SPACE ENERGY INITIATIVE WHITE PAPER
2026

Large-Scale Space Infrastructure

Large-Scale Space Infrastructure as a Catalyst for Sustainability, Security, and Economic Growth in Space and on Earth

Space Energy Initiative

SPACE ENERGY INITIATIVE
HELPING NATIONS ACHIEVE NET ZERO WITH SPACE-BASED SOLAR POWER AND CREATING NEW COMMERCIAL OPPORTUNITIES

We are at the threshold of a new industrial revolution in space.

Introduction

This paper outlines a new direction for space, whereby emerging heavy-reusable launch capabilities and in-orbit robotics enable alternative, complementary architectures to invigorate the space economy. These are based on Large-Scale Space Infrastructure that could support a move toward a model of modular, serviceable, and recyclable orbital infrastructure. These include Large Space Structures (LSS), which are physically connected, and Clustered Hubs of assets. They have the potential to enable abundant energy, abundant compute, low carbon materials production, next generation communications, observations and scientific research, and habitats for human expansion, arguably some of the largest new markets of the coming decades.

This paper outlines strategic opportunities and initiatives linked to Large Space Structures that the UK could lead to transform the space economy, such that our high technology industries can participate in an economically transformative, environmentally responsible, and strategically resilient approach. The aim of the paper is not to advocate one way or another for mega constellations versus Large-Scale Space Infrastructure, and both will likely coexist. Each has distinct strengths: for many communications applications a larger number of smaller satellites offers real advantages, whereas for power, aspects of compute, manufacturing, large apertures and human habitation a smaller number of larger structures can be more effective. Where the paper does take a clear position is that large-scale structures can provide step-change, sustainability-compliant solutions for critical near-term applications, including space domain awareness, secure communications, orbital compute, and space-based solar power and a pathway to the longer-term vision of an in-orbit industrial economy. The aim is to present ideas that widen thinking and start to shape UK policy, research and regulatory activities.



Contents



Executive Summary 4
Overview and key strategic interventions

About the SEI 7
The core principles and technology-driven mission of the organisation

Introduction 8
A global inflection point for space

The Industrial Revolution in Space 9
A transformational decade

Typologies for Space Systems 10
Examples and categorisation

Sustainability of Space 12
Managing large structures deployed in orbit

Large-Scale Space Infrastructure as a New Paradigm 13
Sustainability, resilience, and economic growth

Why Might Large-Scale Space Infrastructure Be Needed for New Applications? 15
Physical and energetic economies of scale

A Staged Pathway of Applications 16
From demonstration to gigawatt scale

Engineering Considerations and Challenges 17
Important considerations for large structures in space

Regulatory Considerations and Pathways 19
A clear and effective environment as a building block

Summary and Next Steps 20
Recommendations and milestones for UK leadership

Contributors, Notes and References 22

Executive Summary

The space sector is at an industrial inflection point, moving from a niche domain to becoming critical global economic and security infrastructure, facilitated by the availability of heavy reusable launch technologies. The initial response to such capability has been more of the same, the development of even bigger "mega-constellations" of disposable monolithic satellites. Whilst benefits will be delivered, questions over long term sustainability are increasingly entering the public consciousness. If not managed effectively, the very systems deployed to provide environmental and societal benefits on Earth could eventually undermine the long-term viability of the orbital environment due to congestion and debris.

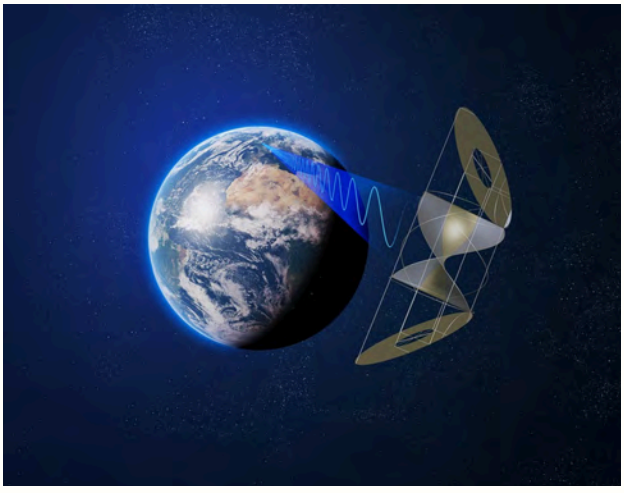
This paper outlines a new direction for space, whereby emerging heavy-reusable launch capabilities and in-orbit robotics enable alternative, complementary architectures to invigorate the space economy. These are based on Large-Scale Space Infrastructure that could support a move toward a model of modular, serviceable, and recyclable orbital infrastructure. These include Large Space Structures (LSS), which are physically connected, and Clustered Hubs of assets. They have the potential to enable abundant energy, abundant compute, low carbon materials production, next generation communications, observations and scientific research, and habitats for human expansion, arguably some of the largest new markets of the coming decades.

The UK continues to be a pioneer in space sustainability. Alongside this, the space priorities of today are, first and foremost, questions of national security and economic growth. Against a sustainability and resilience framing, the paper is therefore focused around the two priorities that dominate current UK government thinking: security and growth. Space is now critical national infrastructure. It is not only central to intelligence, security and economic growth but the exposure of that infrastructure to congestion, debris, hostile action and space weather is also a national security matter. As the transition to heavy reusable launch and in-orbit robotics is opening, the UK has relevant strengths in AI and autonomy, energy systems, advanced materials and robotics. These capabilities can enable leadership in sustainable, resilient Large Space Structures which can benefit the resilience of assets in space and supercharge both security and economic growth.

This paper outlines strategic opportunities and initiatives linked to Large Space Structures that the UK could lead to transform the space economy, such that our high technology industries can participate in an economically transformative, environmentally responsible, and strategically resilient approach. The aim of the paper is not to advocate one way or another for mega constellations versus Large-Scale Space Infrastructure, and both will likely coexist. Each has distinct strengths: for many communications applications a larger number of smaller satellites offers real advantages, whereas for power, aspects of compute, manufacturing, large apertures and human habitation a smaller number of larger structures can be more effective. Where the paper does take a clear position is that large-scale structures can provide step-change, sustainability-compliant solutions for critical near-term applications, including space domain awareness, secure communications, orbital compute, and space-based solar power and a pathway to the longer-term vision of an in-orbit industrial economy. The aim is to present ideas that widen thinking and start to shape UK policy, research and regulatory activities.

Beyond enabling the next generation of transformative services, large-scale space infrastructure has a great deal to offer space sustainability. It can act as a catalyst for progress in three critical areas for space sustainability, all of which are needed as the sector evolves:

They have the potential to enable abundant energy, abundant compute, low carbon materials production, next generation communications, observations and scientific research, and habitats for human expansion.



1. A circular, resilient orbital economy

Large, hyper-modular structures and clustered hubs offer a route away from the sector's single-use, "de-orbit and burn" model, which risks atmospheric pollution. They can move us toward a true circular economy in which assets are designed for in-orbit repair, upgrade, component harvesting, and recycling rather than disposal, also leading to greater resilience.

2. End-to-end lifecycle assessment across Earth and space

The benefits of large-scale space infrastructure span both Earth and space, though this is not always obvious. Large structures can lead the adoption of comprehensive lifecycle assessment across terrestrial and orbital environments, ensuring the net impact of space activity at scale remains demonstrably positive.

3. Rules of the road and new regulatory frameworks

The presence of large infrastructure in space reinforces the need for clear rules of the road and, more importantly, reduces the complexity of managing vast numbers of disparate assets to a smaller number of defined orbital volumes within which assets are maintained, monitored, and serviced.

Key Strategic Interventions, grouped by these themes

A circular, resilient orbital economy

1. Undertake studies into the recycling of materials and components used in large space structures.
2. Urgently commission rigorous analysis of the environmental consequences of de-orbiting hundreds of thousands of tonnes of materials annually from planned mega-constellations, both on the atmosphere and in terms of the continued mining and extraction required for replacement.
3. Derive models that evaluate the resilience of large space structures as a contribution to national security and sovereignty.
4. Treat space weather as an explicit design and resilience requirement for large structures, and sustain the UK's space weather monitoring and forecasting capability.

End-to-end lifecycle assessment across Earth and space

1. Adopt full lifecycle assessment frameworks across both Earth and space impacts, so that benefit-versus-impact relationships can be quantified and compared.
2. Assess knowledge gaps and stimulate targeted research on the sustainability of large space structures, engaging research councils toward funding this work.
3. Study the effect of heavy lift and orbital depot architectures on the efficiency and environmental footprint of Earth-to-space transportation.

Rules of the road and new regulatory frameworks

1. Undertake analysis of space traffic management and operational approaches with large structures included as part of a managed space environment.
2. Ensure short-term constellation deployments do not create an unmanageable debris field that forecloses future orbital "highways" and the economically transformative infrastructure they could carry.
3. Develop regulatory and physical testbeds (both on the ground and in orbit) for large space structures and clustered hubs of assets, establishing pathways for regulation, insurance, and orbital management, and engage with current legal developments, such as the EU Space Act, alongside international partners and UNOOSA.
4. Engage the astronomy community directly on dark and quiet skies, so that large structures are designed to minimise optical and radio impacts and protected regions of high scientific value are defined.

Three actions are proposed to drive UK leadership

1

UK to take the lead in defining and spearheading an ESA programme on Large Space Structures at the ESA Ministerial Council in 2028, so that ESA member states create a coherent programme of work that facilitates collaboration and cooperation and capability at global scale.

2

UK to identify and support the UK supply chain in preparedness for participation in such a future programme, through active promotion and engagement via the Regional Space and Defence clusters.

3

UK to revisit and update its in-orbit servicing, assembly and manufacturing (ISAM) roadmap, moving decisively beyond the debris-removal first step toward assembly and the large structures that create a servicing market.

Anchored around high value, deliverable milestones

Consistent with the way government sets strategy, as a framework of outcomes rather than a direct investment plan, this paper proposes a small number of specific, measurable milestones for the UK: an in-space assembly demonstration within three years; a megawatt-class pilot platform in orbit, with a UK anchor role, within five years, alongside first commercial revenue from a service enabled by large-scale infrastructure. Needs on Earth are becoming more urgent and AI is seeing development times compressing. Baking such goals into future national objectives would give industry and investors the market signal needed to make the concepts economically self-sustaining.

Success of such interventions would be two shifts: 1) moving the conversation from “large is risky” to “large could be the foundation for a sustainable, and increasingly circular, economy in space”; 2) a shift of the narrative from imagination and discovery to delivery of transformational new space capabilities over a 10-year time frame. Many other ecosystems, from the microscopic to the macroscopic, have evolved as large structures and clusters due to the economics of interaction and exchange, and so the space sector would benefit from ensuring that this option remains open. Leading this agenda would strengthen the UK’s role and influence in shaping, and participating in, the new space economy.

A success of the paper would be shifting the conversation from “large is risky” to “large could be the foundation for a sustainable, and increasingly circular, economy in space”

Many other ecosystems, from the microscopic to the macroscopic, have evolved as large structures and clusters due to the economics of interaction and exchange, and so the space sector would benefit from ensuring that this option remains open.

About the SEI

We recognise the challenges of Net Zero, and the need for new baseload energy technologies to complement our intermittent renewables. The SEI will lead the development of Space Based Solar Power for the UK, offering large scale, safe, and secure energy day and night, through all seasons and weather. Through a structured and collaborative programme of design, research and technology demonstration, the SEI will promote integration and innovation between Space, Energy, Digital, and Manufacturing ecosystems.

Space Energy Initiative



Climate change and the pressures on global energy resources are urgent problems.

The Space Energy Initiative (SEI) is bringing together government, research and industry in the energy and space sectors to develop and deliver a co-ordinated programme of technology development and demonstration.

Introduction

An inflection point

The space sector is at an inflection point. With the step changes in launch cost and capacity expected with the onset of heavy, reusable launch from SpaceX, Blue Origin, and others, there is the potential for vastly increased activity and number of assets operating in space, both in the form of mega-constellations and a range of new options based on large space structures.

This paper investigates whether Large-Scale Space Infrastructure, ranging from consolidated platforms to modular clusters, could offer a more sustainable long-term approach to using space. It does not claim that large structures are inherently superior, nor that distributed constellations of monolithic satellites are inherently flawed. Rather than advocate for an outcome, the intent is to broaden the field's imagination, introduce decision-makers to alternative architectures, and highlight areas where quantitative analysis is needed. The paper does, however, argue that the UK should deliberately build the capability to design, assemble and operate large structures, starting with near-term applications where the case is already strong, so that the option remains open rather than being foreclosed by default. For governments, regulators, and space-sector leaders, the paper aims to prompt fresh thinking about strategic trajectories before path dependency around the current paradigm of highly distributed constellations becomes irreversible.

Over the past decade, the recognition of the commercial value of satellites for delivering communications and intelligence services has led to exponential growth in the number of satellites in low Earth orbit. With further enhancements to launch capability, new services from space are developing, including in-space manufacturing (pharmaceuticals and novel materials), AI data centres, and space-based solar power, all of which benefit from higher power or larger aperture.

The conventional approach towards satisfying the demand for more space-based services has been to proliferate the number of satellite constellations in orbit, generating justifiable concerns about long-term sustainability, traffic management, and the future governance of space. Despite these challenges, current sustainability initiatives largely focus on making the existing paradigm work, looking at debris mitigation, improving space-domain awareness (SDA), and refining disposal practices. However, there is limited questioning of whether the underlying paradigm for the way space is used is itself sustainable, let alone optimal. As a result, the field may be unintentionally reinforcing a trajectory that becomes increasingly difficult to manage as satellite numbers scale by orders of magnitude.

Emerging launch capabilities, particularly the rapidly developing ability to place more than a hundred tonnes of payload into orbit in a single launch, enable architectures that were previously infeasible. These include large space structures assembled in space and/or tightly integrated on-orbit clusters with assets that can manoeuvre and continue to co-locate. From a sustainability perspective, these options have received comparatively little attention, in part because "large" is often equated with unsustainable when, in fact, both on Earth and in space, the intended outcome needs to be considered across a range of different measures where large structures and smaller developments have distinct characteristics. Economies of scale often mean fewer materials are used in larger developments providing clear environmental benefits. There are many examples on Earth but in space a current example is how radiation shielding increases with size of satellite where shielding mass per unit of compute decreases as satellites or orbital containers scale up.

With concepts such as gigawatt (GW)-scale orbital data centres requiring Starlink-sized constellations for each GW installed if delivered in a distributed manner (100 kW per satellite), the implications of filling orbits with hundreds of thousands of independent satellites become especially salient. If the future involves Starship-scale mass flows to orbit, the management burden of vast numbers of monolithic satellites across multiple shells may become untenable, along with burning up hundreds of thousands of tonnes of critical minerals in the atmosphere each year[1].

By assembling preliminary considerations and identifying where large structures may hold advantages or face challenges, this paper seeks to catalyse analytical, regulatory, and industrial collaboration. As launch, robotics, and in-orbit assembly technologies evolve, reconsidering the foundational assumptions of how we most effectively occupy orbital space is both timely and necessary. Many systems, from the macroscopic to the microscopic, evolve as clusters and connections between clusters, due to simple economics of interaction and exchange. Is there a reason why space should be different, now that the constraints that led to the current paradigm are being reduced?



The Industrial Revolution in Space

Over the last decade, the space sector has been transformed from a niche scientific and commercial domain into critical infrastructure underpinning modern society. Space-based systems now provide essential intelligence for managing economies, supply chains, and environmental change, while enabling near-ubiquitous connectivity and supporting national security.

Yet a further step-change transition is emerging, driven by launch capability. Reusable heavy-lift vehicles, including SpaceX's Starship, Blue Origin's New Glenn, and comparable systems under development globally, are poised to radically lower the cost of access to orbit and increase mass delivery by over an order of magnitude. This evolution can enable a fundamental shift: both in the number of satellites launched and in moving toward building substantial, economically transformative large infrastructure directly in orbit.

This shift represents the beginning of an industrial revolution in space, a transition toward an in-orbit economy that will shape the next century of growth. One of the defining features of this new era can be large, modular platforms assembled robotically, sustained by advanced AI and autonomous operations, and optimised to deliver services with direct benefits for Earth. These capabilities extend far beyond traditional satellite functions. They encompass clean energy generation, new materials and pharmaceuticals manufactured in microgravity, advanced data-processing architectures, and next-generation communications systems. Together, they point to a future in which space becomes an adjacent economic sphere, immediately "next door" to terrestrial markets and integral to solving major global challenges.

UK companies are already shaping the next generation of in-orbit infrastructure. Companies in the Space Energy Initiative are advancing space-based solar power as a continuous, and potentially transformative, clean-energy technology (the global energy market is expected to reach 60 Bn MWh / $9 trillion per annum by 2050, excluding AI demands)[2]. Space Forge is pioneering microgravity manufacturing of advanced materials and semiconductors, while BioOrbit is developing pharmaceuticals that cannot be produced on Earth. Axiom, expanding its UK presence, is working toward orbital data centres. Companies such as Astroscale, OrbitFab, and Magdrive are laying the foundations of a circular, service-oriented space economy through refuelling, debris removal, and on-orbit logistics. These efforts collectively open multi-trillion-dollar markets, from space-derived clean energy and AI data infrastructure to microgravity materials, biopharmaceuticals, high-power radar for security, and direct-to-mobile communications. Many of the capabilities required, including radar and antennas, AI and autonomy, energy systems, advanced materials and robotics, are areas of existing UK strength, which is why the growth opportunity is a national rather than a niche one.

Robotics and AI are accelerating this transition, enabling sophisticated proximity operations, in-orbit assembly, and the construction of hyper-modular structures with potentially transformative economies of scale and operational paradigms. They are also compressing development timeframes.

In-orbit servicing, assembly and manufacturing (ISAM) deserves particular attention. The UK's earlier roadmap for space robotics and in-orbit servicing[3] set out a deliberate sequence: build proficiency and public confidence through sustainability and debris removal missions, then use that proficiency for economically valuable activity such as refuelling, repair, recycling and, ultimately, the assembly of large structures. More than five years on, the UK has largely remained on the first step. This matters because a substantial commercial ISAM market is unlikely to develop until there are assets in orbit worth servicing. Defence is the exception, but commercial demand requires large, long-lived, high-value structures first, and until such assets exist government remains the customer of last resort. There is an acknowledged tension in arguing for building large things that need servicing in order to create a servicing market, but the reverse logic is equally



This emerging in-orbit economy, underpinned by large-scale infrastructure, launch evolution, robotics, and AI, can define not only the future of space but also the trajectory of global economic and environmental resilience.

uncomfortable: ministers back ISAM because they see an international competition for a servicing market, and that market only materialises if someone builds the infrastructure to be serviced. Large-scale infrastructure turns ISAM from a sustainability cost centre into a near-term growth opportunity, which was always the point of ISAM.

For the first time since the aviation industry took flight over a century ago, humanity is again laying the foundations to build the “roads and railways” of a new frontier. The sustainable development of Earth and the economic development of space are becoming coupled: the urgent needs on Earth are meeting the expanding art of the possible in orbit. This emerging in-orbit economy, underpinned by large-scale infrastructure, launch evolution, robotics, and AI, can define not only the future of space but also the trajectory of global economic and environmental resilience.

However, unlike with previous industrial innovations, we must ensure that this revolution is delivered sustainably, both in space and on Earth. Until now, space proliferation has followed much the same trajectory as previous industrial evolutions: build fast and leave the potential consequences to future generations. As a nascent opportunity, the space sector can be different. We have the knowledge and tools to ensure it does not follow the same predictable pattern.

Typologies for Space Systems

Today we are familiar with satellites ranging from the size of a shoebox to the size of a bus, constructed on Earth and deployed on orbit, and from individual satellites to constellations of many thousands.

There are a wide range of typologies for space systems that become possible with changes in launch capability. In terms of Large-Scale Space Infrastructure, there are several options. “Large” does not always mean a single solid object; it can refer to the scale of the coordinated system. Some example typologies of Large-Scale Space Infrastructure, split by Large Space Structures and Clustered Hubs of assets, are presented below to frame the discussion.

For the first time since the aviation industry took flight over a century ago, humanity is again laying the foundations to build the “roads and railways” of a new frontier.

Large Space Structures (physically joined)

- **Integrated Sparse Structures:** These are large, lightweight structures, often assembled or manufactured in orbit, designed to support vast surface areas. Examples include Space-Based Solar Power (SBSP) arrays for energy collection and next-generation telescopes that require long, rigid baselines for high-resolution interferometry. Future AI data centre options may also combine elements of large sparse structures, particularly for solar panels.
- **Mega-Monolithic Payloads:** These are essentially scaled-up versions of traditional satellites, designed to maximise the use of the massive fairing volume of next-generation heavy-lift rockets. They provide a "plug-and-play" approach for high-value assets that require immense internal volume and shielding, such as large-scale scientific laboratories.
- **Pressurised Habitation Complexes:** Large-scale, shielded structures designed for long-term human occupancy, such as space stations or orbital hotels. These require the highest level of structural integrity and life-support redundancy, serving as the primary hubs for human-in-the-loop research and orbital commerce. There may also be options for connecting multiple Starships for either habitation or other commercial services.



Clustered Hubs of Assets (independent assets in the same volume of space)

- **Co-located High-Density Clusters:** Rather than a single frame, these consist of independent modules flying in a "swarm" or "cloud" formation within a very tight "orbital box". This typology is ideal for distributed satellite communications and some orbital compute architectures, where multiple assets work as a single virtual antenna while maintaining the flexibility to swap out individual nodes.
- **Orbital "Villages" (Logistics Hubs):** These are heterogeneous clusters where diverse assets (power tugs, data relays and fuel depots) are grouped closely with a range of other satellite assets that deliver different services (observation, navigation, communications) to share overhead. This "village" approach enables localised logistics and simplified end-of-life management, as a single servicing craft can maintain dozens of nearby assets without high-delta-v manoeuvres. A further application of this approach is the positioning of "depots" near common launch trajectories, enabling onward transportation to other orbits, in-orbit assembly, and other functions. An orbital depot architecture of this kind could make Earth-to-space transportation logistics considerably more efficient than point-to-point delivery for many, though not all, applications, and the combined effect of heavy lift and orbital depots on transport efficiency merits study in its own right.
- **Industrial Power and Manufacturing Depots:** These are infrastructures characterised by high power-to-mass ratios, specifically designed to host microgravity foundries. By centralising MW-level power and thermal rejection in one "factory" hub, the economics of producing semiconductors or fibre optics are enhanced through shared infrastructure.
- **Circular Economy and Recycling Facilities:** These specialised structures act as orbital "scrapyards" and refineries, equipped to capture, dismantle, and repurpose decommissioned assets. They are the cornerstones of sustainability, converting "space junk" into raw feedstock for in-space 3D printing and structural repair.

Sustainability of Space

Space systems are critical enablers of sustainability, supporting climate monitoring, communications, navigation, and more, with emerging concepts such as SBSP, orbital data centres (ODCs) and in-space manufacturing adding further capability. However, the growing use of space to deliver downstream environmental and societal benefits on Earth feeds into the space sustainability paradox, whereby the increased number of deployed systems undermines the long-term sustainability of both the space and terrestrial environment. Technological capability has advanced to the point where highly complex and autonomous systems can be routinely launched, yet environmental stewardship of space activities has not progressed at a comparable pace.

More specifically, the orbital space environment today is characterised by growing congestion, rising collision risk, and an expanding debris population, driven by increasing launch rates, mega-constellations, and limited end-of-life compliance. Although post-mission disposal and de-orbiting guidelines exist, they remain inconsistently applied and weakly enforced, effectively resulting in no clear rules of the road for space operations. This governance gap increases systemic risk, particularly for large-scale infrastructures that may rely on long operational lifetimes and extensive orbital presence. With proposed constellations of up to a million satellites from SpaceX, paradigms and regimes that may have been appropriate at smaller scale require serious reconsideration. The most recent stability assessment by Lewis and Kessler[4] concludes that the debris environment is unstable across a greater extent of low Earth orbit than the 2001 analysis suggested, with the regions between roughly 600 and 1,500 km approaching thresholds at which collisions could trigger cascading debris generation. The path through business as usual is therefore already complicated, and the decision by constellation operators to move toward lower altitudes so that debris decays faster can be read as real-world acknowledgement that the current model does not scale indefinitely. Burning satellites up in the atmosphere is also a growing concern: only early academic research is available to understand the potential impacts of unprecedented atmospheric deposits.

From an environmental perspective, in the UK, spaceport and launch operators are required to conduct an Assessment of Environmental Effects (AEE) under the Space Industry Act 2018[5]. However, these assessments focus on localised impacts at a specific stage of a space mission's life cycle. Recent life cycle assessment (LCA) studies[6] have highlighted that a significant proportion of space-sector emissions arise on Earth, including from manufacturing, testing, launch services, data processing, and ground infrastructure.

Large structures in space, or growing mega-constellations, sit at the heart of the space sustainability paradox[7] given that their deployment can exert environmental pressure beyond the traditional status quo. This makes the benefit-versus-impact relationship critical: do the benefits of deployment outweigh the environmental cost of building and operating them? This must be assessed with respect to carrying capacities, and the maximum population size that can be sustained indefinitely, as the paradox warns that if the scale of our space-based solutions destroys the long-term viability of the orbital or terrestrial environment, the net result is a global sustainability deficit rather than a gain. This draws into question whether we are merely embedding an existing orbital paradigm, rather than thinking about the optimal way to use space.

As an example, the environmental footprints of several modern SBSP system designs have been calculated using process-based LCA methodologies[8]. Although not strictly comparable to one another, results range from 5.13 gCO_2e/kWh (for low technology readiness level (TRL), non-terrestrial, eco-designed concepts) to 35.74 gCO_2e/kWh (for mid-TRL, terrestrial, conventionally designed concepts), both significantly lower than terrestrial solar. The emissions per unit of energy delivery can then be compared to terrestrial generation technologies, meaning that the benefit-versus-impact of these systems can be clearly quantified, at least from an energy delivery perspective. However, defining equivalent relationships for other large space structure applications (such as space telescopes, orbital data centres, and space stations) is less straightforward, due to their different use cases.

What is clear is that we are at a point where space can become a powerful new tool in the movement toward sustainability. However, we must not simply push environmental issues into space. We need to consider the end-to-end life cycle across Earth and space, and to ensure that the net impact is positive. His Majesty King Charles III's frameworks of the Terra Carta and Astra Carta provide an excellent reference for ensuring that we drive toward a sustainable future both on Earth and in space.



Large-Scale Space Infrastructure as a New Paradigm for Sustainability, Resilience, and Economic Growth

Modern space operations remain rooted in a paradigm of dispersal: satellites are launched individually and positioned to minimise interaction, largely driven by insurance constraints, interference concerns, and the desire to avoid collisions. This approach made sense when space was sparsely populated, but it has created a management model that becomes increasingly untenable as satellite numbers scale by orders of magnitude. Assets are spread widely across orbital regimes, controlled with limited proficiency in proximity operations, and often lack basic manoeuvring capability. In effect, we are attempting to maintain a complex, high-risk environment using practices comparable to operating a transport network with no rules of the road, a lack of consistent regulation, and vehicles scattered randomly across a continent.

By contrast, many natural and engineered systems, from biological organisms to cities to industrial supply chains, evolve toward clustered or modular structures[9,10]. Dense subgroups of interacting components connected by well-defined corridors are a universal motif, because clustering reduces transaction costs, improves information flow, enables specialisation, and concentrates resources where they can be used most effectively. If space follows similar principles, then large structures and clusters may represent not only a feasible architectural alternative but a more sustainable and economically efficient one. Economics in its broadest sense is about interaction and exchange. If space moves toward structures that are clustered or connected, the acceleration could be equivalent to that which followed humans moving from fields to villages and towns. It would be perverse for space to deny itself that opportunity by ploughing too fast down the existing track.

Several sustainability advantages can emerge from adopting a clustered or large-structure model:

1. Economies of Learning and Operational Proficiency

Sustainability in orbit ultimately depends on routine, reliable, and precise close-proximity operation, yet today these skills are deployed rarely. Companies developing rendezvous and proximity operations (RPO) capability do not get the regular practice needed to accelerate. Clusters concentrate activity, enabling frequent interaction, servicing, assembly, and reconfiguration. This “learning by doing” effect can accelerate the development of the operational competence needed to sustainably manage a dense, long-lived orbital environment. Innovation is a numbers game. To date the sector has become very good at putting smart things into space but, having been launch constrained, is not yet good at operating and moving about in space. Building large structures and clusters would naturally develop that proficiency, which is arguably the single biggest, if least tangible, contribution they can make to making space sustainable.

2. Resilience – Protecting and Maintaining On-orbit Assets

When satellites are widely distributed, debris removal becomes energy-intensive, expensive, and logistically challenging. The economics of debris removal are challenging under the current “throw away” paradigm. In clustered environments, assets and any associated debris are maintained within predictable volumes, co-located with protection, repair, refuelling, and recovery systems. The effort required to protect, service or clean a cluster is orders of magnitude lower than chasing dispersed objects across orbital shells. Many large space structures are also hyper-modular, comprised of hundreds of thousands of similar modules, which builds in natural resilience through redundancy.

3. Design for Sustainability and End-of-Life Management

Large, modular structures can be designed very differently from monolithic satellites. Modules can be engineered to "tear rather than shatter" to reduce debris generation risk. Debris clearance assets can also be co-located. Structures can be designed for continual upgrade and repair, rather than de-orbiting, which can be detrimental to the atmosphere.

4. Enabling In-Space Recycling and a Circular Orbital Economy

A distributed debris field makes any form of in-orbit recycling economically infeasible. By contrast, clusters concentrate both materials and robotic capabilities in one place, creating a realistic pathway toward circularity. With sufficient density, recycling becomes logistically viable, transforming waste objects into inputs for manufacturing and reducing future launch mass.

5. More Focused Monitoring and Targeted Intervention

Clusters and associated clean corridors reduce the scope of space surveillance and traffic management from "everywhere" to "specific, structured locations". This concentrates monitoring requirements, simplifies governance, and provides clear priorities for clean-up or risk mitigation. Rather than policing an entire orbital regime, regulators would focus on defined nodes and transit paths. Such patterns support the establishment of logistics hubs and shared infrastructure at key nodes, much like early villages served as nuclei for economic acceleration on Earth.

6. Foundations for Long-Term Infrastructure and Behaviour Change

Clustered architectures create identifiable orbital neighbourhoods, volumes of space that operators, insurers, and regulators have incentives to care about. This aligns behaviour with stewardship: currently operators focus almost entirely on what is inside their satellite, rather than on the wider environment.

7. Enabling Earth-Benefiting Applications at Scale

Large structures provide the physical foundation for high-impact capabilities such as space-based solar power, orbital data centres, high-power radar, microgravity manufacturing, and high-capacity communications systems. These applications offer direct sustainability, resilience, security, and economic benefits for Earth and will have improved economics when built on modular, expandable, and serviceable platforms, rather than scattered constellations. The economic case matters as much as the environmental one. With the launch costs that would make orbital data centres viable, space-based solar power could become among the cheapest forms of power available.

Of these, the factors that most clearly differentiate large-scale infrastructure from a proliferated constellation are maintainability and end-of-life management within predictable volumes, design for upgrade rather than de-orbit, and the viability of in-space recycling. The others apply to both models in differing degrees and should be argued as matters of degree rather than kind.

Taken together, these considerations suggest that large structures and clusters may offer an alternative, or parallel, paradigm that scales more gracefully, more safely, and more sustainably than continuing to deploy hundreds of thousands of isolated satellites. By enabling concentrated activity, reducing operational complexity, and opening pathways to circularity and in-orbit industry, clustered architectures and large structures could be an important part of the basis for long-term orbital stewardship. There are also different types of resilience. Proliferation provides resilience through numbers and by not putting all eggs in one basket; large structures provide it through protection, redundancy, repairability and upgradeability. There is probably a sweet spot between mega-constellations and a very small number of monolithic platforms, and it is important to understand where that balance lies, and to create an environment in which the two can coexist, before deploying at scale.

This is not an argument against distributed systems; both models will coexist. It is, however, an invitation to examine whether the next phase of space development should mirror how complex systems naturally evolve: toward structure, modularity, and purposeful concentration, rather than dispersal.

Why Might Large-Scale Space Infrastructure Be Needed for New Applications?

While distributed constellations offer resilience and global coverage†, large-scale structures provide a physical and energetic economy of scale that is unattainable through fragmentation. Ultimately, architecture decisions will come down to trade-offs between economics, performance, and sustainability. This section explores the unique functional advantages of these systems across power, manufacturing, and sustainability. Not every application favours large structures. For personal communications and some surveillance missions, signal strength, latency, resolution and coverage arguments explain the existence of large constellations in low Earth orbit, and the latency of LEO cannot be replicated from higher orbits. The applications that most clearly benefit from large, co-located structures are those limited by power, thermal rejection, aperture or the presence of humans, for example energy, compute, manufacturing, large-aperture sensing and communications from higher orbits, and habitation.

Concentrated Power and Thermal Management

Power is the primary bottleneck for next-generation orbital operations. Large structures allow for the aggregation of massive solar arrays or nuclear reactors capable of generating megawatt-level (MW) output.

- **Wireless Power Transmission (WPT):** Power beaming relies on high-efficiency energy transfer. For distributed systems, the "thinned-array curse"[11] means that while a transmitting antenna comprised of a coherent phased array of spaced-apart sub-apertures achieves a smaller minimum beam spot, the power delivered into that main lobe is reduced proportionally, so that the total power density in the beam remains constant. Co-location or rigid integration allows for high-efficiency power distribution, minimising transmission losses and eliminating the fuel overhead required for thousands of individual satellites to maintain precise station-keeping relative to a power source.
- **Thermal Dissipation:** High-power applications require massive radiator surfaces to reject waste heat into the vacuum. A large, centralised structure can utilise a consolidated, high-efficiency thermal management system that would be mass-prohibitive to replicate across hundreds of smaller units.
- **AI Compute:** In-space assembly of large structures is critical for the scale-out of orbital data centres. Current deployable solar arrays can realistically reach a maximum of around 500 kW, with engineering challenges above 200 kW[12] (SpaceX is working on 80 m deployables). As AI service architectures are scaled, assembled structures capable of supporting power levels from hundreds of kilowatts to gigawatts are a key enabler. Distributed GPU architectures will also benefit from physical fibre connections, as formation flying adds complexity, limits recycling, and requires free-space optics, which have higher power draw and more limited bandwidth than fibre. A large, concentrated orbital data centre should also offer better computational performance, because the interconnect latency inherent in a constellation of separate compute nodes is avoided, for the same reasons that hyperscale data centres dominate on Earth.

Industrial-Scale Orbital Manufacturing

While small-scale microgravity experiments have proven successful, the transition to orbital foundries, specifically for high-quality semiconductors or optical fibres, requires an industrial energy footprint. Terrestrial semiconductor foundries consume hundreds of megawatts. To achieve meaningful throughput in space, we must move beyond individual kW-scale modules to at least hundreds of kilowatts. A large-scale structure can act as a central hub for logistics, increasing efficiency by enabling multiple specialised processing units to dock to a single power bus and aggregate their outputs via locomotion across the structure for a single, consolidated re-entry vehicle, rather than managing the complex orbital mechanics and fuel costs of recovering dozens of independent small manufacturing craft.

Precision Instrumentation and Apertures

Large structures enable large antenna communications and large monolithic sensing that fragmented swarms struggle to match:

- **Next-Generation Telescopes:** While interferometry can be achieved with free-flying swarms, the optical precision and phase stability required for high-resolution imaging often favour rigid or semi-rigid structures. Physical connections allow for sub-wavelength stability in mirrors, which is important for detecting biosignatures on exoplanets or performing deep-space surveys.

† Also possible with multiple distributed clusters of assets, like villages.



While distributed constellations offer resilience and global coverage, large-scale structures provide a physical and energetic economy of scale that is unattainable through fragmentation.

- **Enhanced Communications:** Large structures can support massive antenna arrays with high gain, allowing for high-bandwidth communication to Earth or deep-space assets using significantly less power per bit than a distributed swarm of low-gain antennas. Consolidating many channels onto fewer, larger platforms may also ease radio-frequency spectrum coordination.
- **Enhanced Earth Observation and Science:** Large structures can support multi-functional systems by leveraging common platform infrastructure capabilities, for instance facilitating combined sensing and communications capabilities to provide very high resolution, high sensitivity measurements of both climate parameters and human activity, such capabilities transcending current space systems. Satellite architectures still look largely as they did in the 1970s. With heavy reusable launch, new structures become possible with step-change scientific and commercial potential. A lot could be achieved with orders of magnitude more power and large solar sails.

Orbital Habitats

Where humans are involved, structures are almost by definition going to be large. The International Space Station is a useful baseline, but as the space economy develops, space stations will likely grow in size significantly.

Sustainability and the Circular Economy

Large structures can also support the shift toward a circular orbital economy.

- **Recycling and Refurbishment:** In a distributed mega-constellation, a "dead" satellite is often simply debris. De-orbiting hundreds of thousands of tonnes of critical minerals into the atmosphere can cause atmospheric impacts and necessitates more mining on Earth to replace them. In a large-scale structural ecosystem, specialised robotics can harvest components, solar cells, or structural materials from decommissioned sections. Being physically close to, or attached to, a recycling hub makes the economics of space-to-space manufacturing and recycling viable. This is where the resource depletion argument closes. Economies of scale reduce the material required per unit of service, and in-space recycling, which returns material to productive use rather than to the atmosphere, reduces primary extraction on Earth.
- **Safety and Traffic Management:** Managing a few large, predictable structures is likely to be safer than tracking tens of thousands of free-flyers, and simplifies the orbital right-of-way.

Ultimately, if humanity's goal is a permanent presence in the solar system, we must move beyond the "disposable cell" model of monolithic satellites toward orbital infrastructure that can be powered, maintained, and recycled in situ.

A Staged Pathway of Applications

The applications outlined do not all arrive at once, and a credible roadmap can turn the vision into a deliverable programme. A plausible sequence, which SEI proposes as a basis for discussion, is:

- **Near term (to around 2029) –** in-space assembly demonstrations and first large-aperture platforms
- **Medium term (to around 2032) –** megawatt-class pilot platforms for orbital compute, manufacturing, space-based solar power, orbital depots and refuelling nodes, and the first commercial revenues from serviceable, upgradeable large infrastructure
- **Longer term (beyond 2032) –** gigawatt-scale space-based solar power, industrial-scale manufacturing hubs and habitation complexes

Each step builds the operational proficiency, supply chain and regulatory precedent for the next, each is valuable in its own right, and the pathway does not depend on any single application succeeding.

Engineering Considerations and Challenges

There are a number of important considerations with respect to the sustainability of large structures.

Collision Rate versus Collision Impact

Collision rate is proportional to the cross-sectional area of an object, so larger objects have a higher likelihood of collision. However, many of the large structures proposed are lightweight and sparse, so the impact of a collision is likely to be less than for a denser satellite with a standard form factor. This holds whether the area is co-located or distributed. What differs is the number of objects that must be tracked, the ability to co-locate protection and clearance assets, and the consequence of a fragmentation event, which for a sparse structure is more likely to be a tear than a debris cloud.

It is important to note that for a certain power output or radiative cooling capability, the total area required will be similar, given performance in terms of W/m^2. The difference is whether the assets are distributed, co-located or joined.

This leads to a range of effects to consider. The co-location of debris removal assets is more likely to be the case with large structures. The difference in impact between a series of assets of a smaller surface area following each other around an orbit versus a larger structure with a larger surface area then depends on the debris field. If assets are “daisy chaining” there is also the consideration of satellites flying behind other satellites being in any debris field created by satellites in front. All of this merits modelling and investigation.

Manoeuvrability

Manoeuvrability is also a consideration. Smaller assets with appropriate propulsion can avoid collisions more readily, although some larger space assets also have a good ability to manoeuvre.

Space Weather

Space weather is an explicit risk factor for any large, long-lived orbital asset and is often absent from current sustainability discussions. Coronal mass ejections and severe geomagnetic storms are difficult to predict, can degrade or disable electronics and power systems across whole orbital regimes, and can increase atmospheric drag enough to affect thousands of objects at once, as the loss of a batch of newly launched Starlink satellites in 2022 demonstrated[13]. Given the dependence of critical national infrastructure on space, a severe solar event is an existential economic risk. Large structures must be designed for it, through shielding, graceful degradation, safe modes and the ability to repair or replace modules in orbit after an event, which is itself an argument for serviceable rather than disposable architectures. The UK has been a leader in space weather science and operational forecasting, including through the SWIMMR programme[14], and sustaining that capability is a precondition for operating large infrastructure safely.

The Choice of Orbital Regime

The choice of orbital regime for a large structure is key to understanding its impact.

Immersing large structures in an environment with many non-manoeuvrable small objects significantly increases the probability of collisions. For example, recent analyses have shown that deploying multiple large reflectors in low Earth orbit presents significant environmental challenges.[15–17] From the point of view of induced risk, collisions with the main membrane reflecting light are possibly a minor issue; however, the reflector still requires structural elements, which increases the risk of cascade fragmentation if multiple reflectors are deployed. The damage to the space environment is only part of the problem: changes in illumination conditions on Earth are equally harmful, as is the impact on the night sky. The choice of a low-altitude orbit also faces a problematic trade-off between coverage (which would increase the number of reflectors required), lifetime (the lower the altitude, the shorter the lifetime but also the lower the induced risk), and the service the reflectors are intended to provide.

Many large space structures propose to use much clearer orbital regimes, such as high LEO or geosynchronous orbit (depending on application), which significantly reduces this risk.

Astronomy and Dark and Quiet Skies

The astronomy community has been among the most consistent critics of proliferated constellations, through the dark and quiet skies work coordinated by the International Astronomical Union[18], on account of both optical brightness and radio-frequency emissions. Large structures, particularly in geosynchronous orbit, need a credible answer on the same points. There are reasons to think the answer can be a good one: a small number of large structures at known locations is far easier to schedule observations around than tens of thousands of moving satellites, and large structures can be designed from the outset to minimise reflectivity, control out-of-band emissions and keep radio-quiet directions clear. A potential analogy is conservation areas on Earth: defined regions of orbital space and of the electromagnetic spectrum of

high scientific value could be protected. Large structures could be designed and sited to respect them. Engaging the astronomy community early, rather than after deployment, is key and an important source of design requirements.

Management of Orbital Space

Large structures are easier to track and can help shift the management of space from monitoring everywhere at the same level to focusing on clusters and the pathways connecting them. This can support the establishment of rules of the road and a properly managed orbital environment.

Servicing a single cluster is also more tractable than covering the whole space environment. The economics of reuse, debris removal, and sustainability in space are challenging when regular movement between assets requires propulsion. However, large-scale space infrastructure brings with it a need for a supporting ecosystem of elements, with an associated increase in overall space traffic.

Limiting Kessler Syndrome

One of the principal aims of the space sector is to avoid the Kessler syndrome[19], in which a compounding debris field renders orbits unusable. Key considerations include the collision rate and impact discussion above, along with the altitude of the orbit (lower orbits carry reduced risk as debris de-orbits more quickly through atmospheric drag) and trade-offs between large structures versus many satellites in close orbital proximity, where trailing satellites could collide with debris from those ahead.

There are a number of open questions requiring further research, engineering, and regulatory development. The different typologies of large-scale space infrastructure will also have different considerations and impacts. The important thing is to make conscious decisions, to be aware of path dependency, and to ensure that potentially superior architectures are not foreclosed by having created too congested an orbital environment in the short term.

The important thing is to make conscious decisions, to be aware of path dependency, and to ensure that potentially superior architectures are not foreclosed.

Regulatory Considerations and Pathways Toward Large Space Structures

In addition to the technical and operational considerations reviewed above, a clear and effective regulatory environment will be a key building block in the future viability of Large-Scale Space Infrastructure and Clustered Hubs of assets in space.

At the heart of the existing space regulatory environment is the 1972 Liability Convention (Convention on International Liability for Damage Caused by Space Objects), which lays down the global framework for allocating liability among the nation states involved in space activity.

Under the Convention, one of the foundational principles is that liability for damage caused in space is based on fault (Article III of the Convention). While this principle is clear on paper, its application to Large-Scale Space Infrastructure and Clustered Hubs will need to be evaluated carefully as these new operating models evolve. Key questions include what constitutes fault when operating a large-scale structure or cluster in space, and how fault can be demonstrated. Will certain types of large structures or clusters enable operators to demonstrate lower risk profiles or greater risk mitigation, thereby reducing overall risk?

At a time when these new space operation concepts are being developed, industry and regulators will need to examine how far the accepted liability and risk assessment principles should be updated to accommodate the new models. For those promoting these innovative models, the focus will be on achieving consensus on the degree of care that should realistically be expected in practice, ensuring that the burden of any new regulatory requirements is proportionate to the degree of risk and the benefits that can be delivered.

Looking more broadly, the underlying principle of fault-based liability will also affect how national regulators engage with the licensing of these new space operations. Where the licensing state carries liability under the Convention for damage caused in space, regulators will need to assess how to manage the state's legal exposure to a potentially new scale of liability arising from this emerging operational model. At the same time, national governments will be looking at how to encourage a burgeoning commercial space landscape and respond to industry's desire for a supportive and transparent regulatory framework.

In addition to the key liability issues, regulation of new Large-Scale Space Infrastructures and Clustered Hubs will need to engage with the emerging frameworks for sustainability, safety, and resilience of space operations, not least those in the draft EU Space Act. While the finer detail of this draft Act is currently under review by the European Union, it will introduce a broad-ranging set of requirements for operators on how they manage their space operations, and how state regulators engage with licensing, in the context of the increasingly congested space domain.

Among other issues under the Space Act will be how, for example, a new space cluster will meet evolving cyber security requirements. Will the cluster provide an enhanced level of cyber resilience by using a form of distributed architecture, or is it more likely to create a higher risk profile due to the multiple inter-satellite links?

Large structures are likely to depend on an increasingly diverse range of in-orbit servicing activities. While a number of jurisdictions have supported the licensing of experimental in-orbit servicing missions, the applicable regulatory frameworks are in their infancy. Where large-scale structures require in-orbit assembly, servicing, and maintenance, their operators will look for clarity on how these vital activities will be regulated and licensed throughout the life cycle of these structures.

When examining these regulatory frameworks, discussions should include input from the insurance and finance sectors, whose support is critical to the industry. Insurers and financiers will be keen to understand the implications of the evolving regulatory environment for the overall risk profile of new projects, so that they can craft appropriate policy coverage and assess investments in growing space businesses.

Politics and policy matter as much as law. Good ideas in space governance often founder at the United Nations, where a collective voice on space traffic coordination has proved elusive, and the largest actors are pressing ahead with deployment regardless. The UK cannot wait for international consensus. A practical route is to use its own licensing regime, influence within ESA and relationships with like-minded partners to set precedents. This can include defining what responsible large-scale infrastructure looks like, licensing the first demonstrations, and showing that a managed orbital environment with defined nodes and corridors is workable. Regulatory precedent set early by a trusted jurisdiction has a way of becoming the international norm, and this is an area in which the UK has repeatedly punched above its weight.

With its long-standing strengths in leading developments in space regulation, the UK has clear opportunities to take a major role in forging the regulatory environment for the growth of large structures and clusters.

Summary and Next Steps

We are at the threshold of a new industrial revolution in space, one in which orbital infrastructure becomes a major driver of prosperity, sustainability, and security on Earth – particularly for an island nation with limited factors of production and challenges balancing growth with sustainability like the UK. The enabling technologies are emerging at pace, the commercial ecosystem is maturing, and the scale of the economic opportunity is substantial. Large infrastructure and clusters have the potential to deliver the next generation of transformative services, and to change the paradigm for how space is used.

For the UK, the case rests on the two priorities that dominate current government thinking. On national security, space is critical national infrastructure whose exposure to congestion, debris, hostile action and space weather is growing. Large, resilient, serviceable structures with co-located protection offer a different and complementary model of resilience to proliferation alone, along with step-change security and resilience capabilities. On growth, in-orbit servicing, assembly and manufacturing only becomes a real market once there are assets worth servicing, and large-scale infrastructure is what can deliver into trillion-dollar market opportunities to create that demand. The UK's strengths in radar, AI and autonomy, energy, advanced materials and robotics put it in a strong position to capture a share of it and offer a genuine route to re-industrialisation.

Large-scale space infrastructure also has a great deal to offer space sustainability and can act as a catalyst for progress in three critical areas which are all needed as the sector evolves:

1. A circular, resilient orbital economy

Large structures and clustered hubs offer a route away from the sector's single-use, throwaway model toward a true circular economy. Assets can be designed for repair, upgrade, component harvesting, and recycling rather than disposal, also leading to greater resilience. Large-scale, hyper-modular structures offer this in ways that make a circular economy viable rather than encouraging upgrade of systems that make little sense to upgrade.

2. End-to-end lifecycle assessment across Earth and space

The benefits of large-scale space infrastructure span both Earth and space, but this is not always obvious. Large structures can lead the adoption of comprehensive lifecycle assessment across terrestrial and orbital environments, ensuring that the net impact of space activity, from manufacturing and launch through operations to end of life, is demonstrably positive.

3. Rules of the road and new regulatory frameworks

The presence of large infrastructure in space reinforces the need for clear rules of the road. More importantly, it reduces the complexity of managing vast numbers of disparate assets to a smaller number of defined orbital volumes within which assets are maintained, monitored, and serviced.

However, rigorous engineering, detailed modelling, and systematic investigation are needed to understand sustainability impacts and to determine how structures, systems, and operational models can be designed to mitigate challenges and adverse effects. The concepts explored in this paper require technical validation, operational experimentation, and coordinated policy and regulatory development. Specific recommendations, grouped by these themes, include:

Specific recommendations

Toward a circular, resilient orbital economy

- Undertake studies into recycling of materials and components used in large space structures. **(UKSA/ESA)**
- Urgently undertake analysis of the environmental impact of de-orbiting hundreds of thousands of tonnes of materials into the atmosphere each year, as implied by planned constellations, including the consequences of continued mining and extraction for replacement. Does the extension of the current paradigm scale sustainably? **(UNOOSA/UKSA/ESA)**
- Derive models that evaluate the resilience of large space structures as a contribution to national security and sovereignty. **(UKSA/ESA)**
- Treat space weather as an explicit design and resilience requirement for large structures, and sustain the UK's space weather monitoring and forecasting capability. **(UKSA/Met Office/UKRI)**

Toward end-to-end lifecycle assessment

- Adopt full lifecycle assessment for applications across both Earth and space impacts, so that benefit-versus-impact relationships can be quantified and compared. **(UKSA/ESA)**
- Assess knowledge gaps and stimulate targeted research on the sustainability of large space structures. Research councils should be engaged to fund this work, and specific programmes could be directed toward research groups with established expertise in space lifecycle assessment, space environment modelling, and resilient space systems, building on the academic foundations already contributing to this field. **(UKRI/UKSA/ESA)**
- Study the effect of heavy lift and orbital depot architectures on the efficiency and environmental footprint of Earth-to-space transportation. **(UKSA/UKRI)**

Toward rules of the road and new regulatory frameworks

- Undertake analysis of space traffic management and operational approaches with large structures included as part of a managed space environment, including consideration of orbital separation between large structures and the trajectories of smaller assets. **(CAA/UKSA/ESA)**
- Ensure that short-term decisions do not foreclose the ability to introduce large structures by making the debris field too large and unmanageable, protecting future orbital "highways". **(UNOOSA/UKSA/ESA)**
- Develop regulatory and physical testbeds (both on the ground and in orbit) for large space structures and clustered hubs of assets, establishing pathways for regulation, insurance, and orbital management. **(UKSA/ESA)**
- Engage the astronomy community directly on dark and quiet skies, so that large structures are designed to minimise optical and radio impacts and protected regions of orbital space and spectrum of high scientific value are defined. **(UKSA/RAS/IAU CPS)**

To make this actionable, as a set of outcomes, the following milestones are proposed: an in-space assembly demonstration by 2029; a megawatt-class pilot platform in orbit with a UK anchor role by 2031, alongside first commercial revenue from a service enabled by large-scale infrastructure; and scaling from there. Endorsement of goals of this kind in future national objectives would provide the market signal that makes the concept economically self-sustaining.

This is an opportunity to lead the evolution of the global regulatory landscape toward large space structures, including engagement with international partners and UNOOSA. Leading this agenda would strengthen the UK's role and influence in shaping, and participating in, the new space economy. The goal is not to prescribe a definitive path but to illuminate the possibilities, clarify the questions that matter, and invite collaboration across government, industry, and academia. With focused analysis and sustained investment, we can help shape an orbital future that is economically transformative, environmentally responsible, and strategically resilient.

To this end, three final recommendations are proposed to allow the UK to take a lead in the transformation of the space sector towards a new economy: 1) UK to take the lead in defining and spearheading an ESA programme on Large Space Structures at the ESA Ministerial Council in 2028, so that ESA member states create a coherent programme of work that facilitates collaboration and cooperation and capability at global scale. 2) UK to identify and support the UK supply chain in preparedness for participation in such a future programme, through active promotion and engagement via the Regional Space and Defence clusters. 3) UK to revisit and update its in-orbit servicing, assembly and manufacturing (ISAM) roadmap, moving decisively from the debris-removal first step toward assembly and the large structures that create a servicing market.

Large-Scale Space Infrastructure

Contributors

- **Dr Andrew Ross Wilson, FHEA**, Lecturer in Environmental Management, Glasgow Caledonian University
- **John Worthy**, Partner, Fieldfisher
- **Dr Massimiliano Vasile, PhD, FRAS**, Professor of Space Systems Engineering, University of Strathclyde
- **Richard Jones**, Senior Communications Manager, Viasat
- **Paul Febvre**, Professor and Director of Cranfield Centre for Resilient Space Systems, Communications and PNT, Cranfield University
- **Dr Sam Adlen**, Co-CEO Space Solar and co-Chair, Space Energy Initiative

The Space Energy Initiative (SEI) is bringing together government, research and industry in the energy and space sectors to develop and deliver a co-ordinated programme of technology development and demonstration

Notes and references

1. Indicative estimate: a constellation of one million satellites of one to two tonnes each, replaced on a five-year cycle, implies of the order of 200,000 to 400,000 tonnes re-entering the atmosphere annually. Larger satellites or shorter lifetimes would push this figure towards a million tonnes.
2. Net Zero by 2050: A Roadmap for the Global Energy Sector, International Energy Agency, 2021.
3. UK In-Orbit Servicing Capability: A Platform for Growth, Astroscale, UKSpace, FAIR-SPACE, Satellite Applications Catapult, 2021.
4. H.G. Lewis and D.J. Kessler (2025). "Critical number of spacecraft in low Earth orbit: a new assessment of the stability of the orbital debris environment." 9th European Conference on Space Debris, ESA/ESOC. https://conference.sdo.esoc.esa.int/proceedings/sdc9/paper/305
5. Space Industry Act 2018, UK Public General Acts 2018.
6. A. Chanoine (2017). "Environmental impacts of launchers and space missions," in Clean Space Industrial Days 2017, Noordwijk, the Netherlands.
7. A.R. Wilson and M. Vasile (2023). "The space sustainability paradox," Journal of Cleaner Production, 423, 15 October 2023, 138869. doi: https://doi.org/10.1016/j.jclepro.2023.138869.
8. A.R. Wilson, H.B. Oqab, and G.B. Dietrich (2024). "Avoiding greenwash in reporting life cycle greenhouse gas emissions of space solar power: environmentally-extended input-output versus process-based approaches," in: 75th International Astronautical Congress, Milan, Italy.
9. Porter, M. (1998). "Clusters and the New Economics of Competition," Harvard Business Review.
10. West, G. B. (2017). Scale: The universal laws of growth, innovation, sustainability, and the pace of life in organisms, cities, economies, and companies.
11. Glennon, E.P.; Dempster, A.G.; Aboutanios, E. (2018). "Distributed Beamforming Architectures: Taxonomy, Requirements & Synergies." IGNSS Conference 2018, International Global Navigation Satellite Systems Association.
12. SEI member conversation with orbital data centre company 2026.
13. SpaceX (2022). "Geomagnetic storm and recently deployed Starlink satellites," 8 February 2022, reporting the loss of up to 38 of 49 newly launched satellites following a geomagnetic storm.
14. Space Weather Instrumentation, Measurement, Modelling and Risk (SWIMMR), UKRI Strategic Priorities Fund. https://www.ukri.org/what-we-do/strategic-priorities-fund/space-weather-innovation-measurement-modelling-and-risk/
15. De Marchi, P. et al. (2025). "The environmental impact of collisions with large space structures: the case of solar power satellites."
16. SOLERO – Solar Power Satellite vs the Space Environment. ESA. https://activities.esa.int/4000144200
17. De Marchi, P., Wang, Y., & Vasile, M. (2025). "Space environment impact of solar power satellites." Paper presented at 35th AAS/AIAA Space Flight Mechanics Meeting, Lihue, Hawaii, United States.
18. IAU Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (CPS). https://cps.iau.org
19. Kessler, Donald J.; Cour-Palais, Burton G. (1978). "Collision Frequency of Artificial Satellites: The Creation of a Debris Belt". Journal of Geophysical Research.

GET IN TOUCH
E: INFO@SPACEENERGYINITIATIVE.ORG.UK
WWW.SPACEENERGYINITIATIVE.ORG.UK