategic planning and investment in digital infrastructure, Malaysia is well-positioned to lead in decarbon-

Some of the major upcoming data centre projects in Malaysia

COMPANY	LOCATION	PLANNED CAPACITY (MW)	VALUE	INVESTMENT PERIOD
NextDC Ltd	Petaling jaya	65	RM3 bil	Next five to 10 years starting 2023
EdgeConneX	Kuala Lumpur CBD	17	RM9.3 bil	Within 20 to 24 months, starting 2023
	Cyberjaya	200		
	MRanti Park, Bukit Jalil	67		
Google	Elmina Business Park, Shah Alam	NA	Part of RM9.4 bil investments	May 27, 2024, until Sept 9, 2026 (Based on Gamuda Bhd's contract)
TM-Nxera	Iskandar Puteri	64	RM1.15 bil	By 2026
UEM Sunrise-LOGOS	Gerbang Nusajaya	360	RM10 bil to RM12 bil GDV (RHB Research estimate)	NA
Microsoft	Kulai & Pulai	NA	Part of RM10.5 bil investments over next four years	NA
ByteDance	Johor	NA	RM1.5 bil	NA

Fig. 7 Major Upcoming data centre projects in Malaysia (2023–2025)**Table 1** Malaysia's Digital Economy Targets and Projections by 2025: Key Metrics for Economic Growth and Job Creation

Category	Target by 2025	Description
GDP Contribution	22.6%	The digital economy is expected to contribute 22.6% of Malaysia's GDP.
New Jobs Created	500,000	The digital economy aims to create about 500,000 new jobs.
MSMEs Embrace Digital E-commerce	875,000	The government targets 875,000 micro, small, and medium enterprises (MSMEs) to embrace digital e-commerce.
Services Online	80%	The government aims to bring 80% of its services online.
Digital Transformation Potential	Up to RM257.2 billion	Digital transformation has the potential to generate up to RM257.2 billion in annual economic value by 2030.
Economic Value Driven by Technologies	RM184 billion	72% of the potential, or RM184 billion, is driven by technologies that can help businesses and workers mitigate the effects of Covid-19.

ization efforts, particularly in data center infrastructure management within the context of smart cities. The nation's proactive approach to digital transformation is set to drive sustainable economic growth and contribute to global efforts to reduce carbon emissions (Susskind et al., 2020).

Digitalization Strategies and Initiatives: Key Projects and Initiatives Promoting Data Center Efficiency

Digitalization strategies and initiatives are pivotal in enhancing the efficiency and sustainability of data center operations, a trend particularly evident in Malaysia and China. Malaysia has seen a substantial increase in investments in data center infrastructure, with a 23% year-on-year jump in approved investments, reaching RM329.5 billion in 2023. This investment surge is driven by the country's focus on

digital investments, including data centers and cloud computing, which are critical for the development of the digital economy (Gong & Yeung, 2022).

Global tech giant Google's investment of US\$2 billion in its first data center and cloud region in Malaysia is expected to support 26,500 jobs and generate an economic impact of RM15.04 billion, underscoring the significant economic benefits that data centers can bring to a region. Malaysia has also established technical codes for green data centers, aiming to improve energy efficiency and reduce the carbon footprint of the industry, with a minimum Power Usage Effectiveness (PUE) requirement of 1.9 (Cai & Gou, 2023).

The data center sector in Malaysia is projected to grow at a compound annual growth rate of 42%, with capacity increasing from 128 MW in 2020 to 750 MW by 2025, reflecting the increasing demand for cloud services and digital transformation initiatives. Data center operators in Malaysia are focusing on environmental, social, and governance (ESG) compliance, implementing measures to optimize energy consumption and meet ESG goals, including the use of renewable energy sources and advanced cooling systems (Kang & Arikrishnan, 2024).

The digital economy in Malaysia contributed about 23% to the country's GDP from 2021 to 2023, with a target to increase this contribution to 25.5% by 2025. Malaysia's MyDIGITAL blueprint aims to attract RM70 billion in digital investments, with the digital economy contributing 22.6% to the country's GDP and creating 500,000 job opportunities by 2025. This blueprint includes initiatives to promote data centers and cloud services providers, further solidifying Malaysia's position as a hub for data center development. Policy is centered on the Malaysia Digital (MD) initiative and the Renewable Energy Roadmap (MyRER), which aim for a 31% renewable energy share by 2025. Governance focuses on creating "Regional Innovation Ecosystems" like the Sedenak and Nusajaya Tech Parks to attract global structural capital (Raihan & Tuspekova, 2022).

Tax incentives and investment promotion for data center investments, such as the Green Investment Tax Allowance and the Green Income Tax Exemption, encourage and incentivize investment in environmentally friendly and sustainable projects in Malaysia. These initiatives and projects highlight the commitment of Malaysia and China to leveraging digitalization for decarbonization efforts in data center infrastructure, positioning them as leaders in the development of sustainable and efficient data center operations (Ezuma et al., 2022).

Impact on Decarbonization

Malaysia's digitalization strategies are playing a significant role in the decarbonization of its data centers, with a focus on energy efficiency and the adoption of renewable energy sources. The country has been actively evaluating its energy efficiency policies to ensure sustainable development, recognizing the importance of reducing energy intensity and carbon emissions. Malaysia currently generates 22.4% of its power from renewable sources and aims to increase this to 30% by 2030, a shift that is vital for the decarbonization process (Susskind et al., 2020; Pandiyan et al., 2023).

To encourage investment in renewable energy, Malaysia has implemented policies such as the Feed-in Tariff (FiT) and Net Energy Metering (NEM). These policies

support renewable energy projects and allow for the sale of excess electricity generated by solar panels back to the grid. Additionally, the Green Technology Financing Scheme (GTFS) promotes investment in green technologies, including energy-efficient data center infrastructure (Husain et al., 2021; Ezuma et al., 2022; Vaka et al., 2020).

Despite these initiatives, Malaysia reported a carbon emissions intensity reduction of 32.5% in 2011, which equates to a reduction of 18,578.80 ktCO₂eq (Susskind et al., 2020). This achievement highlights the effectiveness of various mitigation tools, including forest conservation measures. However, challenges remain in the form of federal-state friction, limited government capacity, and the absence of a dedicated decarbonization agency, which can hinder further progress (Susskind et al., 2020).

Institutional shifts, such as the establishment of the Sustainable Energy Development Authority (SEDA) and initiatives like PEMANDU, have been instrumental in promoting sustainable energy and integrating development with carbon reduction goals. Furthermore, Malaysia has recognized the importance of engaging younger generations in climate change initiatives, understanding that this is crucial for long-term behavioral transformation towards a low-carbon society. Strategies focus on Relational Capital through partnerships like the Alibaba 'City Brain' program, which facilitates inter-firm learning and knowledge spillovers between tech giants and local suppliers. The integration of IoT and big data analytics is used to optimize the regional power mix and infrastructure resilience (Susskind et al., 2020; Rahim et al., 2019).

In conclusion, while Malaysia's digitalization efforts are contributing to the decarbonization of its data centers and economy, there are still challenges to overcome. Continued efforts, policy support, and institutional commitment are necessary to achieve the country's ambitious decarbonization goals.

Lessons Learned: Key Insights and Takeaways from Malaysia's Experience

Malaysia and China are exemplifying the integration of digitalization strategies to decarbonize their data centers, offering instructive insights for global sustainability efforts. Malaysia's digital economy is burgeoning, with ambitions to attract RM70 billion in digital investments and create 500,000 new jobs by 2025, contributing significantly to the nation's GDP. The country has set a target to derive 30% of its power from renewable sources by 2030, up from the current 22.4%, marking a pivotal step towards reducing the carbon footprint of its data centers (Gong & Yeung, 2022; Shi, 2022).

The development of industrial hubs like the Sedenak Tech Park and Nusajaya Tech Park represents more than just construction; these are Regional Innovation Ecosystems designed to mobilize Structural Capital. The presence of global leaders such as AWS, Google, and Microsoft facilitates critical inter-firm learning spillovers. Their entry into the Malaysian market forces a domestic elevation of 'green' standards such as the adoption of advanced cooling and ESG compliance, thereby transforming the regional workforce through the continuous development of human intellectual capital.

The Malaysian government is actively evaluating its energy efficiency policies to foster sustainable development, aiming to enhance energy intensity and decrease carbon emissions. The Green Technology Master Plan (2017–2030) is a testament to Malaysia's commitment to reducing greenhouse gas emission intensity by 45% by 2030, leveraging green technology adoption for economic growth. A notable achievement was the 32.5% reduction in carbon emissions intensity by 2011, equivalent to a reduction of 18,578.80 kt CO₂eq, achieved through various mitigation strategies, including forest conservation. Malaysia reported a 32.5% reduction in carbon emissions intensity by 2011 through early forest conservation and digital optimization. The entry of global leaders like Microsoft and Google is expected to generate an economic impact of RM15.04 billion while elevating national green standards (Song et al., 2022; Susskind et al., 2020; Isa et al., 2021).

Despite these strides, Malaysia faces challenges such as federal-state friction, limited government capacity, and barriers to renewable energy investment, which could impede further decarbonization. However, institutional shifts, like the establishment of the Sustainable Energy Development Authority (SEDA) and initiatives like PEMANDU, signal a concerted effort to align development with carbon reduction goals. Additionally, Malaysia emphasizes the importance of engaging younger generations in climate change initiatives, recognizing the need for long-term behavioral change towards a low-carbon society (Gong & Yeung, 2022; Susskind et al., 2020).

China, similarly, has set ambitious carbon reduction targets, committing to peak carbon dioxide emissions before 2030 and achieve carbon neutrality by 2060. The country is investing substantially in renewable energy and energy-efficient technologies to meet these objectives (Yi et al., 2022; Zeng & Yang, 2023).

The experiences of Malaysia and China underscore the importance of digitalization in driving decarbonization efforts within data centers. Their strategic initiatives and the challenges they face provide valuable lessons for other nations seeking to develop effective strategies for sustainable development in the digital era (Chang et al., 2024).

Case Study 2: China

Overview of China's Smart City Initiatives and Data Center Growth

China is a leading force in the global digital innovation landscape, with its digital economy surging to a value of 45.5 trillion yuan by 2021, accounting for nearly 40% of the nation's GDP. This robust digital growth is complemented by significant expansion in the data center market, which is projected to reach revenues of US\$95.74 billion by 2024, with an expected compound annual growth rate of 8.97% leading to a market volume of US\$147.10 billion by 2029. These data centers are not only drivers of the digital economy but also critical components in China's decarbonization strategy (Au, 2023; Li et al., 2015; Li, 2022).

China has set forth ambitious carbon neutrality targets, aiming to achieve net-zero carbon emissions by 2060. Toward this goal, the country plans to increase the share of non-fossil energy consumption to around 20% by 2025, 25% by 2030, and over 80% by 2060. This transition is already underway, with China's renewable energy

capacity expected to reach 1,200 gigawatts by 2030, a goal that may be met as early as 2025, positioning the country as a global leader in renewable energy. Governance is driven by strict macro-level mandates, such as the “New Data Centre Development Three-year Action Plan,” which enforces aggressive energy-saving standards. A central instrument is the East-West Computing Resources Transmission (EWCRT) Project, a macro-level knowledge governance strategy designed to balance data and power resources by shifting processing to green-energy-rich western regions (Cai & Gou, 2023).

The country’s digital innovation is not limited to economic growth; it extends to sustainability initiatives as well. China is actively developing and deploying AI, IoT, and advanced communication networks to transform various sectors, including data centers, which are becoming increasingly energy-efficient and environmentally friendly. Smart city initiatives further amplify these efforts, integrating digital technologies to optimize urban energy use, waste management, and overall operational efficiency (Cao et al., 2022).

In summary, China’s comprehensive approach to digitalization, with a focus on both economic growth and environmental sustainability, is setting a precedent for the global transition towards smart, sustainable urban development. The country’s strategic investments and ambitious goals are steering it towards a future where digitalization and decarbonization go hand in hand, creating a blueprint for other nations to follow (Li et al., 2015; Zenglein & Holzmann, 2019).

Digitalization Strategies and Initiatives: Key projects and initiatives in digital infrastructure management

Given that China is set to dominate the global digital innovation sector, its data centre market is likely to expand tangentially. According to the current statistics, the Digital Economy will increase to 45.5 trillion yuan, which accounts for over 40% of the Chinese GDP, by 2021. The same picture can be observed in the anticipated data centre market volume and growth. It will raise to US\$95.74 billion in 2024 with a Compound Annual Growth Rate (CAGR) of 8.97%. By 2029, the size of the market is expected to inflate to US\$147.10 billion. The affirmation can be explained thus, where data centres play a dual role of driving the nation’s economic growth and supporting its decarbonisation aim (Li, 2022; Qiu et al., 2021).

Nevertheless, China has made ambitious statements regarding carbon neutrality. It has expressed its hopes to be carbon neutral by 2060. In the process of implementing this goal, the country is intending to elevate the non-fossil proportion of energy consumption to around 20% by 2025, 25% by 2030, and beyond 80% by 2060 (Cai & Gou, 2023). The said transformation is currently underway, and the experts predict that China will achieve renewable energy capacity being 1,200 gigawatts by 2030. China will undoubtedly soon be the most developed state in the realm of renewable energy. The ecosystem prioritizes Algorithmic Capital, utilizing AI-driven energy management and 5G networks to optimize real-time resource allocation. Specific strategies include the adoption of immersion cooling, reducing energy consumption per server by at least 20% and a drive to lower the local Power Usage Effectiveness (PUE) to below 1.3 by 2025 (Amighini, 2019).

Interestingly, their digital innovation aims incorporated not only the issues of megascopic economic growth but the matter tackle the issues of sustainability. Therefore, China is actively investing in building artificial intelligence, internet of things, and advanced communications networks. The said are used to promote advancements in differing industries that, in their turn, assist in making the data centre industry significantly more prompt and green sustainable. The agglomeration of various advancements in sustainable use and smart grids lead to the development of Smart Cities. This way, everchanging cities make it possible to maximize energy usage and efficiency, waste management, and other operations. China's strategic investments, planning, and calculation with their differences from other countries, are on the rise thus leading to a future, in which digitalisation and reduced carbon dioxide emissions will be inseparable. The said goal positions Chinese case as a role model for others (Kshetri, 2017; Dhar Dwivedi et al., 2024; Chander et al., 2022).

Macro-level Knowledge Governance

China's digitalisation strategies have positioned it as a leader in decarbonisation efforts within its data centres. The scale of the digital economy serves as the primary driver for infrastructure expansion. For example, China's digital economy valued at CNY 45.5 trillion as of 2021 (representing 39.8% of national GDP) is not just an economic indicator but a metric of Structural Capital intensity. The expansion has been accompanied by a significant increase in the number of racks providing computational power, showcasing the country's dedication to digital infrastructure. Nevertheless, the advancements made in recent years have resulted in an increase in energy usage. This \$7.5 trillion market scale (2022 baseline) provides the economic rationale for why data centers have transitioned from supportive utilities into knowledge-intensive nodes that now dictate regional energy policy. In 2020 alone, data centres consumed a staggering 150.7 billion kilowatt-hours of electricity, making up 2.01% of the national total. Additionally, this energy consumption led to the emission of over 94.85 million metric tonnes of CO₂ (Xie et al., 2024).

To tackle these challenges, the Chinese government has launched the East-West Computing Resources Transmission Project (EWCRT Project). The project's objective is to achieve a more equitable distribution of data and power resources. By harnessing the ample green energy resources in the western regions, the project aims to minimise carbon emissions from data centres through data processing. With the aim of achieving a 100% green electricity usage by 2040, the initiative is set to make a substantial impact on reducing carbon emissions in data centres (Guo et al., 2022).

China's experience with the EWCRT Project underscores a strategic shift toward Macro-level Knowledge Governance. This initiative is not merely a logistical solution for moving data to western regions with green energy; it is a deliberate effort to mobilize Structural Capital (computational power) into regions that traditionally lack the Relational Capital (innovation networks) and infrastructure found in the east. By integrating 5G networks and energy-efficient data nodes, the project reconfigures regional innovation systems, allowing the western provinces to capture economic value by becoming central players in the green digital knowledge economy.

In addition, the project seeks to enhance the Power Usage Effectiveness (PUE) of data centres, with a specific focus on achieving a PUE of 1.1 by 2030. With these advancements and the greater adoption of renewable energy, carbon emissions could potentially decrease by almost 6% when compared to the current situation. With its cutting-edge advancements, the EWCRT Project is expected to significantly decrease carbon emissions by almost 64% (9500 Mt CO₂) from 2020 to 2050. This showcases the immense potential for substantial decarbonisation in China's digital economy (Seymour and Herrlin, 2015, Lam et al., 2020).

Although there are potential advantages, there are still obstacles to overcome. These include the necessity of a significant upfront investment in digital infrastructure and the need for skilled workers to handle these advanced technologies. Nevertheless, the potential benefits of digitalisation, including significant energy savings and a decrease in carbon emissions, are quite substantial. China's experience highlights the significance of strategic planning and policy support in utilising digitalisation for decarbonisation, establishing the country as a frontrunner in sustainable digital economy development (Zhang et al., 2022; Dhar Dwivedi et al., 2024; Feijóo et al., 2020).

Lessons Learned: Key Insights and Takeaways from China's Experience

China's rapid digitalization has a significant impact on the decarbonization of its data centers, as it primarily revolves around improving the country's energy efficiency and carbon emissions. The Power Usage Effectiveness of the data centers will be lower than 1.3 by 2025, much lower than the current 1.6–1.7, indicating that less energy will be used to power them. In addition to that, this goal is supported by a larger incentive to obtain a higher percentage of renewable energy due to China's goal to peak its carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060. Chinese data centers were responsible for 99 million metric tons of CO₂ emissions in 2018, and this amount will presumably be reduced over time due to the aforementioned advantages of digitalizing China's economy (Iea, 2022; Yi et al., 2022).

The consistent market growth can be seen as evidence of the Chinese government's commitment to the development of data centers in the country. According to the data, the market will be worth US\$95.74 billion by 2024. The policy efforts, such as the "New Data Centre Development Three-year Action Plan (2021–2023)", further emphasize that the Chinese government's priority in constructing data centers over the long run requires constructing data centers that decrease the primary energy consumption and increase its energy efficiency. Considering the significant advantages to these efforts, the challenges that still exist include a lack of renewable energy integration into the grid and too high of a cost of computing resources. The EWCRT Project is projected to reduce carbon emissions by nearly 64% (9500 Mt CO₂) between 2020 and 2050. Measurable success is seen in the systematic lowering of PUE scores, with a target of 1.1 by 2030, potentially decreasing total emissions by 6% compared to current baselines.

However, the ongoing progress of the energy efficiency of their digital infrastructure, as well as the innovation of communication technology in this country such as

5G networks, indicates that China's digitalization is inseparable from its efforts to diminish carbon emissions. Therefore, it can be concluded that both types of data center decarbonization strategies do not matter in itself for Chinese data operators, since digitalization benefits both (Ni et al., 2024; Shabalov et al., 2021; Nazari & Musilek, 2023).

Comparative Analysis

Comparison of Digitalization Strategies Between Malaysia and China

China and Malaysia are taking a joint approach in the digitalization strategies aimed at decarbonizing their data centers with an emphasis on energy efficiency and improved sustainability. China's digital economy has drastically grown to become one of the leading growth engines of the country where the market value will reach approximately 45.5 trillion yuan in 2021, and 39.8% of the GDP. In this light, the country's data center market is expected to grow as well, and China's present goal is to increase the share of non-fossil energy consumption to around 20% by 2025 and 25% by 2030, which is also in line with China's carbon-neutrality promise by 2060. At the same time, Malaysia is also proving to become a powerhouse in data centers with a projected market worth the increase of up to USD 1.4 billion by 2026. The country has seen a promising future and set ambitious targets, such as 31% of its installed capacity is to come from renewable sources by 2025 and 40% by 2035 (IRENA, 2023). The real-life applications of decarbonization through digitalization are well illustrated in Malaysia's project YTL Green Data Centre Park where the data center created will be self-sustained by on-site solar power, leading to a significant reduction in carbon emissions (Can et al., 2023; Hu, 2024; Raihan & Tuspekova, 2022).

In addition, both countries have demonstrated a remarkable digitalization effort with a significant investment in digital infrastructure (Table 2). For instance, China is already in the process of implementing 5G technology, and the number of 5G connections is set to increase to almost five billion by 2026. Malaysia, too, is attracting considerable investment in the digitalization sector, including big companies such as AWS, Google, and Microsoft, who are setting up data centers in the country. However, these projects present a certain level of the non-negligible risk, including the necessity of a substantial investment in the nation's digital infrastructure as well as a requirement for skilled manpower to operate new gadgets and programs. Meanwhile, the opportunities, which far outweigh the risks, such as energy savings and benefits to other parts of the economy, especially in the range of environmental benefits, make the projects worth pursuing. Both ecosystems face a critical gap in intellectual capital, as the "twin transitions" (digital and green) require highly specialized technical and managerial competencies that are currently in short supply.

High initial financial investments in digital infrastructure and the need to integrate renewable energy into an overstressed national grid remain significant hurdles. The summarized evidence indicates that China and Malaysia's digital policies and strategic investments have effectively put them on the course of becoming the leading decarbonized data center countries (Lei et al., 2022, Priharsari et al., 2023).

Table 2 Knowledge Spillover Mechanisms in Green Data Center Ecosystems

Spillover Mechanism	Cyberjaya (Malaysia) Ecosystem Context	Shenzhen (China) Ecosystem Context
Targeted Training & Human Capital Upgrades	The presence of global tech firms (AWS, Google, Microsoft) creates localized learning loops, forcing the domestic workforce to master interdisciplinary green tech competencies.	High-density computing workloads drive smart infrastructure groups to train engineers in AI-driven predictive modeling and sustainable thermal management.
Supplier Upgrades & Infrastructure Alignment	Data center operators demand strict ESG compliance, directly forcing local utilities and industrial parks (e.g., Sedenak and Nusajaya) to advance their green technological capabilities.	Enforced macro-level targets (PUE < 1.3 by 2025) force local cooling, electrical component, and power distribution supply chains to systematically green their operations.
Co-Development & Inter-firm Learning	Cross-border institutional partnerships, exemplified by Tencent Cloud and global resource groups, foster regional collaborative platforms for digital infrastructure deployment.	Collaborative networks within the Smart Cities Research Center encourage joint R&D models between universities, startups, and data center operators.

Analysis of Different Approaches and Their Effectiveness in Decarbonization

China and Malaysia are actively pursuing digitalization strategies to decarbonize their data centers, with significant initiatives and policies in place to support this transition (Table 3). China's digital economy has seen remarkable growth, nearly doubling since 2016 to reach 45.5 trillion yuan by 2021, accounting for 39.8% of its GDP. This growth is complemented by ambitious plans to increase the share of non-fossil energy consumption to around 20% by 2025 and 25% by 2030, with a long-term target of over 80% by 2060, aligning with China's goal of carbon neutrality by 2060 (Yu et al., 2023; Myllyvirta et al., 2022).

Malaysia's digital economy has also experienced substantial growth, reaching RM 205 billion by the end of 2022, representing 14% of the country's GDP. The country has set a target to achieve 31% renewable energy in its installed capacity by 2025 and 40% by 2035, which will significantly impact the energy consumption and carbon footprint of data centers (Raihan & Tuspekova, 2022).

In terms of energy consumption, China's data centers consumed 150.7 billion kWh in 2020, accounting for 2.01% of the country's total electricity consumption, with over 94.85 million metric tons of CO₂ emissions resulting from fossil fuel-based electricity generation (Xie et al., 2024). Malaysia, while not providing specific data center energy consumption figures, is focusing on increasing the share of renewable energy in its electricity generation capacity mix to 31% by 2025 (Shen et al., 2023).

Table 3 Digitalization strategies to decarbonize their data centers in China and Malaysia

Country	Digital Economy Growth	Data Center Market (Revenue)	Energy Consumption (Data Centers)	Carbon Emissions	Renewable Energy Targets	Key Projects and Initiatives
China	CNY 45.5 trillion (2021)	US\$95.74 billion (2024)	150.7 billion kWh (2020)	94.85 million Mt CO ₂ (2020)	20% by 2025, 25% by 2030, over 80% by 2060	East-West Computing Resources Transmission Project
Malaysia	RM 205 billion (2022)	N/A	N/A	N/A	31% by 2025, 40% by 2035	MyRER – Renewable Energy Malaysia

Both countries are investing in digital infrastructure, with China leading the way in 5G technology and Malaysia attracting investments from tech giants like AWS, Google, and Microsoft. China's East-West Computing Resources Transmission Project (EWCRT Project) aims to balance the distribution of data and power resources, shifting data processing activities to regions with abundant green energy resources, potentially reducing 2125 metric tons of CO₂ between 2020 and 2050 (Raihan & Tuspekova, 2022).

Malaysia's Renewable Energy Roadmap (MyRER) is commissioned to support further decarbonization of the electricity sector in Malaysia through the 2035 milestone. These initiatives and targets demonstrate the commitment of China and Malaysia to leveraging digitalization for decarbonization, positioning them as leaders in sustainable data center operations and contributing to global decarbonization efforts (Tee et al., 2024; Wong & Li, 2023).

Common and Unique Challenges Faced by Both Countries in Digitalizing Data Center Management

China and Malaysia are exemplifying the integration of digitalization strategies to decarbonize their data centers, showcasing the potential for sustainable digital economy growth. China's digital economy has nearly doubled since 2016, reaching a substantial 45.5 trillion yuan by 2021, which accounts for 39.8% of its GDP. This growth is complemented by a thriving data center market, projected to reach revenues of US\$95.74 billion by 2024, with an annual growth rate of 8.97% leading to a market volume of US\$147.10 billion by 2029. In terms of energy consumption, China's data centers consumed 150.7 billion kWh in 2020, representing 2.01% of the nation's total electricity usage, and emitted over 94.85 million metric tons of CO₂, primarily from fossil fuel-based electricity generation (Ordóñez De Pablos et al., 2024; Zhang et al., 2024; Zeng & Yang, 2023).

Malaysia, similarly, is experiencing growth in its digital economy, contributing 23% to its GDP from 2021 to 2023. The country is also focusing on the data center sector, with significant investments from global tech companies, aiming to increase the share of renewable energy in its electricity generation capacity mix to 31% by 2025. Both countries are actively investing in digital infrastructure, with China lead-

ing in 5G technology development and Malaysia attracting major tech players to establish data centers within its borders (Raihan, 2023; Raihan & Tuspekova, 2022).

China has set ambitious targets to increase its renewable energy capacity to 1,200 gigawatts by 2030, more than doubling its capacity from 2020 levels. Malaysia is also committed to increasing its renewable energy share, with a target of 31% by 2025, aligning with its goal to reduce economy-wide carbon intensity by 45% in 2030 compared to 2005 levels (Chan & Sopian, 2022).

Despite these efforts, challenges such as the initial investment required for digital infrastructure and the need for skilled labor persist. However, the opportunities presented by digitalization, including energy savings and reduced carbon emissions, are substantial. The experiences of China and Malaysia underscore the importance of strategic planning and policy support in leveraging digitalization for decarbonization, positioning both nations as leaders in sustainable data center operations and contributors to global sustainability initiatives.

Regulatory, Technical, and Economic Barriers

China and Malaysia are exemplifying the integration of digitalization strategies to decarbonize their data centers, showcasing the potential for sustainable digital economy growth. China's digital economy has nearly doubled since 2016, reaching a substantial 45.5 trillion yuan by 2021, accounting for 39.8% of its GDP. This growth is complemented by ambitious plans to increase the share of non-fossil energy consumption to around 20% by 2025 and 25% by 2030, aligning with China's goal of carbon neutrality by 2060 (Gong & Yeung, 2022; Shi, 2022).

Malaysia's digital economy has also experienced substantial growth, contributing 23% to its GDP from 2021 to 2023. The country has set a target to achieve 31% renewable energy in its installed capacity by 2025 and 40% by 2035, which will significantly impact the energy consumption and carbon footprint of data centers (Hu, 2024).

In terms of energy consumption, China's data centers consumed 150.7 billion kWh in 2020, representing 2.01% of the nation's total electricity usage, and emitted over 94.85 million metric tons of CO₂, primarily from fossil fuel-based electricity generation. Malaysia, while not providing specific data center energy consumption figures, is focusing on increasing the share of renewable energy in its electricity generation capacity mix to 31% by 2025 (Susskind et al., 2020; Ni et al., 2024).

Both countries are investing in digital infrastructure, with China leading the way in 5G technology development and Malaysia attracting investments from tech giants like AWS, Google, and Microsoft (Malcomson, 2020). China's East-West Computing Resources Transmission Project (EWCRT Project) aims to balance the distribution of data and power resources, shifting data processing activities to regions with abundant green energy resources, potentially reducing 2125 metric tons of CO₂ between 2020 and 2050 (Qiu et al., 2021).

Malaysia's Renewable Energy Roadmap (MyRER) is commissioned to support further decarbonization of the electricity sector in Malaysia through the milestone (Wong & Li, 2023). These initiatives and targets demonstrate the commitment of

China and Malaysia to leveraging digitalization for decarbonization, positioning them as leaders in sustainable data center operations and contributors to global sustainability initiatives (Sovannarith & Nhiep, 2021).

Identification of Best Practices for Digitalizing Data Centers to Achieve Decarbonization

China and Malaysia are at the forefront of adopting digitalization strategies to achieve decarbonization within their data centers, showcasing a commitment to sustainable growth. China's digital economy has experienced remarkable expansion, reaching a value of 45.5 trillion yuan by 2021, which accounts for nearly 40% of its GDP. This robust digital growth is complemented by a thriving data center market, projected to reach revenues of US\$95.74 billion by 2024, with an annual growth rate of 8.97% leading to a market volume of US\$147.10 billion by 2029. In terms of energy consumption, China's data centers consumed 150.7 billion kWh in 2020, representing 2.01% of the nation's total electricity usage, and emitted over 94.85 million metric tons of CO₂, primarily from fossil fuel-based electricity generation (Ni et al., 2024; Zeng & Yang, 2023).

Malaysia, similarly, is actively growing its digital economy, contributing 23% to its GDP from 2021 to 2023. The country has set ambitious renewable energy targets, aiming for 31% of its installed capacity to be from renewable sources by 2025. Both countries are investing in digital infrastructure, with China leading in 5G technology development and Malaysia attracting significant investments from tech giants like AWS, Google, and Microsoft to establish data centers within its borders (Gong & Yeung, 2022; Li & Wang, 2022).

China has pledged to increase its renewable energy capacity to 1,200 gigawatts by 2030, more than doubling its capacity from 2020 levels (Liu et al., 2018). Malaysia is also focusing on increasing the share of renewable energy, with a target of 31% by 2025, aligning with its goal to reduce economy-wide carbon intensity by 45% in 2030 compared to 2005 levels (Gong & Yeung, 2022). These initiatives underscore the importance of digitalization in driving decarbonization efforts. With strategic investments and policy support, China and Malaysia are positioning themselves as leaders in sustainable data center operations, contributing to global sustainability goals. These efforts indicate a clear trend towards a greener, more efficient digital future (Susskind et al., 2020; Ni et al., 2024).

Policy Recommendations and Strategic Approaches for Other Developing Countries

China and Malaysia are exemplifying the integration of digitalization strategies to decarbonize their data centers, showcasing the potential for sustainable digital economy growth. China's digital economy has nearly doubled since 2016, reaching a substantial 45.5 trillion yuan by 2021, accounting for 39.8% of its GDP. This growth is complemented by ambitious plans to increase the share of non-fossil energy consumption to around 20% by 2025 and 25% by 2030, aligning with China's goal of carbon neutrality by 2060 (Zeng & Yang, 2023).

Malaysia's digital economy has also experienced substantial growth, contributing 23% to its GDP from 2021 to 2023. The country has set a target to achieve 31% renewable energy in its installed capacity by 2025 and 40% by 2035, which will significantly impact the energy consumption and carbon footprint of data centers (Raihan & Tuspekova, 2022).

In terms of energy consumption, China's data centers consumed 150.7 billion kWh in 2020, representing 2.01% of the nation's total electricity usage, and emitted over 94.85 million metric tons of CO₂, primarily from fossil fuel-based electricity generation (Guo et al., 2022). Malaysia, while not providing specific data center energy consumption figures, is focusing on increasing the share of renewable energy in its electricity generation capacity mix to 31% by 2025 (Yi et al., 2022; Yu & Liu, 2024; Zhang et al., 2024).

Both countries are investing in digital infrastructure, with China leading the way in 5G technology development and Malaysia attracting investments from tech giants like AWS, Google, and Microsoft. China's East-West Computing Resources Transmission Project (EWCRT Project) aims to balance the distribution of data and power resources, shifting data processing activities to regions with abundant green energy resources, potentially reducing 2125 metric tons of CO₂ between 2020 and 2050 (Qiu et al., 2021; Xie et al., 2024).

These initiatives and targets demonstrate the commitment of China and Malaysia to leveraging digitalization for decarbonization, positioning them as leaders in sustainable data center operations and contributors to global sustainability initiatives.

Value Capture Syntheses

Within the green knowledge economy, Value Capture represents the mechanisms through which firms and regional ecosystems retain economic and intellectual rents generated by green transitions, moving away from being passive infrastructure hosts to becoming active owners of proprietary knowledge assets (Papiashvili et al. 2025).

Value capture is driven by macro-level knowledge governance and standards-setting. By executing the East-West Computing Resources Transmission (EWCRT) Project, China reconfigures its regional innovation system. Rather than acting as a standard utility, Shenzhen leverages its digital economy (valued at CNY 45.5 trillion) to establish proprietary low-PUE architectural standards (targeting a PUE of 1.1 by 2030), capturing high-value green intellectual property (IP) that can be exported globally (Erokhin & Gao, 2024).

Value capture is achieved by transitioning from low-cost land hosting to the ownership of AI energy infrastructure services. Confronted with an induced demand of 5 gigawatts by 2035 due to expanding AI workloads, the Malaysia Digital (MD) initiative leverages investments from tech leaders (Microsoft, Google) to build local dynamic capabilities. This enables domestic firms to co-develop cloud-based energy optimization software, shifting Malaysia's role from a consumer of hardware to an exporter of digital sustainability expertise.

Future Perspectives

Emerging Technologies: Potential Future Technologies that Enhance Decarbonization Efforts

The future of data center decarbonization is ripe with potential, as emerging technologies promise to enhance sustainability and efficiency. Artificial Intelligence (AI) and Machine Learning are projected to play pivotal roles in optimizing data center operations, with Gartner forecasting that by 2027, 60% of data center infrastructure teams will possess relevant automation and cloud skills, a significant increase from 30% in 2022. The rise of edge computing will also reduce latency and energy consumption by processing data closer to its source, aligning with the faster data transmission capabilities of 5G networks (Ramphele et al., 2020; Thangam et al., 2024; Wang et al., 2015).

Renewable energy integration is another key area, with China aiming to increase non-fossil fuel energy consumption to around 20% by 2025 and 25% by 2030, in line with its goal of carbon neutrality by 2060 (Cai et al., 2024). Advanced cooling technologies like liquid cooling systems can potentially reduce energy consumption by at least 20% compared to traditional air-cooling, making them an essential tool for managing heat in high-density server environments (Channi & Kumar, 2024; Lam et al., 2020).

Rather than just optimizing cooling, AI is framed as a generator of predictive structural knowledge. By 2027, the evolution of data center teams from basic maintenance to advanced automation signifies a growth in Human Intellectual Capital. AI-driven models create proactive energy management systems that represent a 15–25% reduction in operational costs through the creation of new algorithmic capital.

Energy storage solutions, particularly batteries, will become more integral to managing the intermittent nature of renewable energy sources. China's plans to add approximately 100 GW of storage capacity by 2030 underscore the country's commitment to sustainable energy management. Digital twins will enable virtual modeling and simulation, leading to more efficient data center design and operation, with potential energy savings of 10–20% (Hassan et al., 2024; Huang et al., 2024; Sharvini et al., 2018; Chen et al., 2023). Virtual modeling via digital twins is used to illustrate the transition into a knowledge-intensive design phase. This technology allows nations to simulate and fine-tune energy consumption before physical implementation, creating a repository of Structural Capital that can be exported as a global standard.

Sustainable building design, incorporating efficient layout planning and sustainable materials, will further reduce data centers' carbon footprints. Technologies like Carbon Capture and Storage (CCS) will be crucial for mitigating carbon emissions from growing data centers. The nascent field of quantum computing holds the promise of revolutionizing data processing, leading to more efficient and energy-saving data centers (Martínez-Peláez et al., 2023; Ordóñez De Pablos et al., 2024; Bhavsar et al., 2023).

Government policies, such as China's green data center development policies and Malaysia's MyRER, will continue to drive the adoption of sustainable technologies in data centers. These future technologies and strategies indicate a promising trajectory for data centers to become more sustainable and efficient, aligning with global decarbonization goals. The scale of efforts and the potential impact of these technologies help reducing energy consumption and carbon emissions in data centers (Yu & Liu, 2024; Susskind et al., 2020).

Advanced AI, machine learning, and blockchain technologies are revolutionizing energy management within data centers, contributing significantly to decarbonization efforts. AI-driven models optimize energy consumption by analyzing patterns and predicting future usage trends, leading to proactive energy management and substantial cost savings. A study on AI-based modeling for data center energy management demonstrated the potential for these techniques to reduce energy waste and improve resource utilization rates (Khan et al., 2023; Ezzeddine et al., 2024).

Blockchain's secure and transparent nature is being explored for energy transactions, with its application in data centers that highlighting improvements in the security and efficiency of energy consumption monitoring. The integration of renewable energy sources is also enhanced by AI and machine learning, managing the variability of solar and wind power to create a more sustainable energy mix (Mehta et al., 2018, Ramphela et al., 2020, Todd et al., 2021). Blockchain is repositioned from a security tool to a facilitator of Relational Capital. Its transparent nature allows for secure energy transactions and the monitoring of energy consumption, creating a trusted "knowledge network" for peer-to-peer energy trading and green energy verification.

The reduction of carbon emissions is another critical area where these technologies excel. A report on sustainable energy technologies and assessments emphasized AI's role in reducing carbon emissions by improving energy efficiency and optimizing consumption patterns. Economically, the implementation of AI-driven energy management systems can lead to significant savings, with potential operational cost reductions of 15–25% (Lee et al., 2022; Arévalo et al., 2024).

Looking ahead, the role of AI, machine learning, and blockchain in energy management is expected to expand as data centers grow. A report on key technologies for smart energy systems noted that these technologies are essential for achieving carbon neutrality and optimizing future energy management. The integration of these advanced technologies underscores their transformative potential in decarbonizing data centers and enhancing energy management, positioning them as key drivers in achieving sustainable energy goals (Martínez-Peláez et al., 2023, Zhu et al., 2021).

Policy Implications: Recommendations for Policymakers to Support Digitalization and Decarbonization Efforts

Policymakers have a pivotal role in steering the digitalization of data centers towards decarbonization, and their strategies can significantly influence the sector's sustainability. By promoting the integration of renewable energy sources, such as China's goal to increase non-fossil energy consumption to around 20% by 2025 and 25% by 2030, they can contribute to a substantial reduction in carbon emissions. Incentives for energy efficiency, supported by the IEA's findings that digital technologies

can enhance efficiency across sectors and reduce global CO₂ emissions by 15%, can encourage data centers to adopt more sustainable practices (Li & Wang, 2022; Ni et al., 2024; Qian et al., 2023; Dwivedi et al., 2022).

Investing in research and development of advanced cooling systems and AI-driven energy management can lead to innovations that save energy. Implementing carbon pricing mechanisms, such as carbon taxes or cap-and-trade systems, can provide financial incentives for data centers to reduce their carbon footprint. Developing digital infrastructure, including 5G networks, can facilitate the deployment of smart grids and IoT devices, which enhance the efficiency of energy use in data centers (Mehta et al., 2018; Ramphele et al., 2020; Thangam et al., 2024).

Regulating energy consumption and emissions, as seen in China's strict controls on energy consumption and CO₂ emission intensity, can ensure that data centers operate within sustainable limits. Encouraging public-private partnerships can drive innovation in data center sustainability through joint initiatives for research, technology deployment, and knowledge sharing. Ensuring robust data security and privacy regulations is essential as data centers become more reliant on digital technologies, maintaining public trust and responsible data use (Li and Wang, 2022, Ni et al., 2024, Qian et al., 2023). A new focus on education and training programs highlights that the net-zero transition is a human-centric knowledge evolution. Without a workforce equipped with interdisciplinary competencies, technological innovations remain "static hardware" rather than dynamic assets.

Investing in education and training programs develops a skilled workforce capable of managing advanced data center technologies and sustainability initiatives. Establishing systems to monitor and evaluate the progress of decarbonization efforts in data centers, including setting performance benchmarks and regularly reviewing policy effectiveness, is crucial for continuous improvement (Pandiyan et al., 2023; Hanus et al., 2023).

By adopting these recommendations, policymakers can support the digitalization of data centers in a manner that aligns with decarbonization objectives, fostering a more sustainable future for the digital economy. Policymakers have a pivotal role in steering the digitalization of data centers towards decarbonization, and their strategies can significantly influence the sector's sustainability. By promoting the integration of renewable energy sources, such as China's goal to increase non-fossil energy consumption to around 20% by 2025 and 25% by 2030, they can contribute to a substantial reduction in carbon emissions. Incentives for energy efficiency, supported by the IEA's findings that digital technologies can enhance efficiency across sectors and reduce global CO₂ emissions by 15%, can encourage data centers to adopt more sustainable practices (Iea, 2022; Rissman et al., 2020; Li & Wang, 2022; Ni et al., 2024). Future policy frameworks (like China's EWCRT and Malaysia's MyRER) are now analyzed as Macro-level Knowledge Governance. This involves the deliberate effort to mobilize Structural Capital (computational power) and Relational Capital (innovation networks) across regions to ensure inclusive, sustainable growth.

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digital infrastructure, including 5G networks, can facilitate the deployment of smart grids and IoT devices, which enhance the efficiency of energy use in data centers (Ullah et al., 2024; Martínez-Peláez et al., 2023; Rissman et al., 2020). This work now emphasizes that these nations are no longer just passive hosts for foreign tech giants. By pioneering low-PUE targets and integrating clean energy, they capture economic value by establishing the standards for Green Intellectual Capital.

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Investing in education and training programs develops a skilled workforce capable of managing advanced data center technologies and sustainability initiatives. Establishing systems to monitor and evaluate the progress of decarbonization efforts in data centers, including setting performance benchmarks and regularly reviewing policy effectiveness, is crucial for continuous improvement (Al Kez et al., 2022; Orikpete et al., 2023; Zhu et al., 2021).

By adopting these recommendations, policymakers can support the digitalization of data centers in a manner that aligns with decarbonization objectives, fostering a more sustainable future for the digital economy.

Suggestions for Future Research Areas to Explore the Intersection of Digitalization, Smart Cities, and Decarbonization

The digital transformation of data centers is a critical pathway to achieving sustainability and decarbonization objectives. Future research in this area should focus on several key directions. The impact of digitalization on energy efficiency is paramount, with potential studies analyzing the energy savings from AI-driven optimization and IoT-based monitoring systems. Additionally, the integration of renewable energy sources into data center operations presents an opportunity for research, examining how digital tools can manage the variability of renewable energy supply and demand.

Lifecycle analysis of data centers, considering the environmental impact throughout their lifecycle, is another area ripe for exploration. The policy implications of digitalization should also be scrutinized to understand how regulations can either support or impede the adoption of sustainable practices. Economic models could assess the cost-effectiveness of digitalization strategies, providing a clear picture of the return on investment for energy-saving technologies.

Social and environmental impact assessments can offer a broader perspective on the consequences of digitalization, taking into account job creation, resource consumption, and waste reduction. Investigating emerging technologies like edge computing, quantum computing, and advanced cooling systems could reveal new avenues for reducing data centers' carbon footprints. Case studies and comparative

analyses can provide practical insights and cross-regional comparisons, respectively, highlighting the success factors and challenges of digitalization initiatives.

Longitudinal studies tracking long-term trends can identify patterns and opportunities for future development. The percentage reductions in energy consumption, renewable energy integration levels, cost savings, and CO₂ emissions reductions, is crucial in quantifying the effectiveness of digitalization strategies. By pursuing these research directions, future studies can enhance our understanding of how digitalization can contribute to decarbonization efforts in data centers, offering valuable guidance for policymakers, industry professionals, and the research community at large.

Conclusion

Summary of Findings

The conclusion of the analysis on digitalization strategies for decarbonization in data centers, with a focus on Malaysia and China, has yielded several key findings and insights. Both countries have witnessed substantial growth in their digital economies, with China's digital economy contributing 39.8% of its GDP and Malaysia's contributing 23%, underscoring the potential for digitalization to drive decarbonization efforts.

The data center market in China is projected to reach a revenue of US\$95.74 billion by 2024, and Malaysia is also experiencing growth in this sector. This expansion underscores the critical role of digital infrastructure in supporting the digital economy and the necessity for sustainable management practices in data centers. Energy consumption and carbon emissions are significant concerns, with China's data centers consuming 150.7 billion kWh in 2020 and emitting over 94.85 million metric tons of CO₂, highlighting the urgency for sustainable energy solutions.

Renewable energy targets are a cornerstone of these efforts, with China aiming for a 20% share of non-fossil energy consumption by 2025 and Malaysia targeting 31% renewable energy in its installed capacity by 2025. Investments in digital infrastructure, particularly in 5G technology and smart grids, are essential for enhancing energy efficiency in data centers.

Policies and regulatory support are crucial, as evidenced by China's "New Data Centre Development Three-year Action Plan (2021–2023)" and Malaysia's Renewable Energy Roadmap (MyRER). These initiatives demonstrate a commitment to promoting sustainable development and decarbonization in data centers. Despite the progress, challenges such as the need for substantial initial investment and skilled labor persist.

Recommendations for policymakers include promoting renewable energy integration, providing incentives for energy efficiency, supporting R&D in digital technologies, and fostering public-private partnerships to drive innovation in data center sustainability. In summary, the case studies and comparative analysis of China and Malaysia reveal that digitalization strategies can significantly contribute to the decarbonization of data centers. With sustained investment, innovation, and supportive policies, these countries are poised to lead in sustainable data center operations and global decarbonization efforts.

Contributions to the Field

China and Malaysia are exemplifying the integration of digitalization strategies to decarbonize their data centers, showcasing the potential for sustainable digital economy growth. China's digital economy has nearly doubled since 2016, reaching a substantial 45.5 trillion yuan by 2021, accounting for 39.8% of its GDP. This growth is complemented by ambitious plans to increase the share of non-fossil energy consumption to around 20% by 2025 and 25% by 2030, aligning with China's goal of carbon neutrality by 2060.

Malaysia's digital economy has also experienced substantial growth, contributing 23% to its GDP from 2021 to 2023. The country has set a target to achieve 31% renewable energy in its installed capacity by 2025 and 40% by 2035, which will significantly impact the energy consumption and carbon footprint of data centers. The manuscript proves that decarbonization strategies are not merely mechanical adjustments but fundamental transformational drivers of regional intellectual capital. By shifting the focus from physical utility assets to an integrated framework of Human, Structural, Relational, and Algorithmic Capital, we demonstrate that green transitions convert raw digital inputs into highly structured knowledge repositories. Operational efficiency metrics (such as PUE values) serve as direct evidence of a firm's underlying green dynamic capabilities.

In terms of energy consumption, China's data centers consumed 150.7 billion kWh in 2020, representing 2.01% of the nation's total electricity usage, and emitted over 94.85 million metric tons of CO₂, primarily from fossil fuel-based electricity generation. Malaysia, while not providing specific data center energy consumption figures, is focusing on increasing the share of renewable energy in its electricity generation capacity mix to 31% by 2025. We confirm that sustainable data center investments function as anchors for regional innovation systems. The presence of advanced computing hubs creates cross-sector spillovers that drive supplier upgrades, localized training ecosystems, and co-development networks, directly enhancing the knowledge assets of the broader smart city environment.

This study demonstrates that the shift to green data centers allows emerging leaders like Malaysia and China to capture economic value not just through physical infrastructure, but by establishing global standards for 'Green Intellectual Capital'. By pioneering low-PUE targets and renewable energy integration, these nations transition from being hosts for foreign technology to becoming architects of the Green Digital Knowledge Economy.

Both countries are investing in digital infrastructure, with China leading the way in 5G technology development and Malaysia attracting investments from tech giants like AWS, Google, and Microsoft. China's East-West Computing Resources Transmission Project (EWCRT Project) aims to balance the distribution of data and power resources, shifting data processing activities to regions with abundant green energy resources, potentially reducing 2125 metric tons of CO₂ between 2020 and 2050. This study illustrates that the transition to net-zero allows emerging digital leaders to replace passive infrastructure hosting with active value capture. Through macro-level knowledge governance instruments, such as China's EWCRT Project and Malaysia's MyRER roadmap nations can strategically distribute computing assets and energy grids, capturing sustainable economic value through standards-setting, green IP ownership, and the export of advanced digital energy services.

Malaysia's Renewable Energy Roadmap (MyRER) is commissioned to support further decarbonization of the electricity sector in Malaysia through the 2035 milestone. These initiatives and targets demonstrate the commitment of China and Malaysia to leveraging digitalization for decarbonization, positioning them as leaders in sustainable data center operations and contributors to global sustainability initiatives (Jianzhong et al., 2018).

The governance of these systems is reshaped from traditional utility management into Macro-level Knowledge Governance. Strategies like China's EWCRT Project and Malaysia's MyRER roadmap exemplify how governance now involves the strategic mobilization of Structural and Relational Capital to ensure regional innovation ecosystems are both competitive and sustainable.

Final Thoughts

Digitalization is a pivotal force in the decarbonization of data centers, as evidenced by the strategic initiatives undertaken by China and Malaysia. China's digital economy has seen remarkable growth, reaching a value of 45.5 trillion yuan by 2021, which accounts for 39.8% of its GDP, indicating the substantial potential of digitalization to drive economic development and sustainability. The country's data center market is also experiencing significant expansion, with projections reaching revenues of US\$95.74 billion by 2024, showcasing the importance of data centers in the digital transformation journey.

Renewable energy integration is a key component of China's decarbonization strategy, with targets set to increase the share of non-fossil energy consumption to around 20% by 2025 and 25% by 2030, aligning with the ambitious goal of carbon neutrality by 2060. This transition is crucial for reducing the carbon footprint of data centers, which consumed 150.7 billion kWh in 2020, accounting for 2.01% of the nation's total electricity consumption.

China's investment in 5G technology and the "New Data Centre Development Three-year Action Plan (2021–2023)" are indicative of the government's commitment to constructing environmentally friendly data centers that prioritize energy efficiency. Despite these strides, challenges such as the need for substantial initial investment and skilled labor persist, yet the opportunities for energy savings and carbon emissions reduction are substantial.

The experiences of China and Malaysia underscore the importance of strategic planning, policy support, and investment in digital infrastructure to leverage digitalization for decarbonization. Their initiatives serve as a blueprint for other countries seeking to develop sustainable data center operations, highlighting the significant role of digitalization in driving decarbonization in data centers and contributing to global sustainability goals. Historically, knowledge economy literature has treated digital infrastructure as a secondary variable or a neutral baseline utility. This study contributes to theory by repositioning green digital infrastructure as a primary, active domain of Green Intellectual Capital. We prove that the digital-green transition is fundamentally a human-centric knowledge evolution, where the velocity of carbon reduction is directly determined by an ecosystem's capacity to create, mobilize, and govern intellectual assets.

Ultimately, this research contributes to the field by illustrating that the transition to net-zero is not merely a mechanical or structural upgrade, but a human-centric knowledge evolution. As emphasized throughout the manuscript, the development of human intellectual capital extending from technical expertise to behavioral and managerial competencies, is the fundamental requirement for navigating the complexities of the twin digital and green transitions. Without this focus on human capital, technological innovations remain static hardware rather than dynamic, sustainable assets.

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Data Availability The data that support the findings of this study are available from the corresponding authors upon reasonable request.

Declarations

Competing Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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