

The development of carbon-neutral data centres in space

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The increasing occupation of space orbits by fleets of satellites has led to increasing generation of data in space. At the same time, the expansion of technologies such as artificial intelligence (AI) has led to an increasing number of energy-intensive data centres, which have large carbon footprints, back on Earth. The former calls for space-based computing solutions, whereas the latter calls for carbon-neutral computing solutions. Here we explore the potential of developing carbon-neutral data centres in space. Such an approach would be enabled by the sustainability features of space: abundant solar energy that can be captured with high-efficiency solar cells and a giant cold heat sink (deep space itself) that can spontaneously take in large amounts of waste heat released from computing. We outline a framework for orbital edge data centres, which would be equipped with data sensors and AI accelerators, for carbon-neutral data processing at source in space. We then outline a framework for orbital cloud data centres in the form of a constellation of computational satellites equipped with servers and broadband connectivity, for both in-space and ground-outsourced computing applications. We also provide a method to evaluate the life-cycle carbon usage effectiveness of these cloud data centres.

With the continuing expansion of technologies such as high-performance computing and artificial intelligence (AI), the demand for data centres has grown rapidly^{1–4}. However, the proliferation of such data centres is accompanied by problematic increases in energy use and carbon footprints. Achieving carbon neutrality in data centres has thus become a crucial sustainability goal^{5,6}.

At the same time, recent years have seen increasing occupation of space orbits by expanding fleets of satellites, which are used for purposes such as telecommunications and Earth observation^{7,8}. These satellite services involve creation and communication of big data⁹. Conventionally, big datasets generated in space are sent back to ground stations, and the tasks of storing and processing are typically handled by data centres on land⁹. The processing on land of data generated in space increases latency in satellite services and further increases the already high energy consumptions of data centres on land. Sending numerous satellites into space also leads to the release of greenhouse

gases into the atmosphere during the launch process and beyond¹⁰. It is thus crucial to maximize the use and performance of satellites by fully exploiting and enhancing their capabilities, such as by adding advanced edge and cloud computing capabilities.

In this Perspective, we consider the potential of developing carbon-neutral data centres in space. We first examine the expansion of the space and data centre sectors. The two sectors share similar challenges related to large numbers of data and large carbon footprints^{5,10}. However, space possesses two sustainability features necessary for carbon-neutral data centres: abundant solar power that can be captured with high-efficiency solar cells¹¹, and a giant cold heat sink (deep space itself) that can spontaneously take in large amounts of waste heat released from computing¹².

To evaluate the use of deep space as a heat sink for future energy-intensive data centres in space, we model and compare the power densities of a state-of-the-art silicon solar module and a state-of-the-art

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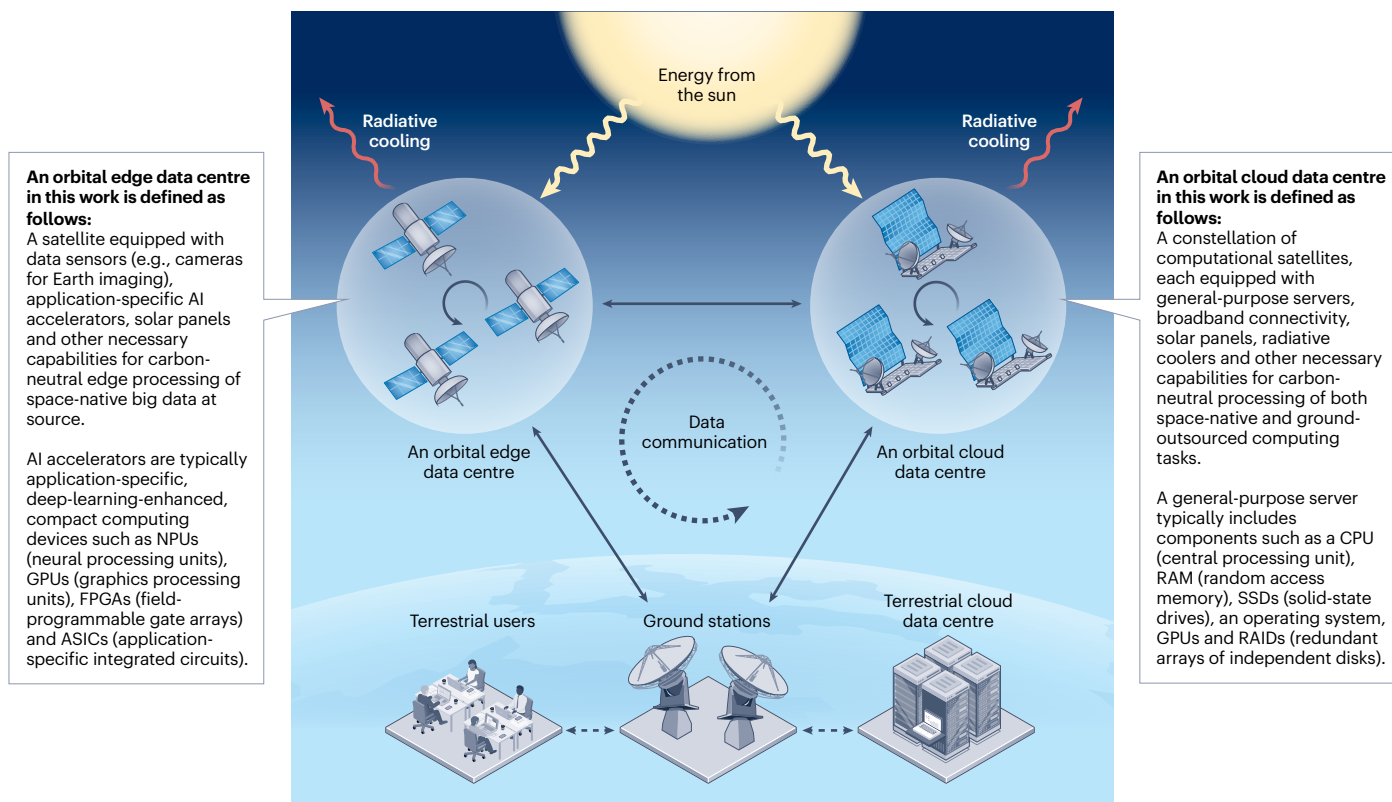


Fig. 1 | Frameworks of carbon-neutral orbital data centres. An end user could use a carbon-aware multicloud solution to outsource computing tasks to orbital or terrestrial cloud data centres on the basis of their life-cycle CUE. Sidenotes: definitions of the orbital edge and cloud data centre frameworks.

radiative cooler as a function of their surface temperature (Supplementary Section 1). This shows that radiative cooling is more effective in space than on land due to the extremely low temperature of deep space (Supplementary Fig. 1). In addition, the radiative cooling power density matches the solar power generation density at a much lower temperature in space than on land. These features should allow low cost, low weight and thermal safety in active radiative cooling systems in space.

We develop frameworks for carbon-neutral edge and cloud data centres in space (Fig. 1), which we collectively term orbital data centres (see Fig. 1 for definitions of the two frameworks). We argue that fleets of data-sensing satellites can be equipped with application-specific AI accelerators to offer carbon-neutral edge processing of space-native big data at source. We articulate the framework of an orbital cloud data centre in the form of a constellation of computational satellites, each equipped with general-purpose servers and broadband connectivity, to offer carbon-neutral processing of computing tasks from sources on land and in space. We propose a carbon-aware multicloud solution that chooses between orbital and terrestrial cloud data centres on the basis of their life-cycle carbon footprints. We provide a modelling method to evaluate the life-cycle carbon usage effectiveness (life-cycle CUE) of cloud data centres.

Occupation of orbits by data-sensing satellites

The term ‘big data’ can, in fact, be traced back to a 1997 publication by NASA scientists¹³, and for decades NASA has been operating satellites that gather enormous numbers of data. For instance, NASA’s Surface Water and Ocean Topography (SWOT) and NASA-ISRO Synthetic Aperture Radar (NISAR) satellites collectively produce about 100 TB of data each day (Fig. 2a)¹⁴. Use of space is no longer limited to governmental space agencies. Space is being occupied by numerous commercial satellite constellations that generate and transit large numbers of data^{7,8}. Space has already become a major industry with a total economic revenue of as much as US\$469.3 billion in 2021 alone¹⁵.

Commercial services offered by satellites cover a wide range of crucial sectors such as telecommunications (broadband, telephone, television, aviation, maritime) and remote sensing (earth observation, agriculture, disaster mitigation, meteorology, space sciences, national security)¹⁶. All these crucial services involve collection, transmission and processing of large numbers of data^{8,9}.

While it is difficult to quantify the exact number of data produced and transmitted across the whole space sector, it is reasonable to correlate the total number of data to the number of satellites in orbits. The population of operational satellites has seen a marked increase in the past few years, reaching nearly 7,000 by the end of 2022 (Fig. 2b)¹⁷. In 2022 alone, more than 2,000 spacecraft were placed in orbits¹⁸. As of March 2023, the top five satellite operators by the sheer number of operational satellites are (Fig. 2c): SpaceX (~4,500 broadband Internet satellites¹⁹), OneWeb (~630 broadband Internet satellites²⁰), Planet Labs (~150 earth observation satellites²¹), Swarm Technologies (~120 low-bandwidth satellites for internet of things devices²²) and Spire Global (~90 multipurpose satellites for global data and analytics)²³. Apparently, these satellite constellations deliver a wide range of services. If each satellite delivered the same volume of data as NASA’s SWOT and NISAR satellites (~50 TB each per day, Fig. 2a), it would be roughly equivalent to filling up 44,000 hard drives of 8-TB capacity each day. A more conservative estimation of data delivery in space can be made from the statistics of the Starlink satellites, which delivered over 42,000 TB of data for customers per day through more than 9,000 space lasers²⁴. Given that each Starlink satellite is equipped with three space lasers²⁵, an average Starlink satellite delivers over 14 TB of data each day. In addition, the same number of Starlink space lasers have a peak throughput of 5.6 Tbps (ref. 24), which translates into a daily peak data delivery of 20.16 TB per satellite. These estimations show that the data delivery by most satellites is probably in the range of 10–20 TB per satellite each day, indicating the vastness of data being created or transmitted across space.

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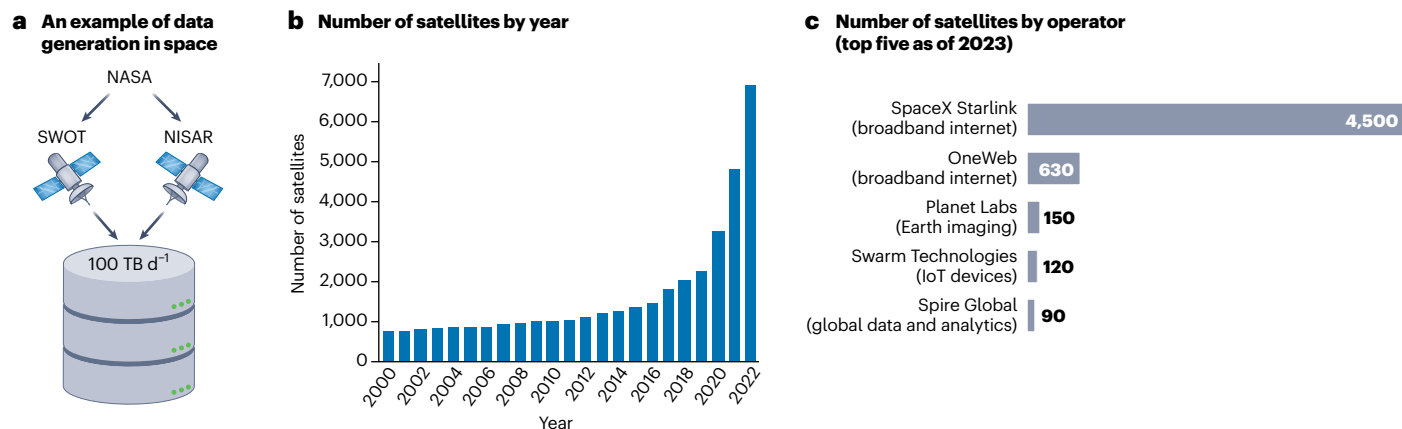


Fig. 2 | Occupation of space orbits by data-sensing satellites. **a**, An example of data generation in space: NASA's SWOT and NISAR satellites collectively generate around 100 TB of data each day¹⁴. **b**, Number of operational commercial satellites by year¹⁷. **c**, Number of operational commercial satellites by top five operators as of 2023^{19–23}. IoT, internet of things.

Q9 The conventional approach of processing space-generated data on land comes with several consequences. Latency is a major challenge in the conventional 'bent-pipe' architecture of space-to-Earth data communication²⁶, especially in situations such as disaster management and risk mitigation with geostationary satellites²⁷. Increasing numbers of satellites in orbits put further strain on this bent-pipe architecture and worsen latency²⁶. Another major challenge is that the task of storing and processing of big data sent from satellites are often handled by data centres on land⁹. However, existing terrestrial data centres are already suffering from large energy consumptions and carbon emissions, as we separately review in the following section. These challenges associated with the occupation of orbits by data-sensing satellites call for in-space edge computing solutions.

Proliferation of energy-hungry data centres on land

Existing terrestrial data centres house critical applications as well as storing and processing vast numbers of data from around the world. As of 2022, the top 15 countries in total hosted nearly 7,000 data centres (Fig. 3a), with the United States leading far ahead²⁸. Moreover, the need for supporting scalable applications in an effective, reliable and energy-efficient manner has led to the rise of hyperscale data centres, whose number had nearly tripled from 259 in 2015 to 700 in 2021 (Fig. 3b)²⁹. On the basis of this trend, the numbers and scales of terrestrial data centres will continue to grow for the foreseeable future³⁰.

Terrestrial data centres and data transmission networks have notoriously high electricity and carbon footprints³¹. This is because the global electricity sector itself performs poorly in terms of sustainability as fossil fuels, especially coal, are still the main source of electricity, with a more than 60% contribution in 2021³² (Fig. 3c). Data centres and data transmission networks around the globe each consumed 'only' 1–1.5% (220–340 TW-h) of the world's total electricity and collectively released ~0.9% (300 million tons) of energy-related greenhouse gases in 2021 (Fig. 3d)^{33,34}. However, the total number of major data centres around the world is only in the thousands, indicating an extremely high energy intensity and large carbon footprint for individual data centres. In terms of water consumption, data centres in the United States alone collectively used nearly 620 billion litres of water in 2019³⁵. These numbers trend even higher in countries with expanding concentrations of data centres. For instance, data centres in Singapore and Ireland account for around 7.0% and 21.0% of each country's national electricity consumptions^{36,37}.

Growths in data centre energy consumption and carbon footprints have been slowed by approaches such as transition to renewable energy resources, improved energy efficiency, adoption of enhanced cooling

technologies, utilization of ultrahigh-density storage, shifts to hyperscale and cloud data centres, and deployment of smart energy management technologies^{1,6,38,39}. However, certain approaches such as shifts to hyperscale and virtual data centres may simply hide greenhouse gas emissions in the 'cloud'⁴⁰. Accelerated growth could be retriggered by the emergence of game-changing and yet energy-intensive technologies in the fields of AI⁴¹, blockchain⁴², metaverse⁴³ and new-generation mobile networks⁴⁴. Purchasing renewable energy has always been a go-to option adopted by major cloud data centre operators to reduce their operational carbon emissions^{45,46}. However, this practice does not necessarily reduce their location-based carbon emissions⁴⁷. All these sustainability challenges point to the necessity of continuous efforts to decarbonize the data centre sector.

A framework for orbital edge data centres

Rapid developments in the commercialization of space reviewed above indicate an increasingly crowded and competitive landscape hungry for even more computing resources to provide crucial satellite services in a fast and reliable manner. The feasibility of adding powerful computing capability to satellites has recently seen a boost largely thanks to marked reductions in launch costs⁴⁸, advances in high-rate data communication⁴⁹, development of radiation-tolerant and radiation-hardened high-density storage and advanced computing devices^{50,51} and combination of AI and advanced processors for edge computing in space^{50,51}. Technological advancements have motivated others to think further outside the box by proposing 'orbital edge computing (OEC) architecture'²⁶.

Building upon these previous developments, we outline the framework of carbon-neutral orbital edge data centres for processing space-native big data at source. As illustrated in Fig. 4a, an orbital edge data centre is a satellite equipped with data sensors (for example, cameras for Earth imaging) and compact advanced data processors (for example, AI accelerators for vision processing⁵⁰), along with sufficiently large solar panels and even active radiative coolers. AI accelerators are typically application-specific, deep-learning-enhanced, compact computing devices such as NPUs, GPUs, FPGAs and ASICs⁵² (see sidenote in Fig. 1 for a more detailed description). AI accelerators would immensely enhance the onboard computing capability of data-sensing satellites by supporting raw data collection and high-performance edge computing at the source of data generation in space. Unlike the conventional bent-pipe space-to-Earth data communication approach, this orbital edge data centre approach ensures that only processed, analysed and selected data of much smaller volumes are sent to ground stations or an orbital cloud data centre, which is outlined in the next section, at reduced costs of time and downlink bandwidth.

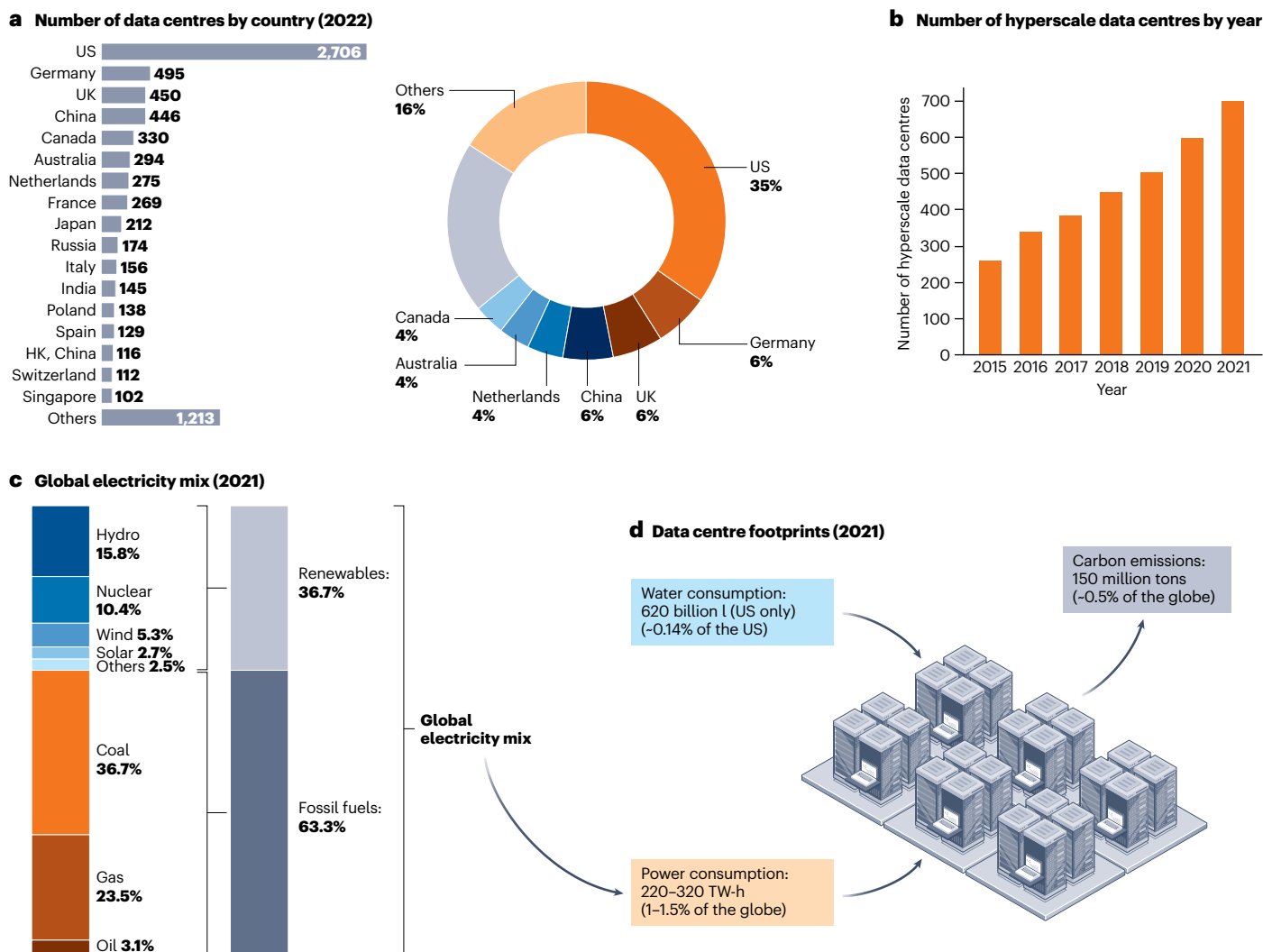


Fig. 3 | Expansion of energy-hungry data centres on land. a, Number and relative share of data centres by country as of 2022²⁸. **b**, Number of hyperscale data centres by year²⁹. **c**, Global electricity mix in 2021³². **d**, Energy and carbon footprints of data centres worldwide in 2021³³, along with the water footprint of data centres in the United States³⁵.

Several studies^{26,53} have discussed the feasibility of orbital edge computing in terms of network latency, population of satellite constellations, downlink bandwidth, required extra power budget, added weights and costs, and hardware readiness. Solar panels must be scaled up to meet the power requirements of both data collection and processing²⁶. Meanwhile, radiative free cooling occurs spontaneously thanks to the large temperature difference between heat-generating surfaces and the cold deep space⁵⁴ (Supplementary Section 1). If localized heat generation is large and passive cooling is insufficient, an active radiative cooling system that recirculates a heat transfer refrigerant could be considered^{55,56}.

Current satellite constellations are each formed by hundreds or even thousands of satellites of various sizes (see Fig. 2c). If each data-sensing satellite in a constellation were equipped with AI accelerators along with necessary power and cooling systems, the whole constellation could be organized into distributed pipelines of orbital edge data centres²⁶, as illustrated in Fig. 4b (based on the OneWeb constellation tracked by Satellitemap, <https://satellitemap.space/>). In a pipeline, an edge data centre collects data and then processes it until the next round of data collection occurs. Such orbital edge data centre architecture would have the advantage of broad availability and fast response as thousands of satellites are scattered in orbits all around the world, ready to collect and process data on the spot.

Computing hardware reliability has historically been a challenge in the cosmic radiation of space, and it would be even more so in future orbital data centres equipped with advanced chips that consume even more power. Furano et al.⁵⁰ tested a commercial off-the-shelf vision-processing unit in a radiation environment and showed that it may be qualified for deployment in planned orbital missions as a computer vision and AI edge processor. Šwope et al.⁵⁷ benchmarked a variety of remote sensing, image processing and analysis algorithms within a small-size and low-power Qualcomm Snapdragon system on a chip, currently hosted by HPE's Spaceborne Computer-2 onboard the International Space Station⁵⁸. AMD have designed 'radiation-hardened' and 'radiation-tolerant' AI accelerators for space applications, with its Versal Adaptive systems on a chip being one example combining FPGAs with many other capabilities such as application processors, real-time processors and vector processors⁵¹. Goodwill et al.⁵⁹ have stated that high-performance, embedded, commercial off-the-shelf processors that are up-screened for space use offer a promising solution for more risk-tolerant missions, while stressing that these devices may not be able to be used in extremely harsh radiation environments.

The above promising developments imply that efforts will continue to test the radiation tolerance of more types of commercial advanced computing device for space applications. However, for

a An orbital edge data centre framework

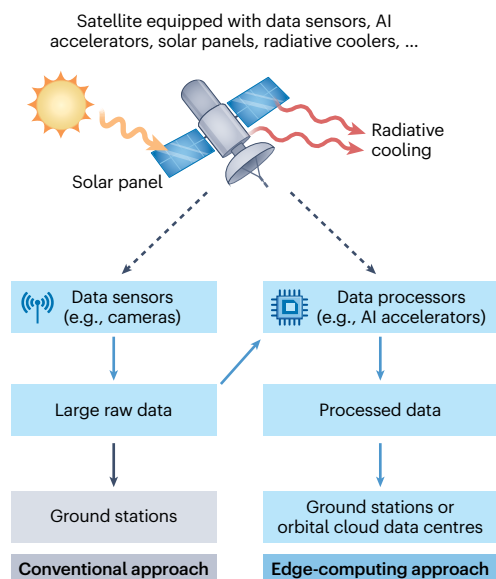
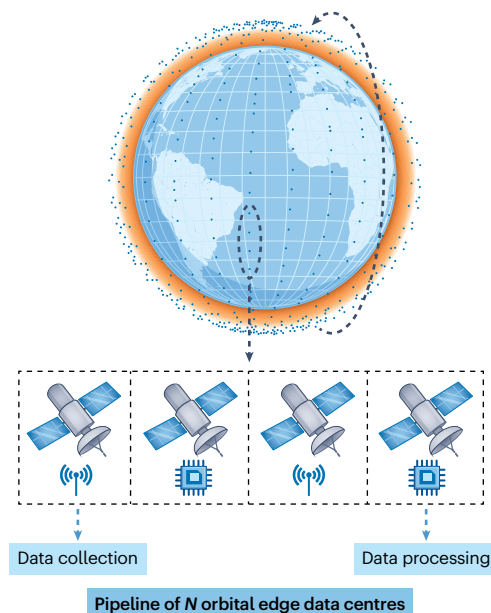


Fig. 4 | Framework of orbital edge data centres. **a**, An orbital edge data centre: a satellite equipped with data sensors (for example, cameras), application-specific data processors (for example, AI accelerators for image classification⁵⁰), solar panels and radiative coolers, all of which enable carbon-neutral data collection

b A constellation of orbital edge data centres



and processing onboard the satellite. **b**, A LEO constellation of edge data centres organized into pipelines, where an edge data centre collects data and then processes it until the next cycle repeats²⁶. Credit: **b**(top), satellitemap.space.

applications in extremely harsh space environments, custom-designed radiation-hardened advanced computing devices would still be necessary to withstand the intensity and duration of cosmic rays and to ensure long-haul operation. Radiation-hardening could increase the manufacturing cost, complexity and power consumption of advanced computing hardware⁶⁰.

The development of commercial-scale edge data centres is gaining traction. Companies such as NTT, OrbitsEdge and the Space Development Agency are designing orbital edge data centres to conduct commercial activities involving high-capacity communication and computing infrastructure for 5G/6G and beyond^{61–63}. Startup Lonestar Data Holdings secured funding to build edge data centres on the moon to support future lunar explorations⁶⁴. All these efforts suggest that orbital edge data centre infrastructure will gradually scale up.

Datasets collected by an orbital edge data centre can still be very large, exceeding the limit of even state-of-the-art onboard AI accelerators. In such situations, it is imperative to explore other alternative green computing approaches, rather than relying on energy-hungry cloud data centres on land. We next outline the framework of a carbon-neutral orbital cloud data centre, which handles computing tasks not only from in-orbit satellites but also from terrestrial sources.

A framework for orbital cloud data centres

As reviewed, existing terrestrial cloud data centres around the world are notorious for their large environmental footprints, and thus renewable energy and free cooling are the ideal resources desired by cloud data centre operators¹. Therefore, at least from a carbon-neutral data processing perspective, it would make sense to place cloud data centre infrastructure in space, given the sustainable features of space such as offering abundant solar energy and being a giant heat sink (Supplementary Section 1). Figure 5a illustrates such an orbital cloud data centre framework, in the form of a low-Earth-orbit (LEO) constellation of computational satellites orbiting at an altitude of only a few hundred kilometres above ground (the illustration is based on operational Starlink satellites tracked by Satellitemap). Each computational satellite is equipped with both broadband connectivity and one or more

general-purpose servers. Each server contains components such as CPUs, RAMs, SSDs, GPUs, RAIDs and an operating system⁶⁵ (see the sidenote in Fig. 1 for a more detailed description). Compared with the orbital edge data centre framework outlined in the previous section, this orbital cloud data centre framework could offer more varieties of service including satellite broadband, data processing, data storage, hosting applications and more, based on user-side needs. Such multiple types of cloud service are generally achieved via virtualized environments inside the server⁶⁶.

The distributed nature of the orbital cloud data centre would be technologically less challenging with existing satellite and information technologies. It would be readily scalable whenever needed and easily accessible from land via satellite broadband. Most importantly, an orbital cloud data centre could serve dual purposes—satellite broadband and cloud computing—to maximize its cost-effectiveness. By comparison, existing terrestrial cloud data centres are scattered all around the world⁶⁷, sometimes thousands of kilometres apart (Fig. 5b). That is, a terrestrial user could be much closer to an orbital cloud data centre than to a terrestrial cloud data centre.

Traditional low-power processors on satellites are passively cooled simply through conduction and then thermal radiation to deep space. However, the combination of high-performance servers and satellite broadband would probably lead to intensive heat generation during computing⁶⁸. In this case, a computational satellite could be cooled by active radiative cooling systems that dissipate large amounts of heat to outer cold space via radiative cooling^{54,55}. Miniaturized deployable active radiative cooling systems can be integrated into spacecraft as on the International Space Station^{56,69}.

Carbon-neutral data processing in terrestrial cloud data centres is typically implemented with carbon-aware, geographically distributed, multicloud solutions^{70–73}. A similar solution can be adopted for outsourced computing with the proposed orbital cloud data centre. As illustrated in Fig. 5c, such a carbon-aware multicloud solution involves both terrestrial and orbital cloud data centres, as well as terrestrial and satellite broadband. Informed with the carbon footprints of all available cloud computing resources, a terrestrial end

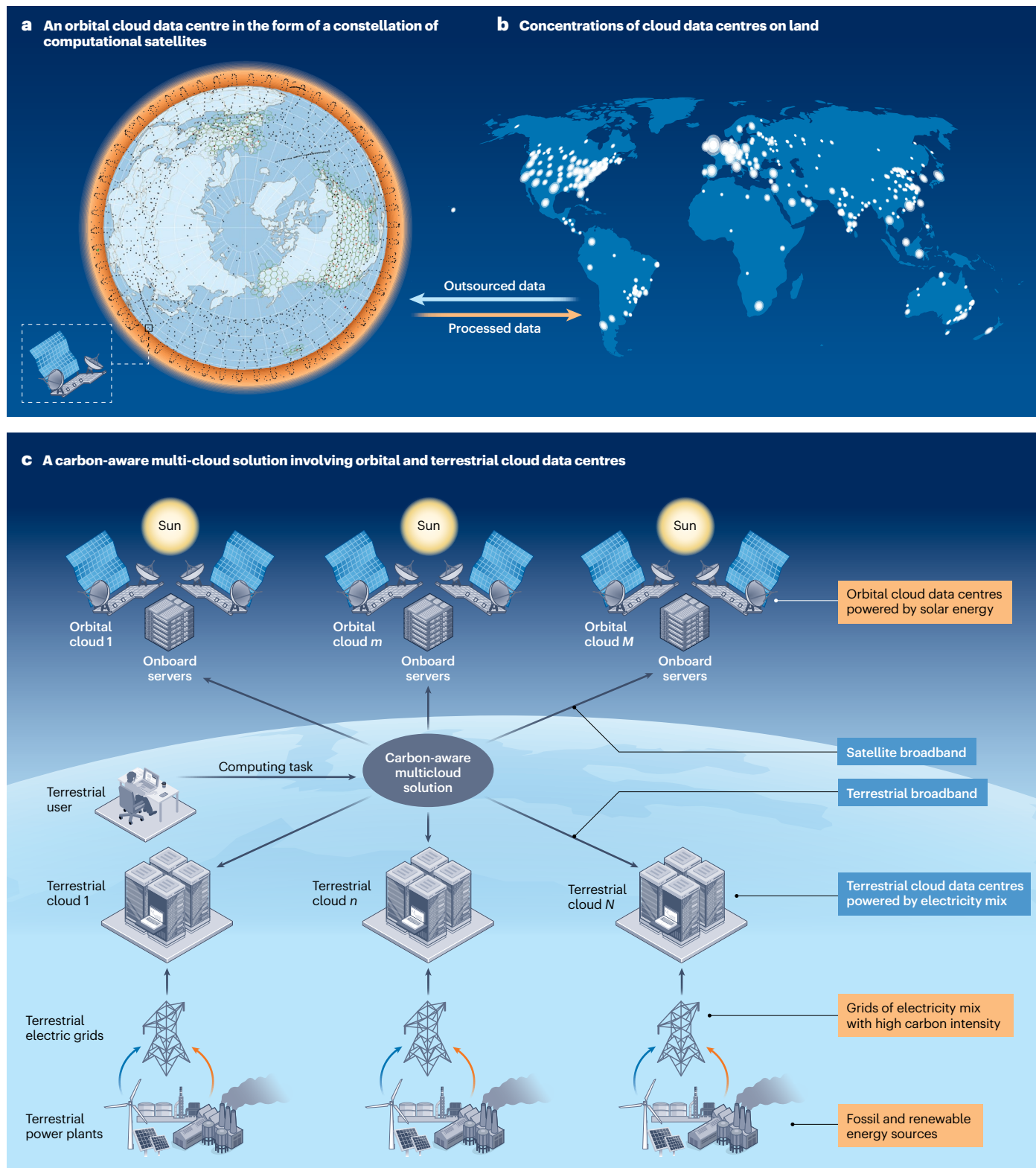


Fig. 5 | Framework of an orbital cloud data centre. a, A LEO cloud data centre, in the form of a constellation of computational satellites, each equipped with general-purpose servers and broadband connectivity. **b,** Concentrations of terrestrial cloud data centres around the globe. Regional numbers were plotted for

the following seven counties: United States, China, Russia, Canada, India, Australia and Brazil. **c,** Framework of a carbon-aware multicloud solution involving both orbital and terrestrial cloud data centres. Data in **b** from DataCenterMap (<https://www.datacentermap.com/cloud/>). Credit: **a,** satellitemap.space.

user could choose to offload computing tasks to a cloud data centre in space or on land. For this purpose, we detail in the next section a comprehensive evaluation method that considers emissions beyond data processing.

Carbon-neutral orbital cloud data centres could also be used to process exceedingly large space-native big data beyond the computing capability of an orbital edge data centre discussed in the previous section. In this case, space-native big data can be directly sent to the orbital

cloud data centre for processing. An orbital cloud data centre would be beneficial to multiple constellations of data-sensing satellites that deliver different services. With this approach, datasets from multiple orbital edge data centres could be further fused into more consistent and useful information within the orbital cloud data centre to offer digital services effectively in a carbon-neutral manner.

Life-cycle CUE of cloud data centres

Even though data processing in space is carbon neutral, there are other directly or indirectly involved processes that may not be carbon neutral. For instance, sending computing hardware into space could be a much more carbon-intensive process than sending it into data centres on land¹⁰. Therefore, a comprehensive method is needed to evaluate and compare the carbon footprints of orbital and terrestrial data centres. To this end, we propose life-cycle CUE, which includes carbon emissions from all major processes including, but not limited to, data processing.

The Greenhouse Gas Protocol separates carbon emissions of a value chain into three scopes⁷⁴. Scope 1 emissions are direct emissions, for instance, from a data centre operator's backup generator. Scope 2 emissions are indirect emissions from the generation of electricity used by a data centre. Scope 3 emissions are all other indirect emissions in the value chain. The emission scopes of major processes associated with an orbital cloud data centre are as follows.

- Computational satellites. Manufacturing of computational satellites (including the carrier satellite, broadband hardware, computing devices, solar arrays, radiative coolers and so on) accounts for indirect scope 3 one-time emissions from energy consumptions for manufacturing. This category of emissions, especially that from chip manufacturing, can be significant^{75,76}.
- Launch vehicles and launching. Manufacturing of propellants and launchers as well as the launching and return events also release substantial amounts of scope 3 one-time emissions, especially if launch vehicles use fossil fuels such as the rocket-grade kerosene used by SpaceX's Falcon 9¹⁰. Osoro et al.⁷⁷ conducted a comprehensive life-cycle assessment of launching-related emissions from several spacecraft manufacturers. Reusing launchers helps offset emissions from manufacturing, and the launching process may be decarbonized with hydrogen fuel as NASA has been doing since 1958⁷⁸.
- In-space computing. Carbon-neutrality naturally occurs in orbital computing as it is directly enabled by solar energy and radiative free cooling. The significance is that the scope 2 emissions of an orbital data centre are technically zero.
- End of life-cycle. Currently, there is no proven technique to recycle or reuse orbital debris⁷⁹. Retired hardware ends up as space junk and eventually could burn up in the atmosphere, releasing a small amount of scope 3 emissions and other harmful chemicals^{80,81}. This is a disadvantage compared with terrestrial data centres, where retired components can be readily reused or recycled⁸².
- Long-distance data transmission. This category of emissions mostly lies beyond the three emission scopes of a data centre³³. A brief analysis (Supplementary Section 2) shows that transmitting a unit size of data using Starlink overall consumes less electricity than using the terrestrial broadband^{83,84}, probably because of the overall shorter transmission distance between terrestrial users and LEO satellites (also see Fig. 5a,b).

On the basis of the above categorizations of carbon emissions, we define the life-cycle CUE of an orbital cloud data centre more broadly as the life-cycle equivalent carbon emissions (C , kgCO₂e) from all three scopes divided by the life-cycle information technology equipment energy consumptions (E_{IT} , kWh). That is,

$$\begin{aligned} \text{CUE}_{\text{life-cycle}} &= \frac{\text{life} - \text{cycle total emissions (C, kgCO}_2\text{e)}}{\text{life} - \text{cycle IT energy consumptions (E}_{IT}\text{, kWh)}} \\ &= \frac{C_{\text{scope1}} + C_{\text{scope2}} + C_{\text{scope3}}}{E_{IT,\text{life-cycle}}} \end{aligned} \quad (1)$$

where $C_{\text{scope } i}$ is the expected equivalent carbon emissions in scope i ($i = 1, 2, 3$) accrued over the lifespan of servers. Each scope of emissions can be further broken into subcategories⁷⁴, which could be one-time or recurrent. Recategorizing emissions on the basis of recurrence, equation (1) is then rewritten as (see Supplementary Section 3 for derivation)

$$\text{CUE}_{\text{life-cycle}} = \widetilde{\text{PUE}} \left(\frac{\bar{E}_1}{\bar{E}_2} \bar{I}_1 + \bar{I}_2 + \frac{\bar{E}_{3,\text{rc}}}{\bar{E}_2} \bar{I}_{3,\text{rc}} + \frac{\bar{E}_{3,\text{ot}}}{\bar{E}_2 \cdot \tau} \bar{I}_{3,\text{ot}} \right) \quad (2)$$

where $\widetilde{\text{PUE}}$, $\bar{E}_1$, $\bar{E}_2$, $\bar{E}_{3,\text{rc}}$ and $\bar{E}_{3,\text{ot}}$ are respectively the annual average power usage effectiveness of the data centre and the energy consumptions of the scope 1, scope 2 and scope 3 recurrent categories and scope 3 one-time category; $\bar{I}_i$ is the corresponding annual average carbon intensity of energy consumed. Equation (2) implies that the life-cycle CUE of a data centre can be improved by decarbonizing all energy sources, by reducing the scope 1 and scope 3 energy consumptions and by increasing the lifespan of servers.

As a baseline, we first evaluated the life-cycle CUE of Google data centres on the basis of our reanalysis of their location-based emissions and energy consumptions between 2019 and 2022⁴⁵ (see Supplementary Section 4 for the analysis; see Supplementary Figs. 2-4 and Supplementary Tables 1-3 for the variable values in equation (2)). We found that the average life-cycle CUE of Google data centres is 1,050 gCO₂e kWh⁻¹, in which the carbon intensity of scope 2 electricity consumptions ($\bar{I}_2$) accounts for 380 gCO₂e kWh⁻¹. This represents a medium-carbon-intensity electric grid, implying substantial room for decarbonization. For reference, we also evaluated the life-cycle CUE of hypothetical terrestrial data centres powered by mixed and all-renewable electric grids.

We then systematically evaluated the life-cycle CUE of an orbital cloud data centre framework (see Supplementary Information Section 5 for the analysis). The following assumptions are made: (1) each computational satellite is equipped with Dell R740 servers⁸⁵; (2) each server is connected to an external radiative cooler; (3) each computational satellite is also equipped with the same broadband capability as Starlink v1.0 satellites^{7,86}; (4) the computational satellite constellation has the same size as Starlink; (5) Falcon 9 is the launcher^{86,87}; (6) the orbital data centre has the same PUE of 1.1 as the terrestrial data centres⁴⁵ (see Supplementary Tables 4-9 for the technical specifications of these components). The evaluated energy consumptions and carbon emissions of major components are summarized in Supplementary Table 10. The energy ratio and corresponding carbon intensities used in equation (2) are listed in Supplementary Table 11.

We must point out that we selected Dell R740 as the reference server solely because a necessary systematic life-cycle assessment is available⁸⁵. To our knowledge, it is not radiation-hardened, nor has its radiation tolerance been tested for space applications. Selection of a server not tailored for space brings major uncertainties to its computing power and lifespan in space, which is a major limitation of our analysis.

Our analysis shows that it is possible to equip each satellite with three servers while ensuring power availability for both computing and data communication. Figure 6a shows the evaluated life-cycle CUE of the orbital and terrestrial data centres as a function of the satellite or server lifespan. As expected, the life-cycle CUE improves in all scenarios with an increasing lifespan. In particular, the life-cycle CUE of the orbital data centre powered by solar energy ($\bar{I}_2 = 0$) falls between a terrestrial data centre powered by an all-renewable electric grid (20 gCO₂e kWh⁻¹, ref. 88) and a terrestrial data centre powered by a

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a Life-cycle CUE of data centres powered by electricity grids of different carbon intensities

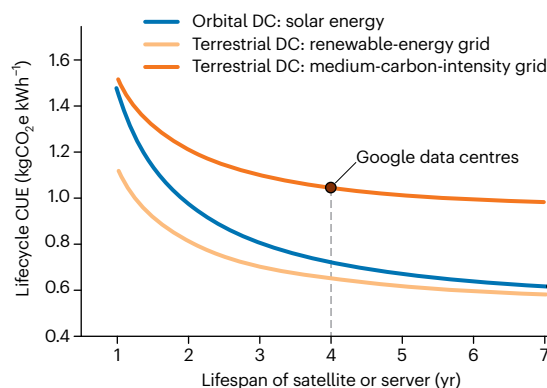


Fig. 6 | Life-cycle carbon footprints of orbital and terrestrial cloud data centres. **a**, Modelled life-cycle CUE as a function of the satellite or server lifespan. Carbon intensity of electricity: $I_e = 0$ for the orbital cloud data centre powered by solar energy; $I_e = 20 \text{ gCO}_2\text{e kWh}^{-1}$ for the terrestrial data centre powered by a renewable electric grid⁸⁸; $I_e = 380 \text{ gCO}_2\text{e kWh}^{-1}$ for the terrestrial data centre powered by a medium-carbon-intensity electric grid⁸⁸ and for

medium-carbon intensity electric grid ($380 \text{ gCO}_2\text{e kWh}^{-1}$, ref. 88). At a 4-yr server lifespan⁸⁵, the life-cycle CUE of the orbital data centre approaches that of the terrestrial data centre powered by all-renewable energy. By comparison, the life-cycle CUE of Google data centres is still well above that of the orbital cloud data centre.

Figure 6b shows the relative breakdown of one-time emissions. For each computational satellite, the manufacturing emissions of the servers, including radiative coolers, account for the bulk of one-time emissions at 54%. Manufacturing emissions of the carrier satellite are lower but still significant at 36%. Launching-related emissions accounts for about 10%, which is significant compared with the transportation emissions of servers on land⁸⁵. The orbital cloud data centre gradually makes up for the substantial manufacturing and launching-related emissions via carbon-neutral computing powered by solar energy in space.

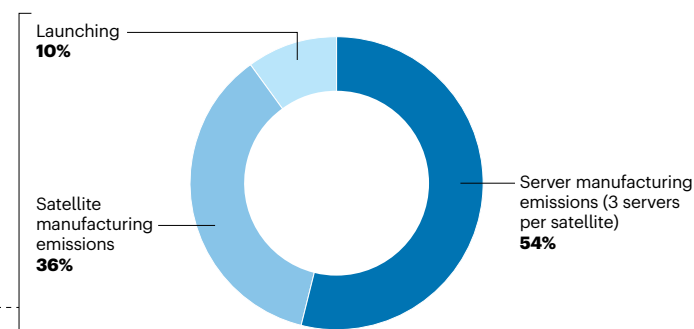
The above evaluation method based on life-cycle CUE can be implemented as part of the carbon-aware multicloud solution proposed in the previous section (see also Fig. 5c). Multicloud solutions involving orbital cloud data centres could prove environmentally beneficial to energy-intensive applications such as training AI models and conducting large-scale scientific simulations^{89–91}.

Technical and economic limitations

Although there are successful demonstrations using some commercial off-the-shelf advanced computing hardware in space radiation environments^{50,51,59}, the complex circuitry of advanced servers implies even higher probability of failure when exposed to high levels of space radiation. It may thus be too early to expect the selected reference server to function for a designed full lifespan in space. In particular, radiation-hardening of advanced servers would be necessary for their long-term operation in extremely harsh space environments⁵⁹. Radiation-hardening, however, could negatively impact the computing capability and energy consumptions of advanced computing hardware⁶⁰. Therefore, the evaluated life-cycle CUE of the orbital cloud data centre framework represents a best-case scenario. When radiation-hardened high-performance servers are ready for deployment in space, the life-cycle CUE assessment can be updated to give a better insight into the carbon footprint of future orbital cloud data centres.

We also evaluated the per-server capital cost of a computational satellite by including the individual costs of major components (see Supplementary Section 6 for the analysis). We found that its capital cost is almost

b Relative breakdown of one-time emission components



Google data centres averaged over 2019–2022⁴⁵. **b**, Relative breakdown of one-time emission components including server manufacturing emissions (based on Dell 740⁸⁵), satellite manufacturing emissions (based on Starlink v.1.0⁸⁶) and upstream transportation emissions from launching into LEO (based on Falcon 9 and Starlink⁷⁷).

20 times that of the server alone, which indeed appears prohibitive, and it could be even higher if costs associated with radiation-hardening and redesigning are accounted for. However, we reemphasize that the carrier satellite also has a broadband capability, meaning that a computational satellite has dual capability that could increase the previously lower utilization rate and cost-effectiveness of network-only satellites⁵³.

Outlook

We have provided frameworks for future carbon-neutral edge and cloud data centres in space from a carbon-neutrality perspective. We argued that data-sensing satellites, equipped with specific-purpose AI accelerators, could turn into orbital edge data centres to achieve carbon-neutral data processing at source without overly relying on remote and energy-hungry data centres on land. We proposed that a constellation of computational satellites each equipped with general-purpose servers and broadband connectivity could form orbital cloud data centres for both ground-outsourced and space-native computing applications. We also discussed a carbon-aware multicloud solution for selecting orbital and terrestrial cloud data centres on the basis of their life-cycle CUE. Our evaluation of life-cycle CUE suggests that future orbital cloud data centres could be substantially more carbon-efficient than their existing terrestrial counterparts powered by electric grids with large carbon intensity.

Small-scale orbital edge data centres for space-native applications are already making initial progress, with preliminary successful tests and capital investments. This has been made possible by the smaller scale and the better technical feasibility of orbital edge computing enabled by advancements in application-specific AI accelerators. We suggest that, although technologically more challenging and costly, constellation-scale orbital cloud data centres could prove a more impactful endeavour due to the larger scale and computing capabilities. This large-scale approach to computing in space does though require breakthroughs in developing radiation-hardened high-performance servers suitable for space.

In addition to the two distributed data centre frameworks discussed here, there are also proposals of monolithic orbital data centre frameworks. This includes ASCEND, for which a feasibility study is being conducted by Thales Alenia Space for the European Commission⁹². We did not discuss this monolithic framework in detail here because there is already an ongoing feasibility study; it is centralized, contrary to our two distributed approaches; and we believe it would be even more challenging to build (compare here the difficulty of building the

International Space Station). However, it is still crucial to examine the feasibility of all these orbital data centre approaches from technical, environmental and economic perspectives.

We have focused on outlining the frameworks and assessing the expected carbon footprints of future orbital edge and cloud data centres and have not restricted this to a specific application. However, numerous questions remain. To start, further effort is needed to test the radiation tolerance of more types of commercial AI accelerator for future orbital edge data centres, and radiation-hardened general-purpose servers dedicated to in-space cloud computing must be designed and manufactured. Moreover, initiatives must be taken to develop secure hardware and software solutions suitable for the space environment and energy-intensive applications such as processing space-native big data, training AI models and conducting large-scale scientific simulations within the proposed orbital data centres.

Data availability

Data sources are cited throughout this paper and the Supplementary Information. Component specifications, scope energy consumptions and carbon emissions, life-cycle CUE coefficients and component costs are summarized in Supplementary Tables 1–11.

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Author contributions

Y.W. proposed the idea. A.A. developed the conceptual frameworks and the modelling approaches, conducted surveys and analyses and wrote the manuscript. Y.W., J.C. and Y.S.O. provided iterative feedback and participated in revising the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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