Imperial College London

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LONDON INSTITUTE OF SPACE POLICY AND LAW

IMPERIAL COLLEGE LONDON – LONDON INSTITUTE OF SPACE POLICY AND LAW PROJECT

ISPL REPORT

INFORMING UK SPACE POLICY

ENVIRONMENTAL SUSTAINABILITY:

IMPACT OF MEGA-CONSTELLATIONS AND PRIVATE SPACE LAUNCHES

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Abbreviations

DEFRA	Department for Environment, Food, and Rural Affairs
EPA	Environmental Protection Agency
ESA	European Space Agency
FCC	Federal Communications Commission
ICL	Imperial College London
ISPL	London Institute of Space Policy and Law
LEO	Low Earth Orbit
NSS	National Space Strategy
SpaceX	Space Exploration Technologies Corp.
UK	United Kingdom
UN	United Nations

Executive Summary

Over the past few years, there has been increased activity in the deployment of larger satellite systems, often referred to as satellite mega-constellations, mostly comprising small satellites of short life-span, and in the development of private space launchers, e.g., for space tourism.

If just the four satellite mega-constellation projects called GuoWang, the Kuiper Project, OneWeb, and Starlink come to fruition, the international community will soon have to deal with nearly 65,000 mega-constellation satellites operating in Low Earth Orbit (LEO), as well as many related usage of private space launchers. This overall trend will likely continue for the foreseeable future.

This increased activity has an impact on the terrestrial environment.

Aiming to advance decision-makers knowledge, research for this Report identifies the following essential known and potential - local and global - impacts of satellite mega-constellations and private space launches on terrestrial environmental sustainability:

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Research for this Report further allows formulating the following core policy recommendations on appropriate next steps that relevant decision-makers should take to tackle these impacts:

1) Putting out an immediate call for holistic, in-depth, peer-reviewed and transparent studies evaluating and providing solutions to the identified essential environmental sustainability impacts of satellite mega-constellations and private space launchers in the UK and beyond.
2) Establishing a national or international research hub focusing on environmental sustainability impacts of space activities, including satellite mega-constellations and private space launchers in the UK and beyond.
3) Fostering investment and engagement domestically and through the European Space Agency (ESA) in the development of green space technology for satellite mega-constellations and private space launchers.
4) Promoting information transparency of actors involved in satellite mega-constellations and private space launchers.
5) Establishing strong incentives in the UK and elsewhere to ensure environmental sustainability without causing actors involved in satellite mega-constellations and private space launchers fleeing to flag-of-convenience jurisdictions.

1 Background

The Imperial College London (ICL)-London Institute of Space Policy and Law (ISPL) report of 2020 touched on ICL's potential to contribute evidence-based information to inform United Kingdom (UK) Space Safety Policy.[1] The ICL-ISPL report of 2021 took a closer look at satellite mega-constellation safety and security and relevant evidence-based information when developing related UK Space Policy.[2] Research for those reports indicated that there are terrestrial environmental impacts linked to satellite mega-constellations and private space launches.

This Report examines satellite mega-constellations and private space launches' impact on environmental sustainability, including climate change (hereinafter, references to 'environmental' include the climate), with a view to generating core policy recommendations to relevant decision-makers in the UK and beyond. This is highly warranted for three reasons:

First, over the past few years, satellite mega-constellation and private space launch activities have grown considerably, and the available information suggests this trend will continue for the foreseeable future. Examples of ongoing satellite mega-constellation projects are GuoWang, the Kuiper Project, OneWeb, and Starlink. If just these four projects come to fruition, and there are many others under consideration, the international community will soon have to deal with nearly 65,000 mega-constellation satellites operating in Low Earth Orbit (LEO), in addition to space traffic generated by other activities.[3] Besides that, 2021 also saw the first fully crewed suborbital flight of Virgin Galactic,[4] the first crewed suborbital flight of Blue Origin,[5] and "the world's first civilian mission to orbit" by Space Exploration Technologies Corp. (SpaceX).[6] According to its CEO Michael Colglazier in 2020, Virgin Galactic "targets flying 400 flights per year per spaceport",[7] a rate far in excess of current launch activity. These activities are only those receiving the most attention in the general press. The overall number of actors engaged in private space launches is much higher and still rising, especially in the case of satellite launch services.[8] Taking into account Viikari's observation

1 Christoph Beischl, 'Contribution of Evidence Based Information By Imperial College London Informing UK Space Safety Policy' (Report, March 2020) <https://www.imperial.ac.uk/media/imperial-college/research-centres-and-groups/space-lab/public/Informing-UK-Space-Safety-Policy_ICL-ISPL-Final-Report_20200910.pdf> accessed 25 March 2022.

2 Christoph Beischl, 'Informing UK Space Policy. Satellite Mega-Constellation Safety and Security: Importance of Evidence-Based Information' (Report, March 2021) <https://www.imperial.ac.uk/media/imperial-college/research-centres-and-groups/space-lab/public/1624274461_Final_Draft_v1_-__Policy_Paper_ICL-ISPL_UK_Satellite_Mega-Constellation_Policy_Project_cb_ISPL_20210331.pdf> accessed 25 March 2022.

3 See this Report's Section 3.1 for more information on prominent satellite mega-constellation projects.

4 Tania Steere, 'Virgin Galactic successfully completes first fully crewed spaceflight' (*Virgin.com*, 11 July 2021) <https://virgin.com/about-virgin/latest/virgin-galactic-successfully-completes-first-fully-crewed-spaceflight> accessed 25 March 2022.

5 'Blue Origin's first astronaut spaceflight breaks four Guinness World Records titles' (*Blue Origin*, 1 October 2021) <https://www.blueorigin.com/news/first-astronaut-crew-receive-guinness-world-records> accessed 25 March 2022.

6 'Inspiration4 Mission' (*SpaceX*, 30 September 2021) <https://www.spacex.com/launches/inspiration4/> accessed 25 March 2022.

7 Michael Sheetz, 'Virgin Galactic says each spaceport it launches from is a $1 billion annual revenue opportunity' (*CNBC*, 6 November 2020) <https://www.cnbc.com/2020/11/06/virgin-galactic-each-spaceport-is-1-billion-annual-revenue-opportunity.html> accessed 25 March 2022.

8 See this Report's Section 3.2 for more information on prominent private actors with space launchers.

that “[s]pace exploration is a polluting industry in various ways and in all its phases”,[9] these activities' impact on environmental sustainability needs urgent attention.

Second, in 2021 the UK and other states have reiterated their intention to tackle environmental impact of human activities. The UK position is evidenced by its high-profile involvement in the 26th United Nations (UN) Climate Change Conference of the Parties, commonly referred to as COP26, in late 2021,[10] and various statements related to environmental sustainability in its National Space Strategy (NSS), published in September 2021. The latter includes the statements:

- "We will continually improve safety standards, implement relevant consents, and mitigate the negative environmental impacts of our space activities."[11]
- "We will support our rapidly expanding space sector to integrate net zero thinking into its growth, monitor its environmental impact and encourage low-carbon and sustainable development."[12]
- "We will build on UK early advantage in robotics and in-orbit servicing and manufacturing to establish global leadership in space sustainability. This includes positioning the UK at the forefront of modern regulation for novel space activities, while keeping space sustainable, safe, and secure. The UK is leading efforts at the UN to promote safe space operations that will benefit all."[13]
- "The Department for Environment, Food, and Rural Affairs [(DEFRA)] is responsible for ensuring appropriate environmental regulation for England around space activities and promoting use of Earth observation technologies across government, both in the UK and internationally in support of the environment and our rural economy, contributing to national prosperity."[14]

Third, humans have so far had a terrible track record in considering the impact of technological development and private industry on terrestrial environmental sustainability before the damage has been done and finding political solutions has become highly burdensome. Examples are the global plastic pollution, which now even affects the deep sea,[15] the depletion of the ozone layer due to overuse of chlorofluorocarbons,[16] the anthropogenic facilitation of climate change,[17] and acid rain as a consequence of the excessive anthropogenic release of sulphur dioxide and nitrogen oxides into Earth's atmosphere.[18]

9 Lotta Viikari, *The Environmental Element in Space Law. Assessing the Present and Charting the Future* (Martinus Nijhoff Publishers 2008) 29.
10 ‘UN Climate Change Conference UK 2021’ (*UN Climate Change Conference UK 2021*) <https://ukcop26.org/> accessed 25 March 2022.
11 HM Government, ‘National Space Strategy’ (September 2021) 26 <https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1034313/national-space-strategy.pdf> accessed 25 March 2022. Underlines added in this Report.
12 ibid 29. Underlines added in this Report.
13 ibid 42. Underlines added in this Report.
14 ibid 49. ‘The Department for Environment, Food, and Rural Affairs’ is originally in bold letters. Underlines added in this Report.
15 See e.g.: Sarah Gibbens, ‘Plastic Bag Found at the Bottom of World’s Deepest Ocean Trench’ (*National Geographic*, 3 July 2019) <https://www.nationalgeographic.org/article/plastic-bag-found-bottom-worlds-deepest-ocean-trench/> accessed 25 March 2022.
16 See e.g.: ‘Ozone layer’ (*National Geographic*) <https://www.nationalgeographic.org/encyclopedia/ozone-layer/> accessed 25 March 2022.
17 See e.g.: Government Office for Science and others, ‘Release of Intergovernmental Panel on Climate Change report’ (*GOV.UK*, 9 August 2021) <https://www.gov.uk/government/speeches/release-of-intergovernmental-panel-on-climate-change-report> accessed 25 March 2022.
18 See e.g.: ‘What is Acid Rain?’ (*EPA*) <https://www.epa.gov/acidrain/what-acid-rain> accessed 25 March 2022.

2 Research objectives and approach

This Report's particular objectives are

- raising awareness about essential known and potential impacts of satellite mega-constellations and private space launches on terrestrial environmental sustainability among relevant decision-makers in the UK and beyond; and
- providing core policy recommendations on appropriate next steps to said decision-makers.

The Report highlights the potential contribution, especially producing evidence-based information, that ICL can offer in this context.

Towards that end this Report first puts forward reasonable definitions of

- mega-constellations;
- private space launches; and
- environmental sustainability.

Some information on the status quo of satellite mega-constellations and private space launches is added to illustrate the relevance of the Report's topic.

Subsequently, this Report

- examines the known and potential impacts of satellite mega-constellations and private space launches on terrestrial environmental sustainability; and
- formulates core policy recommendations on appropriate next steps to inform relevant decision-makers in the UK and beyond, highlighting ICL's potential contribution in this regard.

The Report considers relevant data and information from dedicated research interviews with selected experts at ICL and beyond in February 2022, as well as from publicly available material such as academic writings, news articles, and official statements by governmental and other space-related actors.

3 Definitions

3.1 Mega-Constellations

There is no authoritative 'satellite mega-constellation' definition. This Report follows the definition developed in the (upcoming) ISPL Dictionary of Space Terminology: "A satellite constellation designed to consist of a hundred or more satellites that provide certain services such as global broadband." This aligns with many references within the space community.[19] Researchers and others interested may further categorise mega-constellations by factors such as satellite type, service function, user base, orbit, or swarm behaviour.

Numerous satellite mega-constellations have been announced over the past years.[20] While many will likely never come to fruition, the deployment of even a few of them will add considerably to the number of satellites in LEO. Table 1 shows prominent satellite mega-constellation projects announced, under development or having already entered the deployment phase by March 2022. Most of them focus on providing communications services, especially broadband connectivity:

Constellation project name	**Principal entity**	**Activity area**	**Considered/planned total number of operational satellites in orbit**	**Considered/planned orbital altitudes**
国网 *[GuoWang; 'National Network']*	**中国卫星网络集团有限公司** *[China Satellite Network Group Co., Ltd]*	Communications	12,992	~500-1,145 km[21]
Astra Constellation	Astra Space Platform Services, LLC	Communications	13,620	~380-700 km[22]
Cinnamon-217 Cinnamon-937	E-Space	Communications	327,320	~550-640 km[23]
OneWeb	Network Access Associates Limited; WorldVu Satellites Limited	Communications	6,372	~1,200 km[24]
Dove SkySat *[Pelican; under dev.]*	Planet Labs Inc.	Remote Sensing	~180 21 *[unknown]*	LEO LEO *[presumably LEO]*[25]
Project Kuiper	Kuiper Systems LLC	Communications	3,236	~590-630 km[26]

19 See e.g.: ‘A satellite mega-constellation’ (*ESA*, 18 July 2018) <https://www.esa.int/ESA_Multimedia/Images/2018/07/A_satellite_mega-constellation> accessed 25 March 2022; Jeff Foust, ‘Mega-constellations and mega-debris’ (*The Space Review*, 10 October 2016) <https://www.thespacereview.com/article/3078/1> accessed 25 March 2022; ‘What is Mega-Constellation’ (*IGI Global*) <https://www.igi-global.com/dictionary/mega-constellations/71927> accessed 25 March 2022.

20 For a broad list, see e.g.: ‘NewSpace Constellations’ (*NewSpace Index*, 1 January 2022) <https://www.newspace.im/index.html> accessed 25 March 2022.

21 Based on information in: Andrew Jones, ‘China’s megaconstellation project establishes satellite cluster in Chongqing’ (*SpaceNews*, 12 January 2022) <https://spacenews.com/chinas-megaconstellation-project-establishes-satellite-cluster-in-chongqing/> accessed 25 March 2022; Andrew Jones, ‘China establishes company to build satellite broadband megaconstellation’ (*SpaceNews*, 26 May 2021) <https://spacenews.com/china-establishes-company-to-build-satellite-broadband-megaconstellation/> accessed 25 March 2022; ‘国资委关于组建中国卫星网络集团有限公司的公告 [SASAC Announcement on Establishment of China Satellite Network Group Co., Ltd]’ (*国务院国有资产监督管理委员会 State-owned Assets Supervision and Administration Commission of the State Council*, 29 April 2021) <http://www.sasac.gov.cn/n2588030/n2588924/c18286531/content.html> accessed 25 March 2022.

22 Based on information in: Jeff Foust, ‘Astra files FCC application for 13,600-satellite constellation’ (*SpaceNews*, 5 November 2021) <https://spacenews.com/astra-files-fcc-application-for-13600-satellite-constellation/> accessed 25 March 2022; ‘Astra Space Platform Services, LLC.’ (*FCC*) <https://fcc.report/company/Astra-Space-Platform-Services-LLC> accessed 25 March 2022.

23 Based on information in: Jason Rainbow, ‘Wyler raises $50 million for “sustainable” megaconstellation’ (*SpaceNews*, 7 February 2022) <https://spacenews.com/wyler-raises-50-million-for-sustainable-megaconstellation/> accessed 25 March 2022; Alice Kagina, ‘Rwanda Files to Acquire Over 300,000 Satellites’ (*AllAfrica*, 20 October 2020) <https://allafrica.com/stories/202110210274.html> accessed 25 March 2022; Peter B de Selding, ‘Rwanda submits ITU filing for constellation of 327,320 satellites – 27 orbital shells at 550-640 km’ (*Space Intel Report*, 20 October 2021) <https://www.spaceintelreport.com/rwanda-submits-itu-filing-for-constellation-of-327320-satellites-27-orbital-shells-at-550-640-km/> accessed 25 March 2022.

24 Based on information in: Jeff Foust, ‘OneWeb slashes size of future satellite constellation’ (*SpaceNews*, 14 January 2021) <https://spacenews.com/oneweb-slashes-size-of-future-satellite-constellation/> accessed 25 March 2022; ‘Privacy Notice’ (*OneWeb*) <https://oneweb.net/privacy-policy> accessed 25 March 2022; ‘WorldVu Satellites Limited’ (*FCC*) <https://fcc.report/company/Worldvu-Satellites-Limited> accessed 25 March 2022.

25 Based on information in: Will Marshall, ‘44 SuperDove Satellites Successfully Launch on SpaceX Falcon 9 Rocket’ (*Planet*, 13 January 2022) <https://www.planet.com/pulse/44-superdove-satellites-successfully-launch-on-spacex-falcon-9-rocket/> accessed 25 March 2022; Debra Werner, ‘lanet unveils Pelican Earth-imaging constellation’ (*SpaceNews*, 12 October 2021) <https://spacenews.com/planet-explore-2021-pelicans/> accessed 25 March 2022; ‘Our Constellation’ (*Planet*) <https://www.planet.com/our-constellations/> accessed 25 March 2022; ‘Planet Labs Inc’ (*FCC*) <https://fcc.report/company/Planet-Labs-Inc> accessed 25 March 2022.

	[Amazon]			
Starlink	SpaceX	Communications	~42,000	~328-580 km[27]
Telesat Lightspeed	Telesat Canada	Communications	298	~1,015-1,325 km[28]
[Unknown; currently discussed under 'Union Secure Connectivity Programme']	*[presumably: EU, while developed through public-private partnership]*	Communications	LEO: ~100 MEO: Selected existing satellites GEO: Selected existing satellites	LEO: ~400-500 km MEO GEO[29]
[Unknown]	Hanwa Systems	Communications	2,000	LEO[30]
[Unknown]	The Boeing Company	Communications	LEO: 132 GEO: 15	LEO: ~1,056 km GEO: ~27,355-44,221 km[31]

(Table 1: Prominent satellite mega-constellation projects announced, under development or having entered the deployment phase by March 2022)

3.2 Private space launches

Similarly without an authoritative definition in place, in this Report 'private space launches' are viewed primarily from the perspective of space transportation via terrestrially based launchers under control of private (commercial) entities or individuals. As such, the Report focuses on private space launchers when discussing environmental impacts. Transportation services enabled by private space launchers are, for example, launch of mega-constellation and other satellites, supply missions to the International Space Station, or crewed missions for space tourism. Table 2 lists several prominent examples of private actors with space launchers under development or in operation as of March 2022:[32]

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26 Based on information in: ‘Kuiper Systems LLC Request for Experimental Authorization’ (Narrative Statement, FCC, 1 November 2021) <https://apps.fcc.gov/els/GetAtt.html?id=285359&x=.> accessed 25 March 2022; Jeff Foust, ‘Amazon unveils flat-panel customer terminal for Kuiper constellation’ (*SpaceNews*, 16 December 2020) <https://spacenews.com/amazon-unveils-flat-panel-customer-terminal-for-kuiper-constellation/> accessed 25 March 2022; Caleb Henry, ‘Amazon’s Kuiper constellation gets FCC approval’ (*SpaceNews*, 30 July 2020) <https://spacenews.com/amazons-kuiper-constellation-gets-fcc-approval/> accessed 25 March 2022; ‘Kuiper Systems LLC’ (*FCC*) <https://fcc.report/company/Kuiper-Systems-LLC> accessed 25 March 2022; ‘Project Kuiper’ (*Amazon*) <https://www.aboutamazon.com/news/tag/project-kuiper> accessed 25 March 2022.

27 Based on information in: ‘Petition of Starlink Services, LLC for Designation as an Eligible Telecommunications Carrier’ (FCC 2021) <https://ecfsapi.fcc.gov/file/1020316268311/Starlink%20Services%20LLC%20Application%20for%20ETC%20Designation.pdf> accessed 25 March 2022; Caleb Henry, ‘SpaceX submits paperwork for 30,000 more Starlink satellites’ (*SpaceNews*, 15 October 2019) <https://spacenews.com/spacex-submits-paperwork-for-30000-more-starlink-satellites/> accessed 25 March 2022; Matt Williams, ‘Starlink’s satellites will be orbiting at a much lower altitude, reducing the risks of space junk’ (*Phys.org*, 6 May 2019) <https://phys.org/news/2019-05-starlink-satellites-orbiting-altitude-space.html> accessed 25 March 2022; ‘Space Exploration Technologies Corp.’ (*FCC*) <https://fcc.report/company/SpaceX-Services-Inc> accessed 25 March 2022.

28 Based on information in: Sandra Erwin, ‘Thales Alenia selected to build Telesat’s broadband constellation’ (*SpaceNews*, 9 February 2021) <https://spacenews.com/thales-alenia-selected-to-build-telesats-broadband-constellation/> accessed 25 March 2022; ‘Telesat Canada’ (*FCC*) <https://fcc.report/company/Telesat-Canada> accessed 25 March 2022; ‘Telesat Lightspeed™’ (*Telesat*) <https://www.telesat.com/leo-satellites/> accessed 25 March 2022.

29 Based on information in: Jeff Foust, ‘European Union advances broadband constellation despite negative assessments’ (*SpaceNews*, 16 February 2022) <https://spacenews.com/european-union-advances-broadband-constellation-despite-negative-assessments/> accessed 25 March 2022; ‘Commission Staff Working Document. Impact Assessment Report. Accompanying the document Proposal for a Regulation of the European Parliament and of the Council establishing the Union Secure Connectivity Programme for the period 2022-2027 {COM(2022) 57 final} - {SEC(2022) 77 final} - {SWD(2022) 30 final}’ (SWD(2022) 30 final, European Commission, 15 February 2022) <https://ec.europa.eu/info/sites/default/files/impact_assessment_union_secure_connectivity_programme.pdf> accessed 25 March 2022.

30 Based on information in: Si-soo Park, ‘Hanwha Systems to launch 2,000 LEO communications satellites by 2030’ (*SpaceNews*, 30 March 2021) <https://spacenews.com/hanwha-systems-to-launch-2000-leo-communications-satellites-by-2030/> accessed 25 March 2022.

31 Based on information in: Jason Rainbow, ‘FCC approves Boeing’s 147-satellite V-band constellation’ (*SpaceNews*, 3 November 2021) <https://spacenews.com/fcc-approves-boeings-147-satellite-v-band-constellation/> accessed 25 March 2022.

32 ‘Small Satellite Launchers’ (*NewSpace Index*, 1 January 2022) <https://www.newspace.im/launchers.html> accessed 25 March 2022.

Private (commercial) actors	Launcher types[33]
Astra Space, Inc	Small launcher (uncrewed)[34]
Blue Origin, LLC	Suborbital launcher (crewed; reusable) Heavy launcher (crewed/uncrewed; reusable)[35]
Isar Aerospace Technologies GmbH	Small launcher (uncrewed)[36]
Rocket Lab USA, Inc.	Small launcher (uncrewed; reusable) Medium launcher (uncrewed/crewed; reusable)[37]
SpaceX	Medium launcher (uncrewed; reusable) Heavy launcher (crewed/uncrewed; reusable)[38]
Virgin Galactic	Suborbital launcher (crewed; reusable)[39]
United Launch Alliance	Heavy launchers (uncrewed; potentially crewed)[40]

(Table 2: Prominent examples of private actors with space launchers under development or in operation by March 2022)

3.3 Environmental Sustainability

There have been numerous attempts to define or describe key elements of sustainability in general and environmental sustainability in particular. This Report uses 'environmental sustainability' to mean keeping the environment free from significant adverse impacts now and for future generations - with a focus on the terrestrial and not the space environment.

This builds on the UN Brundtland Commission's prominent definition of 'sustainable development' as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."[41] It also fits the statement of a former UK Government explaining its sustainable development commitment as "making the necessary decisions now to realise our vision of stimulating economic growth and tackling the deficit, maximising wellbeing and protecting our environment, without negatively impacting on the ability of future generations to do the same."[42] The UK Government's current 25 Year Environment Plan, linking, among others, to sustainability and climate change, promotes a policy "focus[ing] on:

33 References to 'crewed' and 'reusable' are used broadly as the specifics differ greatly among the private entities. 'Crewed' includes the option to lift other actors' crewed spacecraft. 'Reusable' means either reusability of certain parts or the whole launch system.

34 Based on information in: ‘Satellite Launch Service’ (*Astra*) <https://astra.com/launch-services/> accessed 25 March 2022.

35 Based on information in: ‘New Glenn’ (*Blue Origin*) <https://www.blueorigin.com/new-glenn> accessed 25 March 2022; ‘New Shepard’ (*Blue Origin*) <https://www.blueorigin.com/new-shepard> accessed 25 March 2022.

36 Based on information in: ‘Spectrum’ (*Isar Aerospace*) <https://www.isaraerospace.com/spectrum> accessed 25 March 2022.

37 Based on information in: ‘Electron’ (*Rocket Lab*) <https://www.rocketlabusa.com/launch/electron/> accessed 25 March 2022; ‘Neutron’ (*Rocket Lab*) <https://www.rocketlabusa.com/launch/neutron/> accessed 25 March 2022.

38 Based on information in: ‘SpaceX’ (*SpaceX*) <https://www.spacex.com> accessed 25 March 2022.

39 Based on information in: Virgin Galactic, LLC, ‘Purpose of Experiment’ (FCC) <https://apps.fcc.gov/els/GetAtt.html?id=258651&x=> accessed 25 March 2022; ‘Virgin Galactic’ (*Virgin Galactic*) <https://www.virgingalactic.com/> accessed 25 March 2022.

40 Based on information in: ‘Rockets’ (*ULA*) <https://www.ulalaunch.com/rockets> accessed 25 March 2022.

41 World Commission on Environment and Development, ‘Report of the World Commission on Environment and Development: Our Common Future’ (Report 1987) 41[unpaginated] <https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf> accessed 25 March 2022. The Commission authoring this report has also been known as ‘Brundtland Commission’.

42 Defra FOIA and EIRs Team, ‘REQUEST FOR INFORMATION: Government Definitions of Sustainability’ (Letter, DEFRA, HM Government, 16 February 2015) 1[unpaginated] <https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/404521/RFI_7241_-_20150216_Government_Definitions_of_Sustainability_Redacted__2__amended.pdf> accessed 25 March 2022.

- Using and managing land sustainably[;]
- Recovering nature and enhancing the beauty of landscapes[;]
- Connecting people with the environment to improve health and wellbeing[;]
- Increasing resource efficiency, and reducing pollution and waste[;]
- Securing clean, productive and biologically diverse seas and oceans[; and]
- Protecting and improving the global environment[.]"[43]

Lastly, the Environmental Protection Agency (EPA) in the United States holds that "[t]o pursue sustainability is to create and maintain the conditions under which humans and nature can exist in productive harmony to support present and future generations."[44] Notably, DEFRA and EPA each have considered various indicators to assess environmental impacts.[45]

Using the above, this Report finds that environmental sustainability impacts of mega-constellations and private space launches can be categorised into the following broad categories:

- Natural resource consumption;
- Local environmental pollution;
- Local noise pollution and radio frequency exposure;
- Light pollution; and
- Changes to composition of the atmosphere, including climate change impact.

4 Environmental sustainability impacts

While some academic research and regulatory considerations for environmental impacts of space activities exist, research for this Report indicates that holistic, in-depth, peer-reviewed and transparent studies on environmental sustainability impacts of satellite mega-constellations and private space launchers in the UK and beyond remain absent. Previous academic research has mostly focused on evaluating the environmental impact of one actor's specific activity, or a particular satellite or launcher aspect such as rocket emissions. Environmental studies required in the context of licensing procedures are generally provided by those requesting a licence and usually lack holistic views by focusing on the licence-specific space activity. They can form part of future studies but should be critically interpreted.[46]

43 HM Government, 'A Green Future: Our 25 Year Plan to Improve the Environment' (2018) 23 <https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/693158/25-year-environment-plan.pdf> accessed 25 March 2022.

44 'Learn About Sustainability' (*EPA*) <https://www.epa.gov/sustainability/learn-about-sustainability> accessed 25 March 2022.

45 See e.g.: DEFRA, HM Government, 'Measuring environmental change: outcome indicator framework for the 25 Year Environment Plan' (May 2019) <https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/925779/25-yep-indicators-2019.pdf> accessed 25 March 2022; 'Explore ROE Indicators' (*EPA*) <https://cfpub.epa.gov/roe/indicators.cfm> accessed 25 March 2022.

46 ISPL expertise.

Consultation of available material and dedicated research interviews with selected experts at ICL and beyond suggest the following essential known and potential - local and global - impacts of mega-constellations and private space launchers on terrestrial environmental sustainability that decision-makers need to take into account. All these impacts require further study to arrive at a synoptic short- and long-term understanding, and to enable development of reasonable solutions, ultimately benefiting all on Earth.

4.1 Natural resource consumption

Resource consumption for satellite and launcher production, testing and use: Production, testing and use of mega-constellation satellites and private space launchers consume finite natural resources, including in the form of energy that is usually produced by consuming natural resources such as coal, gas, krypton, oil, water, and xenon. The prospective number of mega-constellation satellites and private space launchers will result in an increase in consumption of such resources. One needs to only consider that each unit of the earlier[47] Starlink satellite version reportedly weighed around 227 kg, while the current[48] ones each weigh about 260-295 kg. The next generation[49] might each weigh even more, with one news article putting it at potentially between 850-1250 kg. A constellation of around 42,000 Starlink satellites of 227 kg would amount to the consumption of 9,534,000 kg (9,534 t) of material, including Hall thrusters using krypton[50] for orbital manoeuvring. This is not taking account of resources wasted in production, testing, and launch, and of need to replace and launch replacements for de-orbited or non-functional satellites throughout the constellation's lifetime, further increasing the constellation's overall consumption of finite natural resources.[51] Starlink launches have so far mainly involved SpaceX's Falcon 9 launchers with a launch capacity of up to around 60 units of the earlier satellite version, and will in the future also involve its Starship with a reported potential capacity of up to around 120 units of the next satellite generation.[52]

Reusability and recycling of de-orbiting mega-constellation satellites and private space launchers to reduce overall natural resource consumption still remain limited. While some progress has been made by a growing

47 Stephen Clark, ‘SpaceX releases new details on Starlink satellite design’ (*Spaceflight Now*, 15 May 2019) <https://spaceflightnow.com/2019/05/15/spacex-releases-new-details-on-starlink-satellite-design/> accessed 25 March 2022.

48 ESPI (2022) (24) ESPI Insights. Space Sector Watch 14 <https://espi.or.at/component/jdownloads/send/72-espinsights/602-espi-insights-february-2022> accessed 25 March 2022; Adam Mann and Tereza Pultarova, ‘Starlink: SpaceX’s satellite internet project’ (*Space.com*, 7 January 2022) <https://www.space.com/spacex-starlink-satellites.html> accessed 25 March 2022.

49 Eric Ralph, ‘SpaceX says Starship will launch the next generation of Starlink satellites’ (*TESLARATI*, 19 August 2021) <https://www.teslarati.com/spacex-starship-next-generation-starlink-satellites/> accessed 25 March 2022.

50 Clark (n 47).

51 Based on ISPL expertise, information provided during interviews with selected experts at ICL and beyond in February 2022, and previous findings in: Beischl (n 2) 13–15. For some indication of the satellite and launcher production cycles behind the deployment of mega-constellations, see: Cat Hofacker, ‘How to make a megaconstellation’ (*Aerospace America*, March 2020) <https://aerospaceamerica.aiaa.org/features/how-to-make-a-megaconstellation/> accessed 25 March 2022; Caleb Henry, ‘Three rules for building a megaconstellation’ (*SpaceNews*, 8 July 2019) <https://spacenews.com/three-rules-for-building-a-megaconstellation/> accessed 25 March 2022.

52 Mann and Pultarova (n 48); Ralph (n 49); Clark (n 47).

number of private actors developing reusable launchers or parts thereof,[53] there is, due to technological complexity, a long way to go before reusable launch technology dominates the field, especially when it comes to fully reusable satellite launchers. Also, the launchers or parts thereof designed for reusability still have to undergo rigorous checks and repairs before being used again, consuming at least some finite natural resources. At this stage there is little or no recycling of de-orbiting mega-constellation satellites and non-reusable launchers or their parts. These are usually designed to burn up completely, or at least substantially, in the Earth atmosphere when they reach their end-of-life. Operators commonly try to have elements surviving re-entry fall into the ocean or uninhabited areas, not enabling reasonable recycling options.

Resource consumption for extraction and transportation of particular resources relevant for, and during storage and transport of satellites and launchers: Terrestrial extraction and transport of the particular natural resources required for mega-constellation satellite and private space launcher production, testing and use, and terrestrial storage and transport - from production to launch sites - of satellites, launchers or their parts involve consumption of finite natural resources. This consumption increases with the number of mega-constellation satellites and private space launchers.

Resource consumption for ground station and launch site construction and operation: Construction and operation of ground stations and launch sites to operate satellite constellations and private space launchers also consume finite natural resources.

Resource consumption for satellite constellation user equipment production, storage, transport and operation: All end users of satellite mega-constellations offering communications services usually need to locally set up certain equipment such as a dedicated terminal to receive signals from and connect with constellation satellites. Such equipment, in the case of Starlink a dish reportedly weighing around 4.2 kg[54] in its latest version, needs to be produced, stored, transported and operated, adding to satellite mega-constellations' overall consumption of finite natural resources. With various constellation operators hoping for customers globally, this should not be ignored from an environmental sustainability perspective.[55]

Resource consumption for environmental studies: Lastly, dedicated environmental studies of satellite mega-constellations or private space launchers themselves potentially leave a high environmental footprint,

53 E.g. see the launcher reusability references in Table 2 in this Report's Section 3.2.
54 Jon Brodkin, 'Starlink's new Dishy McFlatface is smaller and lighter, still costs $499' (*Ars Technica*, 12 December 2021) <https://arstechnica.com/information-technology/2021/11/starlink-unveils-2nd-generation-satellite-dish-and-new-wi-fi-router/> accessed 25 March 2022.
55 Based on ISPL expertise, information provided during interviews with selected experts at ICL and beyond in February 2022, and previous findings in: Beischl (n 2) 13–15.

including natural resource consumption.[56] It is, however, not a strong argument against conducting those. Without them, there is the risk to overlook more serious environmental sustainability impacts.

4.2 Local environmental pollution

Local environmental pollution due to toxic satellite and launcher production by-products: Toxic waste material can be a by-product of mega-constellation satellite and private space launcher production, jeopardising environmental sustainability, e.g. in the form of severe soil pollution, if there is no appropriate disposal mechanism in place. The expansion of satellite and launcher production can increase the amount of toxic by-products. If such mechanism exists but is burdensome or expensive, there is the danger that involved parties try to circumvent it by moving problematic production aspects into countries with lax environmental regulations, facilitating this particular local environmental pollution.

Local environmental pollution due to toxic fuel storage and release of toxic exhausts and particles during launch: The number of annual launches, including the use of private space launchers, required for the deployment and replenishment of the various current or proposed satellite mega-constellations will lead to increased fuel storage and release of exhausts and particles around local launch sites and flight paths. The expanding usage of private space launchers for space tourism and other activities will further add to local fuel storage and exhaust and particle levels. This will amplify the risk of local environmental pollution if the stored fuel or produced exhausts and particles are toxic or lead to toxic reactions. For example, certain exhausts and particles can cause local air pollution or acid rain. Fuel leakages, either intentional, e.g. due to cyber attacks, or unintentional, e.g. due to accidents, can heavily pollute local soil. Lax local regulations raise the local environmental pollution risks further.

Local environmental pollution due to launch accidents and direct hits by satellite and launcher parts surviving atmospheric re-entry: While mega-constellation satellites and non-reusable private space launchers are often designed to burn-up completely or substantially upon re-entry into the atmosphere,[57] there is no guarantee that some surviving parts do not hit environmentally sensitive areas on Earth's surface and cause local pollution, on land and at sea. Notably, propulsion tanks are often designed to withstand strong forces and shaped in a way that makes them act like ballistic objects. Besides parts surviving re-entry, there could be launch accidents spreading satellite and launcher parts over a certain area. The resulting

56 Somewhat indicated in: 'Commission Staff Working Document. Impact Assessment Report. Accompanying the document Proposal for a Regulation of the European Parliament and of the Council establishing the Union Secure Connectivity Programme for the period 2022-2027 {COM(2022) 57 final} - {SEC(2022) 77 final} - {SWD(2022) 30 final}' (n 29) 34–35.

57 For example, Starlink satellites shall become fully demisable upon re-entry into the atmosphere: 'Space Exploration Holdings, LLC Request for Modification of the Authorization for the SpaceX NGSO Satellite System' (FCC 21-48, Order Authorization, FCC 2021) 47 <https://docs.fcc.gov/public/attachments/FCC-21-48A1.pdf> accessed 25 March 2022.

environmental pollution becomes especially an issue if surviving parts carry toxic material, e.g. hydrazine fuel or radioactive material. Additionally, whether toxic or non-toxic material is involved, direct collision with certain terrestrial infrastructure by surviving mega-constellation satellite or private space launcher parts can significantly pollute the local environment if they hit infrastructure such as chemical storage tanks. The overall risk will arguably increase with the number of spent private space launchers and constellation satellites re-entering Earth's atmosphere, which is the current trend. Uncontrolled re-entries, which account for most, make it also more complicated to prepare or react to these events in time. Unwillingness of operators to provide information on the end-of-life of their constellation satellites and private space launchers can further complicate timely preparations or reactions. Lax local regulations enhance these environmental pollution risks.[58]

4.3 Local noise pollution and radio frequency exposure

Local noise pollution by satellite and launcher production, testing, and launch activities: Production and testing of mega-constellation satellites and private space launchers, as well as the frequent launches, involving private space launchers, required to deploy and replenish satellite mega-constellations or conduct other activities such as space tourism, can induce high stress to wildlife around local production, test and launch sites through noise pollution. The current trend suggests that such noise pollution will continue to grow.[59]

Local radio frequency exposure by satellite transmissions: While research for this Report did not come across information that suggests immediate concern to environmental sustainability, it should be pointed out that satellite mega-constellations create radio frequency exposure.[60] Involved actors need to make sure the satellite constellation deployments do not to exceed safe local limits now and in the future.

58 Based on ISPL expertise, as well as information provided during interviews with selected experts at ICL and beyond in February 2022 and in: Aaron C Boley and Michael Byers, 'Satellite mega-constellations create risks in Low Earth Orbit, the atmosphere and on Earth' (2021) 11 Scientific Reports <https://www.nature.com/articles/s41598-021-89909-7> accessed 25 March 2022; Beischl (n 2) 13–15; Debra Werner, 'Aerospace Corp. raises questions about pollutants produced during satellite and rocket reentry' (*SpaceNews*, 11 December 2020) <https://spacenews.com/aerospace-agu-reentry-pollution/> accessed 25 March 2022; Department of Transport, HM Government, 'Guidance to the regulator on environmental objectives relating to the exercise of its functions under the Space Industry Act 2018. Given by the Secretary of State under section 2(2)(e) of the Space Industry Act 2018' (2021) 10,14-16,22-26 <https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/995153/guidance-to-the-regulator-on-environmental-objectives-relating-to-the-exercise-of-its-functions-under-the-space-industry-act-2018.pdf> accessed 25 March 2022; Ron Macbeth, 'Spaceports: keeping people safe' (PE06415/8, Health and Safety Laboratory, 28 September 2018) <https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/780509/Spaceports_keeping_people_safe.pdf> accessed 25 March 2022; the Federal Communications Commission (FCC) assesses risks of human casualty from surviving elements, taking into account factors such as material composition and kinetic energy at impact: 'Space Exploration Holdings, LLC Request for Modification of the Authorization for the SpaceX NGSO Satellite System' (n 57) 47; Fourie and others are concerned about mercury emissions during space activities: Dan Fourie and others, 'Are mercury emissions from satellite electric propulsion an environmental concern?' (2019) 14 Environmental Research Letters <https://iopscience.iop.org/article/10.1088/1748-9326/ab4b75/pdf> accessed 25 March 2022.

59 Based on ISPL expertise, as well as information provided during interviews with selected experts at ICL and beyond in February 2022 and in: Department of Transport, HM Government (n 58) 10,16-22.

60 'Space Exploration Holdings, LLC Request for Modification of the Authorization for the SpaceX NGSO Satellite System' (n 57) 51.

4.4 Light pollution

Light pollution: Publicly available information indicates that most mega-constellation satellites are to be situated in LEO. Satellites are known to reflect sunlight, making them appear very bright in the (night) sky. This light pollution is a problem for astronomical observations conducted from Earth. There are also concerns that such light pollution leads, in the long run, to detrimental effects on human health and terrestrial ecology. There are animals that navigate by aspects of the sky such as star patterns. Their sense of orientation could be impacted.[61]

4.5 Changes to composition of the atmosphere, including climate change impact

Changes to composition of the atmosphere, including climate change impact: The research for this Report suggests that satellite mega-constellations and private space launchers have at this time a much smaller impact on Earth's atmosphere and climate than other human activities, e.g. aviation, and natural phenomena, e.g. volcanic activities. However, the individual space activity can have a higher impact than an individual aviation activity.

There is concern that the increasing number of private space launchers required to deploy and replenish satellite mega-constellations, for space tourism and other space transport services, and the eventual burn-up of increasing numbers of de-orbiting mega-constellation satellites and private space launcher parts could cumulatively lead to critical upsurge of particles and gases[62] in the atmosphere affecting environmental sustainability. For example, some particle and gas release is linked to radiative forcing and ozone depletion that can advance climate change. Some release could affect global circulation and cloudiness patterns. Generally speaking, the higher the particles and gases are released, the longer they will stay in the atmosphere. With still rather limited research available, the overall and specific short- and long-term consequences for the atmosphere and Earth's climate remain uncertain or unknown.[63]

61 Based on ISPL expertise, as well as information provided during interviews with selected experts at ICL and beyond in February 2022 and in: 'Viasat asks FCC to halt Starlink launches while it seeks court ruling' (*SpaceNews*, 25 May 2021) <https://spacenews.com/viasat-asks-fcc-to-halt-starlink-launches-while-it-seeks-court-ruling/> accessed 25 March 2022; 'Space Exploration Holdings, LLC Request for Modification of the Authorization for the SpaceX NGSO Satellite System' (n 57) 47–50; Beischl (n 2) 13–15; for a broader discussion of the impact of light pollution, see e.g.: Patrizia Caraveo, *Saving the Starry Night. Light Pollution and Its Effects on Science, Culture and Nature* (Springer 2020); for some more information on animals using aspects of the sky to navigate, see e.g.: Fiona McMillan, 'From dung beetles to seals, these animals navigate by the stars' (*National Geographic*, 4 November 2019) <https://www.nationalgeographic.com/animals/article/stars-milky-way-navigation-dung-beetles> accessed 25 March 2022.

62 These include aluminium, black carbon, carbon dioxide, chlorine, hydrogen oxides, nitrogen oxides, soot, and water vapour.

63 Based on ISPL expertise, as well as information provided during interviews with selected experts at ICL and beyond in February 2022 and in: Mann and Pultarova (n 48); Boley and Byers (n 58); 'Viasat asks FCC to halt Starlink launches while it seeks court ruling' (n 61); Jason Rainbow, 'Connecting the Dots | Assessing top-down pollution' (*SpaceNews*, 3 May 2021) <https://spacenews.com/connecting-the-dots-assessing-top-down-pollution/> accessed 25 March 2022; 'Space Exploration Holdings, LLC Request for Modification of the Authorization for the SpaceX NGSO Satellite System' (n 57) 45–47; Beischl (n 2) 13–15; Shelia Scott Neumnann, 'Environmental Life Cycle Assessment of Commercial Space Transportation Activities in the United States' (PhD thesis, The University of Texas at Arlington, United States of America, May 2018) <https://rc.library.uta.edu/uta-ir/bitstream/handle/10106/27352/NEUMANN-DISSERTATION-2018.pdf> accessed 25 March 2022; Martin Ross and James A Vedda, 'The Policy and Science of Rocket Emissions' (Center for Space Policy and Strategy, The Aerospace Corporation, April 2018) <https://csps.aerospace.org/sites/default/files/2021-08/RocketEmissions_0_0.pdf> accessed 25 March 2022; Slimane Bekki and others,

One estimation is that around 60-90% of de-orbiting satellites' and around 60% of re-entered non-reusable launchers' mass is added to the atmosphere during their burn-up.[64] Exhausts and particles released during launch contribute further mass.

Boley and Beyers argue in their article that "[m]odelling of the cumulative effect of emissions from 1000 annual launches of hydrocarbon-fuelled rockets found that, after one decade, the black carbon would result in radiative forcing comparable to that resulting from sub-sonic aviation." Being aware that 1000 annual launches of such rockets goes much beyond present activity, they point out deployment and replenishment of the various mega-constellation projects will necessitate a significant increase of launches and there will be some impact. They further deliberate that "12,000 [Starlink] satellites will total 3100 tonnes", suggesting that "[a] 5-year cycle would see on average almost 2 tonnes re-entering Earth's atmosphere daily. [... D]epending on the atmospheric residence time of material from re-entered satellites, each mega-constellation will produce fine particulates that could greatly exceed natural forms of high-altitude atmospheric aluminum deposition, particularly if the full numbers of envisaged satellites are launched." They also assert that establishing the many satellite mega-constellations amounts to an uncontrolled experiment on geoengineering considering that proposals to change Earth's albedo include the idea of human-induced atmospheric deposition of aluminium.[65]

In keeping with the above, in recent years there have been various public calls for comprehensive studies of such activities' atmospheric impacts. For example, according to a January 2022 news article, David Fahey, the director of the National Oceanic and Atmospheric Administration's Chemical Sciences Laboratory, and Martin Ross at The Aerospace Corporation hold "that more research is urgently needed to understand the effects of burning increasing amounts of satellites in the atmosphere."[66] The Aerospace Corporation's William Ailor was quoted in late 2020 that "[o]ur preliminary work suggests that given the present and anticipated increase in large satellite constellations, there is potential for environmental impact, and further study is therefore recommended. [... T]he space enterprise has seen little environmental oversight, and continuing space operations without reliably quantifying and mitigating for its environmental impacts has costs."[67]

'Impacts of space vehicles' launch & re-entry on the ozone layer and climate' (Presentation, Clean Space Industrial Days & AeroThermoDynamics Design for Demise Workshop, ESTEC, 24-26 October 2017, 24 October 2017) <https://indico.esa.int/event/181/contributions/1487/attachments/1318/1543/01_2017_CSID_Bekki_CNRS.pdf> accessed 25 March 2022; Erik JL Larson and others, 'Global Atmospheric Response to Emissions from a Proposed Reusable Space Launch System' (2017) 5 Earth's Future 37.

64 Werner (n 58); notably, Starlink satellites shall become fully demisable upon re-entry into the atmosphere: 'Space Exploration Holdings, LLC Request for Modification of the Authorization for the SpaceX NGSO Satellite System' (n 57) 47.

65 Boley and Byers (n 58).

66 Mann and Pultarova (n 48).

67 It was in the context of a news article covering a poster presentation on 'Environmental Impact of Satellites from Launch to Deorbit and the Green New Deal for the Space Enterprise': Werner (n 58); the abstract to the presentation can be found here: M Hobbs and others, 'Environmental Impacts of Satellites from Launch to Deorbit and the Green New Deal for the Space Enterprise' [2020] AGU Fall Meeting Abstracts <https://ui.adsabs.harvard.edu/abs/2020AGUFMGC0420004H> accessed 25 March 2022.

5 Core Policy Recommendations

In addition to raising awareness of above essential known and potential - local and global - impacts of mega-constellations and private space launchers on terrestrial environmental sustainability, this Report puts forward the following core policy recommendations to relevant decision-makers in the UK and beyond to ensure such sustainability.

1) **Putting out an immediate call for holistic, in-depth, peer-reviewed and transparent studies evaluating and providing solutions to the identified essential environmental sustainability impacts of satellite mega-constellations and private space launchers in the UK and beyond.**

As mentioned in Section 4, research for this Report suggests that there are no holistic, in-depth, peer-reviewed and transparent studies on the identified essential environmental sustainability impacts of satellite mega-constellations and private space launchers in the UK and beyond. Previous academic research has mostly focused on evaluating the environmental impact of one actor's specific activity, or a particular satellite or launcher aspect such as rocket emissions. Environmental studies required in the context of licensing procedures are generally provided by those requesting a licence and usually lack holistic views by focusing on the licence-specific space activity.

With evermore increasing numbers of satellite mega-constellations and private space launchers, a cumulative perspective of all these activities and their environmental sustainability impacts is urgent to avoid mistakes of the past, e.g. the now burdensome tackling of acid rain as a consequence of the excessive anthropogenic release of sulphur dioxide and nitrogen oxide into Earth's atmosphere. There is no present knowledge of the environmentally significant tipping point of the creation and use of a growing number of satellite mega-constellations and private space launchers. In particular, it is critical to gain a better understanding of their impact on the composition of the atmosphere, including climate change impact, and natural resource consumption.

The promoted future research does not need to start from zero. It can and should take into account previous findings and recommendations.[68] For example, concerning rocket emissions, Ross and Vedda hold that "[a] vigorous research program should incorporate global atmospheric models (e.g., for ozone loss, climate forcing, and pollutant interaction) and include the following components:

- Stratospheric plume measurements using in situ and remote sensing instruments[;]
- Lab measurements to validate propellant-specific emissions and interactions[;]

68 Various literature is linked under the specific Report sections.

- Engine test stand measurements to determine bulk properties and measure exit plane exhaust composition[; and]
- Application of state of the art global chemistry and climate models using measured emissions and likely launch growth scenarios[.]"[69]

In the UK, such a call for studies aligns with the Government's 25 Year Environment Plan "on [...]

- Increasing resource efficiency, and reducing pollution and waste[;]
- Securing clean, productive and biologically diverse seas and oceans[; and]
- Protecting and improving the global environment[.]"[70]

It is also consistent with the NSS declaration that the UK "will continually improve safety standards, implement relevant consents, and mitigate the negative environmental impacts of our space activities."[71]

Advanced knowledge of environmental sustainability impacts due to UK promoted studies will allow the UK to play a leading role in international environmental policy and law-making concerning satellite mega-constellations and private space launchers.

UK academic institutions such as ICL have excellent facilities and experts, from environmental, climate to space (launch) engineering experts and a large student body to take on and lead such studies, producing relevant evidence-based information. For example, ICL already has an interdisciplinary Space Lab network of excellence in place. ICL experts have, among others, engaged in Environmental Impact Assessments and other risk assessments, foresight activities, climate change research, modelling of re-entry and demisability of satellites and launchers, investigation of eco-friendly satellite material and propulsion options, and research on flexibility and optimisation under uncertainty.[72]

2) **Establishing a national or international research hub focusing on environmental sustainability impacts of space activities, including satellite mega-constellations and private space launchers in the UK and beyond.**

Environmental impacts of space activities will remain a constant issue for the foreseeable future. New or expansion of certain activities can also create new challenges. Having established a research hub focusing on impacts of space activities, including the growing range of satellite mega-constellations and private space

69 Ross and Vedda (n 63) 9.
70 HM Government (n 43) 23.
71 HM Government (n 11) 26.
72 Based on information provided during interviews with selected experts at ICL in February 2022 and previous findings in: Beischl (n 2) 13–15; Beischl (n 1) 9–12; as an example for ICL expertise in water propulsion solutions, see its involvement in URA Thrusters: ‘About us’ (*URA Thrusters*) <https://www.urathrusters.com/about-us/> accessed 25 March 2022.

launchers, would significantly reduce the time to organise research, work on holistic perspectives on environmental impacts, and establish timely solutions.

Such research hub can have a beneficial effect for the UK and other states' economy because its research output can provide prospective actors in the respective space sector with useful information and tools to conduct environmental assessments required under local regulations such as the UK's Space Industry Act 2018. This can reduce involved actors time and monetary investment. Additionally, research findings can trigger development of green technology in the UK, strengthening and future-proofing the UK space industry.

Similarly, ICL facilities and experts can make valuable contributions within such a hub. Depending on its setup and organisational requirements, ICL could even play a central organisational role.[73]

3) **Fostering investment and engagement domestically and through the European Space Agency (ESA) in the development of green space technology for satellite mega-constellations and private space launchers.**

Development of green space technology supports dealing with several identified essential environmental sustainability impacts of satellite mega-constellations and private space launchers, and enables hedging against further problematic findings in the future. For example, green technology development benefits tackling natural resource consumption, local environmental pollution, and changes to composition of the atmosphere, including climate change impact. Even small mitigation measures against environmentally harmful impacts can, cumulatively, contribute to ensuring environmental sustainability. Also, to arrive at mature technology, small steps are often the starting point. Interesting technologies in this regard are green fuel, manufacturing aimed towards resource utilisation optimisation, fully reusable private space launchers, fully demisable private space launchers and mega-constellation satellites that do not release potentially problematic particles and gases into the atmosphere during burn-up, and the option for in-orbit servicing and recycling of mega-constellation satellites and private space launcher parts.

For the UK, it is reasonable to invest and engage more fully in ESA's EcoDesign branch[74] as the UK is already a member of ESA and the branch offers international exchange of expertise, a cornerstone of modern

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73 Based on ISPL expertise and information provided during interviews with selected experts at ICL and beyond in February 2022.

74 For more information on the EcoDesign branch, see: ‘ecodesign’ (*ESA*) <https://www.esa.int/Safety_Security/Clean_Space/ecodesign> accessed 25 March 2022; Beischl (n 1) 10–11.

scientific research. Arguably, cooperative investment and engagement of UK and other European entities also lowers individual research costs and leads to faster results.[75]

As indicated before, ICL has expertise in the development of green technology for space and beyond. For example, it has researchers engaging in the development of green satellite propulsion.[76]

4) **Promoting information transparency of actors involved in satellite mega-constellations and private space launchers.**

Linked to the above, research on environmental sustainability impacts of satellite mega-constellations and private space launchers and related solutions requires much data and information from involved actors. The UK and other states should promote data and information transparency to researchers as much as possible, including requiring industry to timely provide information of material composition of private space launchers and mega-constellation satellites and re-entry trajectories.[77]

5) **Establishing strong incentives in the UK and elsewhere to ensure environmental sustainability without causing actors involved in satellite mega-constellations and private space launchers fleeing to flag-of-convenience jurisdictions.**

Some states such as the UK have already put forward guidances concerning domestic licencing procedures that take account of certain environmental impacts of space activities.[78] While stricter regulatory requirements would be favourable to ensure environmental sustainability, this is currently unlikely due to the strong political support for NewSpace in many states. Until potential future research findings trigger the establishment of stricter requirements in the UK and beyond, it is a reasonable approach to offer actors involved in satellite mega-constellations and private space launchers some incentives such as reduced licencing costs to make them more open to employing primarily environmental friendly technology, while avoiding flag-of-convenience approaches by them.[79]

75 Based on ISPL expertise and information provided during interviews with selected experts at ICL and beyond in February 2022.
76 Beischl (n 1) 11–12.
77 Based on ISPL expertise and information provided during interviews with selected experts at ICL and beyond in February 2022.
78 See e.g.: 'Guidance for the assessment of environmental effects' <https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/904454/guidance-for-the-assessment-of-environmental-effects..pdf> accessed 25 March 2022; Department of Transport, HM Government (n 58).
79 Based on ISPL expertise and information provided during interviews with selected experts at ICL and beyond in February 2022.

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Research and Preparation

This Report was researched and drafted by Christoph Beischl, PhD, Associate Deputy Director, ISPL.

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