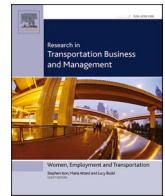




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When launch costs fall, do satellites shrink and constellations grow? The role of SpaceX in the SmallSat revolution

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ABSTRACT

The rapid growth of small satellites has transformed the structure of the global space sector, yet the extent to which declining launch costs have contributed to this transition remains underinvestigated. This paper examines the relationship between launch affordability and the proliferation of satellites with a mass below 500 kg using a comprehensive dataset covering all operational satellites launched between 2003 and 2022. Six linear regression models are estimated to assess whether reductions in average launch costs are associated with changes in payload composition and average satellite mass. Results indicate a strong statistical association between lower launch costs and both an increasing share of small satellites and a substantial decline in average satellite mass after 2013. When low-cost, high-cadence launch services are excluded from the analysis, the relationship weakens, indicating that recent changes in launch supply conditions have played a major role in shaping deployment patterns. Evidence suggests that declining launch costs significantly contributed to the transition toward a small satellite-dominated orbital environment, while also interacting with broader technological, organizational, and market developments. These results shed empirical light into how access-to-orbit economics influences system design choices, investment strategies, and competitive dynamics in the contemporary space economy.

1. Introduction

In the last twenty years, the number of objects launched into space has exploded, especially in Low Earth Orbit (LEO). The proliferation of ever smaller satellites has been a major driver of this trend, and it radically changed the global satellite market. To describe the scope of such disruption, many have used the expression “SmallSat (Small Satellite) revolution”. In line with the prevailing opinions in the literature, this paper assumes a SmallSat to have less than a 500 kg mass (e.g., Dos Santos Paulino & Le Hir, 2016; Motta et al., 2024; Pelton & Madry, 2020; Weinzierl et al., 2020). The cost of launching objects into space has declined, with Space Exploration Technologies Corporation (SpaceX) leading the way (Adilov et al., 2022; Badikov et al., 2021; Jones, 2018a, 2018b; Li et al., 2022; Motta et al., 2024; Roberts, 2022; Vittori et al., 2024; Weinzierl et al., 2020).

Satellite miniaturization and launch prices reduction are part of a larger shift in the space business sector, often characterized as the emergence of a “New Space Economy” (NSE). This shift has brought a “different ethos for space” (Sweeting, 2018), with private enterprise ascending to higher prominence in a historically government-

dominated environment. As the NSE emerged, the traditional, centralized system of government procurement was gradually flanked and overshadowed by a new, decentralized ecosystem of private firms, sharing both the risks and returns of their own space projects (Motta et al., 2024; Weinzierl, 2018). In the modern space economy, large conglomerates coexist with start-ups backed by venture capital and risk-taking investors, emphasizing innovation and efficiency over risk-aversion (Sweeting, 2018; Van der Veen et al., 2012; Weinzierl, 2018).

Business analysts paid more attention to the NSE's growth than academic scholars (Motta et al., 2024). In fact, a rigorous analysis on the association between the SmallSat revolution and lower launch is still lacking, with Adilov et al. (2022) being the only exception. Therefore, it is worthwhile asking: is there a connection between lower launch prices and satellites' miniaturization? And if so, what is the role SpaceX played in the SmallSat revolution?

This paper explores the possible nexus between reductions in average launch costs and SmallSats. The goal is to provide conjectural and empirical insights on this nexus, while also examining the role of SpaceX in the NSE.

The paper is divided into six sections. The next reviews the literature

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on satellite miniaturization and launch cost trends, suggesting a possible association between the two. The third describes both data and models used. The fourth reports results, while the fifth discusses findings. Section six concludes and addresses limitations and future research.

2. Literature review

Adilov et al. (2022) attribute the recent LEO satellite exponential growth to technological innovation, which reduces the cost of manufacturing and launching satellites into space. As the cost of assembling and launching satellites fell, new nations and firms began to debut in the previously restrictive space sector, developing their own space programs and commercial ventures (Sweeting, 2018).

A large body of literature investigates the radical breakthroughs in satellite manufacturing, underlining the importance of commercially available, high-volume, and low-cost microelectronics (Behrens & Lal, 2019; Motta et al., 2024; Sweeting, 2018). Their availability allowed much cheaper space systems, which also proved more reliable and up to date. These technological innovations went hand in hand with organizational innovations. Sweeting (2018) and Behrens and Lal (2019) describe how new management models from the IT industry brought faster development cycles and innovation into a generally risk-averse business sector, where novelties usually came at incremental steps (Van der Veen et al., 2012). All of this meant the emergence of new scientific endeavours and business models relying on SmallSats platforms, like modular CubeSats and LEO constellations (Behrens & Lal, 2019; Li et al., 2022; Pelton & Madry, 2020; Sweeting, 2018). Beyond manufacturing innovations and organizational change, the literature identifies a set of autonomous techno-economic drivers of satellite miniaturization operating independently of launch cost dynamics. Advances in microelectronics, subsystem integration, and component standardization have generated strong technological substitution effects, enabling reductions in payload mass, power consumption, thermal loads, and structural requirements while preserving or increasing functional performance (Behrens & Lal, 2019; Motta et al., 2024; Sweeting, 2018). These processes reflect a shift in the satellite production function, whereby functionality is increasingly decoupled from physical scale through digitalization, software-defined systems, and high-density component integration. In parallel, developments in phased-array antennas, software-defined payloads, and onboard digital signal-processing architectures have altered system cost functions by reducing reliance on large mechanical structures and enabling distributed sensing, adaptive communications, and flexible spectrum management within compact platforms (Li et al., 2022; Pelton & Madry, 2020). At the system-design level, the diffusion of mission disaggregation principles and modular system architectures has promoted the decomposition of complex missions across multiple interoperable units, replacing vertically integrated spacecraft with distributed multi-node configurations (Dos Santos Paulino & Le Hir, 2016; Mowry & Grasso, 2020; Weinzierl et al., 2020). From an industrial economics perspective, these trajectories reflect a structural transition toward modular production, platform standardization, and scalable system architectures, where satellite miniaturization emerges as the outcome of cumulative technological substitution, economies of replication, and architectural efficiency gains, rather than as a purely cost-mediated response to changes in access-to-orbit costs.

However, a crucial piece of the puzzle is still missing. According to the literature, all these changes took place from the late 80's onward, and particularly during the 90's and 2000's. Still, there was no sign of a proper SmallSat revolution until the early 2010's, when SmallSats began growing at an accelerating pace (Wekerle et al., 2017). Arguably, what lit the fuse of the revolution was falling launch costs due to technological innovations.

The research on falling launch costs is sparser than the one on satellite miniaturization. Still, launch costs are crucial in space mission planning, as they constrain payload mass and the mission's scope

(Badikov et al., 2021; Jones, 2018a, 2018b). Together with manufacturing costs, putting a satellite into orbit is often the largest expense manufacturers and operators face, especially in the case of satellite constellations (Adilov et al., 2022; Li et al., 2022; Motta et al., 2024; Mowry & Grasso, 2020; Sweeting, 2018).

Nevertheless, launching objects into space has recently become much cheaper than in the past, particularly in the United States (Henry, 2004; Jurist et al., 2006; Reddy, 2018; Sweeting, 2018; Toman & Macauley, 1989; Weinzierl et al., 2020). Jones (2018a), Li et al. (2022) and Roberts (2022) date the onset of such a trend to the turn of the millennium, in stark contrast to the period of launch cost stagnation of 1975–2000. During this period, Jones (2018a) reports that the typical launch cost to LEO was in the \$10,000–\$32,000/kg range, with an average of \$18,500/kg. SpaceX plays a fundamental role in the recent rapid cost decline. In fact, Falcon 9 reduced launch cost to LEO to \$2700/kg and Falcon Heavy to \$1400/kg (Jones, 2018a).

SpaceX based its success on high reliability, high flight cadence and low cost. Falcon 9's partial reusability played a relevant part in the company's cost-savings, prompting competitors to follow its example. However, an overlooked reason behind the success of SpaceX is its Silicon Valley-style business approach, predicated on horizontal organization, fast iteration, high risk tolerance and vertical integration (Jones, 2018a; Li et al., 2022; Reddy, 2018; Seedhouse, 2022; Vittori et al., 2024; Weinzierl et al., 2020).

One could also note that, in principle, reductions in launch prices may not necessarily reflect proportional reductions in underlying production costs across all launch providers. Competitive pressure, particularly following SpaceX's market entry, may have induced margin compression among incumbent operators, whereby prices adjust downward through strategic pricing behaviour rather than through realized cost efficiencies. In principle, this would imply that part of the decline in launch prices could reflect changes in profit margins rather than technological or organizational cost reductions. While this could be a plausible interpretation, it is also important to recognize that this distinction cannot be empirically assessed with available data, as reliable information on providers' internal cost structures, pricing strategies, and operating margins is not publicly accessible and is largely protected by commercial confidentiality. As a result, one cannot disentangle cost reductions from possible margin compression effects in a systematic way and launch price trends should therefore be interpreted as market outcomes reflecting both technological change and, possibly, competitive pricing dynamics.

Affordable launch services are vital for space businesses. In fact, many space practitioners have emphasized their importance for stimulating the Space Economy and launch demand at least since the 1990s (Henry, 2004; Jones, 2018a, 2018b; Jurist et al., 2006). While their effects on demand are clear, those on its composition are not. If lower launch costs benefited SmallSat firms more than traditional satellite producers, they could, in principle, help explaining recent SmallSats proliferation. So far, there is no strong empirical support for this hypothesis.

Jones (2018a, 2018b) suggest that lower launch costs might result in heavier spacecrafts being designed and launched. In fact, cheaper launch services would ease existing incentives to limit payload mass. This already happened in the early Space Age, when improving launch capabilities lifted such constraints on satellite producers and gave way to heavier, more complex satellites (Pelton & Madry, 2020; Sweeting, 2018).

While this logic looks reasonable at first, however it ignores key factors at play in the contemporary satellite industry. Literature suggests that falling launch costs can be a powerful enabler of SmallSat-based business models for different reasons discussed in what follows.

The heart of the argument lies in the differing cost structures of traditional satellite operators and SmallSat firms. While manufacturing and launching are always the main cost drivers for a satellite business, a SmallSat producer faces much lower manufacturing costs than a

traditional incumbent, making launch costs its main expense. SmallSat businesses benefit from falling launch costs relatively more than traditional operators. All else being equal, the SmallSat firm's profitability increases more than the traditional operator's, prompting new competitors to enter the market with new SmallSat-based business models (Adilov et al., 2022). One can more explicitly explain this asymmetry referring to differences in production regimes, cost structures, and market positioning, rather than by firm size per se. In fact, the differential impact of declining launch costs should not be interpreted as a function of firm size alone, but rather as a consequence of distinct production regimes, cost structures, and market strategies. SmallSat-oriented firms are not necessarily "small" in organizational or revenue terms; instead, they operate under fundamentally different techno-economic configurations than traditional incumbents. These firms are characterized by standardized manufacturing processes, modular platform architectures, scalable production models, and constellation-based deployment strategies, which generate cost structures dominated by high replication volumes and low unit manufacturing costs. In this context, launch services represent a structurally larger share of total mission expenditure, not because firms are small, but because production is standardized and marginal manufacturing costs are compressed through scale and learning effects. Moreover, SmallSat-oriented business models are typically oriented toward distinct market segments and value propositions, including high-frequency data services, low-latency applications, coverage density, redundancy-intensive operations, and incremental deployment strategies. These are structurally different from the mission profiles of traditional satellite operators focused on single-asset, high-capacity, long-lifecycle platforms. The asymmetric effect of launch cost reductions therefore emerges from differences in system architecture, production economics, and market segmentation, rather than from organizational size alone, grounding the argument in industrial organization and techno-economic structure rather than circular firm-size logic.

Additionally, SmallSats are rarely designed to operate alone. Their strategic advantage usually lies in being part of larger LEO constellations, reaching high coverage and revisit rates that traditional systems cannot ensure (Dos Santos Paulino & Le Hir, 2016; Mowry & Grasso, 2020). Motta et al. (2024) corroborate this assumption, reporting that 85% of SmallSats to be launched in 2023–2032 will be part of constellations. Li et al. (2022) conclude that cheap, mass-produced SmallSats are the best techno-economic solution for large constellation architectures, whose economic viability depends on affordable launch services. Large constellations typically require many launches to become operative. High launch costs hinder profitability, as for the first LEO constellations (e.g., Iridium, Orbcomm and Globalstar. See Sweeting, 2018; Mowry & Grasso, 2020; Adilov et al., 2022; Li et al., 2022; Motta et al., 2024). Cheap access to space is important for SmallSat firms, but critical for SmallSat constellations. For instance, SpaceX could orbit its mega-constellation significantly faster and much more cheaply than competitors, thanks to Falcon 9, whose launch cost per satellite was 3–4 times lower (Li et al., 2022; Ogutu & Oughton, 2021).

Building large SmallSat constellations has another, subtler effect on the relationship between SmallSats and launch costs. Traditionally, the satellite industry was (and largely still is) based on small batches of large, complex, and highly unit-customized satellites, preventing the emergence of scale and learning economies (Dos Santos Paulino & Le Hir, 2016; Li et al., 2022; Sweeting, 2018; Weinzierl et al., 2020). As SmallSat constellations become a viable business model, however, standardized mass manufacturing becomes a necessity, and the subsequent scale and learning economies allow marginal unit costs to fall. If manufacturing becomes increasingly cheaper, the cost of launching will make up a growing portion of the firm's expenditure, making further decreases in launch costs even more beneficial.

Declining launch costs constitute a structural driver of technological choice and industrial organization within the satellite sector by altering relative cost structures, system architecture incentives, and risk

allocation mechanisms. Lower launch costs relax the mass constraint that historically shaped satellite design but generate asymmetric responses across firm typologies. For traditional satellite operators, whose cost functions remain dominated by bespoke manufacturing, long development cycles, and asset-specific capital investments, cheaper launch services reduce the marginal incentive to minimise payload mass and may induce a shift toward heavier and more capable spacecraft. By contrast, for SmallSat-oriented firms, launch costs represent a substantially higher share of total mission expenditure; consequently, reductions in launch prices disproportionately increase expected profitability, lowering entry barriers and strengthening incentives for the deployment of small, standardized, mass-produced platforms. In parallel, falling launch costs reshape optimal system architectures by shifting the economic trade-off between concentrated and distributed designs. As launch affordability increases, it becomes economically efficient to distribute functionality across multiple small satellites rather than concentrate it in single large spacecraft, favouring constellation-based architectures that optimize coverage density, revisit rates, redundancy, and incremental deployment strategies. Finally, lower launch costs reduce the expected financial losses associated with failure and replacement, transforming risk management logics: high-cost launch environments incentivize long-lived, highly reliable, capital-intensive assets, whereas low-cost, high-frequency launch regimes support shorter lifecycles, modularity, rapid replenishment, and iterative upgrading. Through these mechanisms, declining launch costs operate not merely as a reduction in access-to-orbit expenses, but as a systemic factor shaping firm behaviour, market entry dynamics, production models, and the industrial organization of the contemporary satellite economy, thereby structurally favouring the diffusion and scalability of SmallSat-based business models.

In short, falling launch costs provide a much greater opportunity for SmallSat businesses compared to traditional satellite manufacturers, since the launching cost makes up a bigger share of their total costs. The increased profitability of SmallSat businesses, combined with the deployment of small satellites in large numbers, makes their number grow rapidly across time, igniting, and catalysing the SmallSat revolution.

The SmallSat transition should therefore be interpreted as the outcome of interacting technological, architectural, and economic dynamics rather than as the product of a single dominant driver. Electronics miniaturization, subsystem integration, modular design, and mission disaggregation created the technical feasibility of smaller platforms, while constellation architectures and distributed systems generated new operational logics and service models. Within this structural transformation, declining launch costs function as a catalytic and enabling factor that amplifies, accelerates, and stabilises these trajectories, rather than as their primary origin. The observed reconfiguration of satellite markets thus reflects a multi-causal process in which technological substitution, system-architecture innovation, production regime transformation, and cost-structure reweighting co-evolve, jointly reshaping firm behaviour, market segmentation, and system design choices in the New Space Economy.

3. Data and models

Satellite operators respond to launch prices rather than to providers' internal production costs. However, reliable data on transaction prices are not publicly available, as launch contracts are typically confidential and prices vary widely depending on payload characteristics, contractual arrangements, and bundled services. Consequently, most empirical studies must rely on estimated unit production costs (e.g., cost per kilogram to LEO) as proxies for launch affordability. While such measures do not capture profit margins or strategic pricing behaviour, they reflect underlying technological and organizational changes that constrain feasible market prices over time. The analysis therefore interprets launch cost estimates as indicators of the economic accessibility of orbit

rather than as actual prices paid.

In principle, lower launch costs can translate into *more* or *less* SmallSats being launched. While the first case is compelling, the second is backed by solid historical evidence. The paper uses available data to capture the relationship between launch costs and number of SmallSats put into LEO orbit, asking if satellites shrink when launch services are cheaper. The empirical analysis conducted in this paper models observed launch cost dynamics as market-level outcomes and does not attempt to decompose the internal mechanisms through which such price reductions are generated. Although the literature identifies multiple potential drivers (e.g., technological efficiencies, reusability, learning effects, organizational innovation, competitive pricing strategies, margin compression), there is no publicly available disaggregated data that would allow these mechanisms to be empirically isolated, measured, or ranked across providers. As a result, the analysis cannot distinguish between price reductions driven by cost efficiencies and those arising from strategic pricing behaviour under competitive pressure. Consistent with the multi-causal framework adopted in this study, launch cost trends are therefore interpreted as emergent market signals reflecting interacting technological, organizational, and competitive dynamics, rather than as direct proxies for specific underlying cost-reduction processes.

Moreover, SpaceX's crucial role in bringing launch costs down creates the basis for an interesting thought experiment: what would have happened if the company never reached the market? In such a scenario, one could imagine launch costs to fall at a slower pace, to stagnate or even to increase, thereby influencing the satellite market. How would the SmallSat industry have performed in a scenario with higher launch costs? The Research Dataset (RD) contains data on all the 6514 operational satellites launched between 2003 and 2022 and still in Earth orbit on May 1st, 2023. The information included in the RD are date of launch, official name of the satellite, launch mass in kg, launch vehicle (with corresponding country of origin and launch cost per kg), type of orbit, type of user (civilian, military, commercial etc.) and operator/owner (with corresponding country of origin).

The first RD's source is the Satellite Database by the Union of Concerned Scientists (UCS), which lists satellites' main attributes and operational characteristics. The second is a data repository on rocket launch costs by Center for Strategic and International Studies (CSIS), indicating the launch costs per kg to LEO of several rockets produced from the 1960s to 2020, expressed in 2021 \$.

Launch costs for 42 out of the 55 launchers, listed in the UCS database, came from the CSIS data repository. Other minor sources provided launcher manufacturing costs estimations for six less known, more recent Chinese rockets. Finally, the RD excludes seven of the launchers indicated by the UCS database, either for lack of precise data or because they were non-rocket launchers (e.g., the Lockheed L-1011 airplane or the Nanorack Deployer on the ISS).

The paper uses data from the RD to estimate six models showcasing the scope of the SmallSat revolution. The core hypothesis is that falling launch costs have enabled the SmallSat revolution and, by reducing average launch costs, SpaceX has played an indirect yet crucial role in shaping it. On a cautionary note, one should also consider a potential reverse causal interpretation. In fact, one could, in principle, assert that the proliferation of SmallSats reduces launch costs because launch vehicles are not fully utilized. This mechanism appears unpalatable for several reasons. First, the launch cost measure used in this study reflects the estimated production cost of a launch vehicle per kilogram of maximum payload capacity, which is largely determined by vehicle design, manufacturing processes, and technological characteristics rather than by the specific payload mix of a given mission. Additionally, launch providers typically optimize payload utilization through ride-share arrangements, aggregation of multiple satellites, or delayed scheduling to ensure economic viability, limiting the occurrence of systematically underfilled launches. Finally, while increased demand from SmallSat operators could raise launch cadence and potentially

generate learning effects, such cost reductions would stem from aggregate production volume rather than from the small size of individual payloads. Available evidence suggests that learning rates in modern launch vehicle production are modest, implying that even substantial increases in launch frequency would translate into limited cost reductions. Overall, there is no plausible mechanism substantiating the hypothesis that a higher number of SmallSats, per se, would mechanically reduce unit launch costs, whereas the opposite is well supported by both economic logic and industry evidence.

The first part of the analysis shows why a connection between SpaceX's entry in the market and the unfolding of the SmallSat revolution is plausible, laying the groundwork for the second part of the analysis. Table 1 reports the six models estimated. The independent variable is the weighted average (WA) of global launch costs to LEO per kg (C_{WA}), whereas the dependent variable is either the percentage of SmallSats (satellites with a < 500 kg mass) on all satellites launched each year (I_{SM}) or the average mass of all satellites launched in a year (M_A). For each combination of variables (i.e., $X = C_{WA}$, $Y = I_{SM}$ or $X = C_{WA}$, $Y = M_A$) the paper estimates three models: 1) all available data ("all data") in 2003–2022; 2) all data in 2013–2022; 3) all data minus Falcon 9 (F9) and Falcon Heavy (FH) rockets ("no F9/FH") in 2013–2022. Parameters are estimated using Ordinary Least Squares.

WA weights each launch according to the number of satellites it delivers to orbit, capturing payload composition heterogeneity across missions. This is important since SmallSats are frequently deployed as secondary payloads on multi-manifest launches rather than through dedicated missions. Such "rideshare" arrangements allow multiple satellites, often belonging to different operators, to share a single launch vehicle thus significantly reducing effective per satellite costs compared to single payload launches. By incorporating the number of spacecrafts each launch carries, WA increases launch cost approximation accuracy with respect to actual costs satellite owners and operators bear. It represents a more precise indicator of industry-wide launch affordability.

The paper estimates, for the 2013–2022 period, two models one using the whole launch dataset and one only the non-SpaceX launches. Comparing the two model results allows detecting SpaceX impact on the SmallSat revolution. More in detail, models 2 and 5 use $C_{WA,all\ data}$ as independent variable, while models 3 and 6 use $C_{WA,no\ F9/FH}$:

$$Y_{2013-2022} = \beta_0 + \beta_1 X_{2013-2022,all\ data} + \epsilon$$

$$Y_{2013-2022} = \beta'_0 + \beta'_1 X_{2013-2022,no\ F9/FH} + \epsilon'$$

This allows calculating the δ variation rate by using models' residual variance:

$$\delta = \frac{\widehat{\sigma}_{\epsilon} - \widehat{\sigma}_{\epsilon'}}{\widehat{\sigma}_{\epsilon}}$$

that reports models' predictive power changes when excluding SpaceX launches from the calculation of C_A and C_{WA} . If δ is negative, the model more accurately predicts I_{SM} and M_A when including SpaceX. In other words, when δ is negative one can safely assume that the role of SpaceX launches plays the lion heart role in explaining the relationship launch cost reduction and increase in the SmallSats diffusion. The opposite holds true when δ is positive.

It is important to note that assuming no other firm would have

Table 1
Summary of models' equations.

Model no.	Equation	Timeframe
1	$I_{SM,all\ data} = \beta_0 + \beta_1 C_{WA,all\ data} + \epsilon$	2003–2022
2	$I_{SM,all\ data} = \beta_0 + \beta_1 C_{WA,all\ data} + \epsilon$	2013–2022
3	$I_{SM,no\ F9/FH} = \beta_0 + \beta_1 C_{WA,no\ F9/FH} + \epsilon$	2013–2022
4	$M_{A,all\ data} = \beta_0 + \beta_1 C_{WA,all\ data} + \epsilon$	2003–2022
5	$M_{A,all\ data} = \beta_0 + \beta_1 C_{WA,all\ data} + \epsilon$	2013–2022
6	$M_{A,no\ F9/FH} = \beta_0 + \beta_1 C_{WA,no\ F9/FH} + \epsilon$	2013–2022

replaced SpaceX is debatable (Vittori et al., 2024). However, SpaceX's unique production approach and its unprecedented belief in launchers' reusability, evidently in striking contrast with the strong and widespread skepticisms (Jurist et al., 2006; Reddy, 2018), clearly support our assumption.

4. Results

4.1. Descriptive analysis

In 2003, just 28% of all satellites launched weighed less than 500 kg, but 97.3% in 2022 (see Fig. 1). The trend in average satellite mass reflects such radical shift, showcasing a reduction from a little over two tons to less than 300 kg. The massive proliferation of SpaceX's Starlink satellites after 2019 played a major role. Even after excluding Starlink satellites, SmallSats still represent more than 87% of all satellites launched in 2022, and average satellite mass remains comfortably below 500 kg (441.41 kg). The SmallSat revolution is not just a paradigm shift in satellite manufacture; it is a radical and pervasive change in the structure of the satellite market itself.

The SmallSat revolution has been an exceedingly commercial phenomenon, entwined with the private space sector's increasing orbital footprint. In 2003, commercial satellites made up nearly 24% of all spacecrafts launched. Their share hovered between 30 and 50% from 2006 to 2018, but an upward trend began around 2012-'13, bringing the 2022 share at 95% (76.6% without Starlink). As the number of commercial satellites launches increased, their size began to shrink. With some exceptions, SmallSats remained an oddity in the commercial space sector until 2012-'13, when suddenly they began to increase. By 2015, 55% of all commercial spacecrafts launched that year were SmallSats; in 2017, the percentage rose to 78%, reaching 99% of all newly launched commercial satellites in 2020 (see Fig. 2). Even if Starlink is not included, SmallSats' absolute dominance in the private space sector barely budges.

Consequently, the average decrease in commercial satellite mass is staggering, going from 3281.67 kg in 2003 to 248.18 kg in 2022. While there was a nearly sevenfold decrease in average mass for satellites in general, the reduction has been thirteen-fold for commercial satellites.

Finally, trends in launch costs per kg deserve some remarks (see Fig. 3). The 2003 average was \$20,200 and very close to WA (\$19,988/kg). The two remained relatively similar until 2016, when they slowly began to diverge, to then follow completely different trajectories after 2019. In 2022, the global average launch cost was \$8080/kg, while the WA was less than half (\$4029/kg).

Results are remarkably similar to those Adilov et al. (2022) and Corrado et al. (2023) report, especially when considering WA. One can notice both an average and WA launch cost increase when excluding SpaceX's after 2012, while its inclusion results in a substantial launch

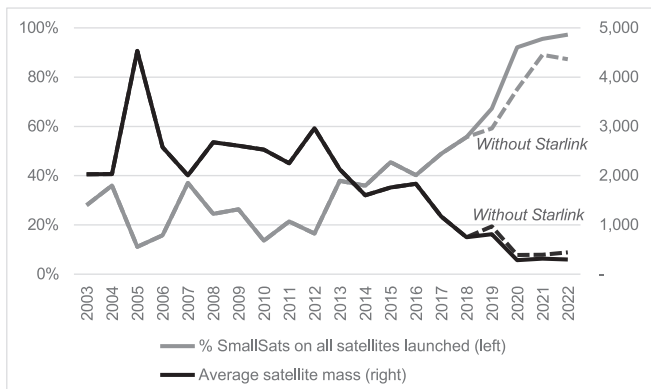


Fig. 1. The scope of the SmallSat revolution (Source: own RD).

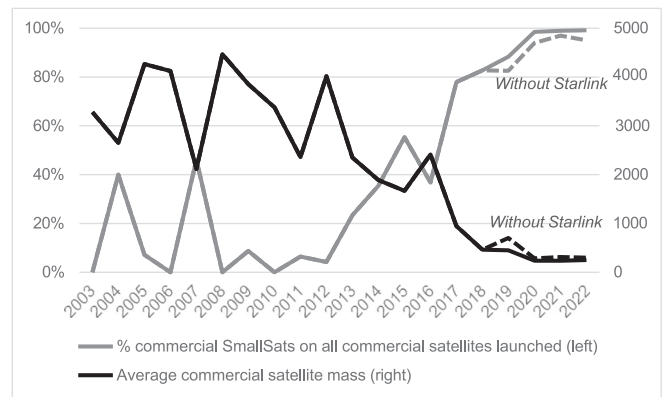


Fig. 2. The scope of the commercial SmallSat revolution (Source: own RD).

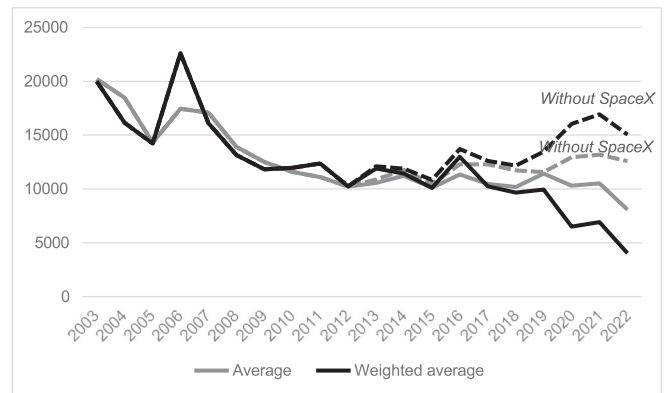


Fig. 3. Launch costs per kg in 2021 \$ (Source: own RD).

cost reduction. Accounting for both issues in 2022 results in around a \$4500/kg cost difference when using cost average and an astonishing \$11,000/kg in the case of WA. This divergence has some interesting implications.

A growing and substantial gap between simple and weighted averages suggests that satellites ride sharing is becoming common practice. This feature represents a peculiar trait of the SmallSat Revolution. A progressively larger share of smaller satellites is designed so to be deployed as secondary or co-primary payloads (Falduto & Peeters, 2023; Motta et al., 2024; Sweeting, 2018).

A relatively faster WA fall compared to simple average after 2017 alludes to a shift in operators' preferences toward more cost-effective launch solutions, possibly driven by the necessity of keeping launch costs down in the face of increasingly distributed satellite systems. A complementary possible explanation could be the enhanced accessibility to cheaper launch options, which is largely compatible with the expansion of SpaceX's launch operations.

4.2. Model results

This subsection, for each model, reports the: (1) scatterplot of dependent and independent variables, (2) estimated coefficients, (3) plot of the difference between actual and predicted values.

Fig. 4 reports the scatterplots of dependent and independent variables for all the six models. Models 1÷3 report the relationship between launch cost (\$/kg) and the share of SmallSat launches (Fig. 4a, b, c), while models 4÷6 show the relationship between launch cost and average satellite mass (Fig. 4d, e, f). For models 1 and 2, higher launch costs are associated with a lower proportion of SmallSats launched, while the relationship reverses in model 3. Similar considerations apply to models 4÷6. While there is a positive relationship between launch

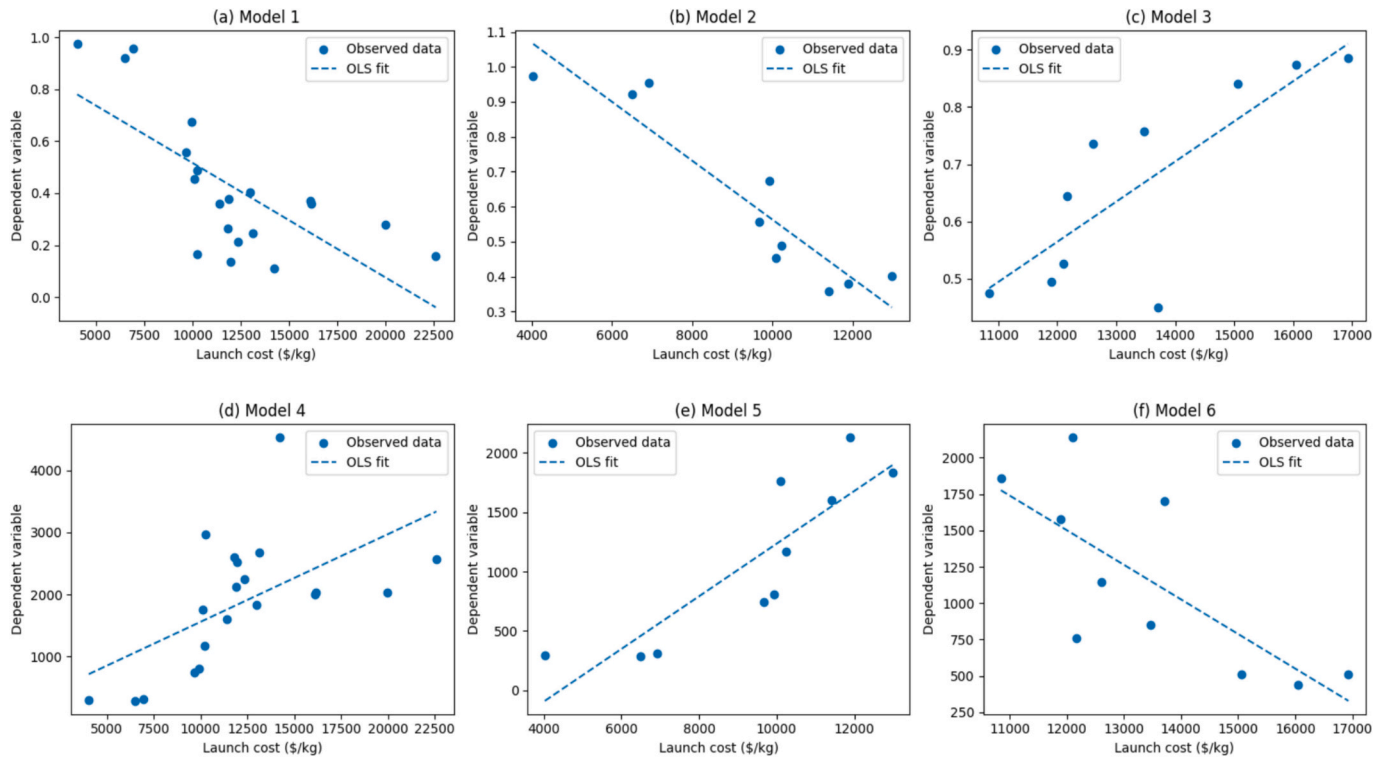


Fig. 4. Scatterplot of dependent and independent variables.

cost and satellite mass in models 4 and 5, the opposite is true in model 6. Taking the results of model 3 and 6 together suggests that when the role of SpaceX is not considered the assumed relationship between dependent and independent variables not only is not confirmed but reversed.

Table 2 reports the estimated coefficients for all the six models. Results reveal a clear relationship between launch cost and payload composition, on one side, and their physical characteristics, on the other. In the full-period models (2003–2022), a \$10,000/kg decrease in launch cost approximately determines a 0.43 increase in the SmallSat proportion ($\beta \approx -4.27 \times 10^{-5}$) and a decrease of about 1412 kg in average satellite mass ($\beta \approx +0.141$). This suggests that lower launch costs increase the number of lighter spacecrafts put into LEO orbit. In the 2013–2022 period, instead, these effects become stronger. In fact, the same \$10,000/kg decrease in launch cost here produces a 0.73 increase of the SmallSat share ($\beta \approx -7.33 \times 10^{-5}$) and a decrease of 2219 kg in average satellite mass ($\beta \approx +0.2219$). Removing SpaceX launches reverses the direction of the relationship: positive for SmallSat share ($\beta \approx +6.70 \times 10^{-5}$) and negative for mass ($\beta \approx -0.224$).

Fig. 5 compares observed values (solid line) with predictions (dotted line) from the six models. For the SmallSat share, restricting the timeframe from the full period (Model 1) to the recent decade (Model 2) substantially improves model performance. Model 1 captures the overall upward trend but exhibits large systematic deviations in both early and late years. Model 2 shows a much closer correspondence between observed and predicted values, suggesting that launch cost explains a

larger share of variation within the more recent and structurally homogeneous period. When Falcon 9 and Falcon Heavy launches are excluded (Model 3), predictive accuracy deteriorates relative to Model 2: the predicted series becomes smoother and less able to reproduce the timing and magnitude of observed increases, indicating that the estimated relationship is sensitive to the composition of launch supply. A symmetric pattern emerges for satellite mass.

Taken together, results suggest that the observed transition toward numerous, lightweight satellites is not merely a gradual market evolution but is quantitatively dominated by the entry of SpaceX low-cost launch services. Overall, the combination of larger coefficients, high explanatory power, and sign reversals across specifications provides supporting evidence of the SpaceX-driven decline in launch costs in reshaping the sector.

Table 3 confirms the results previously presented also when considering the δ rate that measures how the residual variance changes when SpaceX launches are excluded from the estimation. In fact, for the SmallSat share models, residual variance increases from 0.084 (Model 2, including SpaceX) to 0.107 (Model 3, excluding SpaceX), yielding $\delta = -0.274$. Similarly, for satellite mass, residual variance rises from 366.6 (Model 5) to 445.8 (Model 6), producing $\delta = -0.216$. These consistently negative δ values indicate that excluding SpaceX launches reduces predictive accuracy in both cases.

5. Discussion

SmallSats, over the previous two decades, have become the most common type of satellite, particularly in the commercial sector. Building on the shift toward a commercially driven New Space Economy, the increasing affordability of satellite launches has fuelled a rapid rise in the deployment of small satellites also acknowledging that distributed constellations entail structural duplication and redundancy penalties relative to monolithic spacecraft, thus potentially reducing aggregate payload efficiency for a given total system mass. However, assessing such engineering trade-offs requires detailed design data beyond the scope of this paper. The SmallSat revolution enhances entrepreneurial

Table 2
Model results.

Model no.	Intercept	Coefficient	R ²
1	1.016e+00 ***	-4.274e-05 ***	0.5518
2	1.367e+00 ***	-7.325e-05 ***	0.8650
3	-2.392e-01	6.695e-05 **	0.6530
4	146.52352	0.14124 **	0.3381
5	-983.59800 ****	0.22190 **	0.7572
6	4191.8220 **	-0.2243 *	0.5508

Note: *** $p < 0.001$, ** $p < 0.01$; * $p < 0.05$; **** $p < 0.10$.

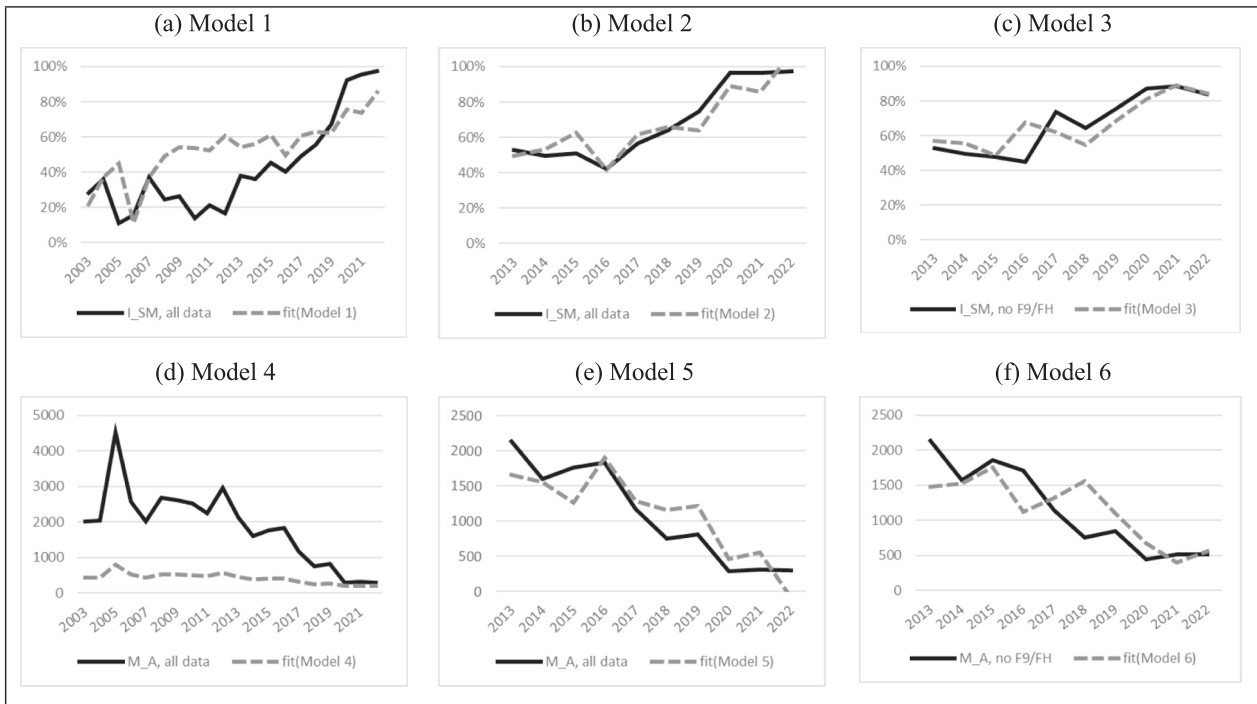


Fig. 5. Observed versus predicted.

Table 3
Residual variances and δ rates.

	$\hat{\sigma}_\epsilon$	$\hat{\sigma}_\epsilon$	δ
I_{SM}	0.084 (Model 2)	0.107 (Model 3)	-0.274
M_A	366.6 (Model 5)	445.8 (Model 6)	-0.216

ventures' ability to exploit space-technology capabilities, thereby expanding their capacity to address sustainability challenges through innovative, scalable business models (Manotti et al., 2025). As the cost of reaching LEO fell, SmallSats started their journey to satellite industry dominance. Even though there is no definitive proof of a causal relation between the two phenomena, the supporting evidence for its existence is strong.

The mechanism linking launch costs influence on satellite mass relies on operators' sensitivity to economic incentives. Commercial enterprises arguably care more about cost-effectiveness than government agencies do, thus changing launch costs will have a relatively greater impact on them. Nearly 97% of SmallSats launched in 2022 were operated by for-profit organizations, compared to an average of 17.2% between 2003 and 2013. This suggests that something has changed dramatically in recent years, especially after 2013 (Dos Santos Paulino & Le Hir, 2016).

One relevant change taking place in launch industry's landscape was SpaceX entering the scene. While the company accounted for 37.2% of the reduction in average launch costs between 2003 and 2022, the figure rises to 69.1% when weighing each launch by its "attractiveness" (i.e., how many satellites it puts in orbit). The trends in Figs. 1 and 2 become increasingly evident after 2012–2013, right when Falcon 9 became regularly available for commercial launches. Commercially operated SmallSats were quite rare before 2012, when they entered a period of sustained and rapid proliferation.

While SpaceX contributed to lower launch costs after 2013, the trend had already started around 2006 (Fig. 6). Indeed, C_A dropped significantly only before 2013 and then inched downward until 2022. An explanation for the 2006–2012 drop is falling launch cadence for several

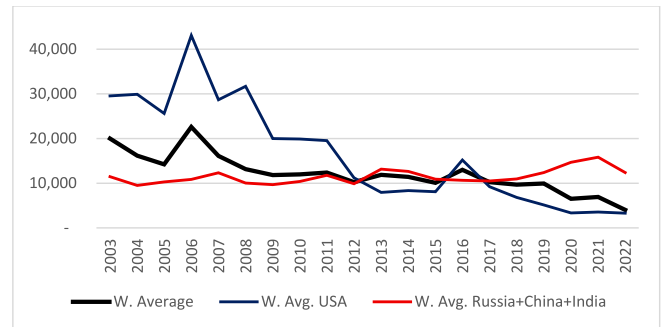


Fig. 6. WA launch costs per kg to LEO (by launcher's country of origin; Source: own RD).

expensive rockets during the 2000s, with relatively cheaper launchers taking their place. While the Japanese M-V (\$45,800/kg) or the American Titan 2 (\$30,600/kg) and Titan 4 (\$30,800/kg) started retiring, and Pegasus-XL (\$50,600/kg) or the Minotaur 1 (\$73,100/kg) launches became rarer, the Atlas 3 (\$16,000/kg), the Atlas 5 (\$8100/kg) and the Delta 4 (\$10,400/kg) began their operational carrier. This turnover mainly impacted the American launcher industry, whose costs were significantly higher than the world average. After converging toward the global average, American rocket manufacturers then started to pull ahead after 2012, while Russian, Chinese, and Indian competitors went from around \$10,000/kg in the 2000s to \$12,000–\$15,000/kg during the 2019–2022 period. In turn, the WA of American launch costs in 2022 was just \$3292/kg, 18% lower than the global average and below the inflation-adjusted elasticity threshold Henry (2004) reports.

One can attribute most of the launch costs fall to SpaceX, whose high launch cadence made it the most active launch provider in the world (Fig. 7). Please also note that the number of U.S. providers' launches increases substantially over time, primarily driven by the rapid growth of SpaceX. In contrast, launches by the Russia–China–India conglomerate grow less, while "Others" remain comparatively smaller. Consistently, the black line rises markedly after the mid-2010s, indicating that

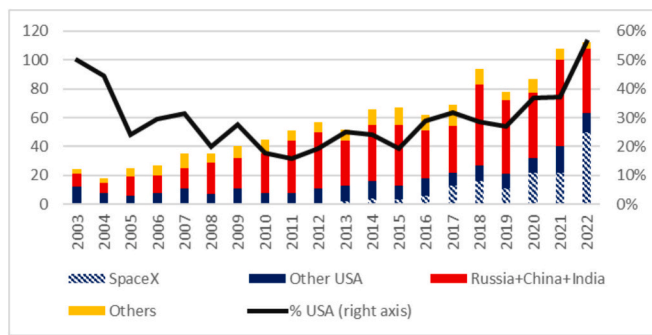


Fig. 7. Number of launches by country of the provider (Source: own RD).

U.S. launches account for a growing share of total global launches relative to non-U.S. providers.

One could, at this point, ask why SmallSats have become so pervasive only after 2013 considering launch costs in Russia, China, and India were already low in the 2000s. One possible explanation is that these countries lagged behind the United States in space applications for microelectronics, and limited access to capital markets thus preventing Russian, Chinese, and Indian firms from emerging. While U.S. companies had both a technological and financial edge, high domestic launch costs were arguably a big deterrent for SmallSat businesses.

Another debatable question relates to the motivation of why the initial sharp decline in American C_{WA} did not affect I_{SM} and M_A , whereas the more modest decrease between 2013 and 2022 had such a significant impact. The simplest possible explanation is that, from 2006 to 2012, American launch costs were simply too high for SmallSat businesses to thrive, keeping their numbers low and, to have any observable influence on I_{SM} and M_A , they had first to converge to the world average.

Finally, regression results appear to support the hypothesis that reductions in WA launch costs are associated either with increases in the SmallSat share or with decreases in average satellite mass, indicating a close link between cheaper access to orbit and satellite miniaturization. This relationship is markedly stronger when considering SpaceX launches, suggesting that had SpaceX never entered the market, the surge in the number of SmallSats would hardly have happened since launch costs would have not declined. Although other technological and institutional factors may also have contributed, the dramatic cost reductions introduced by SpaceX appear to have created a critical enabling condition for industry expansion. In particular, SpaceX could deploy the largest SmallSat constellation to date because of its low-cost proprietary launch capability; reliance on more expensive third-party services would likely have constrained Starlink's scale. Conversely, if comparable low-cost launch capacity were broadly available (e.g., if major SmallSat firms operated Falcon 9-class vehicles), the number and size of large constellations currently in orbit would likely be substantially greater.

6. Conclusion

This paper examines whether declining launch costs have contributed to the emergence and rapid expansion of SmallSats within the contemporary space economy. Drawing on a comprehensive dataset of all operational satellites launched between 2003 and 2022 and a set of regressions, the paper provides consistent empirical evidence that lower launch costs are associated with both a growing share of SmallSats and a substantial reduction in average satellite mass. The relationship is stronger in the most recent decade and weakens significantly when low-cost, high-cadence launch services are excluded, indicating that changes in launch affordability have been closely intertwined with the structural transformation of the orbital market.

Findings suggest that cheaper access to orbit has not automatically caused satellites to become smaller but contributed to changing the economic logic governing system design, investment decisions, and

market entry. As launch costs decline, distributed constellations composed of standardized, mass-produced spacecraft become financially viable and operationally attractive, particularly for commercial actors whose business models depend on scalability, redundancy, and rapid deployment. Launch affordability represents an enabling condition allowing the deployment of existing technological capabilities at an industrial scale. The observed transition toward SmallSat dominance reflects a broader reconfiguration of production regimes, risk management strategies, and competitive dynamics within the space sector.

This interpretation carries direct strategic implications. Decisions about launch procurement, vertical integration, constellation architecture, and timing of market entry seem highly sensitive to expected launch affordability. Organizations able to secure reliable low-cost access to orbit gain a structural advantage in deploying distributed infrastructures, accelerating deployment cycles, and lowering financial exposure to failure. Conversely, higher-cost launch services seem to constrain scale, slow down deployment, and favour more traditional spacecraft architectures. Understanding how launch economics shape technological choices is essential for both public and private actors involved in space activities.

It is important to note that the interpretations provided should be taken *cum grano salis*. In fact, the empirical models adopt a linear specification that may oversimplify relationships unfolding over a period characterized by technological discontinuities, policy shifts, and market shocks. One could, in principle, consider nonlinear dynamics (e.g., thresholds, tipping points, etc.) as appropriate in this context. However, they are difficult to estimate due to the limited historical depth of available data. Furthermore, the study relies on estimated production costs as proxies for launch affordability since actual transaction prices are not disclosed. Considering space economy as representative of a concentrated industry with significant entry barriers, prices might diverge from costs due to mark-ups, strategic pricing, or temporary market power, making it difficult to determine the true economic conditions satellite operators face. Additionally, one should not, a priori, exclude an inherently multi-causal nature of the SmallSat transition, whose causes could also include advances in microelectronics, subsystem miniaturization, software-defined payloads, manufacturing standardization, financing mechanisms, and regulatory frameworks, that are potentially linked to the emergence of distributed satellite systems. Focusing on launch costs alone risks overstating their explanatory power, while their empirical evidence hints to a pivotal enabling role.

All the potential limitations and actual constraints suggest some clear future research directions. More flexible modelling approaches, capable of capturing nonlinear diffusion patterns and structural breaks, would possibly clarify whether reductions in launch costs do trigger discrete shifts in industry behaviour. Access to detailed pricing data, even in aggregated or anonymized form, would allow an accurate assessment of the possible gap between production costs and market prices. Integrating technological, financial, institutional, and market variables into multivariate frameworks would improve understanding how different drivers interact and whether launch affordability acts as a prerequisite or merely plays an enabling role for large-scale constellation deployment. Expanding datasets across longer time horizons would further enable more advanced analyses.

This paper has shown that declining launch costs have not merely enabled smaller satellites but have fundamentally redefined the economics of access to space, making scalable, distributed systems the new strategic paradigm and positioning affordable access to orbit as the decisive lever shaping the future structure, competitiveness, and direction of the global space economy.

CRedit authorship contribution statement

Edoardo Marcucci: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology,

Investigation, Conceptualization. **Valerio Gatta:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Cristiano Ciucci:** Writing – original draft, Resources, Formal analysis, Data curation. **Domenico Cucina:** Writing – review & editing, Software, Methodology, Formal analysis.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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