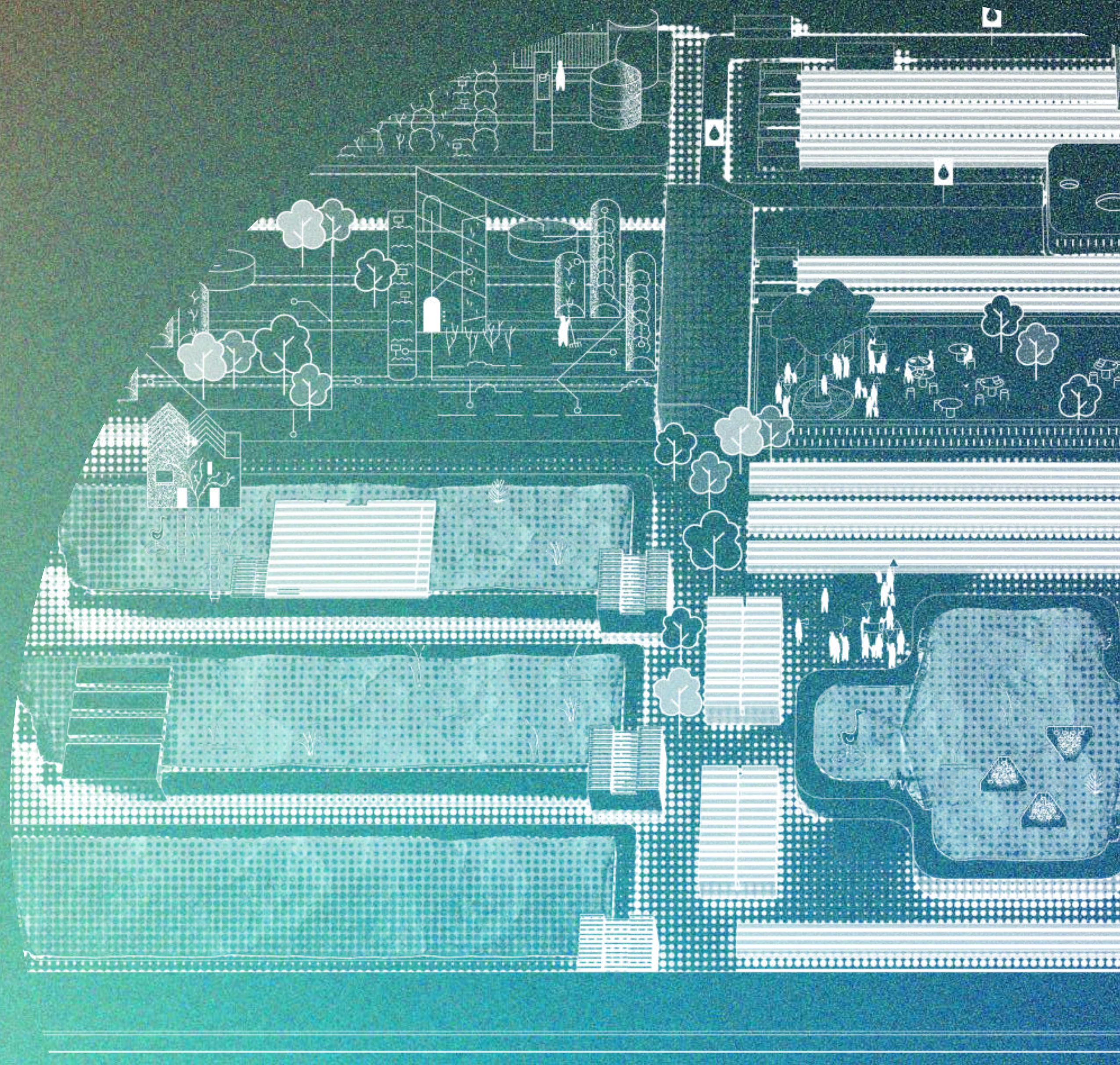
Issue 02

ARUP

Data Centre Futures:

Energy



Reimagining the role of data centres in the energy system

Foresight
November 2025

ARUP

Data Centre Futures – looking beyond the asset

Twenty-first century life — from the smallest everyday interactions to large-scale international and even extraterrestrial systems — is increasingly reliant on flows of data. While we would all feel the effects if these flows were disrupted, few of us pause to reflect on the vital digital infrastructure that transforms this data into meaningful insights, the communications, services, and operations that enhance our everyday lives.

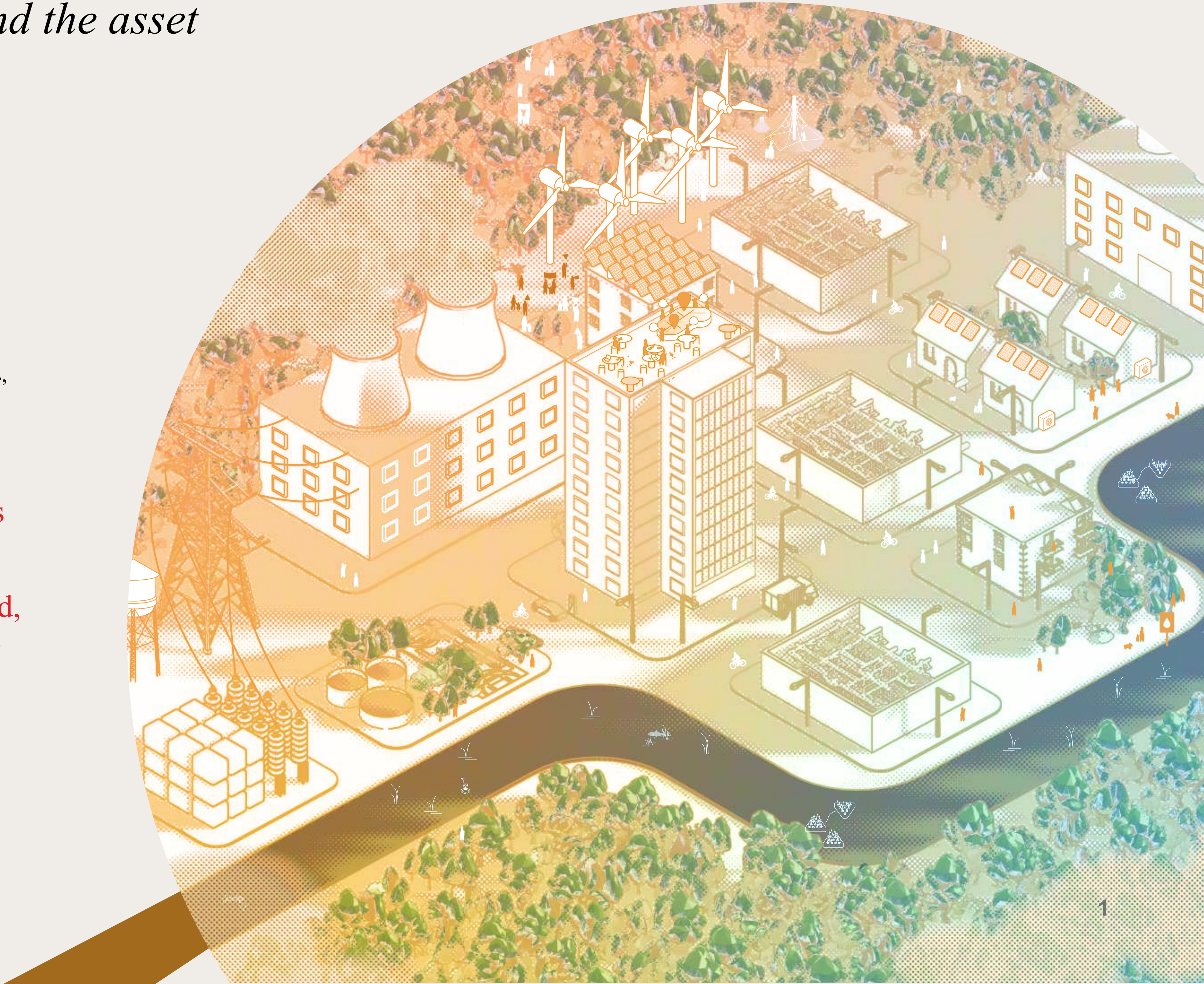
If left unchecked, data centres could also be detrimental to our urban metabolism, destabilising and crowding out resource flows that are vital for short and long-term urban development.

Data centres embody a paradox. Their rapid growth is placing increasing strain on key resources, even as our dependence on them continues to intensify. Managing this tension is critical.

Within an ‘urban metabolism’, data centres are hubs through which flows of water, energy, materials, and people — as well as information — move. And as critical infrastructure, which needs to be protected, they can play a central role in shaping safe, resilient and regenerative places.

Data centres are critical nodes in one of the most prolific infrastructural periods in history. Thinking of them merely as ‘assets’ narrows our field of vision and limits the potential for wider, positive impact through their design.

So, what defines a ‘good’ data centre and how can the facility be both a ‘good neighbour’ and a ‘good ancestor’?



Data Centre Futures – looking beyond the asset

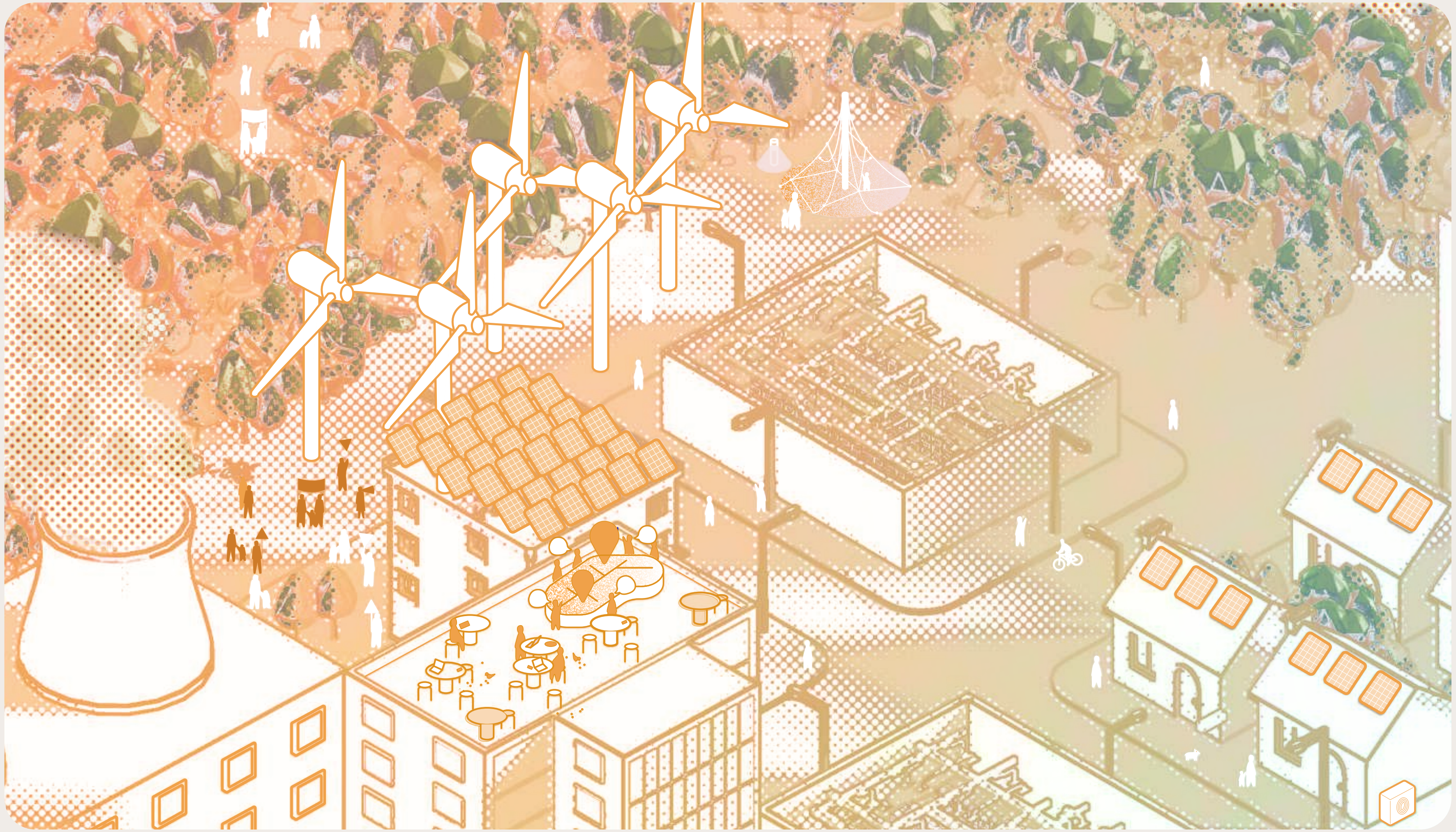
Being a good *neighbour* requires a rethink of 'performance' metrics; a reframing of 'efficiency'; a refocusing on their impact in the areas in which they are built. How can data centres improve their local place and their local ecosystem? Being a good *ancestor* requires an awareness that the infrastructure of today becomes the relics of tomorrow. It also means accounting for the impact of the decisions we make today on future generations.

Creating meaningful impact starts with long-term thinking and designing systems that can adapt to change. What happens when technological and socio-cultural evolutions make data centres, in their current form, redundant?

With this and subsequent issues, we explore the Future of Data Centres, building upon our already broad range of insights on Arup.com.

We aim not to defend a position, but rather elevate the conversation around data centres, encouraging more of us to ask better questions about dangerous assumptions *and* possible futures in this fast-evolving landscape.

Hit pause, look up and look around.



Urban metabolism – organism with flows (in and out)

Data Centre Futures series

In collaboration with technical experts across Arup's global offices, Arup University presents the Data Centre Futures series.

Each issue explores a key theme, emerging issues, trends shaping future context, critical reflections and informed speculation on longer-term possibility.

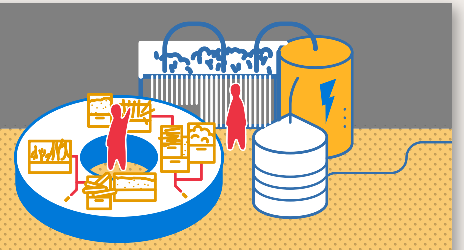
What is a data centre's long-term value and viability when compute technologies evolve faster than the structures built to contain them? Could data centres contribute more than they consume? How might they play a role in cultivating safe, resilient and regenerative places?

The second issue of this series focuses on Energy.

How might data centre design and delivery anticipate challenges in the energy landscape: both increasing demand, volatile supply and potential new sources? Could data centres evolve from passive consumers of energy to active contributors within the energy system?

01 Water

02 Energy



03 Land and space use

04 Tech-readiness

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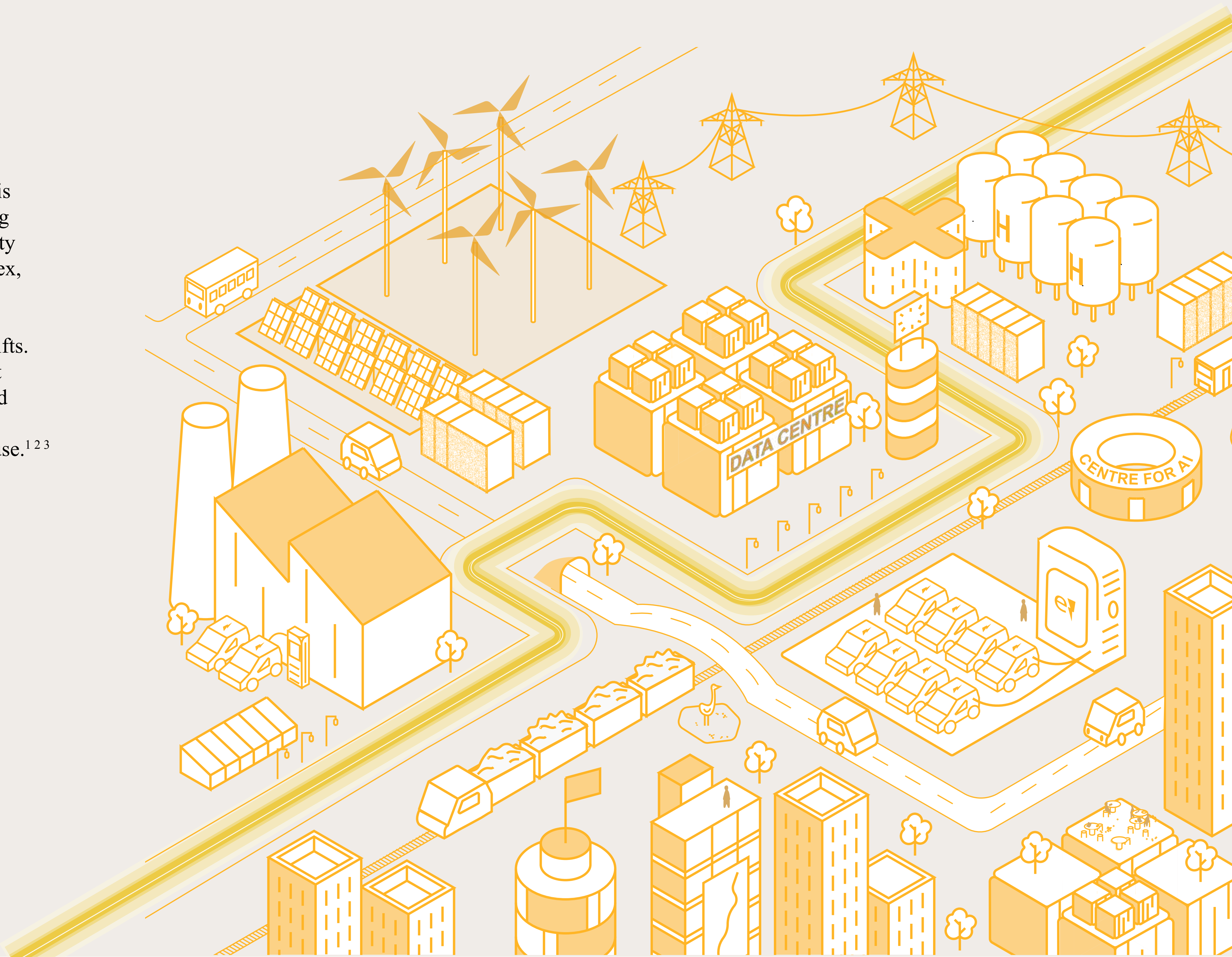
The case for long-term thinking

Another energy transition emerges

The energy use associated with the rapid growth of data centres is becoming an issue at a time when the energy sector is undergoing its most transformative shift since the advent of the first electricity grids, close to 150 years ago. It is a transition that will be complex, fragmented, and unfold over time.

For two centuries, energy has powered industrial and societal shifts. Each wave of technological advancement ignited concerns about escalating power demand. Yet, time and again, those fears proved overstated, as innovation, economies of scale and cost pressures consistently delivered efficiency gains that help contain energy use.[1 2 3]

Now, we are undergoing the next great transformation, driven by the evolution of the internet. Digital business models have caused a sharp rise in system complexity and risk, alongside an explosion in data volumes, particularly video.



[1] In 1999 Forbes suggested that "it was reasonable to project half of the electric grid will be powering the digital-internet economy within the next decade." Instead, by 2023, data centres consumed about 4.4% of total U.S. electricity.

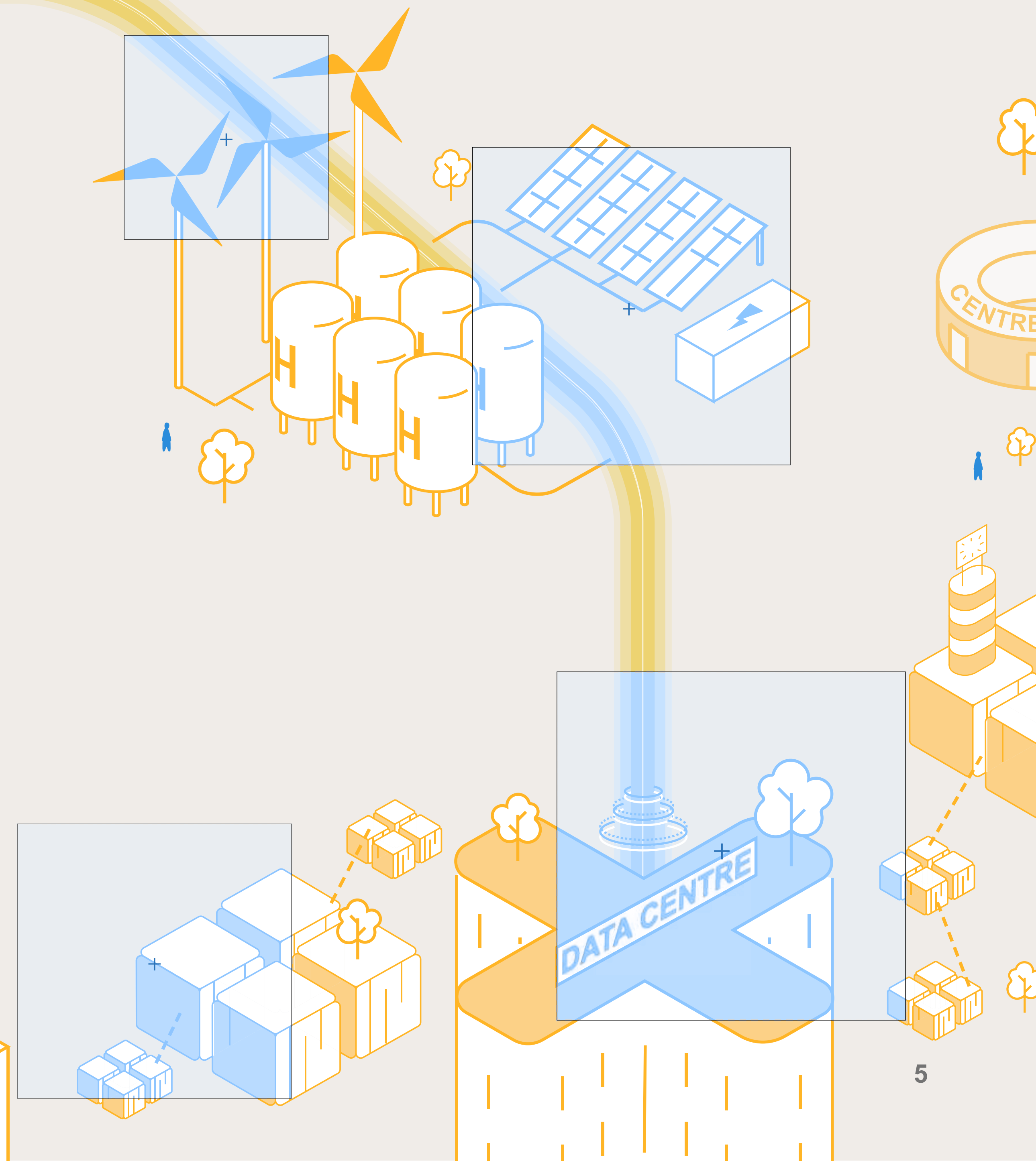
The case for long-term thinking

This time may be different

AI-driven workloads are introducing volatile, high-density power demands that stress both facility infrastructure and regional grids.[4] Future AI demand will be a key driver of data centre energy use, but its scale remains uncertain. Climate policies are tightening, with mandates for 24/7 carbon-free energy, heat reuse, and location-based emissions reporting. New technologies, from small modular reactors (SMRs) to hydrogen fuel cells, are on the horizon, but not yet available at scale.

Today's data centres are increasingly burdening energy resources. Yet, they are also emerging as active participants in energy ecosystems. Many operators are deploying on-site generation, battery storage, and flexible load strategies to navigate grid bottlenecks and regulatory hurdles. However, these adaptations are often reactive, shaped by short-term constraints rather than long-term resilience.

Data centre demand is set to double by 2030 and, as other sectors electrify to replace fossil fuels, competition for power will intensify. The choices made today will shape the sector's future trajectory.



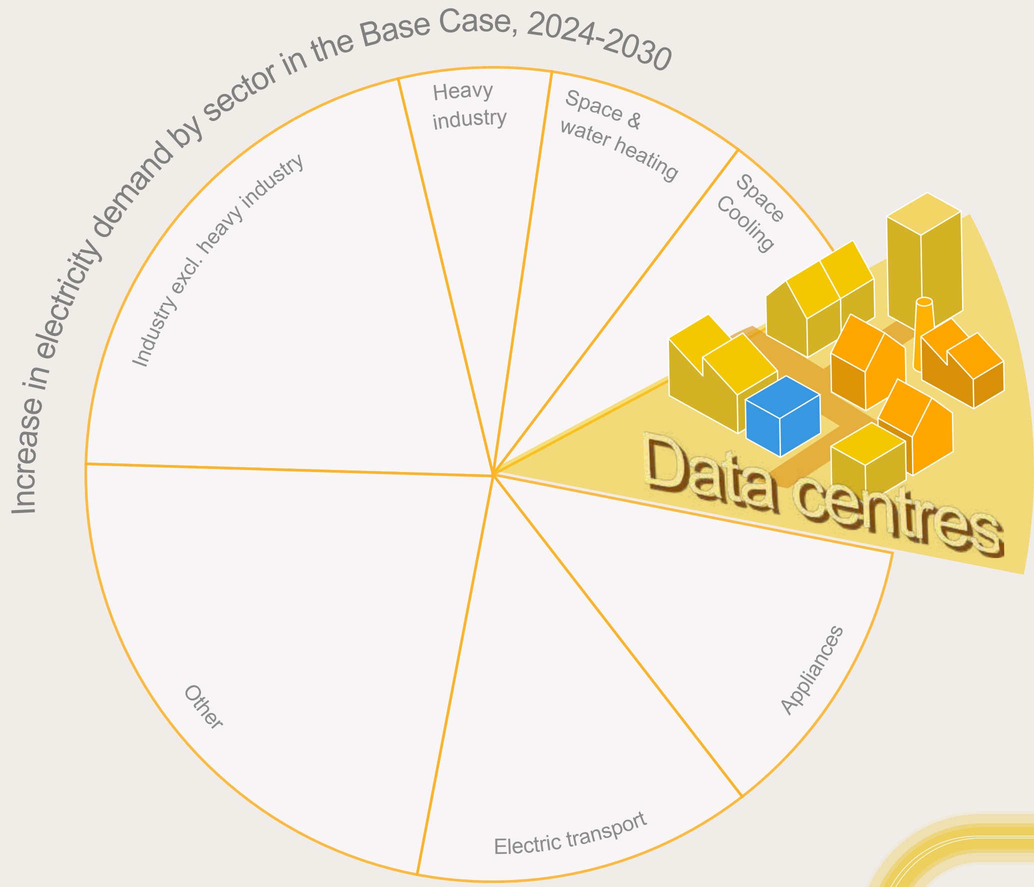
Mapping uncertainty: The changing relationship between energy and data centres

Unpredictable demand

Demand for digital services and AI is accelerating faster than our capacity to build the data centres needed to support them. Globally, data centres consume 1.5% of total electricity demand (around 415TWh).[5] There is a high degree of uncertainty related to future demand, largely contingent upon the scale and energy intensiveness of potential demand from AI and advanced computing. Further uncertainty comes from a growing community of experts questioning the 'hype' surrounding AI, likening it to the dot-com 'bubble'.[6] Conservative estimates suggest demand could double by 2030, while more bullish views predict a threefold (or even greater) increase.[7] Concurrently, technological advancements are contributing to improvements in the energy efficiency of AI, data centres and the wider grid, adding further complexity to demand modelling.[8]

Regionally, certain areas are emerging as hotspots for data centre development. In some places, such as Ireland, electricity demand of data centres now surpasses that of urban residential use; in others, it accounts for over a quarter of total electricity consumption, as in Virginia.[9]

The spatial concentration of data centres is significantly higher than other rapidly electrifying sectors and it puts growing pressure on local grids.[11]



Source: Source: International Energy Agency. Energy and AI. CC BY 4.0 licence.

The U.S. dominates data centre electricity consumption globally *(45%)*, followed by China *(25%)* and Europe *(15%)*.

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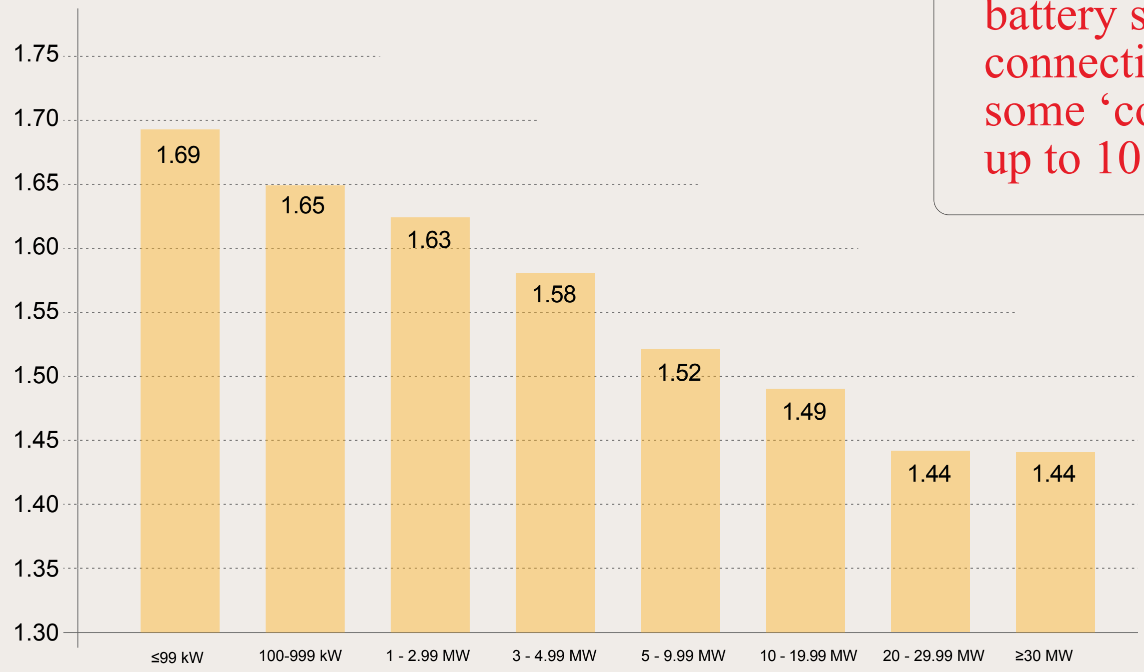
Mapping uncertainty: The changing relationship between energy and data centres

Managing demand is increasingly difficult, as improvements in power usage effectiveness (PUE) for hyperscale data centres have plateaued. PUE is a key indicator for energy efficiency, measuring computational energy used compared to the energy usage in the whole facility. The closer to 1.00, the more efficient. For hyperscale data centres, generally considered to be over 100MW, with more than 5000 servers,[12] PUE has remained at around 1.55–1.60 for the last three years.[13] Achieving further improvements in PUE requires innovative design and engineering approaches. Current solutions include liquid cooling, rack-level heat recovery, and intelligent workload management.[14]

Non-mechanical interventions to incentivise energy efficiency include location-based carbon audits and other forms of 'green' or '100% renewable' certification for sites. Increased scrutiny of 24/7 clean-power pledges are revealing the gap between headline claims of '100% renewable', where renewable generation certificates are purchased to match the actual electricity consumed, and the reality that these pledges depend on the carbon intensity of the wider grid.[15]

Competing and integrating infrastructures

Policymakers are under pressure to respond. Across the globe, planning reforms are underway to speed up grid connection waiting times, prioritising connections that maximise benefits for (feeding back to) the wider grid, albeit slowly.



Weighted average PUE by data centre IT capacity

Source: Uptime Institute Journal (2024).

Data centres coming online now are competing with renewables and battery storage assets for connection to the grid; with some 'connection queues' up to 10 years long.[16]

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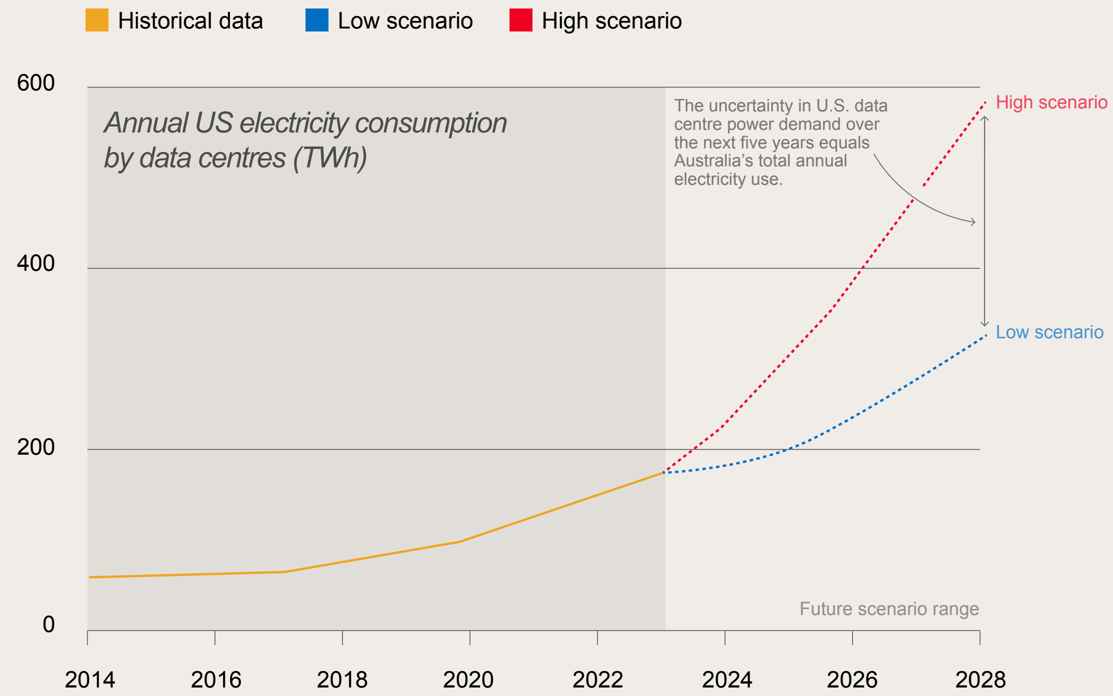
Mapping uncertainty: The changing relationship between energy and data centres

This is driving an evolution of data centres into energy 'hubs', buying their own electricity supplies, installing combined heat and power systems (CHP) powered by gas, deploying diesel generators, and integrating multi-hour battery storage from day one. These investments not only support operational resilience but also provide operators with the opportunity to participate in energy markets, earning revenue by providing frequency response services to the grid.

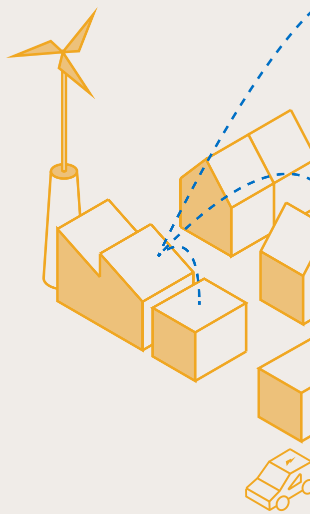
What if data centres were fully integrated assets in national and international grid?

Weak signals of change

Pilot schemes are already looking at heat-reuse quotas, flexible-access contracts and demand-response, recasting the data centre from voracious consumers into energy partners. On an even more speculative front, new forms of social contracts and peer-to-peer markets, novel technologies like small nuclear reactors (SMRs) and post-silicon chips indicate a range of possible energy futures for data centres.



Source: Lawrence Berkeley National Laboratory, December 2024, Ember (2025), "Global Electricity Review 2025", https://ember-energy.org/app/uploads/2025/04/Report-Global-Electricity-Review-2025.pdf



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2040 – What if

Energy will play a key role in the future of data centres, and data centres could also have a significant impact on the future of energy. Rehearsing for a range of longer-term possibilities enables us to anticipate both risk and opportunity to design differently, and better.

Now

1. What if data centres became critical partners in managing the grid?

- Data centres are heavy consumers of electricity and concerns are growing over their energy intensity as power cuts become more frequent.
- Data centres, however, also have the potential to contribute, offering backup supply, supporting frequency regulation, and enabling load shifting to help balance the grid.
- This resilience has proven successful during blackouts, such as that experienced in the Iberian Peninsula in 2025.[17]
- How might we innovate and roll out two-way systems that improve grid balancing and overall resilience?

2. What if data centres were able dynamically to shift compute loads globally to where energy is abundant?

- Data centres are significantly more concentrated geographically than other sectors that are electrifying. This places different strains on the grid.
- The sector itself is also concentrated, with the largest players having multiple data centres spread across regions, allowing services and loads to be redistributed across the geographies.
- Could the ability to shift compute follow abundant energy generation from the sun and wind around the world, to meet uptime requirements?
- What does the regulatory regime look like to achieve such a shift in data centre location and energy access?

3. What if guaranteed data centre energy demand helped scaling new energy technologies?

- Technology firms with large data centre portfolios are already signing power purchase agreements (PPA) with clean energy suppliers.
- To meet the growing energy demand, data centre developers are looking to renewables and emerging technologies such as small modular reactors (SMR) and grid-scale battery storage.
- Renewables and batteries are rapidly scaling. SMRs offer baseload electrical power alongside speed-to-market and scalability which has not been the case with traditional nuclear power stations.
- Could data centres' PPAs with emerging technology developers accelerate their wider rollout and shape the electricity system beyond data centre demand?
- How will this help regions facing energy scarcity and a lack of clean energy supply?

4. What if data centres focused backup power on services deemed critical in times of disruption?

- Even during widespread blackouts, Tier 4 data centres (the highest resilience standard) have shown to continue functioning.
- The services that went down and those that remain available during such times, however, do not always reflect critical necessity.
- Could we define new criteria for types of compute that reserve Tier 4 resilience for truly critical services?
- Could data centres have to demonstrate broader benefits to the public realm, beyond the site boundary, supporting local communities in their energy resilience?
- How could data centres be 'nudged' into offering only Tier 3 (lower but still resilient) to non-critical services, perhaps in exchange for quicker planning and grid connection?

5. What if projected data centre demand does not materialise, or new technologies (e.g. quantum computing) emerge that rapidly shrink data centres' energy demand?

- Current projections see data centre demand (and associated energy use) grow, but the rate of growth is uncertain.
- On the demand-side, most of this uncertainty is related to AI, for which questions remain if or when it will materialise.
- On the supply-side, new chip and cooling design could improve energy efficiency, or whole new ways of computing could emerge.
- Could we end up with an excess of data centre capacity globally or regionally?
- How might the energy grid be affected if we have an oversupply of data centres?

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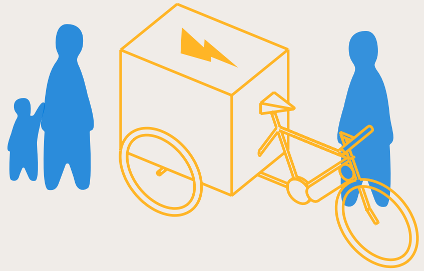
Arup expert piece: Adapting data centres to user demand

Data centres are evolving in step changes that mirror society's appetite for speed and data-rich services. Early facilities grew with basic internet storage, the dot-com boom expanded content creation, cloud computing scaled capacity, and today the training of large AI models is driving a new surge. Each shift preserves the physical concept of a data centre intact while radically altering its power profile, so the main differentiator is no longer floor area but megawatt draw, and the infrastructure required to meet ever tighter latency targets.

Over the next fifteen years, demand will be shaped less by 'tech companies' and more by collective user behaviour. Video streaming, real-time collaboration and AI assistants compress acceptable response times from minutes to seconds, multiplying electricity consumption.

It is essential that society acknowledges its role as a driver of this infrastructure in order to design effective solutions.

Karuna Phillips
Associate Director, Energy, Water and Resources
Arup



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Arup expert piece: Adapting data centres to user demand

Three structural changes emerge as pivotal:

Re-thinking cost recovery and responsibility

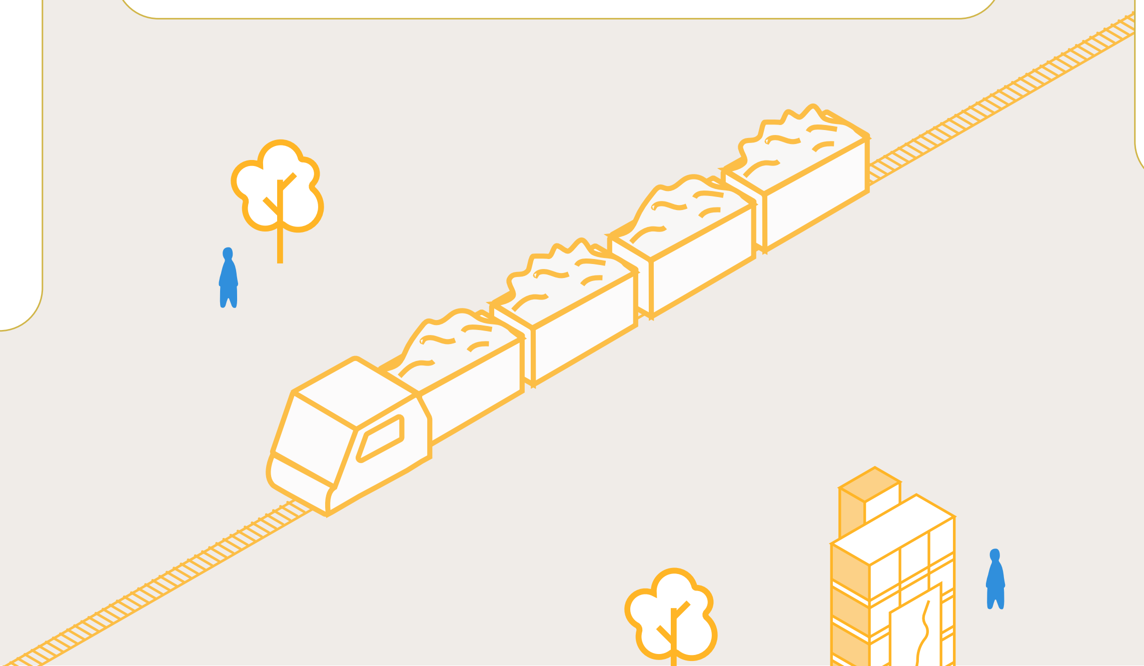
Tariff structures that ignore future system impacts discourage data centres from funding upstream upgrades. Aligning connection charges and contractual obligations with the stress these loads impose would encourage operators to become partners in grid modernisation, rather than passive consumers.

Designing for flexibility, not permanence

Cloud workloads are intolerant of outages, so operators historically specify constant draws backed by diesel or gas. Training workloads for AI models can pause without harming users. If operators exploit that tolerance by integrating large-scale storage, load-shifting controls or on-site renewables, data centres could provide ramping capacity within a few minutes, improving frequency stability.

Shaping consumer behaviour

Latency expectations define infrastructure size. A ChatGPT answer in three seconds, high-definition streaming and always-on collaboration tools require higher instantaneous power than waiting half a minute, lower resolution or asynchronous communication. Educating users, incorporating adjustable service levels and exposing latency-based pricing would dampen peak demand, giving the grid and developers more headroom to optimise capacity.



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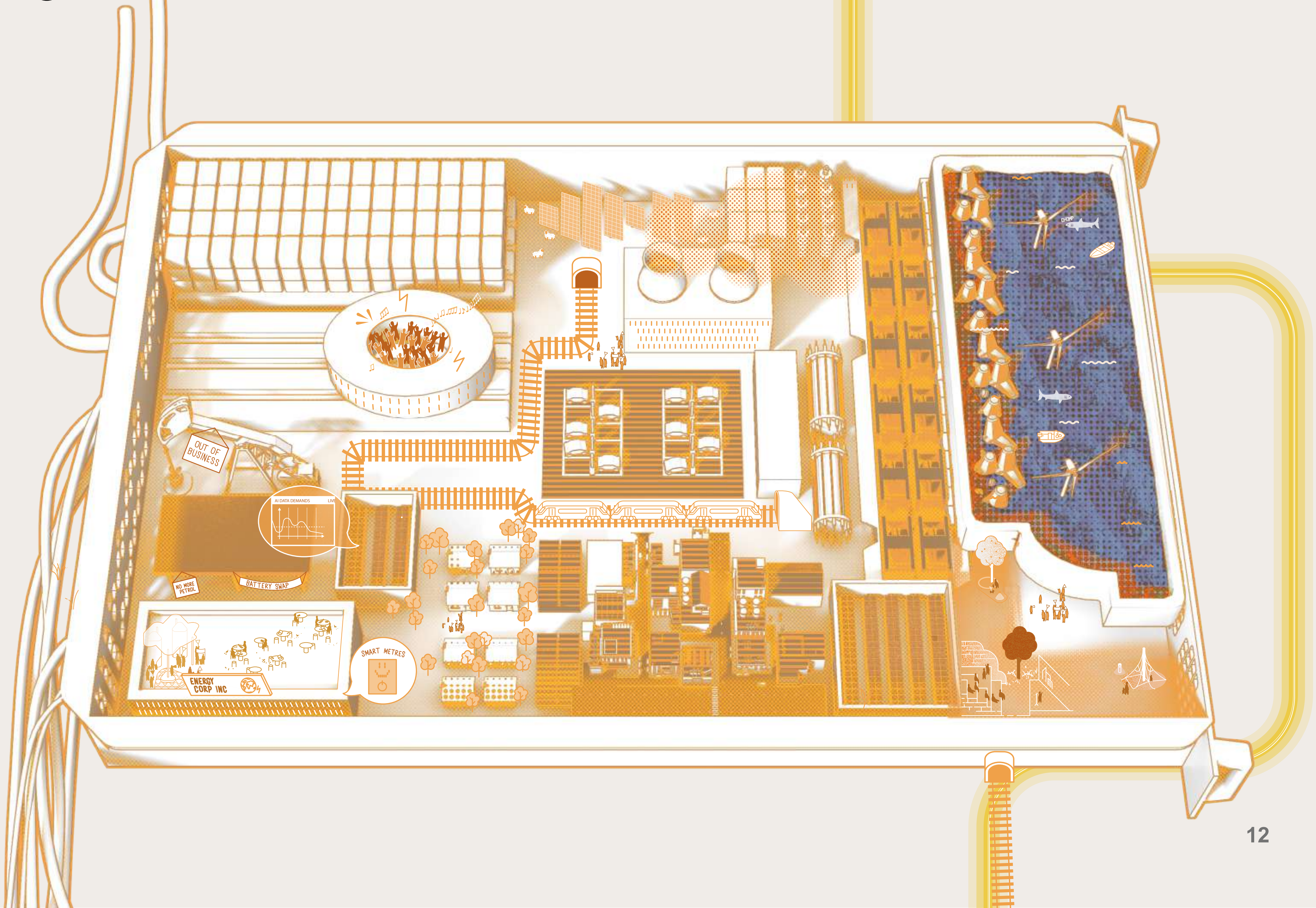
Arup expert piece: Adapting data centres to user demand

A good outcome requires technological design coupled with regulatory reform. Policymakers would treat hyperscale campuses as anchor tenants whose connection charges fund proportional grid reinforcements, while permitting frameworks would reward projects that supply flexibility services or connect waste heat to local networks. Operators and investors, seeing clear returns from reduced tariffs and reputational gains, would embed dispatchable assets and dynamic controls from the outset.

Data centres would then remain engines of economic and digital growth, and evolve into active nodes of a more resilient, decarbonised electricity system, reflecting the same societal demands that drove their expansion.



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External expert perspective: Scaling computation through energy abundance

Deb Chachra
Professor of Engineering and author of
How Infrastructure Works

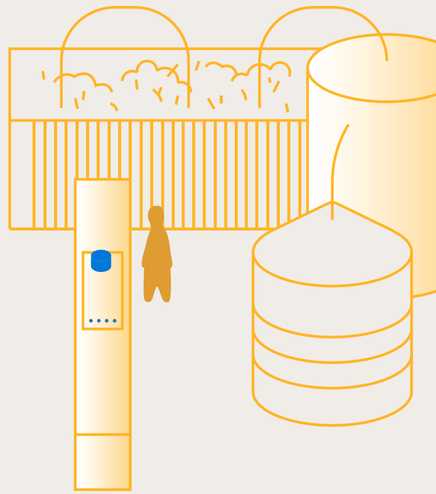
We can think of data centres and the services they provide – streaming, search, computational power, and the types of services that fall under the all-encompassing term of 'AI' – as incipient infrastructure. If they aren't there already, they are well along the path to becoming critical systems that underpin what we can do individually and collectively, that increase our agency, whose presence we take for granted and whose failure is more than an inconvenience. And that means we can learn some lessons from the early days of another general-purpose infrastructural system: electricity.

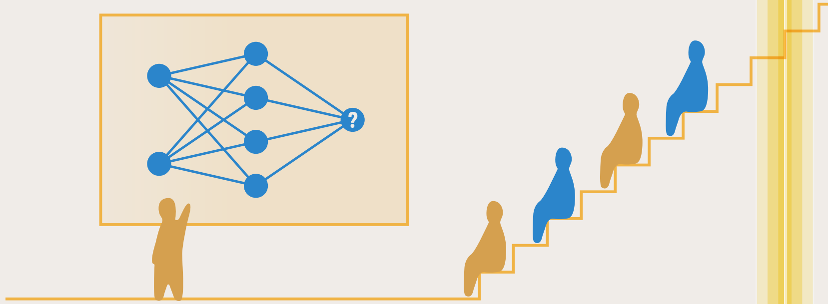
In the late 19th and early 20th centuries, electricity had some immediate, predictable and valuable uses, including its 'killer app', lighting. Artificial light fulfilled a universal need and electric lighting was a public good, not least because it reduced the risk of fire in crowded cities. In the same way that mobile phone providers display the newest models in storefronts to entice people to sign up for the service, electricity showrooms showed off the newest appliances to demonstrate the value of a grid connection.

Nobody then could have envisioned in any detail all the ways in which we use electricity today, just like we can't fully predict what computational services might make possible in the future. But framed this way, we can understand that what we want from our data centres is much the same as what we want from our electricity systems – reliable, affordable and universal provision, contributing to the achievement of human potential. What would it take to make this happen?

> The first and most important element is widespread renewable energy generation. By its nature, renewable energy is abundant and inexpensive.

There are capital, operating and distribution costs, as with all infrastructural networks, but renewable electricity generation sidesteps the need to pay an incremental cost for the energy used. With combustion, you have to pay for every kilogram of fossil fuel that is delivered and burned, in direct proportion to the output joules of energy (never mind the unaccounted costs of greenhouse gas emissions).





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External expert perspective: Scaling computation through energy abundance

With renewables, the input energy (whether it's solar, wind, geothermal heat or running water) is just there in the environment to be converted into electricity. This is why hydroelectric dams were built all over the world, and why many data centres are situated in areas that they serve – not because the power is clean, but because it's cheap and there's a lot of it.

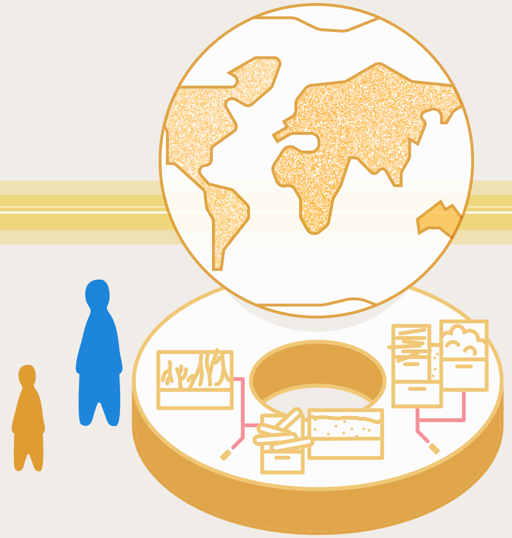
For it to be inexpensive, though, renewable energy must be treated as the public good that it is, rather than as a service in the hands of monopoly providers. In the early 20th century, electricity barons became fabulously wealthy by overcharging for electricity – including that generated from natural features, such as the Niagara Falls – and creaming off the profit. This history is part of why community-based electricity generation, whether as public utilities or as cooperatives, became widespread. A century later, there's an additional issue: the fundamental tension between the huge public benefits of inexpensive, abundant electricity, both for its own sake and as a means of limiting greenhouse gas emissions, and the difficulty of incentivising private investment alone to pay for the energy transition, since profitability depends on cost and scarcity.

But once we have it, abundant, inexpensive energy can be put to work for all of us in ways that go beyond just powering machinery.

Renewable electricity allows for the prospect of limiting or mitigating negative externalities, rather than passing off the social costs, environmental impacts or health hazards to other communities.

In particular, the computing hardware in data centres is inherently disposable, replaced when newer, faster machines become available. Unrestricted access to clean, cheap power makes it economically feasible to close these loops: to recover all of the materials used and incorporate them into newer hardware, rather than adding to the depredations of extraction or to mountains of e-waste.

A century ago, it would have been nearly impossible to predict the ways that widespread access to electricity would transform how people all over the globe live and work, but we still quickly realised that the best way to maximise its potential was community ownership and universal provision. We're now in a similar position with computing, and the future of these two powerful, versatile technologies are closely linked: the harder and faster we go into clean, abundant renewable energy, the more we will be able to explore and build on the true potential for humanity of having access to networked computation.



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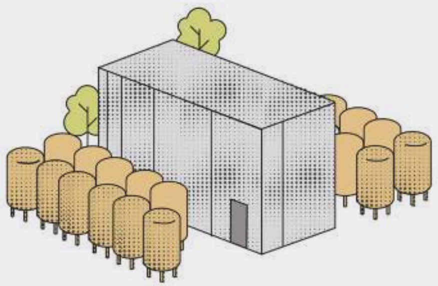
Early signs of the future in the present

Case Studies

Future proof – Citigroup Data Centre, Germany

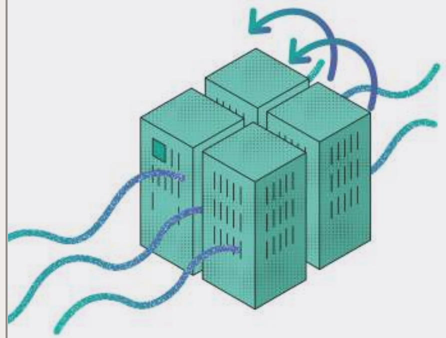
While constructed in 2012, the Citigroup Data Centre was the world's first LEED Platinum certified data centre and remains one of the most efficient data centres in the world today with a PUE (power usage effectiveness) value of < 1.2. It owes its performance to Arup's close work with Citigroup, and an innovative cooling system that reduces demand for chillers.[18]

SMR Data centre development – Amazon, US



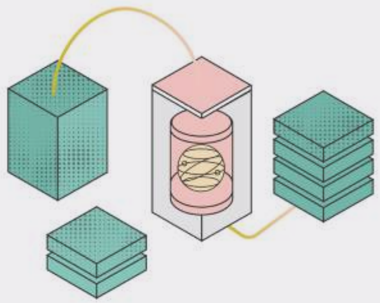
Amazon signed agreements to support the development of several new SMRs in Washington and Virginia as part of its effort to decarbonise its data centre operations. In Washington, as part of a wider consortium, four SMRs will be constructed generating 320MW initially, before ramping up to 960MW. In Virigina, they are exploring the development of 300MW SMR project near an existing nuclear plant, supporting capacity development in a region where demand is expected to increase by 85% over the next 15 years.[19]

Low energy retrofit – EMC², Ireland



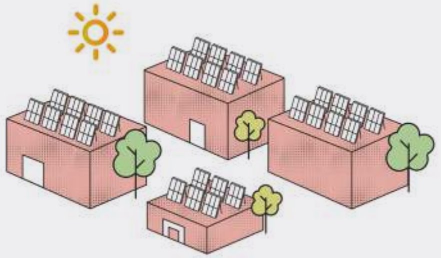
Arup supported EMC² in undertaking a full retrofit project to implement energy saving technologies at its data centre site in Ovens, Ballincollig, Co. Cork, which is set to achieve annual electricity savings of 13 GWh and an annual carbon emission reduction of 7,000 tonnes. Arup designed bespoke engineering solutions for three data centres, ten ambient laboratories and four thermocycling test laboratories at the facility, with the engineering design, equipment procurement and tender process undertaken in five weeks.

Quantum data centres - IBM, Germany



IBM developed a quantum data centre in Germany, hosting both quantum computers as well as a regular data centre. The site is described as a "regular data centre space" despite the need to host liquid helium and nitrogen — with the helium pipes going under the raised floor — as well as accommodating taller systems than typical server racks which required modifications to building entrances. The regular data centre is said to take up "much more" power than the quantum floor.[20 21]

Co-located renewables – Iron Mountain, Netherlands



Arup supported Iron Mountain in constructing a flagship data centre campus in Haarlem. The campus is powered by 100% renewable energy supplemented with additional onsite renewables in the form of a PV array, converting sun energy directly into electricity for use in the office building. To meet the Netherlands' strict PUE requirements, Arup's data centre team will design solutions to lower the annualised PUE of the data centre campus to 1.2, which is below the average for data centres of this size and type.[22]

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Recommendations

CONSIDERATIONS **NOW**

These recommendations focus on immediate operational efficiency, enhanced grid responsiveness and improving local impact given current technological constraints and grid pressures.

Prioritise PUE reduction and efficiency

Huge improvements have been made in achieving PUE reductions, with future reductions seeing diminishing returns. Improvements in PUE should nonetheless continue to be pursued with solutions such as liquid cooling, rack-level heat recovery, and intelligent workload management to minimise energy consumption while respecting water use.

Integrate on-site assets for resilience and revenue

The deployment of integrated energy systems such as multi-hour battery storage, CHP systems and on-site generation should be considered from day one. These investments should not only support operational resilience but also enable operators to begin participating in energy markets.

Ensure transparency in energy sourcing

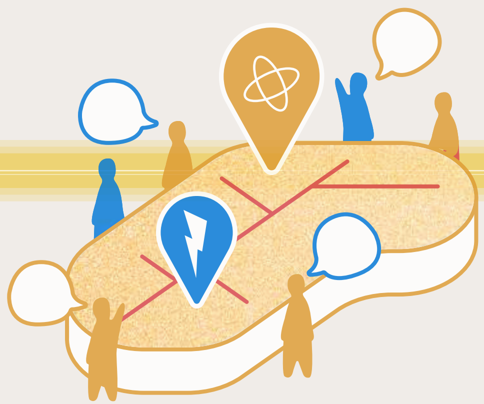
Move beyond merely claiming “100% renewable” energy. Focus should shift to the physical realities of energy use by adopting and implementing market and location-based carbon audits for their emissions and concrete 24/7 clean-power pledges.

Embrace grid flexibility and demand response

Actively participate in pilot schemes involving flexible-access contracts and demand-response programs, recasting the facility from a voracious consumer into a grid ally. Policymakers should reward projects that supply flexibility services.

Shift compute loads based on energy availability

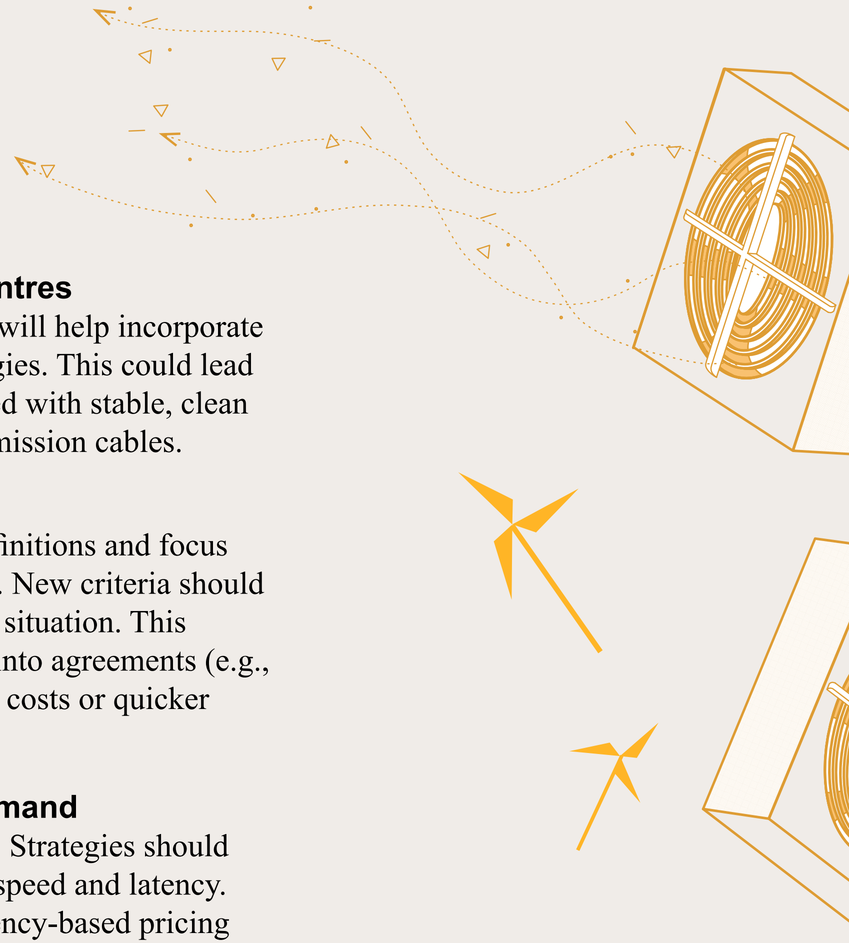
Begin designing systems to dynamically route flexible compute, such as training workloads, batch jobs and non-time-sensitive inference, to locations where there is surplus renewable generation.



Recommendations

AND FOR THE **NEXT FIVE YEARS**

These recommendations focus on structural changes, fundamental grid reform, leveraging future technologies, and shaping societal demand.



Act as anchor tenants to fund grid modernisation
Policymakers and regulators should treat hyperscale campuses as anchor tenants. Tariff structures must be reformed so that connection charges and contractual obligations align with the stress these massive loads impose, thereby funding proportional grid reinforcements and modernisation.

Facilitate dual-purpose backup power
Data centre resilience measures should enhance overall system resilience during emergency events. This could be done through the introduction of restrictions or conditions on data centre back-up capacity, for example, mandating that a portion of it must be reserved for supporting the wider grid.

Accelerate adoption of emerging energy technologies
Large data centre operators should leverage their guaranteed energy demand to accelerate the development and scaling of new energy technologies, as well as recommissioning previously mothballed energy infrastructure such as conventional nuclear power plants. This includes signing long-term PPAs with developers of clean energy technologies (renewables, nuclear SMRs, battery storage, fuel cells and so on), creating the investment conditions necessary for their scaling and commercial rollout.

Implement national energy planning for data centres
Assigning data centres as critical national infrastructure will help incorporate them into long-term planning and national energy strategies. This could lead to fast-tracked planning approvals for facilities co-located with stable, clean energy sources reducing the need to build out grid transmission cables.

Redefine critical compute services
The industry needs to move away from universal tier definitions and focus on the "type of compute" a data centre is responsible for. New criteria should define which services are truly critical during a blackout situation. This framework could "nudge" users of non-critical services into agreements (e.g., tier 3) that accept some downtime in exchange for lower costs or quicker regulatory approvals.

Shape consumer behaviour to manage peak demand
Collective user behaviour drives infrastructure demands. Strategies should be developed to educate users about the energy costs of speed and latency. Incorporating adjustable service levels and exposing latency-based pricing would help stifle peak demand, giving the grid and developers necessary headroom to optimise capacity.

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