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Decarbonising digital infrastructure and urban sustainability in the case of data centres

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This paper critically assesses the complex interplay between urban transitions of digitisation and sustainability. Building on a mixed-method research design, we unpack the challenges of decarbonising digital infrastructure while attending to urban sustainability goals in a land- and water-scarce country facing significant physical climate risks. We identify transferrable lessons on the economic, technological, and environmental synergies and trade-offs behind data centre development and argue that stewarding the global data centre sector towards sustainability requires an ecosystem-wide approach. We identify implementation gaps across five key dimensions: technological innovation, policy and regulation, finance, infrastructure, and people. We find that the progress and uptake of sustainability initiatives are often impeded by risk-averse DC operators, who are most concerned with real and perceived risks of downtime. We conclude with recommendations for data centre stakeholders to align the low-carbon transition of the data centre sector with broader objectives of climate resilience, smart city development, and sustainable finance.

"Going digital" is often associated with "going green"[1–4]. Digitisation offers the potential of using big data and Internet of Things (IoT) technologies to monitor and improve operational efficiencies[5]. Cloud computing provides centralised platforms for data sharing and collaboration and promotes standardised procedures and sustainability across an organisation's operations and value chain[6]. The recent dramatic rise of artificial intelligence (AI) could offer precise predictive analytics to enhance resource use efficiency, including energy consumption and carbon emissions assessments, enabling faster and more accurate decision-making (Feroz et al.)[5]. Smart cities rely heavily on IoT to generate and analyse immense volumes of data to optimise resource management, deliver efficient infrastructural services, and improve the overall urban living environments[7]. However, the material environmental impact of digitisation is often overlooked. Underpinning this digital transition is the physical infrastructure of data centres (DCs). The global demand for DCs has skyrocketed in the last decade due to the increasing demand for Internet services, cloud storage, virtual workplaces, IoT, AI, and financial technology (FinTech).

To the casual observer, DCs are unassuming warehouse-like buildings (or dedicated spaces within a building) that house specialist computer equipment and associated components that support a broad range of activities—from social media to the storage of government documents to blockchain trading. DCs have historically operated behind the scenes and their environmental impacts largely unscrutinised. However, their rapid growth in recent years has caught the attention of investors, governments, and regulators, albeit for conflicting reasons.

For investors, DCs constitute a highly desirable asset class. Accelerating demand for DC services offers favourable returns that hedge against economic volatility. While estimates vary amongst industrial analyses, the DC sector is projected to grow exponentially with a compound annual growth rate of between 5–11% by 2026[8,9]. For governments, DCs are considered critical infrastructure for advancing technological innovation and the growth of digital economies[10]. Moreover, digitisation is now considered integral to facilitating a low-carbon economic transition[11] and in building smart, climate-resilient cities[12,13]. However, such DC infrastructures are highly energy- and carbon-intensive, which could undermine the sustainability transition efforts of various 'green' digital innovations. The International Energy Agency[14] estimates that global DCs and data transmission services currently account for 1% of energy-related greenhouse gas emissions, and DCs contribute to around 0.3% of overall greenhouse gas emissions. To put into perspective, DCs on aggregate contribute to a greater proportion of greenhouse gas emissions compared to many sovereign states. Moreover, these estimates do not fully account for the lasting impact of the

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COVID-19 pandemic on digitising and virtualising professional and social lives[15]. Neither do the estimates account for the explosive expansion of generative AI, whose computational power demand is projected to double every 100 days[16], and is 33 times more energy-intensive than machines running task-specific software[17]. Consequently, future DC development strategies must balance the promotion of digital economies and advancing technological innovation, with consideration of carbon emissions and equitable distribution of energy.

In this study, we examine the opportunities and challenges in stewarding the sustainable transition of the DC sector and feasible pathways. Focusing on the tropical urban context of Singapore, we explore the key economic-environmental trade-offs in developing urban DC capacities on the one hand, and balancing carbon footprint and climate resilience on the other. Our research is set in the context of a unique conjecture for the DC sector in Southeast Asia. Singapore's position as Southeast Asia's DC hub is challenged by its physical constraints that limit further expansion of the sector. Citing energy consumption and carbon emissions concerns, the Singaporean government imposed a ban on new DCs in 2019. When the moratorium was lifted in 2022, new building requirements and restrictions were implemented to manage the sector's environmental impact[18].

Singapore's experience offers useful insights for existing and emerging DC hubs in other parts of the world. First, Singapore's tropical climate presents some of the most challenging conditions for sustainable DC operations, as high temperatures and humidity preclude certain efficiency measures and reduce equipment lifespan[19,20]. As other Southeast Asian economies sharing similar climatic conditions seek to scale up their digital capacities, Singapore's advanced research, industry, and investor networks provide an ideal testing ground for energy efficiency and equipment longevity solutions that could be deployed in the wider region[21,22]. Second, as a land-scarce, highly urbanised city-state, Singapore's DC development competes with other economic and social priorities. To maintain Singapore's financial, technological and digital economic competitiveness while balancing sustainability goals and climate targets, solutions regarding the distribution of land, energy, and other resources are needed. This concern regarding the energy- and carbon-intensity of the DC sector is reflected in the moratorium imposed in 2019 banning the building of new DCs; this was lifted in 2022 with new environmental requirements and a reduced licensing quota for new DCs. More recently, the Irish and Dutch governments have also imposed similar restrictions in Dublin and Amsterdam in 2022 and 2019, respectively, due to energy and environmental concerns[23–25]. Such moves have serious implications for digital capacity distribution, energy grid demands, and potential offshoring of DC activities to regions with higher fossil fuel usage or less stringent environmental regulations.

This research aims to bridge the gap between the ever-expanding *virtual* spaces of cloud and digital platforms and their often overlooked *material* environmental footprints. Our findings highlight viable pathways and future scenarios for the growing DC sector, with particular relevance for both industry and policy stakeholders.

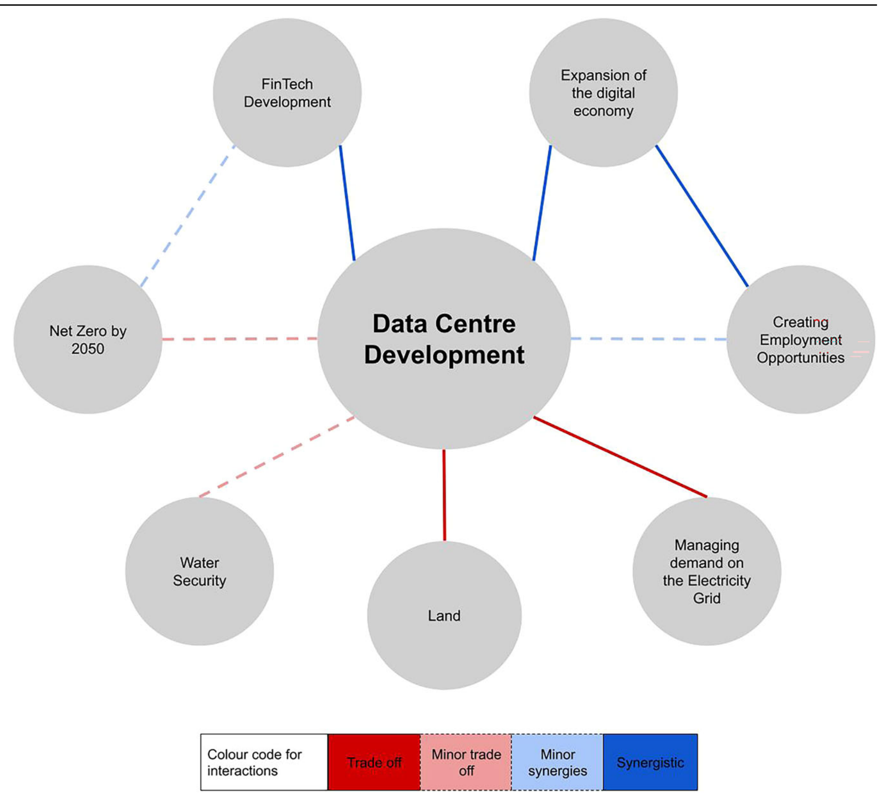
Results

Key challenges of greening data centres

Stewarding a sustainable transition of the DC sector requires careful balancing of economic and environmental trade-offs, while capturing synergies to maximise positive outcomes (see Fig. 1). Despite advances in technological innovation aimed at maximising efficiency, it is not possible to fully decouple DC growth from the sector's growing environmental footprint. While the expansion of the DC sector can enable the growth of FinTech and the digital economy more broadly (blue lines in Fig. 1), the increasing demand for DC services places significant strain on energy, land, and water resources while jeopardising Net Zero commitments (red lines in Fig. 1), as were highlighted as important drivers underpinning Singapore's DC moratorium[26]. While some of these challenges are more acute for the small and densely built-up island state of Singapore, these environmental and economic trade-offs and synergies are common challenges for DC hubs in urban sites[27].

The intensive energy demand of DCs represents their most significant environmental impact. Projections indicate that the electricity consumption of DCs could increase fifteen-fold by 2030, potentially accounting for 8% of global energy demand[28]. However, these figures are subject to considerable variability due to potential advancements in energy efficiency technologies,

Fig. 1 | Synergies and trade-offs between economic and environmental goals in stewarding a sustainable transition of data centres (Source: The authors, based on data from policy and corporate documents, interviews, and stakeholder engagement workshops.)



which could reduce energy consumption, while emerging trends such as cryptocurrency mining and generative AI could substantially increase energy demand.

While enhanced energy efficiency across sectors has resulted in significant reductions in total energy consumption in Singapore[29], switching to renewable energy is crucial to decouple carbon emissions from energy demand. While nuclear energy has been considered, risk levels and public acceptance remain uncertain[30]and ongoing research into small modular reactor deployment remains incipient[31] (see more details below under 'Energy Solutions'). Access to renewable energy in Singapore presents a significant barrier to decarbonising energy sources. Due to land scarcity, it is not feasible to build sufficient solar panels and hydrogen plants to support the country's growing energy needs. Regionally, the absence of a reliable renewable energy import pipeline from neighbouring Southeast Asian countries means that Singapore's DCs rely almost entirely on the country's current natural gas-based grid. A few exceptions exist where operators offset their energy consumption with renewable energy certificates and virtual power purchase agreements, although there are criticisms regarding their efficacy. A renewable energy certificate (REC) is proof of the production of one megawatt-hour of electricity generated from a renewable energy source. RECs allow DCs to offset their use of fossil-based energy sources by investing in renewable energy. However, the traceability of RECs is controversial. In particular, RECs can be sold separately to the physical delivery of electricity (otherwise known as an 'unbundled REC') so a customer can buy a REC associated with energy use on a different electricity grid. In this case, there is no guarantee that the renewable energy was consumed or that any additional renewable energy capacity was built to match the demand[32,33]. Similarly, a virtual power purchase agreement (VPPA) is a financial contract between the renewable energy-generating asset and the off-taker that does not involve physical electricity delivery, so the off-taker can be in a different market area than the location of the renewable energy-generating asset. As such, a similar problem of the lack of additionality and traceability as unbundled RECs persists. Moreover, even if renewable energy sources are available, questions of equitable and affordable access to energy remain. If the growing DC sector consumes disproportionate amounts of energy vis-à-vis other socio-economic sectors, this could drive up energy prices and compromise energy availability.

DCs are also water-intensive, especially with the increasing adoption of liquid cooling technologies as a more energy-efficient alternative to air cooling methods. However, water usage poses an additional environmental strain on water-scarce countries, including many equatorial Southeast Asian nations, and is exacerbated by climate change affecting precipitation patterns and increasing drought risk[34,35]. Some international DC operators and cloud companies advocate for more sustainable approaches to water cooling, such as using desalinated water or treated wastewater. Nonetheless, these technologies are expensive and energy-intensive, potentially offsetting some of their environmental benefits[34].

Additionally, DCs are land intensive. This is especially the case for DC hyperscalers, which are typically constructed as entire campuses rather than standalone buildings to support the most sophisticated workloads such as quantum computing and generative AI. As of 2021, Singapore hosts 93 DCs with a total capacity exceeding 1000 MW, making it the leading DC hub in the Asia-Pacific region and the third largest globally, despite its limited land area[9,36]. Given the scarcity of land, DCs compete with other economic and social activities for space. Consequently, governments must balance land use to meet other requirements for economic productivity, industry diversity, and social needs.

The aforementioned environmental limitations of DCs are particularly pronounced in densely built cities like Singapore, which raises the question: why not simply construct DCs in more environmentally favourable locations - for example in a temperate, rural location with access to renewable energy, land, and free cooling - considering that the service they provide is delivered virtually?

We found that the choice of DC location is driven by multiple strategic considerations that often do not align with low-carbon and sustainability priorities, which accounts for the popularity of cities such as Singapore, London, and Dublin as DC hubs. The primary consideration for DC operators is the reliable provision of services lest they face significant financial and legal liabilities, as well as reputational damage, which requires a mature energy and connectivity infrastructural network[37]. This includes connectivity infrastructure like submarine cables for secure and high-speed international transmission, and a reliable energy grid to ensure uptime (i.e., guaranteed availability of service)[37]. Furthermore, owing to concerns about data security and data sovereignty[38], stable and trusted regulatory environments are also crucial for attracting users handling sensitive data and critical processes, including but not limited to financial, legal, health, and other sensitive information and personal data. To this end, an internationally reputable regulatory system, robust rule of law, and bureaucratic transparency and efficiency are favourable. When physical environmental factors are considered, DC operators mainly focus on avoiding natural disaster-prone locations that could compromise uptime. These strategic political-economic factors contribute to the clustering of DC operators and related industry actors, creating a positive feedback loop that establishes and maintains Singapore as a desirable DC hub despite physical limitations, thus potentially hindering a low-carbon sectoral transition.

To navigate these barriers and trade-offs in stewarding low-carbon transitions of the DC sector, we highlight the following five components of DC ecosystems that need significant investment and coordination, namely: technological innovation, policy and regulation, finance, infrastructure, and people.

Technology providing energy and efficiency innovations

Technological innovation plays an important role in enhancing the resource efficiency of DC equipment, which is crucial for reducing the environmental footprint of the sector[39,40]. While current industry and policy discourse (see the subsequent section on 'Policy and Regulation) have focused primarily on 'greening' energy sources and improving energy efficiency within DC infrastructures, existing research highlights the risk of shifting the burden of negative environmental impact to other parts of the value chain[41]. In response, Kaack et al. [42] propose a systematic approach to estimate the greenhouse gas emissions of machine learning and AI, accounting for computing-related operational and embodied impacts, immediate optimisation and substitution impacts of applying machine learning on various use cases, and system-level impacts such as changes in consumer behaviour and path dependency. This demonstrates the value of a coordinated, value chain-wide approach that looks beyond reducing the carbon footprint of the physical building housing computing equipment to include upstream material sourcing and downstream use cases, as well as the DC lifecycle. Figure 2 shows the complexity of the DC value chain that stretches well beyond the physical building of the DC. Sustainable transition of the DC sector therefore, requires a coordinated, value chain-wide approach for proper measurement and effective solutions to reduce environmental impacts. In the following, we summarise existing and highlight potential sustainable technological innovations that could be adopted across various components of the DC value chain to reduce the sector's environmental footprint. These consist of energy solutions, buildings and materials, and software efficiencies, which we will discuss in turn.

First, energy solutions are crucial to the successful sustainability transition of the DC sector to lower carbon operations. Singapore has physical space limitations that rule out more conventional renewable energy solutions, such as solar or wind farms, so other innovative renewable energy generation solutions must be explored. These innovations must be coupled with technological reliability, given the high sensitivity of DC workload and data storage. Downtime can cause significant disruption to applications and data availability, which could be highly financially and reputationally costly to both DC operators and their clients. Moreover, energy production processes must also be safe for a densely populated urban area.

The Green Data Centre Roadmap published by the Infocomm Media Development Authority (IMDA) outlines renewable options viable within the Singaporean context[43]. Each of these renewable innovation options

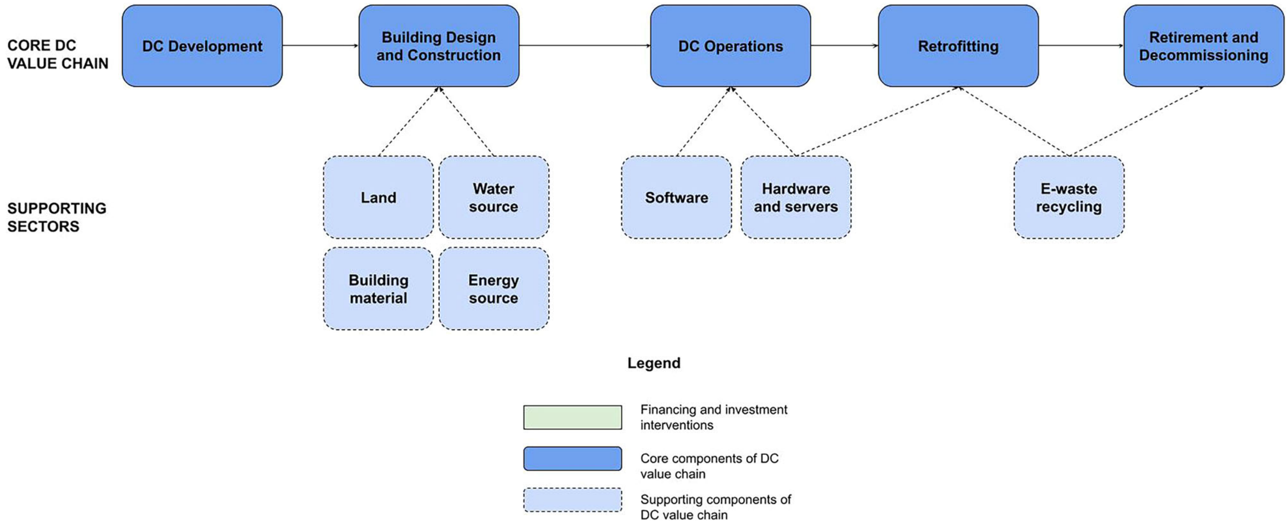


Fig. 2 | The data centre value chain is complex and stretches far beyond the physical building of the data centre, including supporting sectors and suppliers. (Source: The authors, based on data from policy and corporate documents, interviews and stakeholder engagement workshops)

Table 1 | Renewable energy options to power green DCs in Singapore (Source: Authors' compilation from desk-based analysis of corporate and policy documents, academic literature review, interviews, and stakeholder workshops)

Solution	Technology maturity	Environmental benefits	Scalability	Industry/ public acceptance	Reference
Renewable energy					
Solar energy, including on-site solar energy generation, vertical photovoltaics, floating photovoltaics	High	Medium to high	Low	High	45,46
Bioenergy	Medium	Low	Low	Medium	47
Hydrogen energy	Low	Low	Medium	Medium	48,49
Exploring small modular reactor nuclear energy production in Singapore	Low	Low	Medium	Low	50,51
Energy efficiency					
Increased ambient temperature	High	High	High	Medium	20
Water cooling	High	Medium	Medium	Low	55,56
Immersive cooling	High	Medium	Low	Low	56,58
Energy efficient software	Medium	Medium	Medium	High	63,65

entails a unique set of trade-offs related to technological maturity, potential positive and negative environmental impacts, scalability (including financial cost and land intensity), and industry and public perception (see top half of Table 1). For example, solar energy is a mature, widely accepted (especially compared to nuclear power), and relatively affordable solution that is agnostic to Singapore's hot and humid weather. However, scaling solar energy generation is challenging in Singapore's land-scarce urban environment[44]. Other innovative options such as building-integrated photovoltaic and floating photovoltaic, have been suggested, but their unusual design is likely to incur additional costs, which undermines attractiveness to develop this technology at the scale required for notable carbon savings[45,46]. Alternative technologies, such as bioenergy[47] and hydrogen energy[48,49], are at various stages of development, trialling, and scaling. As a result, they are likely to take substantive time before they can be deployed at a sufficient scale to meet the usage and reliability demand of DCs, so as to avoid the additional carbon emissions from drawing more energy from Singapore's natural gas-based grid. While discussions of introducing small modular nuclear energy have resurfaced[50], energy analysts deem them too expensive and too risky to be a viable energy solution[51], especially in heavily built-up urban areas like most global DC hubs.

With limited renewable energy generation options, energy efficiency becomes integral to managing the carbon footprint of DCs (see bottom half of Table 1). The most commonly adopted innovation is operating at a higher ambient temperature in data halls (i.e., the space where racks and computing equipment are stored) to reduce energy demand from cooling. Unlike temperate (such as London, Amsterdam, or Dublin) or Sub-Arctic locations (such as Iceland) that already have lower ambient temperatures, tropical DCs are reliant on air, water, or liquid cooling to mediate the temperature of DC equipment[52], rendering tropical DCs significantly less energy efficient. Informed by research and trials of safely increasing data hall ambient temperature, the IMDA introduced a new Singapore Standards (which are consensus-based, nationally recognised documents that set out specifications and procedures for the design, use, or performance of materials, products, processes, services and systems) guideline for tropical DCs to support a transition towards 24–31 degrees Celsius ambient temperature, which is a significant increase from the current industry practice of 18–22 degrees[53,54]. This was initially met with resistance by the DC sector, primarily citing concerns over the *perceived* safety of equipment operating at a higher ambient temperature. However, with the launch of government-backed guidelines and growing evidence of the safety of higher ambient temperatures, more DC operators should adopt this low-cost approach to enhancing energy efficiency.

Secondary to adjusting ambient temperature, liquid-based cooling measures have been adopted by some DCs as more energy-efficient alternatives to air cooling as they eliminate the need for a chiller unit[55,56]. Water-based cooling technologies, including chilled water systems, airside economisation, waterside economisation, and indirect evaporative coolers, have been tested in various climatic contexts[55]. However, these systems are less effective in hot, humid climates and incur high infrastructure costs and substantial water requirements, making them unsuitable for tropical water-scarce regions like Singapore[55]. Specifically in Singapore, recycled waste-water (termed NEWater) has been suggested for DC cooling purposes. However, studies have also critiqued the carbon intensity of the production process of NEWater[57]. Moreover, water-cooling technology has been met with resistance from DC operators and their clients. They tend to cite the *perceived* increased risk of equipment failure in the event of water spillage, even though equipment vendors are confident that water-cooling technology is well-researched and developed with sufficient safeguards against risks of leakage.

Immersive cooling has been introduced as a form of oil-based liquid cooling, where computing equipment would be fully immersed in mineral oil to maintain its temperature[58]. Liquids are generally excellent heat transfer mediums, and with some chemical engineering, their boiling and condensation points can be precisely tailored, enhancing heat transfer when using dielectric fluids[56]. Recently, a more liquid-efficient approach of spray cooling technology has been tested, where micro-sized coolant liquid fluids are sprayed through a nozzle to a heated surface at high velocities[56]. However, similar to water cooling, oil-based cooling technology incurs a high upfront infrastructural cost because the entire data hall must be built or retrofitted for the immersive infrastructure. Mineral oil is expensive to obtain and must be regularly replaced. Operating immersive DC also requires trained, specialist personnel who are challenging to recruit and retain (see also Section on 'People'). There is also general scepticism from DC operators and users owing to the perceived risk of equipment failure. As such, liquid-based cooling technologies tend to be adopted by hyperscalers rather than client-facing colocation or bare-metal DCs, as the latter two often operate with tighter profit margins and are more sensitive to client pressure.

Second, technological innovation in building and materials hold the key to a sustainable DC transition. With the bulk of innovation and regulatory attention dedicated to energy solutions, the embodied carbon footprint of building and construction materials is often overlooked. Newly developing DCs should be built with low-carbon materials[59] designed to withstand current and projected extreme weather events and be adaptable to evolving energy efficiency technologies.

For existing DC assets, retrofitting efforts should be informed by a comprehensive assessment of the environmental impact of the different components of the asset. Neglecting the importance of embodied carbon could sometimes lead to environmentally counterproductive outcomes. Take a hypothetical example: an operational DC replacing its five-year-old air-cooled data hall for a water- or oil-cooled data hall may reduce its energy usage, but the process of prematurely retiring the data hall infrastructure would increase the emission of embodied carbon. Conversely, retrofitting efforts to improve energy efficiency and extend the longevity of an asset could enable emissions savings.

In addition to the environmental impact of construction materials, DCs should source their hardware responsibly. The mining of critical minerals for technological use can have a significant impact on energy consumption, water consumption, waste production, and biodiversity[60,61]. For bare metal' and colocation DCs where the operator rents out data hall space to clients who supply their own computing equipment, requirements and incentives should be put in place to encourage tenants to utilise sustainably sourced hardware.

As a DC asset comes to the end of its life, there needs to be attention towards implementing an effective e-waste management and decommissioning strategy to optimise the reuse of valuable metals, rare earth elements, and other finite, non-renewable materials, while at the same time avoiding contamination caused by hazardous substances[62]. Compared to the construction and design of new, green DCs, conversations related to retrofitting and decommissioning receive much less attention from sectoral stakeholders.

Third, software efficiency is integral to a sustainable DC transition. Beyond the hardware design of a DC, efficient and responsible utilisation of DC facilities is key to managing the environmental impact of the DC sector. First, software engineering and deployment influence energy usage and intensity of a DC facility: poor design quality and software defects compromise the energy efficiency of the software, while the lack of backwards compatibility could render other software systems or even hardware obsolete, which creates more waste[63]. Moreover, the use of parallel and approximate programming, source code analysers, efficient data structures and coding practices, and specific programming languages can significantly reduce workload energy intensity[64].

Beyond software design and deployment, software could be deployed for power management to optimise energy use and temperature control within DC infrastructures. Katal et al. [65] highlight various power-aware software-driven approaches used for reducing power consumption in DCs at the operating system level (to design an efficient 'pipeline' or mechanism for the execution of instructions, cache storage, and clock), virtualisation level (the segregation of the features of a single computer to 'virtual machines' to cater for different users and to isolate risk), and application level (to reduce energy consumption based on the characteristics of specific workloads). Additionally, software could be designed to better manage the ambient temperature of a data hall, and to trace and track the energy consumption and carbon footprint of DCs[66].

Policies and regulations to standardise sustainability transitions

Government-led policies and regulations create a common language for 'sustainability' and level the playing field of DC sustainability commitments through compliance. This is evidenced by the moratorium halting all DC developments in Singapore. While moratoria can temporarily halt the development of DC to alleviate stress on energy, land, and water resources, they cannot be a long-term solution due to potential impacts on economic and technological competitiveness. Instead, moratoria are useful for buying time to re-strategise and devise appropriate sustainability regulations.

Planning and building regulations standardise the baseline green building expectations for DCs. As of 2022, all newly built DCs in Singapore are required to meet new sustainability design requirements, including achieving a design Power Usage Effectiveness (PUE) of 1.3 or below, obtaining Platinum certification under Singapore's Green Mark for Data Centre criteria, and providing evidence of a clear pathway to achieving 100% renewable energy. Notably, acknowledging that there is a gap between 'design' PUE (which assumes 100% utilisation of a DC, which is when energy efficiency is maximised) and 'operational' PUE (which reflects the energy efficiency at any given point; in reality, most DCs are running at 70–80% capacity), the Green Mark for Data Centres requires DC to disclose a 'PUE curve' that reflects the PUE at different levels of operation[67]. Additionally, the IMDA introduced guidelines for tropical DCs to support a transition towards a higher ambient temperature to enhance energy efficiency[53] (see also Section on 'Technological Innovation'). Furthermore, in May 2024, the IMDA launched the Green Growth Pathways Roadmap for Data Centres, aimed at developing strategic DC assets to maintain Singapore's competitiveness in AI, autonomous and robotic systems, and immersive virtual interaction[68]. The roadmap highlighted government-industry-research partnerships for accelerating the adoption of energy efficiency technology in both hardware and software use, as well as the use of green energy. Although Singapore is one of the first jurisdictions in the world to devise a sustainability strategy for DCs, gaps remain in Singapore's regulatory approach.

The Green Mark standard mainly focuses on energy usage as an indicator of sustainability. This focus on operational efficiency still overlooks deeper issues such as excessive data use and the uncurbed demand for DC services. This approach also falls short of a comprehensive value chain-wide and lifecycle-based approach that integrates environmental commitments and strategies across all aspects of DC design and operations (see Fig. 2). Notably, given that the majority of DC assets in Singapore are 'brownfield' assets with at least 15–20 years of lifespan, the current lack of regulatory guidance and incentives for retrofitting remains a glaring regulatory gap.

Imposing restrictions or enforcing regulations incurs short-term costs for market players, which can reduce the attractiveness and competitiveness of a DC hub, especially when neighbouring or competing countries have more lenient or no regulations. Our interviews and workshop findings indicate that DC operators initially seeking to set up operations in Singapore have shifted expansion plans to neighbouring jurisdictions with fewer restrictions, such as Johor Bahru in Malaysia or Batam in Indonesia[69–71]. This potentially displaces environmental costs to other locations while services are provided to clients in Singapore and regionally, and undermines the intended benefits of more stringent regulatory standards that only apply to certain jurisdictions.

One compromise is to adopt 'soft' regulation in the form of voluntary standards and guidelines. While averting the burden of mandatory regulations, businesses that are compliant with soft regulatory standards nonetheless reap environmental and reputational benefits. These standards tend to represent international industry best practices and have greater flexibility than statutory mandates to reflect the latest technological advancements. For example, in addition to complying with the Singapore Green Mark Standard, some DCs in Singapore opt for the more stringent and comprehensive LEED certification by the US Green Building Council, as well as the Uptime Institute's standard to account for physical environmental risk and energy risks in assessing redundancy, uptime, and security of DCs. With a recently growing interest in the climate risks and impact of DCs, a Climate Neutral Data Center Pact has emerged where signatories commit to 100% carbon-free energy, responsible water consumption, energy efficiency, heat recycling, and reusing and repairing servers. The vast majority of signatories are tech giants (including Amazon Web Services, Google, Meta, and Microsoft) and global colocation players (such as CyrusOne, Digital Realty, EdgeConnex, Equinix, Global Switch, IBM, Iron Mountain, and Vantage). While these global firms have operations in Singapore, the only Singapore-headquartered signatory is Keppel DC REIT[72]. It is also worth noting that European DC industrial associations have joined the pact, but their Singaporean counterparts are not signatories[72].

By going beyond compliance, operators can garner additional reputational benefits and attract environmentally-conscious clients and investors. Over time, as elements of these voluntary standards are incorporated into statutory mandates and regulations, pioneering operators also gain first-mover advantage in regulatory preparedness and get to shape future trajectories as industry advisors.

Scaling sustainable investment into green data centres

Greening the entire DC value chain is a highly capital-intensive endeavour, which in turn presents various opportunities for sustainable finance. The most common form of sustainable finance in the data DC sector is green or sustainable bond investment in new DC assets with sustainability credentials, most of which are related to energy efficiency and renewable energy use (See Table 2). This stems from project financing, which is a typical instrument to support DC construction that is appealing to investors due to its revenue-based repayment structure rather than relying on the company's balance sheet. Motivated by sustainable finance targets, investment banks have begun to advise DC developers to issue green bonds to support the construction of 'green' DCs, typically involving the adopting of energy efficiency technology, renewable energy sourcing (including the purchase of renewable energy certificates), and obtaining green building certifications. In turn, DCs are becoming attractive assets not only to investors specialising in real estate and telecommunications, media, and technology (TMT) sectors but also to broader investors with sustainability mandates. Recently, there has been a push to bundle DC investment with developing connectivity and renewable energy infrastructure to create greener DC hubs in Southeast Asia[73]. Despite being promoted as opportunities for investment in the emerging market digital economy, such deals remain largely theoretical at present.

Secondary to project financing, we note the integral role of private equity (PE) in early-stage development. The majority of these PE firms are headquartered in North America and specialise in DCs or technology investment. They often require more comprehensive and stringent sustainability standards. With significant ownership stakes, PE investors exert considerable influence in prompting DC firms to align with sustainability expectations. Fulfilling these expectations not only demonstrates environmental responsibility but also improves the likelihood of accessing sustainable financing in future developmental stages.

Compared to green bonds and PE investing in greenfield DC assets, there are far fewer examples of existing brownfield assets where sustainable investment is deployed to steward low carbon transition. This can be partially attributed to the lack of regulatory guidance on what constitutes credible retrofitting pathways. Moreover, most investors and developers prefer to invest in greenfield projects, developing the assets from scratch to fully customise their assets. Some perceive that the economics of retrofitting may not be favourable, given factors such as building age and design restrictions, in addition to the risks of downtime when retrofitting works take place in an operational DC. This is particularly the case for investor-owners who may not necessarily have a long-term horizon for keeping DC assets in their portfolios and hence have little incentive to dedicate the capital expenditures towards green retrofits.

However, this is a missed opportunity, given the large number of operational assets in Singapore and in other DC hubs. Moreover, at the operational stage, DC operators commonly seek (re)financing from banks to maintain a healthy cash flow. DC operators can consider obtaining a 'green' or 'sustainability-linked' loan if they possess eligible assets for (re) financing or have corporate sustainability targets to meet. Sustainability-linked loans are appealing because they offer a financial incentive for borrowers to enhance their sustainability performance, typically through a 'step down' clause, entailing a modest interest rate reduction upon achievement of sustainability targets. For financial institutions, offering green or sustainable financing also helps them meet their own climate or sustainability commitments, thus creating an incentive to engage with these kinds of instruments. To bolster the credibility and ambition of these loans, transactions could adopt a more comprehensive value chain approach and incorporate annual interest rate reviews according to sustainability performance, as well as implement a 'step up' clause, where the interest rate will

Table 2 | Strengths and weaknesses of different sustainable investment strategies in the DC sector across asset classes

	Strengths	Limitations
Green bonds	Straightforward guidelines Similar structure to conventional bonds	No clear sectoral guidance or standard on what constitutes a 'green' DC The level of green or sustainability ambition is highly dependent on investor demand Uneven quality of verification and reporting
Green loans/ Sustainability-linked loans	Straightforward guidelines Similar structure to conventional loans	No clear sectoral guidance or standard on what constitutes a 'green' DC The level of green or sustainability ambition is highly dependent on the lender Uneven quality of verification and reporting
Equity	Influence through ownership rights	Minority shareholders lack the sway to engage and influence The opacity of investor expectations

increase to 'penalise' missed sustainability target. This would create a more robust assessment and accountability.

Putting in place mature infrastructural support

Many traditional financial centres are also DC hubs as they enjoy strong governance, availability of investors and professional services, and reliable infrastructure that is highly attractive to DCs. However, these competitive advantages that Singapore enjoys may be slowly eroding as connectivity infrastructures are improving across the region, with Indonesian and Malaysian players beginning to explore the growing ASEAN's subsea connectivity network, especially in the context of recent geopolitical tensions in the region between the US and China[74].

Moreover, due to its physical geography, Singapore's renewable energy production and sourcing are limited. At present, most DCs in Singapore committed to sourcing 100% renewable energy rely on the environmentally controversial virtual PPAs and RECs to offset their energy sourcing from Singapore's gas-powered grid[32,75–77]. There are, therefore strong reputational and competitive imperatives to develop credible and reliable renewable energy infrastructure in Singapore.

To further the competitive imperative for developing renewable energy infrastructure, DC operators and investors are increasingly accounting for the physical environmental credentials and risks of the asset location. While existing standards like TIA-942 are focused on environmental risks (such as extreme weather events), some DC operators and investors have adopted a more liberal interpretation of these criteria to encompass the availability and affordability of low-carbon and climate-resilient infrastructure.

Therefore, in addition to supporting various innovative solutions to produce renewable energy onshore—which would necessarily have limited scalability and therefore economy of scale—Singapore should invest technologically, financially, and diplomatically into developing an ASEAN renewable energy power grid to enable the import of renewable energy produced in other Southeast Asia countries. However, coordination challenges across ASEAN countries to overcome securing investment, information-sharing, profit-sharing, and technical requirement integration (e.g. voltage control) could pose significant barriers to the efficient development of a reliable, investable ASEAN renewable energy grid[78,79].

Developing workforce with sustainability knowledge and skills

Given the complexity of reconfiguring the future economic and environmental sustainability of Singapore's DC sector, it is crucial to develop the right labour market with suitable skills to lead the sustainability transition.

A common observation from our interviewees highlight that the environmental impact of the DC sector has only recently come under scrutiny. As such, industry stakeholders, including DC operators, investors, and end users of DCs, are still in the early stages of defining what constitutes a 'sustainable' DC and pathways to decarbonisation. These shape the capacity and incentive of investors and DC clients to hold DCs accountable for their environmental impact and influence any sustainability transition pathway. One key barrier to building awareness and capacity lies in a skills shortage in the DC sector to navigate a sustainable transition, which a challenge raised by many interviewees. Unlike other sectors (such as the oil and gas sector, and shipping industry) with large environmental footprints and a longer history of public scrutiny, there remains a shortage of sustainability training and certification for DC professionals. While highly skilled individuals can be found in DC hubs, interviewees liken the search for talent to a game of 'musical chairs' where skilled personnel move between DC operators, cloud operators, consultancies, and DC investment firms within short periods. While this rapid turnover of sustainability personnel may contribute to organic knowledge exchange within the industry, it also leads to the highly variegated adoption of sustainability strategies and priorities among operators and investors. Notably, we observed a 'home country' effect from DC operators headquartered or active in the US and EU taking more proactive steps due to increased scrutiny by investors in those jurisdictions. Additionally, we also observed that the sector, including DC operators, consultants, and investors, has recruited sustainability professionals from various fields, including reputation management from the energy, real estate, and information technology sectors. Owing to a lack of consensual standardisation of what a 'sustainable DC' looks like, individuals' prior professional backgrounds have shaped how their respective institutions prioritise and approach sustainability in an ad hoc fashion.

In response to this challenge, the Singaporean government and industry have collaborated to establish subsidised training programmes, for example, DC engineering training offered by the Institute of Technical Education and Microsoft's Data Centre Academy. However, the fruits of these efforts could only be assessed in a few years' time when inaugural graduate cohorts enter the labour market.

Other than a strained labour market, industry culture also plays an important role in shaping sustainability approaches and priorities. We note that the DC sector's conservative and risk-averse culture deters industrial stakeholders from embracing innovations even if those have the potential for lowering environmental impacts. For example, despite the successful demonstration of the reliability of low-carbon technologies such as immersive cooling, liquid cooling, and raising the ambient temperature of data halls, these have not gained widespread acceptance and adoption because they are deemed too risky when weighed against investment costs, potential downtime and service disruption. Similarly, the perceived physical constraints to decarbonise tropical DCs have prompted investors to set lower expectations for Singaporean and Southeast Asian DCs. For example, while DCs internationally aim for a PUE of 1.2 or below, investors only expect a PUE of 1.5 or below for Singaporean and Southeast Asian DCs, citing the challenges of operating in tropical environments compounded with the lack of renewable energy resources. While market stakeholders argue this is a pragmatic, market-friendly strategy, this undermines investor stewardship towards adopting innovative, cutting-edge solutions. The combination of the risk adversity of DC users, the imperative for DC operators to cater to client preferences, and the lack of awareness amongst investors to scrutinise the environmental practices of DC users and operators have fostered a sectoral culture that favours tried-and-tested—and at times outdated and inefficient technology—over adopting cutting edge innovation that could reduce the environmental footprint of the sector.

Additionally, interaction and knowledge sharing amongst stakeholders are crucial. As the DC sector navigates the uncharted territory of decarbonisation and shifting economic landscapes in the region, a common platform such as an industry association could provide important benefits. In addition to knowledge-sharing amongst the diverse range of stakeholders in the sector, such a platform could also function as a collective voice to represent the interests and concerns of the DC sector and engage more effectively with government agencies. This is a particularly critical period as Singapore emerges out of the moratorium. To date, SG Tech and the Singapore Computer Society have pioneered early efforts with slightly parallel developments; further consolidation will be required in coordinating sectoral stakeholders to develop an effective and cohesive collective voice.

Discussion

The successful, sustainable transition of the DC sector will have important implications on climate impacts and the resilience of digital infrastructure and the digital capacity it supports, which in turn has significant repercussions on the sustainability of smart urban futures. It requires coordinated efforts to support and scale low-carbon technological innovations and best practices. Given the highly varied levels of knowledge and capacities of different DC stakeholders in stewarding green transition, efforts need to be directed at improving their awareness and capacities to build climate-resilient digital infrastructure so that different stakeholders could lever their influence for a collective low-carbon transition of the DC sector. To this end, we offer the following policy suggestions for industry, financial, and policy stakeholders in the sector.

1. **Comprehensive assessment of the environmental credentials of DCs**. There are opportunities for mitigating environmental impact across the DC value chain. Prevailing industry standards (and subsequent regulations and sustainable financing criteria) have prioritised

Table 3 | Criteria for assessing DC sustainability (Source: desk-based analysis of sustainable DC standards and regulations, verified by interviews and stakeholder workshops)

Common criteria for assessing DC sustainability	Under-adopted criteria for assessing DC sustainability
• Energy efficiency (measured by design PUE)* • Green building certification* • Renewable energy sourcing (including PPAs and RECs)* • Carbon intensity reduction • Maintenance or improvement of externally assessed ESG scores (for sustainability-linked loans) • Sustainable index listing (for sustainability-linked loans)	• Site selection (including the physical climate risk of the site) • Renewable energy sources that do not involve the purchase of PPAs or RECs • Embedded emissions of building • Other measurements of energy efficiency, such as operational PUE, workload efficiency, responsible use of data, and deployment of energy efficiency maximisation solutions • Absolute carbon emission reduction • Water usage effectiveness • Carbon usage effectiveness • Retrofitting for liquid-based cooling systems • Global Warming Potential (GWP) for cooling refrigerants • Waste management, including electronic waste, building reuse and maintenance of non-structural components, construction waste management, resource reuse, furniture and furnishing, material source • Introduction of year-on-year assessment and imposition of a step-up clause (for sustainability-linked loans) • Indoor environmental quality • Customer engagement

Items highlighted with asterisk * are basic regulatory requirements for newly-constructed DCs in Singapore post-moratorium.

energy efficiency and, to a lesser degree, the integration of renewable energy sources within the physical infrastructure of DCs (see Table 3, left panel). Considering the complexity of the DC value chain, we call for greater regulatory, industrial, and investor attention on environmental criteria that are under-adopted or overlooked by existing standards or taxonomies (see Table 3, right panel)

2. **Policy and regulatory support** are vital for governing an environmentally and economically sustainable transition of the DC sector. Emergent concerns surrounding carbon intensity, energy security, and job provision from DC hubs worldwide suggest that the current trajectory of growth is unsustainable[23–25]. Governments need to strategise and communicate the ideal balance of data centre growth to support economic competitiveness while balancing environmental commitments and social welfare for their local and national contexts. Singapore's leadership in implementing the BCA-IMDA Green Mark for Data Centres and the Singapore-Asia Taxonomy for Sustainable Finance demonstrates a market-based policy approach to govern the environmental impact of the DC sector[80]. Other DC hubs may be able to draw direct references from Singapore's green DC guidelines or transferable lessons of Singapore's policy approach to govern through building requirements and sustainable investment standards. This is not to say that Singapore's current approach is all-encompassing. Future iterations of state- or industry-led sustainable DC standards should include benchmarks for retrofitting existing DCs (brownfield assets) to facilitate policy incentives and regulatory mandates to reduce the carbon footprint and negative environmental impact of existing DC assets. They should also offer a broader range of environmental metrics throughout the value chain, including climate-sensitive site selection, best practices for water sources and usage, retrofitting, decommissioning, e-waste management, and criteria of credible renewable energy transition plans. Transition plans should specifically address the credibility of renewable energy RECs and PPAs, with the ultimate goal of phasing out reliance on these offsetting instruments. Similarly, developing a sustainable investment taxonomy should encompass the latest DC industry best practices and demand the alignment of sustainability standards across the DC value chain.
3. **Individual DC operators** should manage and disclose their targets, strategies, and progress in reducing the environmental risks and impacts of their assets. Sustainability efforts should go beyond maximising energy efficiency to actively engage with and support both upstream suppliers and downstream clients in efforts to mitigate the Scope 3 emissions associated with their DC assets (see Fig. 2). Such efforts can include (but are not limited to) supplier support and screening as well as client education and incentive programmes. Additionally, operators should pay greater attention to the transition of existing (brownfield) assets to operations with lower carbon footprints, evaluating the costs and benefits of various infrastructural or equipment retrofitting measures. Operators can engage with their banks and investors to explore opportunities to align (re)financing with sustainability improvements.
4. **Investors** should constantly revise and update their sustainability expectations according to the newest, scientifically proven low-carbon technological innovation, moving beyond the currently limited focus on energy efficiency and carbon emissions reduction, and advocating for a more comprehensive, value chain-wide sustainability transition (see Table 2). Leveraging their positions as shareholders or creditors, investors have the power to hold DCs accountable for their transition plans, ensuring they are credible, scientifically robust, comprehensive, and subject to regular reporting and auditing. To facilitate a value chain-wide transition, investors should explore the bundling of renewable energy, sustainable DC, efficient software, and hardware innovation investments to create a low-carbon digital economic ecosystem. This will require more collaboration and coordination between investors specialising in the various sectors across the DC value chain. To this end, institutional investors should also align their sustainability demands for DC investment and procurement.
5. **Training sustainability capacity within the digital ecosystem**. Governments and trade associations of DCs, hardware and software engineering, and building sectors should continue to collaborate to establish sectoral best practice and training programmes for students and professionals to enhance awareness of the latest scientific evidence on DC sustainability best practices, as well as to equip industry stakeholders with the capacity to implement sustainability strategies and operations across the DC value chain. Adopting an ecosystem-wide approach and building a collaborative sustainability pipeline can help to overcome the existing risk-averse industry culture in the DC sector, and facilitate the adoption of sustainable initiatives for data centres.

Methods

Our research methodology followed a four-step process. First, we conducted desk-based survey of past, existing, and currently under-construction DC assets in Singapore. To do this, we built an initial dataset using publicly available information of the location, size, and ownership of data centres in Singapore using directories of DCs such as DataCentreMap.com and DataCenters.com. We then verified this information using corporate reports of data centre operators and hyperscalers, investor reports from real estate investment funds, private equity funds, and banks, as well as press releases and other marketing material documenting key data centre expansions, merger and acquisition transactions, and sustainability innovation. While this dataset cannot claim to be comprehensive (for example, we are not able to identify small-scaled data centres that are located within corporate office that exclusively serves a single firm or government department), the purpose of this exercise is not to create an exhaustive catalogue of DCs in Singapore, but rather to gain a fuller understanding of the sectoral landscape, including the locational distribution of DCs, operational size, and ownership patterns, which would inform subsequent economic and environmental analyses.

Second, we conducted further desk-based analyses of government sustainability guidelines, regulations, and policies for DCs in Singapore and the rest of Southeast Asia, which involved the analysis of legislation, speeches from ministers and politicians, as well as government white papers and public consultation reports. We then compared this information with private sector policies and commitments to data centre sustainability. This includes reviewing the sustainability or annual reports of DC operators, green finance frameworks, sustainability requirements from investors and banks, as well as any voluntary, industry-led sustainability initiatives and pledges. In doing so, we identify any sectoral consensus over the definition and priorities of 'sustainable' DCs. This exercise enabled us to identify key actors involved in defining and innovative DC sustainability, which informed our recruitment of interview and workshop participants in steps three and four.

Third, we conducted semi-structured interviews with 59 industry stakeholders between April to December 2023. Interviewees consisted of DC operators ($n = 11$), investors ($n = 15$), regulators ($n = 7$), researchers ($n = 3$), consultants and legal services (n = 11), renewable energy developers ($n = 1$) and financial institutions ($n = 11$). These interviewees provided insights into the key rationales, expectations, barriers, and assessment of outcomes of different DC sustainability initiatives by different stakeholders. In doing so, we gained a more in-depth understanding of the key synergies and trade-offs between economic and environmental priorities in DC development.

Finally, we hosted two workshops in April and November 2023 in Singapore, with a total of 150 in-person and online participants representing DC operators, regulators, technology providers, and investors. These workshops enabled the research team to verify our findings with a range of DC stakeholders. We also discussed potential solutions to some of the key challenges in greening DCs, including the benefits and limitations of regulatory intervention and the role of green finance in stewarding the sustainable transition of the DC sector, which deepened our findings and informed the policy implications of our research.

Data availability

The authors are willing to provide the minimal dataset that would be necessary to interpret, replicate and build upon the methods or findings reported in the article upon request to the corresponding author.

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Author contributions
F.L., K.L. and W.C. designed this study. F.L., K.L, B.S. and W.C. collected data from secondary sources, fieldwork interviews and workshops, and worked on interpreting the data. F.L. did the majority of the manuscript drafting. F.L., K.L. and W.C. commented and edited the manuscript at all stages of drafting until submission.

Competing interests
The authors declare no competing interests.

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