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Space Possibilities for Our Grandchildren: Current and Future Economic Uses of Space

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Space Possibilities for Our Grandchildren: Current and Future Economic Uses of Space

Alessio Terzi and Francesco Nicoli

Abstract

For too long, space has been dismissed as a science endeavour at best, and a delusionary science fiction fantasy at worst. In this paper, we make three fundamental points. First, with strong commercial activity taking place in Low Earth Orbit since the late 1980s, space already today is a market-place and therefore responds predominantly to economic incentives. Second, launch costs have been on a very steep downward trend hitherto, even by historical comparison to other transport technologies. Under a set of credible quantitative scenarios, leveraging Wright's Law, we show how these costs are likely to drop further in a significant way by the end of this decade, and more so in the 2030s. Looking at it through a trade economics framework, we argue that we are entering a period where (space) trade frictions are falling, and new markets will be created as a result. Third, we propose a taxonomy to help think about the creation of further value added in space going forward. For all these reasons, we maintain that space should be worth of greater attention by the economics profession.

JEL Classification: B27, D23, F10, F50, H54.

Keywords: space economy, economic growth, trade theory, innovation, GDP.

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"*How many things have been denied one day, only to become realities the next!*"

Jules Verne, From Earth to the Moon, 1865

1. INTRODUCTION

We stand at the dawn of a new era in space exploration and utilisation. Understanding the economic implications of the expansion of human activities into space is therefore essential. A new economic domain is rapidly unfolding, with momentous (geo-)political, security and economic implications. This new domain of economic competition will generate new opportunities for people, profit and power (Rementeria, 2022), but also open up new challenges, requiring policy-makers' focus and action (Pelton, 2016; Johnson-Freese, 2017; Sasaki, 2022). In our view, the economics profession should rapidly get up to speed with this momentous development with far reaching implications, which is one of the aims of this paper.

Humanity first reached space 70 years ago, mostly driven by the pursuit of science, national security considerations, and a desire to showcase technological superiority during the Cold War era. Today, near-earth orbital space is rapidly evolving into a realm of significant economic opportunities (Pelton, 2016). Multiple actors in the private sector, from the United States to Europe, China, Japan, India and beyond are attempting to exploit this trend, as witnessed by the steady growth of space-related startups (SpaceTech Analytics, 2022). In parallel, China has inserted space in its flagship Belt and Road Initiative, under the Spatial Information Corridor programme, with the goal of promoting Chinese economic growth through the expansion of its space-related activities (Sasaki, 2022; Nature, 2023). Close to 80 countries now have registered satellites in space (OECD, 2022). The race to return to the Moon before the end of the decade is already on, and, at least for the US, it will be executed mostly by the private sector (Schrunk *et al.*, 2008; Marcuzzi and Terzi, 2019). The government-owned International Space Station (ISS) will retire by the end of the decade, and is currently scheduled to be replaced by a combination of private (modular) space stations that will allow the continuation of scientific experiments in Earth's orbit (National Science and Technology Council, 2023).

The enthusiasm is not universally shared, especially among the public. A recent PEW Research survey shows that many still question the utility of space exploration, often citing pressing issues on Earth, such as climate change, as deserving more attention and resources (Kennedy and Tyson, 2023). This scepticism is further fuelled by the current carbon-intensive nature of space ventures and their association with the ultra-wealthy, thus framing space exploration as an environmental burden and a playground for the elite.

Despite these reservations, the economic potential of space is manifest, particularly in Low Earth Orbit (LEO, between 160 km and 2,000 km of altitude). More objects have been launched into space in the last five years than in the preceding six decades. The price of reaching LEO has decreased, and the space sector has become one of the fastest areas of investment growth in western economies. This structural change in pace has been associated with a continued rise of private actors in the space economy, with the result that by now close to 80% of satellites in orbit are commercial.

Existing attempts to quantify and classify the 'space economy,' such as the OECD (2012, 2022), or reports by Bryce Tech (2023) and the European Investment Bank (2019), do not necessarily focus on the economic uses of space, but rather attempt to include in their classifications everything that loosely relates to space activities. While these exercises are useful to understand the overall importance of space in today's world economy, they have some limitations. Conceptually, space activities respond to very specific economic dynamics not necessarily shared by Earth-based, space-related economic activities. Empirically, if one is interested in the genuine economic use of space, these accounts offer a somewhat inflated picture of the space economy, as they include activities only tangentially related to space, such as satellite-enabled precision agriculture, banking services[1], or weather forecasting.

[1] For instance, a third of ATM banking systems in India depend on satellite communication (Pelton, 2016, p. 112).

What are the actual economic uses of space? Under which economic conditions will they emerge? This paper offers a new analytical framework to think about the economic uses of space, shedding light on the ways its unique properties can be harnessed for economic benefit. Rather than treating space as an economic sector, we believe a better way of thinking about the space economy is as a (market)place. We draw comparisons and lessons from theories of international trade, which over the past hundred years have developed sophisticated models to account for difficulties of access, such as barriers and distance, and modelled how these impact relative and absolute advantages of production. We therefore echo Krugman (2010), who used space trade as thought experiment to discuss international trade[2], while turning however the logic around and using international trade to understand the economics of space.

While technical, military and business reports on the space economy are legion, the economics literature on space is rather scant, particularly outside of narrow field journals[3]. Interest in attempting to quantify the commercial implications of space exploration date back at least to Fogel (1966), who drew a comparison to the economic impact of the railroad. In other early (albeit tangential) contributions to the literature, Macauley and Toman (1991) offered a reflection on the potential of scale economies for Earth Observation data generated from space, while Butler and Doherty (1991) discussed how costs of satellites crashes onto Earth should be shared optimally. Some have taken an economic history perspective (Barbaroux and Dos Santos Paulino, 2022), discussing for instance the role of the private sector in space exploration since the 19th century (MacDonald, 2017), or in comparison to other exploratory endeavours, such as the transcontinental railroad in the 1800s in the US or the rise of commercial air transportation between 1915 and 1970s (Launius, 2014). Part of the economics of innovation literature has been devoted to the positive spillover effects of investment in space-related R&D (Jaffe, Fogarty and Banks, 1998; Kantor and Whalley, 2023), including by extending macro models with endogenous growth to include a space sector (Corrado *et al.*, 2023). Scholarship has been dedicated quite extensively to the issue of space debris (Adilov, Alexander and Cunningham, 2015; Grzelka and Wagner, 2019; Béal, Deschamps and Moulin, 2020; Rao, Burgess and Kaffine, 2020; Rouillon, 2020; Phillips and Pohl, 2021; Bongers and Torres, 2023), and economic solutions to address this negative externality problem. A recent Special Issue on the *Proceedings of the National Academy of Sciences* dedicated to space exploration and economic growth represents a substantial enrichment of the literature (Corrado, Cropper and Rao, 2023), upon which this paper builds. In terms of approach, Weinzierl (2018) comes closest to our paper, underlining the economic potential of space going forward, and proposing steps through which a marketplace could be developed in space, though focussing more on the division of labour between the market and the state.

A century ago, John Meynard Keynes wrote a fictional essay where he mused about the many things that would have been possible for humanity over the long run thanks to huge increases in productivity ahead (Keynes, 1930). He was writing it in part as a response to the ongoing economic pessimism at the time, following the beginning of the Great Depression, led by the conclusion that the great advancements characterising the 19th century were no longer replicable. We are likewise experiencing a time when several people, including in the economic profession, are drawing the conclusion that the economy is approaching long-term steady-state (at best). The reasons provided include the fact that technological progress is inexorably slowing down (Gordon, 2016; Jackson, 2021; Smil, 2023), disruptive ideas are becoming harder to generate (Bloom *et al.*, 2020; Park, Leahey and Funk, 2023), also due to slowing population growth (Jones, 2023), and abundant high-density energy sources that were instrumental to the Industrial Revolutions are coming to their end (Jancovici, 2013; Hall, Lambert and Balogh, 2014; Smil, 2017; Kallis *et al.*, 2018). All this, compounded with climate-induced extreme weather events that will substantially hit economic activity across the planet (Burke, Hsiang and Miguel, 2015; Desmet *et al.*, 2021; Carleton *et al.*, 2022), makes it look like the long-run prospects for economic growth are hopeless. Against this background and inspired by a similar spirit to Keynes' during his time, without downplaying current challenges, we "take wings into the future" offering a long-term view of humanity's likely economic progress, for the first time beyond Earth's boundaries. Indeed, we are not

[2] The very title of Krugman's foundational essay on the New Economic Geography, 'Space: the final frontier' (Krugman, 1998) clearly alludes to the similarities between global trade and orbital transportation.

[3] We performed an OpenAlex search across the general interest top economics journals identified in Oswald and Stern (2019). No article has ever been published on the space economy in leading journals of the profession. When we extended our search to all the American Economic Association journals, the count is 1.

alone in believing that the potential of space to reinvigorate economic growth, including by means of accelerated technological progress, could be large, therefore meriting further study (Weinzierl, 2023).

The remainder of this paper is organised as follows. Section 2 serves as a primer on the space economy, placing also the recent fall of launch costs in historical perspective. In Section 3, we provide fresh quantitative estimates on the possible trajectories of development of the space economy in the next two decades, based on the evolution of launch costs. Section 4 reflects on issues of accounting for the space economy. Section 5 is devoted to laying out an analytical framework and classification of the potential economic uses of space. Section 6 provides some concluding remarks and avenues for further research.

2. A PRIMER ON SPACE ACCESS

Space has long inspired wonder, captivating human imagination across civilisations, from the ziggurats of the Sumerians to the early astronomical models behind the sophisticated calendars of Ancient Egypt and the Maya. This long-standing fascination is not merely poetic but has had concrete technological ramifications. For centuries, the study of celestial bodies allowed key advancements in time-keeping and navigation that were instrumental to societal development (Trotta, 2023).

The 1950s marked a significant inflection point when human engagement with space transitioned from mere observation to active exploration, symbolised by the launch of the first artificial Earth satellite – Sputnik – in 1957. This era catalysed a wave of innovation on Earth, and led to the very establishment of the much-praised Defense Advanced Research Projects Agency (DARPA) (Mazzucato, 2021; Terzi, Sherwood and Singh, 2023). The Apollo Project (1961-1973) represented perhaps the culmination of space as a public priority during the Cold War frenzy, costing today's equivalent of $156 billion, or 2.5% of US GDP at the time (Terzi, 2022). The investments and innovations spurred by these space-related ventures had broader, downstream economic effects, enabling the development of novel technologies that found applications far beyond the space sector (Mazzucato, 2021; Kantor and Whalley, 2023; Moretti, Steinwender and Van Reenen, 2023). By some recent estimates, space sector activity in the 1960s and 1970s had large positive impacts on economic growth in the US, increasing real GDP by 2.2% on average after 20 years (Corrado *et al.*, 2023). Qualitatively, it is worth noting that the record of space patents with Earth-applications includes air and water filtration systems, natural soil decontamination techniques, high-efficiency solar cells, electric/solid-state battery enhancements, and electric aviation technology, just to name a few[4]. These technological and economic spillovers have often been used to muster support in favour of the hefty public budgets needed to engage in space exploration. Nevertheless, NASA's budget as a percentage of GDP fell substantially after the termination of Apollo, from 4% then to roughly 0.4% today (Weinzierl, 2018; Peeters, 2021).

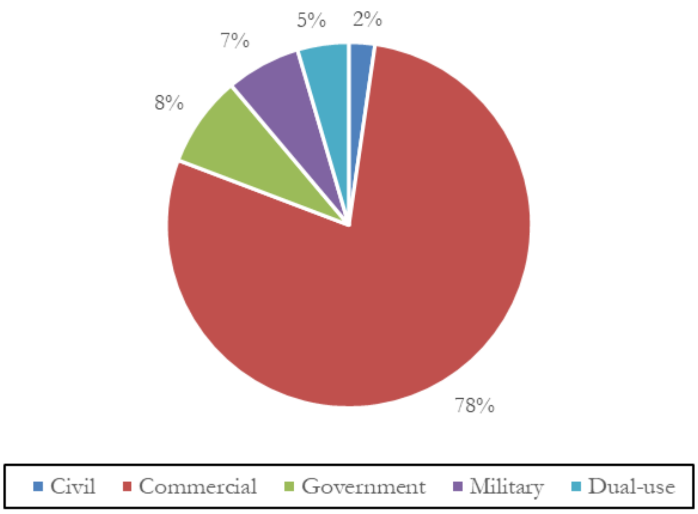
The 1960s and early 1970s were years where a Cold War-led effort into space was disputed on the ground of scientific and technological superiority, not direct military confrontation. As a matter of fact, through the UN-backed 1967 Outer Space Treaty, the Soviet Union and the United States managed to prevent a costly arms race in space, banning the deployment of nuclear weapons or other weapons of mass destruction in Earth's orbit. The 1980s, on the other hand, represented a substantial shift towards more defence applications in space, as the militaries of space-faring nations developed multi-domain defence strategies that saw space assets play a key role in observing rival areas, monitoring troops movements, ensuring communications, and detecting ballistic missile launches. For instance, the famous Global Positioning System (GPS) was rolled out by the US military throughout the 1980s, with the full constellation coming online in the mid-1990s (Duffy and Islam, 2022). While the two initial uses of space – scientific research and defence— are marked by substantial differences, they still shared a common root: the quasi-complete reliance on public budgets, being mostly overseen by public bodies.

In recent decades, however, the character of space has undergone a profound transformation, opening an era known as "New Space" (Pelton, 2016; Peeters, 2021). Its defining element is an evolution of

[4] Through its Technology Transfer Program, NASA maintains a portfolio of patents with commercial potential and makes them available to the public and accessible at: https://technology.nasa.gov/patents.

space from being the mere theatre for the pursuit of certain public objectives, to being a marketplace where economic value can be generated (Figure 1). Early signs of this shift emerged at the end of the 1980s, with the first satellite communications revolutionising global connectivity, serving as vital infrastructure for a host of industries. Yet, the economic exploitation of space remained stymied by prohibitive barriers, most notably the astronomical costs associated with launch operations. To put things into perspective, by some estimates, it cost roughly 1 billion dollars per head to transport astronauts to the International Space Station and back on the Shuttle (Duffy and Islam, 2022). This early space hype came to an abrupt stop at the end of 1990s, simultaneously with the bursting of the 'dotcom' bubble, as investors realised that costs were simply too high for many proposed space applications.

Figure 1. **Satellites orbiting Earth in 2022 by user, share of total**

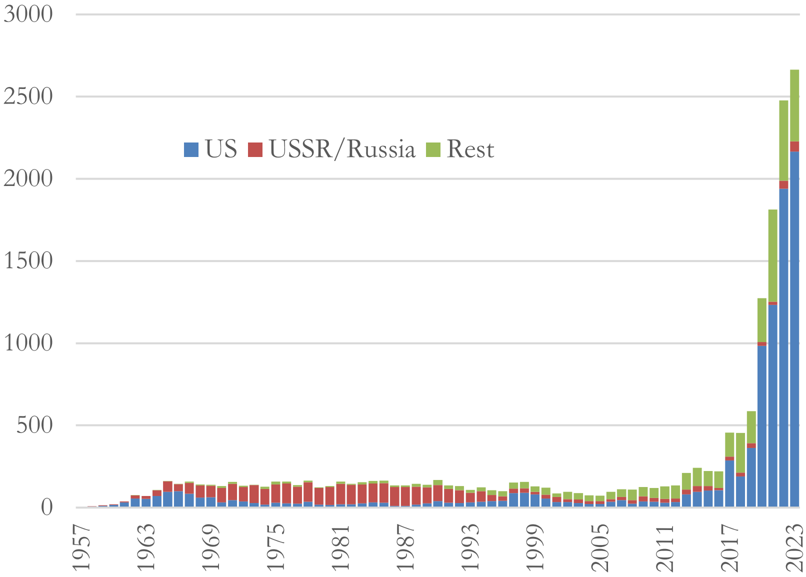


Note: Chart shows percentage shares based on the main purpose of a satellite. However, according to Johnson-Freese (2006), as much as 95% of space technology should be considered as dual-use. The recent use of SpaceX's Starlink within the context of the Ukraine war is a case in point.

Source: Authors' calculations based on Union of Concerned Scientists Satellite Database.

Since the early 2010s, investors' interest in space is experiencing a comeback. As advent of reusable rocket technology (spearheaded by SpaceX in 2016) constitutes a watershed moment in mitigating these cost constraints, the number of proposed economic applications of space has ballooned. From microgravity manufacturing of products such as fibre cable or certain medicines, to beamed solar power, to constellations of earth observation satellites, the number of proposed activities has increased enormously as the costs of access to space descended. The average cost per kg to orbit dropped from around 15.000 dollars in the early 2000s to roughly 4000 dollars in 2023. Simultaneously, the number of launches per year went from a low of 47 in 2005, to a high of 174 in 2022, and because each launch contains several satellites, the total number of objects launched in 2023 was over 2600 (Figure 2). As a result, the number of active satellites increased from about 1000 in 2000 to 7000 in 2022 (Young, 2022), dominated by the United States.

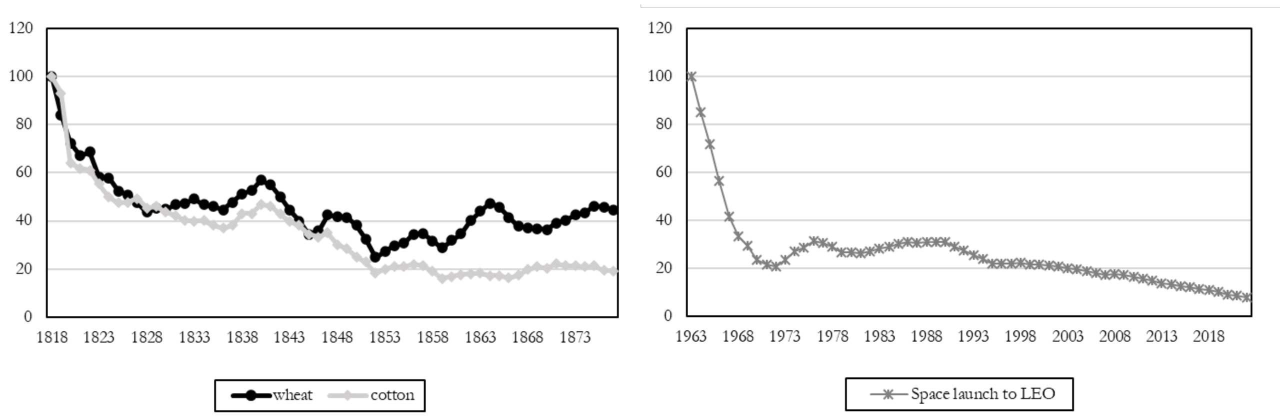
Figure 2. **Number of objects launched in Outer Space**



Note: Annual number of objects launched into space includes satellites, probes, landers, crewed spacecrafts, and space station flight elements launched into Earth orbit or beyond.
Source: Authors' elaboration based on Our World in Data.

The cost reductions associated with space launch are substantial, and therefore likely to be highly consequential (Johnson-Freese, 2017). By means of historical comparison, Figure 3 shows a 5-year rolling average for space launch into Low Earth Orbit over the past 60 years, vis-à-vis the reduction in freight costs following the introduction of steam-powered boats in the Atlantic, starting in 1819 with the SS Savannah (Smil, 2017). Over a comparable time-horizon, space launch cost reductions are quantitatively larger in scale with respect to those associated with the introduction of the steamer, which effectively paved the way for the First Wave of Globalisation. When read through these historical lenses, it should be evident that trade cost reductions of this magnitude effectively have the potential of making a variety of previously inaccessible space-based economic activities viable and profitable.

Figure 3. **Cost related to space launch, compared to historical reductions of cotton and wheat freight costs following the introduction of the steamer**



Notes: Graphs show 5-year rolling average in an index of the costs pertaining to launch into Low Earth Orbit between 1964-2023 (1963=100), cotton freight between the US and UK between 1818-1877 (1818=100), and wheat freight between the US and UK between 1818-1880 (1818=100).
Source: Authors' calculations based on own dataset and Federico and Tena-Junguito (2019).

Another way to look at it is the overall cost performance of satellites (including launch costs, but also their reduced weight, manufacturing efficiency, and so on), which over the past 15 years have been in the order of magnitude of 3500x for medium-resolution and 333x for high-resolution satellites. By means of comparison, in its first 15 years since introduction, in 1908, the much-revered Ford Model-T, which paved the way for widespread car adoption (Terzi and Fouquet, 2023), experienced a 6x improvement in cost performance (McKinsey, 2023).

It is also important to stress that the distance-cost continuum works quite differently in space than on Earth, meaning that large amounts of energy are needed to get off our planet, but once geostationary orbit is reached (about 36,000 kilometres above Earth), the gravitational pull is 1/50th of that at sea level. In other terms, from there onwards, the energy needs to reach the Moon or Mars are somewhat similar (Pelton, 2016, p. 87). In economics terms, transport in space exhibits large fixed costs and very low marginal costs.

On top of launch cost reductions, a factor that will accelerate the race to space in the 2020s is the current confrontation for military and economic supremacy between the United States and China. As things stand, much of military communication, navigation and observation capability relies on satellites. Likewise, civilian activities are increasingly relying on space, for instance for GPS location services, internet access, and in the future, autonomous transportation. For this reason, top-ranking military officials now see space, together with cyber, as a national security priority, and the likely first ground where a potential war between superpowers would be fought[5]. Promoting the development of a national space infrastructure is therefore recognised by both China and the US as urgent and fundamental (PRC National Development and Reform Commission, 2015; National Science and Technology Council, 2023). In this context, also the European Union issued its space strategy for security and defence in 2022, paving the way for the launch of a new secure communication constellation: IRIS^2 (European Commission, 2022).

Despite these numbers and the large amount of proposed space applications, in practice the majority of additional activities have fallen hitherto into the typical uses of space: telecommunications, defence, and scientific research, with the marginal recent addition of space tourism, as a few wealthy individuals have successfully contracted launch companies for tourist experiences in orbit (see Table 1).

Table 1. **Satellites orbiting Earth in 2022, by purpose**

Communications	4823
Earth Observation	1167
Tech development/demonstration	411
Navigation	154
Science	134
Other	15
Surveillance	14
Total	6718

Source: Authors' calculations based on Union of Concerned Scientists Satellite Database.

[5] In 2020, Mark Milley, America's top uniformed military official, declared that "the first shots of a future war between great powers is likely to be in space and cyber" (Manson and Shepherd, 2020).

3. FORECASTING REDUCTIONS IN BARRIERS TO SPACE

Across categories of uses of space, launch costs are essential to determine the viability of space ventures. Profits are ultimately defined as revenues minus costs, and as things stand, going beyond the space applications discussed above is not commercially viable as the revenues are dubious, meaning the value creation and therefore a consumer's willingness to pay for a space-based activity is unclear, and the costs are high (e.g. transportation to and from space).

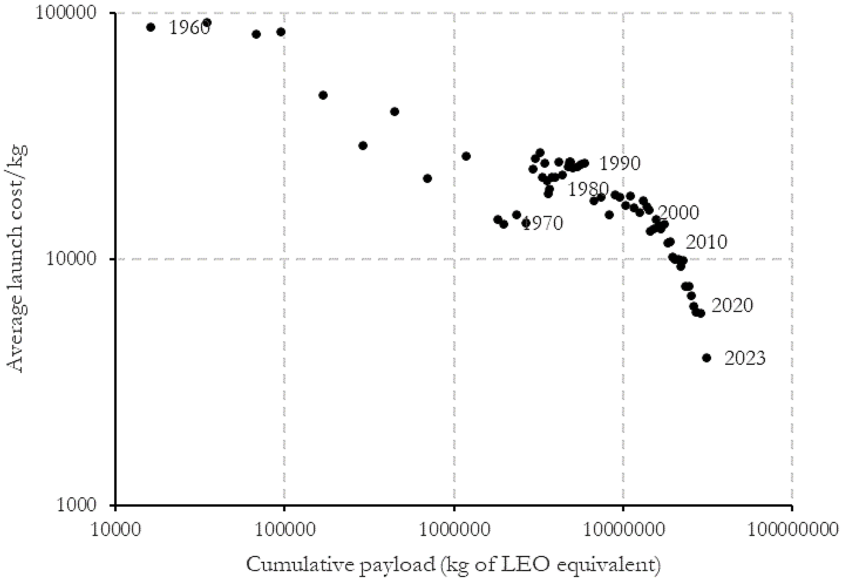
However, space in this context is not different from other markets, which have been extensively studied. By comparing it with the evolution of past technologies and the creation ex novo of new markets (e.g. the digital economy) we can learn which steps merit consideration for space to become a commercially viable endeavour. First typically comes scientific inquiry, led by a desire to expand our understanding of a new space, and test its properties. Once a favourable property is discovered, albeit typically at a prohibitively expensive cost, governments often invest further in moving from the research to technology phase. This typically happens under the headline of military expenditure, which is where considerations of technological advantage trump calculations of lowest-cost-available (Fouquet, 2008). For technologies that prove their usefulness, some commercial actors attempt to replicate military-grade technology to provide it to rich consumers, which are those that can afford the still-high costs of a novel innovation (Terzi and Fouquet, 2023). Finally, in the successful cases, this allows further scaling up which makes the new technology cheap enough to allow its rollout across society. Elsewhere, one of us has called this the 'innovation treadmill' (Terzi, 2022, pp. 102–106). Take the microwave, for instance: first pioneered by defence-company Raytheon and sold to the US Navy for $66,000 (in 2022 prices) in 1947. The first commercial version was available at $22,000 - $33,000 (in 2022 prices) in 1954. Only over a decade later, thanks for further secondary innovation, was the price brought down to a point where it was available to a wider range of consumers. The creation of the digital economy follows a similar path, as the Internet came on the back of military-investment in secure communications, expanding only later to commercialisation. The same is true for airplanes, and many more technologies across history.

Space is already showing signs of following a similar evolution. As discussed above, early on it was the domain of scientific research. Then came interesting applications, which were predominantly military, such as satellite communication and positioning systems (such as GPS). Starting in the 1990s, these applications were scaled up and effectively became commercially viable. The same is true for space travel, which was the prerogative of scientifically-trained astronauts on government-funded missions, and is now commercially available at extremely high prices to rich consumers[6].

Space has already shown throughout the past three decades to hold value and is only likely to do so more in the future as new possibilities become available thanks to science and innovation. The examples given in the previous section are only a selection of applications already being considered by public- and private-sector actors. The real fundamental question is therefore whether space scales, i.e. whether costs can credibly be brought down enough to allow space-based activities to manifest their comparative advantage. To this end, in Figure 4 we plotted launch cost per kg, and cumulative payload launched into space, between 1960 and 2023. A simple interpolation suggests that launch costs are reduced by a third (-32.7%) with each doubling of launched payload.

[6] Along similar lines, Fouquet (2008) argues that "*when Charles Darwin travelled to the Galapagos, the cost of the journey was similar in real terms to what the first space tourists paid*".

Figure 4. **Global launch costs and cumulative payload**



Note: USSR data is omitted due to data quality issues. Both axes are in logarithmic scale. Prices are corrected for inflation (expressed in 2024 $). Payload is standardised to Low Earth Orbit (LEO) equivalent: we consider the equivalent maximal capacity that the rocket might have launched to LEO, rather than the actual mass of the payload launched (which might be smaller by choice or might target more energetic orbits).

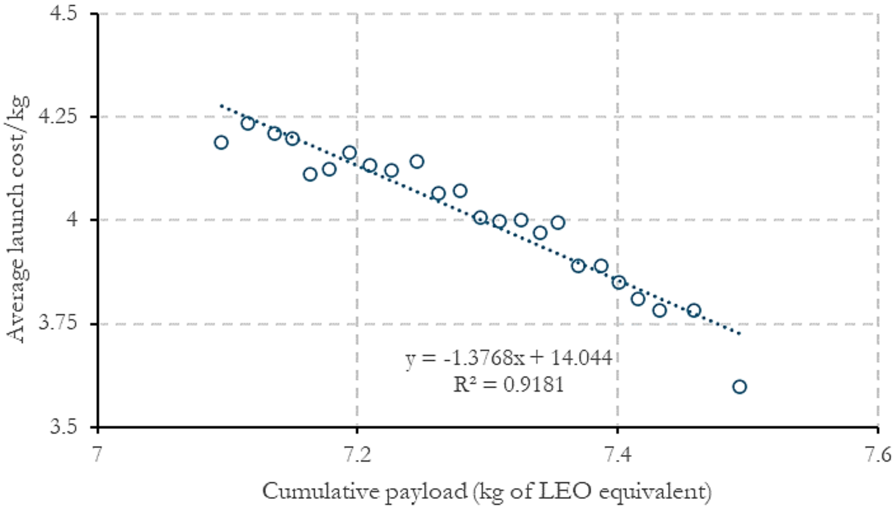
Source: Authors' calculations based on own database.

Wright's Law suggests that cost reductions for a specific technology rather reliably follow a constant rate, and that therefore costs can be described by equation [1].

$$\log(c_t) = \theta + \beta \log(\sum_{0}^{t} m_t) + \varepsilon_t \qquad [1]$$

Where c_t is the launch cost in year t, m_t is the maximal payload capacity launched in year t, and β is a constant cost improvement rate. Our data suggests this has been the case also for what concerns space launch technology, in particular since the turn of the century (R-squared=0.918), and the beginning of the New Space era (Figure 5). This perhaps should not surprise, given Wright's Law was first developed for the aerospace sector, and specifically airplane manufacturing.

Figure 5. **Wright's Law for space launch technology, 2000-2023**



Note: USSR data is omitted due to data quality issues. Both axes are in logarithmic scale. Prices are corrected for inflation (expressed in 2024 $). Payload is standardised to Low Earth Orbit (LEO) equivalent.

Source: Authors' calculations based on own database.

We exploit this technological property to forecast future launch costs, based on cumulative payload under a set of scenarios (Table 2). Scenarios considered range between a highly conservative scenario, whereby payload growth is essentially zero and remains constant and equal to current levels between now and 2040, to a very bullish scenario, whereby payload increases at a similar rate to that observed over the last two years, every three years. Effectively, aside from the conservative scenario, all others are built to follow another standard technological property, namely the fact that technology predictably expands following step-growth S-curves (Sood and Tellis, 2005).

Some considerations are in order. Under any scenario considered, including the most conservative, by 2030 average launch costs per ton are expected to be less than a third vis-à-vis their 2015 value, coming on the back of a 40% reduction since the turn of the century. Even under the most conservative scenario, launch costs to LEO using western providers will be 87% cheaper on average at the end of this decade than they were when the first commercial applications of space started to emerge in the 1990s. Under more bullish scenarios, launch costs could be lower than 1000$ per kg by 2038. This underpins our view that the space economy is about to undergo a significant acceleration due to falling access barriers, enabling the expansion of supply and demand for all types of space goods (*pure uses of space*, *space tradables*, and *space consumables*, discussed in Section 5). In Annex B we run as a robustness check an alternative model where quantities are dependent on launch costs. Should price reductions mimic those observed over the last two decades, mass to orbit would expand even more than in our baseline model, suggesting the results in Table 2 for mass in orbit, and therefore the potential future size of the space economy, should be treated as a lower-bound estimate.

Table 2. **Average launch costs and cumulative LEO-equivalent payload quantities, by year**

	Historical		Conservative		Central		Bullish		Ultra Bullish	
Year	Cost ($/kg)	Cumulative Payload (tons)	Cost ($/kg)	Cumulative Payload (tons)	Cost ($/kg)	Cumulative Payload (tons)	Cost ($/kg)	Cumulative Payload (tons)	Cost ($/kg)	Cumulative Payload (tons)
2015	9337.9	21884.1								
2016	9887.5	22589.4								
2017	7782.8	23428.5								
2018	7739.7	24382.1								
2019	7082.3	25155.7								
2020	6460.4	26020.1								
2021	6063.4	27037.2								
2022	6050.0	28760.5								
2023	3961.2	31183.0								
2024			4804.4	33606	4681.7	34243051	4681.7	34243051	4681.7	34243051
2025			4365.3	36028	4161.2	37303061	4161.2	37303061	4161.2	37303061
2026			3991.2	38451	3733.2	40363072	3733.2	40363072	3733.2	40363072
2027			3669.2	40873	3375.9	43423083	3375.9	43423083	3291.5	44228307
2028			3389.6	43296	3073.7	46483093	3073.7	46483093	2932.9	48093542
2029			3144.8	45718	2815.4	49543104	2753.6	50348328	2636.8	51958777
2030			2929.0	48141	2592.5	52603115	2487.0	54213563	2330.1	56841126
2031			2737.5	50563	2398.3	55663125	2262.0	58078798	2080.2	61723476
2032			2566.7	52986	2227.9	58723136	2070.0	61944033	1873.2	66605825
2033			2413.5	55408	2077.4	61783147	1904.5	65809268	1658.2	72772937
2034			2275.4	57831	1910.9	65648382	1725.8	70691618	1482.5	78940049
2035			2150.4	60253	1766.2	69513617	1574.2	75573967	1336.7	85107161
2036			2036.8	62676	1639.4	73378852	1444.2	80456317	1184.8	92897113
2037			1933.2	65099	1527.5	77244087	1331.7	85338666	1060.5	100687065
2038			1838.3	67521	1428.2	81109322	1233.5	90221016	957.1	108477017
2039			1751.3	69944	1339.5	84974557	1126.2	96388127	849.2	118316850
2040			1671.1	72366	1260.0	88839792	1034.0	102555239	760.8	128156683

Note: Cost refers to the average launch cost per kg in real 2024 dollars, LEO equivalent. Values from 2024 onwards are forecasts under different payload growth assumptions. The conservative scenario assumes yearly equivalent payload will remain constant (and equal to the average 2020-22) until 2040 (zero further growth). All other scenarios assume an S-curve step-growth pattern, whereby payload increases at the rate it has been increasing between 2010-20, every 10 years (central), every 5 years (bullish) and every 3 years (ultra-bullish).

Source: Authors' calculations based on own database.

What do these costs projections mean for different goods and services, and for specific industries? While it is hard to provide point estimates for when certain goods or services become profitable, we can compare our data with available estimates. Among more far-fetched uses, solar space power and widespread orbital tourisms are good cases. An original study by NASA in 1999 estimated that a launch cost of $200/kg in 1999 dollars (about $377 in 2024 terms) would be needed for beamed solar power to be feasible. However, taking into account process and material costs reduction, which cut costs in other phases of production, a recent ESA 2023 study suggested that a cost of around €1000/kg (about $1100/kg) might be sufficient in closing the case for beamed solar economic feasibility. This would be true by the end of the next decade in both our bullish and very bullish scenarios. Note also that Table 2 displays average launch costs, but in order to make some space-based solar power feasible, it is sufficient that at least one provider reaches the break-even launch cost. The average 2040 price in our bullish scenario (1034$/kg) is roughly the launch cost SpaceX is about to reach with its current Starship rocket today. In sum, it is quite plausible to expect that space-based solar power will become economically feasible over a medium-term timeframe.

We can hold a similar reasoning for larger-scale space tourism. Already in 2003, Penn and Lindley (2003) estimated that space tourism would become commercially viable at $529/kg (about 902$/kg in 2024 dollars), and would reach mass diffusion at a price point of approximately 195$/kg (in 2024 values). These levels are well below our average estimates for all but the ultra-bullish scenario, but once again within range of long-term market cost estimates for SpaceX's Starship (Berger, 2024). As in the case of orbital solar stations, therefore, a dedicated space hotel-based orbital tourism requires average costs to fall substantially, but lowest-available industry costs are approaching these levels at a pace.

4. MEASURING THE SPACE ECONOMY

Reading together Section 2 and the analysis in Section 3 suggests that the space economy is large, and likely to expand significantly over the coming years. It therefore becomes fundamental to reflect on how to capture its size. In a similar vein to discussions underlying national accounts, how we measure something reveals how we think about it from a conceptual standpoint, and crucially influences also policy design (Stiglitz, Sen and Fitoussi, 2009; Terzi, 2021). For this reason, this section is devoted to analysing in greater detail how the space economy has been accounted for hitherto, and why this approach carries some pitfalls.

4.1. SPACE AS AN ECONOMIC SECTOR

While discussions about the economic uses of space abound, they often lack a structured framework classifying the uses of space according to economic logic. Early classifications of uses of space have focused on the broad content of the activities deployed in orbit. For instance, classifying satellites as civilian (research), government (communications & observation), commercial and military, emphasising the increasing importance military applications and usages of space had on the total number of satellites fielded.

As the share of commercial satellites has increased to become predominant (Figure 1), other definitions have come to play, aimed at shedding light on the growing economic opportunities of space. These definitions see space-related activities as a sector (or sub-sector) of the global economy. This approach has attempted to identify any activity, among those mostly based on Earth, relying in one way or another on space. For instance, in its Handbook on Measuring the Space Economy, the OECD (2012, p. 20) defines the space economy as "*the full range of activities and the use of resources that create value and benefits to human beings in the course of exploring, researching, understanding, managing, and utilising space*". This is evidently a very broad definition: were this paper remunerated in any way, it would certainly be contributing to enlarge the space economy, based on such wide categorisation. The US Bureau of Industry and Security (2013) on the other hand defined space-related goods and services as "*any product, service, or object that is: i) used in or launched into space; ii) used to directly or indirectly support space applications from Earth; and/or iii) used to manufacture any product that is used in space or directly supports space applications*". The US Congressional Research Service (2012) took a narrower approach, considering that "*the space industry refers to economic activities related to the manufacture and delivery of components that go into Earth's orbit or beyond*". These debates on assumptions and issue of estimations of the size of an economy are not much different from those characterising the time when national accounts were first set up (Coyle, 2014; Terzi, 2021), and represent a prolific avenue for contributions from the economics and statistics profession.

Based on the OECD's broad sector-based approach, the Space Foundation, a leading think tank in this field, estimates the size of all space-related activities to be around \$550 billion in 2022 (Space Foundation, 2023): roughly the size of Thailand's economy. Indeed, historically OECD estimates have aligned quite well with those of the Space Foundation (Crane *et al.*, 2020). Other estimates attempt a more granular accounting of space-related activities. As part of its Space Economy Satellite Accounts introduced in 2019 (Highfill and Surfield, 2023), the US Bureau of Economic Analysis shows that the space-related sector in the US is worth roughly 0.6% of GDP (or 130 billion dollars). This builds on the input-output methodology discussed in Highfill and Macdonald (2022). Analytics and engineering firm Bryce Tech has been producing a consistent time series on the relative importance of different components of the space sector, estimating the total size of the space economy at about \$380 billion in 2022 (BryceTech, 2023). A detailed overview of the subsectors of the space economy is divided in non-satellite industry (which includes government budgets and human space flight) (26% of the total in 2022), satellite services (30%), satellite ground equipment (37%), satellite manufacturing (4%) and launch services (1.8%). McKinsey and the World Economic Forum likewise estimate the size of the space economy at around \$447 billion in 2022 (McKinsey & Co, 2022). Bryce Tech's approach constitutes a narrower, sector-based approach to the classification of the space economy than the one proposed by the Space Foundation. Nonetheless, all these numbers should be taken as ballpark estimates. For instance, some inter-temporal double-counting is likely to affect Bryce Tech's estimates, since public budgets in $year^{T}$ are used to pay for goods and services in the other sub-sectors in $year^{T+n}$.[7]

These issues notwithstanding, these approaches certainly have the merit of shedding light on the growing importance of the space sector for the world economy and have helped demonstrating to public and private investors alike the dynamic nature of the space economy. However, our concern runs deeper, and is of conceptual rather than empirical nature. Approaching the space economy from a *sector* perspective, rather than from a *locus* perspective, comes with two drawbacks. First, it tends to over-estimate the short-term importance of the economic activities actually taking place in space. Despite the increasing value of the space economy, its fabric –the type of economic activities taking place in space— have barely changed since the 1990s (mostly communication, navigation, and Earth observation). The second and perhaps most fundamental drawback is that by focusing the attention of investors and economic agents on the economic subsectors on Earth that display the highest growth rate (i.e., satellite ground equipment, according to Bryce Tech data) the sector approach to classify the space economy tends to overlook emergent *uses of space* which have the potential, in the long term, of creating entire markets. This is a concern expressed also by Crane et al (2020).

By means of a comparison, if we were to treat Panama's economy as a sector rather than a locus, we would be accounting any global activity remotely connected with the canal as part of Panama's economy, regardless of national ownership and location. Such a metric might be important for instance to assess the vulnerability of the global economy and supply chains to climate-induced droughts and disruptions in the operations of Panama's canal (Murray, 2023), but are not appropriate when the interest is on Panama's economy, as it would enormously over-estimate its true size on the one hand (\$270 billion in global trade involved vs \$76 billion in GDP in 2022), but also blur the statistical picture, making it harder to assess real strengths and opportunities.

Table 3 summarises three different approaches to measure the size of the global space economy, and produces comparable estimates for 2013, 2016 and 2022. While all three have drawbacks, discussed in the comments column, Crane et al (2020) comes closer to our parsimonious view that activities primarily for Earth-based consumption, and not actually produced in space but only enabled by space-based technology, should be excluded. We maintain that those activities actually produced in space – even though for Earth-based needs – should still be included in the taxonomy, under the 'tradable exports' category (see Section 5).

In general, the different approaches display some sizeable quantitative differences. Nonetheless, we take comfort in the fact that all three estimates show a solid growth in the space economy, especially vis-à-vis a more meagre 1.9% real GDP growth in advanced economies over the same time period, underscoring our message that space developments should not be overlooked.

[7] We contacted Bryce Tech for a clarification, but their response did little to disparage our doubts on their methodology, as reported here.

Table 3. **Estimates of the global space economy**

	2013	2016	2022	*avg annual growth rate*	General comment
Crane et al (2020)	155.7	166.3		*2.3*	Measures the space economy in value added rather than revenues, to avoid double-counting. Exclude economic activities that are primarily terrestrial in origin.
Space Foundation	314.2	329.3	546	*8.2*	Aligned with OECD (2012). Estimate includes both government budget and commercial revenues, with high risk of double counting
BryceTech/Satellite Industry Association	320	339.1	384	*2.2*	Built on detailed estimates at sectorial level, including government funded. High risk of inter-temporal double counting.

Source: Authors elaboration based on Crane et al (2020) and OECD (2022).

4.2. SPACE AS AN ECONOMIC LOCUS

To avoid these issues, we propose here a complementary approach to the study of the space economy, which sees space as an economic locus for productive activities in its own right. This approach is complementary, rather than a substitute, for looking at space as a sector, especially in the short run. The 'sector' perspective helps investors understand where economic value associated with space is currently being created; the 'locus' perspective allows us to better estimate the actual size of the space economy. By treating space as a locus, we can in fact understand its economic relationships with the rest of the world economy under a different light, for the barriers that separate (economically) space from the rest of the world economy are relatively well understood in international economics. After all, launch costs are just a form of prohibitively high transaction/transportation costs, which mediate any economic relationship between the home-locus (Earth) and the *space-locus:* exports (of goods, and services like tourism), Foreign Direct Investment (building-up of infrastructure, modules, stations, productive activities) as well as imports (mostly of services back to Earth, as of now). In principle, one could indeed think about space imports, exports and investment. A key problem of this approach, however, is that many activities that take place in space at the moment are non-commercial, such as those related to the military or scientific research. It is hard to estimate the value of research, for instance, since no market price exists for government-funded research, and public services more broadly. If we adopt the same perspective as in national accounts, and account for space-related government investments at cost, then space is a net receiver of FDI (e.g. satellites) and – for now – of consumables (e.g. water, fuel, but also materials needed for 3D printing on the International Space Station), while it is a net exporter of services (e.g. navigation systems).

A counterpoint to our proposition is to consider space akin to international waters. Proponents of this approach suggest that space, like the high seas, mediates important shares of the global economy, but this economic value is not produced by residents, who rather use space as a medium. Finally, there are international treaties for space – like for international waters – that do not allow economic ownership or national sovereignty claims. In practical accounting terms, this would suggest it is better to fold space within the current national accounting system as a sector, using an input-output framework to avoid double-counting, as currently done by the US Bureau of Economic Analysis with its Space Economy Satellite Accounts. This is certainly a coherent position, but not one we share, mostly for two reasons. First, in spite of the 1967 Outer Space Treaty, we suspect the arrival of the private sector into space will progressively lead to a *de facto* move towards economic claims that resemble ownership in space. This can be spotted already within the recent Artemis Accords, spearheaded by the United States and signed by 38 other countries including all major space-faring nations except China and Russia. This new framework effectively recognises the right of private sector companies to sell anything they find in space, and to create "safety zones" around the areas of exploitation, which can also be permanent as currently planned for the Moon. Second, we are confident that, in the medium- to long term, as economic activity expands in space, the latter will get residents of its own, rules to manage those interactions, and eventually also governing bodies to oversee their implementation. The confluence of these two elements leads us to consider it more appropriate to start thinking already from now of space as a locus, and therefore of the trade in value-added framework as a relevant accounting framework approach that will stand the test of time.

Developing a full national account perspective to space would allow a more granular and precise characterisation of the space economy: an endeavour we encourage for future economic research. In the next section, we contribute to this objective at the meta-level, by building a conceptual taxonomy of the economic activities that *can* take place in space, and that *can* in principle bring value added, depending on the extent to which space itself carries a comparative advantage in these economic activities.

5. ECONOMIC USES OF SPACE

Space is becoming increasingly accessible. Nonetheless, innovative uses of space beyond Earth observation and communication technology have struggled to gain traction in the new space race, underscoring the formidable challenges (technical, financial, and economic) these ventures entail, from technological hurdles to uncertain long-term return on investment. In what follows, we aim to classify these further applications which, in our view, are closer to materialising than many believe, also thanks to further reductions in trade barriers/launch costs expected once SpaceX superheavy vehicle Starship becomes fully operational over the next 2-3 years (Nicoli, Sekut and Porcaro, 2023).

Our proposed taxonomy encompasses three different categories of economic activities taking place in space, depending on how they relate to Earth (Table 4). Our classification includes *pure uses* of space (i.e., activities that can reasonably only take place in space); *space tradables* (i.e., goods and services that might be produced in space for Earth consumption, if the competitive conditions are right, but reasonable substitutes exist on Earth), and *space consumables* (i.e. goods and services that might be produced in space for space usage if the competitive conditions are right, but reasonable substitutes can be imported from Earth)[8].

Table 4. **Taxonomy of economic activities in Space**

Taxonomy	Definition	Examples	Status
Pure uses of Space	Activities that can reasonably only take place in space	- Low-gravity research	Deployed
		- Orbital tourism	Deployed
		- GPS	Deployed
Space tradables	Goods and services that might be produced in space for Earth consumption, if the competitive conditions are right, but reasonable substitutes exist on Earth	- Made-in-Space fibre cable	Demonstrated
		- Beamed solar power	Demonstrated
		- Asteroid-mined resources	Planned
Space consumables	Goods and services that might be produced in space for space usage if the competitive conditions are right, but reasonable substitutes can be imported from Earth	- Moon-made oxygen (ISRU)	Planned
		- Moon-made solar panels	Planned
		- Space-grown food crops	Planned

Source: Authors.

[8] Of course, all of these uses of space are sensitive to technological progress. However, technological progress cannot be considered exogenous to expected economic opportunity.

5.1. PURE USES OF SPACE

Space has unique properties, such as a microgravity environment, the absence of atmospheric interferences, the absence of pathogens, and natural exposure to extreme temperatures. For these reasons, some activities – economic or otherwise – can only be reasonably performed in space. Since such activities cannot easily be replicated on Earth, the choice is between conducting these activities in space and not conducting them at all. Among these, scientific research is clearly the most important activity whose economic value is associated with a pure use of space. Studying the effect of microgravity on human bodies and materials alike can only be done in space; space exploration can equally only be done in space. Furthermore, some rare resources can exclusively be found in reasonable quantities beyond Earth: this is the case, for instance, of Helium-3, an exotic isotope of Helium which is touted to be a potential breakthrough fuel for nuclear fusion reactors (Schrunk *et al.*, 2008). It is worth noting that, as our knowledge-base was developed through millennia of experimentation on Earth (Henrich, 2016), and our knowledge of space remains extremely patchy, the 'pure' uses of space currently still appear inevitably limited.

Nevertheless, a few considerations are in order. First, our collective knowledge is the real limitation here. There might be a very high number of pure uses of space which we simply have not discovered yet. For instance, new types of resources, or novel industrial processes that exploit microgravity to obtain results which would be impossible on Earth. In other words, it is reasonable to expect pure uses of space to be endogenous to technological progress: the more humanity becomes used to thrive beyond Earth, the more pure uses for space are very likely to emerge. Second, as the space economy expands, there will be demand for services that need to be fulfilled in orbit and cannot reasonably be provided on Earth. Short-term, the most obvious of such services are space debris deorbiting. As orbital slots begin to be filled up, the issue of orbital debris will grow in relevance. At that point, there will be a market for removing inactive satellites. Such market is already well under development, through several start-ups and agencies[9]. Another clear second-order pure use of space is real estate, both in orbit and, later, on celestial bodies. The demand for such properties is, at the moment, driven by public funding (e.g. on the ISS), but we cannot exclude that in the near future there might be private demand for in-space real estate, for instance for the personnel of small production facilities of space-manufactured goods, or for tourism purposes. The commercial LEO destinations that will replace the ISS, as discussed in Section 1, are unlikely to be used exclusively for scientific research, and will in part also be rented out for profit.

Which leads us to our final consideration regarding pure uses of space: as is often the case with taxonomies or classifications of economic activities, the differences fade at the boundary, and the product definition becomes, in fact, dependent on the market definition. Is 'Earth tourism' a substitute for space tourism? Arguably, only in space can one enjoy the unique experience of zero gravity tourism. From this perspective, space tourism is a pure use of space. However, one could also argue that space tourism has its natural substitute/competitor in other exotic forms of Earth-based tourism, such as deep ocean exploration. If the market of reference is 'exotic tourism', then tourism is not a pure use of space, and space tourism would rather fit in the next category of *space tradables*.

5.2. SPACE TRADEABLES

A second class of goods and services that are part of the emerging space economy is what we call 'space tradables', i.e. goods and services that could reliably be produced both in space and on Earth, but largely for Earth-based consumption. Space tradables are where we expect that, in the short term, novel uses of space will mostly emerge. It is also the type of economic activities astro-entrepreneur Jeff Bezos had in mind when he declared his vision for 'millions of people to live and work in space' (Soper, 2015). The idea is simple: space could be used profitably for a high range of activities, were the costs to get there and back be low enough. In international economics terms, space could become a profitable destination for FDI and strong export growth, having a comparative advantage in a set of activities, subject to transaction/transport costs being low enough. To start with, as discussed, the unique orbital environment potentially allows for many types of production to be improved by microgravity

[9] Among many others, see for instance, Germany's Exolaunch (Rainbow, 2021) or US' Starfish Space (Alamalhodaei, 2021). See Nasa (2023, pp. 346–359) for a technology review on space debris deorbiting systems. Many of these startups' 'space tugs' have in fact multiple uses when it comes to the satellite servicing market, for instance refuelling or orbital boosting, both well-established commercial practices demonstrated by several countries; these services, however, are better understood as *space consumables*.

manufacturing. These include, for instance, some types of medicines and fibre cable (Schrunk *et al.*, 2008). However, a very large number of potential applications of microgravity manufacturing are being studied. For instance, a more far-fetched but realistic and very-well studied application is space-based solar power. Since atmospheric diffraction is absent in space, solar panels are extremely efficient, they face no real limits in term of extension, and produce energy 24/7; energy that can be beamed back to the planet to a dedicated collector station, generating much more green energy than their Earth-based competitors. This approach, albeit seemingly remote, is well understood and studied by privates as well as governmental agents (Hollinger, 2023). The real barrier is not primarily technological, but economic in nature: since we do not have manufacturing facilities of solar panels in orbit, the panels need to be shipped from Earth, and at the price tag of well above $11.000/kg that characterised most of the 1990s and early 2000s, the economic case simply did not close. Despite their lack of efficiency, deploying Earth-based solar panels remained economically wiser. There exists, however, a given price point at which the economic case will close, after which space-beamed solar power would be economically efficient. Another example is the placement of data storage centres on the Moon or in orbit: as data storages consume enormous amounts of energy to cool down (Masanet *et al.*, 2020), some have proposed to exploit the natural extremely cold environment of space for natural cooling[10].

These are simply some examples of *space tradables* which are discussed in the industry as feasible within reasonably-contained timelines. Other uses are further afar in the future. For instance, it is reasonable to assume that in a distant future, if prices go low enough, asteroid mining for rare resources might be economically competitive, especially if environmental attitudes of Earth residents will evolve towards fully pricing-in the negative environmental externalities associated with deeper and larger mining operations (Fleming *et al.*, 2023). Similarly, it is possible that certain very polluting economic activities could one day be relocated in space, where they would have no negative greenhouse gas externalities[11]. These approaches are at the core of the visions to turn Earth into a 'planet-sized garden'[12], but they are admittedly far-fetched and require not just a change in the costs of access to space, but also a fundamental change in the way humanity thinks about the environmental costs of economic development.

5.3. SPACE CONSUMABLES

A final class of goods and services to consider are what we call 'space consumables'. These are goods and services that can be produced either on Earth or in space (and in this are no different from space tradables) aimed at satisfying, however, internal demand in space. Things like fuel supplies, satellite components, solar panels, silicon wafers, food and water, or 3D-printed objects, parts or structures fit in this category. So far, these goods and services have always been shipped from Earth; while certainly there are technological challenges still to be faced for in-space production of these items, there are economic barriers at play too. The relationship between transport costs and market size is less straightforward in the case of *space consumables* than it is in the case of *space tradables*, and likely not linear. This is because *space consumables*, produced in space to respond to the space economy internal demand, do not necessarily enjoy an inherent value added from being produced in space, other than proximity and availability to where they are needed. Producing things in space requires, first, to set up production facilities, which need to be launched from Earth. If launch costs are too high, it is cheaper to launch the final product directly from Earth, rather than setting up a production facility. If launch costs decrease enough, setting up a production facility might make sense, since it is now cheaper, but launching large quantities of consumables remains expensive. However, if the launch price decreases too much, then launching goods produced on Earth becomes again a valid alternative, since Earth's larger industrial base, by necessity, delivers lower marginal costs. This non-linear relationship is discussed at greater length in Annex A.

[10] See Moss (2021) for a discussion of Thales Alenia's plans, and Coughlin (2022) for a discussion of Lonestar Data Holdings.

[11] In certain instances, greenhouse gas emissions could even produce a positive externality, for instance on a celestial body in need of warming from a human perspective (such as Mars, for instance).

[12] Bezos in conversation with NASA Administrator Bill Nelson in 2021. Video accessible at: https://www.c-span.org/video/?515984-1/jeff-bezos-nasa-administrator-nelson-dni-haines-us-space-policy.

To sum up, we can consider that the demand for *pure uses of space* is a positive function of (scientific and technological) Progress and Launch Costs; demands for *space tradables* is a positive function of Progress, Launch Costs and (environmental) Preferences; and demand for *space consumables* is a positive function of Progress, but has a non-linear relationship with Launch Costs, depending on the relationship between the relative paces of space industrialisation and of Transport Costs reduction.

6. CONCLUSION

The overarching objective of this paper is to point economists' attention to the stars. For too long, space has been dismissed as a science endeavour at best, and a delusionary science fiction fantasy at worst. In this paper, we make three fundamental points. First, with strong commercial activity already taking place in Low Earth Orbit since the late 1980s, space is today predominantly an economic area and, as such, should be worth of attention by the economics profession. By some estimates, in 2022 over half a trillion dollars of the world economy depended directly or indirectly on space. Second, launch costs have been on a very steep downward trend hitherto, even by historical comparison. Under a set of credible scenarios, we showed how these costs are likely to drop further in a significant way by the end of this decade, and more so in the 2030s. Looking at it through a trade economics framework, we are entering a period where (space) trade frictions are dropping, and new markets will be created as a result. Making these arguments has not required any recurse to the life-changing potential of some futuristic technology but was mostly based on current trends and available technology that will simply need to be perfected, as part of standard processes of efficiency improvement, economies of scale and learning. Third, as the space economy expands – along the lines of what we have called pure uses of space, space tradables and space consumables – we should progressively measure and think about it through the trade lenses, rather than considering it just another sector in national accounts.

The research agenda from here onward is vast. Several concepts from standard economics can easily be applied to space, such as that of resource scarcity, prices, incentives, transaction costs, externalities, economies of scale, tragedy of the commons, and more. Other dynamics will need to be adapted to a space context: balance of payment and national accounts will eventually need to be re-thought to extend them to trade beyond Earth. Considerations of financial transactions with and within space should also be explored. As new missions are heading to the Moon within this decade, many of which with the aim of mining for water and selected minerals, or grow crops in situ, new institutions will need to be designed, starting from a clean slate, and yet having to incorporate incentives, externalities, technology and power relations into the equation. Here again, some branches of institutional economics and political economy would have much to contribute. The market structure of space exploration is likewise worth reflecting on, using microeconomic tools and industrial organisation models. This includes carefully assessing the degree to which space applications display high fixed costs and relatively-low marginal costs, and therefore what shape the space economy will take (perfect competition, oligopoly, monopoly), which class of models should be used to study it (Cournot, Bertrand, Stackelberg, and so on), and hence which outcomes to expect.

Our grandchildren are likely to live in a world where space is just another dimension of economic activity, in the same way in which we grew up in an era where the digital marketplace provides services and utility, in ways that were inexistent to our grandparents. The sooner we realise this, in Europe and beyond, the greater the chance we reap the benefits of this new Age of Discovery.

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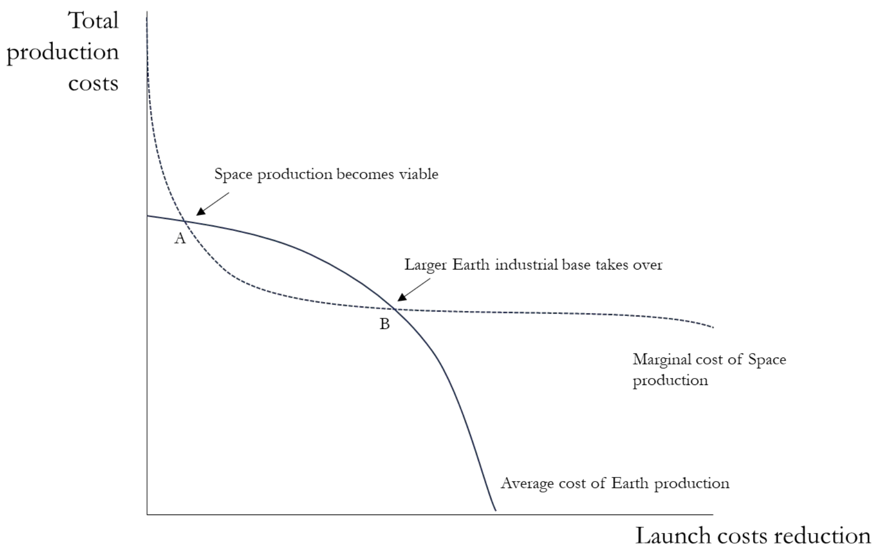
ANNEX A – SPACE CONSUMABES AND LAUNCH COSTS

Consider a simplified space economy where demand for *space consumables* is entirely dependent on the number of 'space residents' (be people or objects, such as satellites) requesting a good or service (for instance, food or fuel), and therefore is a function of launch costs: the lower the launch costs, the higher the number of residents. These demands can be fulfilled either with Earth-based supply, which is readily available but faces the hurdle of high launch costs, or space-based supply, which needs to be built up but once built faces little to none additional transport costs. Under these conditions, Figure 1 presents a stylised view of this economy. Before point A, launch costs are excessive to set up production capacity, and demand is too scarce to justify it. Hence, demands are fulfilled ad-hoc from Earth. As launch costs decrease, demand increases, and therefore the marginal cost of producing in space falls (and so do the costs of setting up a production facility). Eventually, there is sufficient demand for space production to break even, eventually reaching point A, where the marginal cost of producing in space equals the average cost of producing on Earth and shipping upwards. As launch costs continue to decrease, the average cost of Earh production and delivery continues to decrease, but so does the marginal cost of producing additional units of product in space, as demand (driven by decreasing launch costs) expands, allowing for widening use of existing facilities. At some point, existing facilities max out – and importantly, in absence of further economies of scale– marginal costs will stop decreasing; yet, as launch costs keep falling, the average cost of producing on Earth and delivering in orbit continues to fall. Thanks to the larger production facilities existing on Earth, as launch costs become an increasingly negligible part of production costs, eventually Earth production becomes more competitive again (point B).

Figure 1. **Space production costs vs Earth production costs**



Source: Authors.

The relationship between in-space supply of *consumables* and launch costs will be largely determined by the presence or absence of economies of scale. If the *consumable* in question enjoys significant economies of scale, the size of production is a key driver of costs. Hence, if transport costs decrease enough, then eventually the much-larger production capacity of Earth will take over. If instead there are limited economies of scale, in-space production of *consumables* might continue to make economic sense, since launch costs will never be zero, and therefore proximity of supply will always remain at competitive advantage.

Yet, even in the presence of economies of scale, the ultimate evolution of the market might depend on the duration of the intermediate 'transition' period of 'medium' launch costs (when in-space production of consumables is still profitable: the interval between points A & B in Figure 1) to 'low launch costs' (when the larger Earth production facilities take over, beyond point B). To maintain our international trade analogy, this is akin to the temporary protection offered to a late industrialising country through a system of high but continuously decreasing tariffs, like some import substitution schemes. In the latter case, tariffs are progressively adapted downwards by policy choices, as domestic industrial complexes expand and develop economies of scale, enabling them to compete with older, larger, more established corporations. In space, on the other hand, the 'gravity tariff', i.e. the extra cost paid by Earth-based corporations to ship consumables to space, decreases at a given market-induced pace, as we discuss in the paper. Hence, companies interested in supplying consumables for space use are in a race against time to build up capacity: they need to wait until costs are low enough to justify the investment, but then must ramp up production quickly to enjoy the temporary protection offered to their orbital facilities. How long it takes before the inflection kicks in? The longer it lasts, the more in-space supply capacity will be built up, experiencing economies of scale of in-space supply and decreasing their inherited competitive disadvantage vis à vis Earth-based production. Related to this, it is worth considering that it takes 22 times less energy to propel a payload from the Moon than from Earth, due to the lack of an atmosphere and the smaller mass/gravity on the latter (Schrunk *et al.*, 2008, p. 56). For this reason alone, combined with comparatively small transport costs in open space, the Moon might have a comparative advantage vis à vis Earth for the production of *space consumables* over the long term.

A final consideration may be given to the role played by automation. If it is true that Earth-based production enjoys massive competitive advantages given by the sheer scale of the planet's production facilities, it is also true that these make a relatively large use of human labour; relatively large with respect to space. Space is a naturally unwelcome environment for humans; humans in space are tremendously costly, and at risk (Schrunk *et al.*, 2008; Goldsmith and Rees, 2022). Whenever possible, space-based production facilities will take every opportunity of removing human labour from the equation. This in turn may mean that space-based production could be more capital intensive, more efficient, more flexible and more prone to economies of scale than legacy Earth-based production, moderating some of the drawbacks in the in-space production of space consumables described above.

ANNEX B – FORECASTING MASS TO LEO BASED ON LAUNCH COSTS

In our baseline model illustrated in main text, we tested Wright's Law, whereby technology (embodied in economies of scale) determines launch costs. However, from an economic perspective, it could be argued that the relationship works the other way around, i.e. that plummeting launch costs stimulate demand for space applications. In this annex we test this possibility, effectively regressing cumulative mass on launch costs. We tested several specifications, including simply yearly mass on launch costs in levels. The goodness of fit was however the highest in the scenario where log cumulative mass is regressed on log launch costs. We then used this model to forecast cumulative mass in orbit under a set of assumptions on future prices. Notably, in our conservative scenario we assume prices will continue to fall at the average rate observed between 2000 and 2023. In our central scenario, we assume they will continue to fall at the average rate observed between 2010 and 2023. In our bullish scenario, they fall at the rate observed between 2015-2023, and in the ultra-bullish scenario at the average rate observed between 2020 and 2023. Results are displayed below.

Table 1. **Average launch costs and cumulative LEO-equivalent payload quantities, by year**

	Historical		Conservative		Central		Bullish		Ultra Bullish	
Year	Cost ($/kg)	Cumulative Payload (tons)	Cost ($/kg)	Cumulative Payload (tons)	Cost ($/kg)	Cumulative Payload (tons)	Cost ($/kg)	Cumulative Payload (tons)	Cost ($/kg)	Cumulative Payload (tons)
2015	9337.9	21884.1								
2016	9887.5	22589.4								
2017	7782.8	23428.5								
2018	7739.7	24382.1								
2019	7082.3	25155.7								
2020	6460.4	26020.1								
2021	6063.4	27037.2								
2022	6050.0	28760.5								
2023	3961.2	31183.0								
2024			3759.8	68995	3646.6	1411567409	3605.9	1433019802	3469.3	1509586307
2025			3568.6	108145	3356.9	2958570008	3282.5	3028479608	3038.5	3284089581
2026			3387.1	148683	3090.2	4692302364	2988.1	4844305860	2661.2	5413996855
2027			3214.9	190656	2844.7	6635303547	2720.1	6910935783	2330.7	7970489740
2028			3051.4	234116	2618.8	8812833189	2476.1	9263010622	2041.3	11039006360
2029			2896.2	279115	2410.7	11253199869	2254.1	11939956304	1787.8	14722096700
2030			2748.9	325708	2219.2	13988129127	2051.9	14986644302	1565.8	19142849830
2031			2609.2	373951	2043.0	17053175913	1867.8	18454143783	1371.3	24449007549
2032			2476.5	423903	1880.7	20488186808	1700.3	22400577633	1201.0	30817901923
2033			2350.5	475624	1731.3	24337818045	1547.8	26892096728	1051.9	38462381732
2034			2231.0	529177	1593.7	28652116053	1409.0	32003988768	921.3	47637925888
2035			2117.6	584627	1467.1	33487168075	1282.6	37821940262	806.9	58651181551
2036			2009.9	642041	1350.6	38905831325	1167.6	44443472822	706.7	71870212297
2037			1907.7	701488	1243.3	44978550144	1062.9	51979577839	618.9	87736798819
2038			1810.7	763041	1144.5	51784271807	967.5	60556576941	542.1	106781203260
2039			1718.6	826774	1053.6	59411472856	880.8	70318239423	474.7	129639890605
2040			1631.2	892764	969.9	67959309327	801.8	81428192133	415.8	157076799370

We note that aside from the conservative scenario, in this model prices fall faster than our baseline model predicted based on cumulative mass. Under the most bullish scenario, prices would fall below 500$/kg by the end of the next decade. It is interesting to focus however on the conservative scenario. This is because it produces price forecasts that resemble quite closely those in the conservative scenario of our baseline model. However, this model specification produces forecasts for a much larger mass to orbit. This suggests to us that our baseline model estimations should be taken as lower-bound estimates for what concerns the mass to LEO and therefore the potential of the space economy.

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