CENTER FOR SPACE POLICY AND STRATEGY

JUNE 2026

SUPER HEAVY LIFT LAUNCH: UNLOCKING THE FUTURE OF SPACE

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Summary

The modern super heavy lift (SHL) rocket represents a renewed expansion in payload capacity and volume to orbit, creating the potential to enable a wide range of space missions. Today, two space companies, SpaceX and Blue Origin, are investing significant amounts of private capital to build SHL rockets—Starship and New Glenn, respectively. Both companies are striving to achieve lower launch costs per payload (e.g., cost per kilogram) through increased lift capacity, large cargo fairings, and full or partial launch vehicle reusability. For these rocket rivals, greater launch vehicle mass and volume might enable new and economically sustainable commercial opportunities.

In the world of transport logistics, bigger is often cheaper, as greater economies of scale are achieved from filling a ship's cargo hold or a plane's fuselage. Likewise, SHLs can achieve lower cost per payload by maximizing total mass to orbit. But there are limits before a launch provider could reach a point of diminishing returns wherein increased rocket capacity demands greater cost, time, or operational complexity. For now, however, it is too early to tell if SHL has reached that point. Instead, the commercial launch sector is focused on launch vehicle reusability, a necessary ingredient to make the greater size of SHL economically viable. Indeed, hypothetical cost scenarios in this analysis show that it is possible for SHLs to be viable if they meet certain reuse thresholds.

Even with adequate reusability, SHL will require new markets to emerge that demand greater mass and volume capabilities. Conversely, SHL's greater mass and volume capabilities may catalyze new markets—if the price is right. For now, SHL's commercial realization is tightly tethered to its ability to efficiently deploy and replenish large broadband constellations. Other potential and more speculative markets include new commercial space stations, sustained lunar presence, space tourism, orbital data centers, space-based solar power, Mars colonization, and point-to-point space transportation.

It is too early to tell if the SHL launch vehicle will result in a boom for an audacious space race or a bust for a space economy where existing and more agile rockets succeed. The market maturation path will most likely involve serving megaconstellations with a regular launch cadence. Such an ordinary effort will define the SHL rocket not as simply an engineering marvel but a proven commercial success and the necessary foundation for unlocking and building the *extraordinary*.

Introduction

The modern super heavy lift (SHL) rocket represents a renewed expansion in payload capacity and volume to orbit, creating the potential to enable a wide range of space missions. Reprising its Apollo glories, NASA has developed and flown the SLS around the Moon. China is also developing two SHLs, Long March 9 and Long March 10, to enable future lunar and deep-space missions. Unique to today, however, two commercial launch competitors, SpaceX and Blue Origin, are each building SHL rockets, Starship and New Glenn, respectively. All of these SHL providers are striving to achieve lower launch costs per payload (e.g., cost per kilogram) through increased lift capacity, large cargo fairings, and full or partial launch vehicle (LV) reusability. For the commercial companies, this greater launch vehicle mass and volume might enable new—and economically sustainable—opportunities.

> ***"Loved by travelers but shunned by accountants, the A380 remains aviation's grandest reminder that innovation alone can't defy economics."***
>
> ***—FlightDrama***

It is not a given, however, that SHL rockets will be economically successful. The history of other transport industries shows that higher cargo volume does not automatically equate to higher margins. In the maritime sector, commercial shipping has largely optimized around vessels with the largest carrying capacity, with modern ultra-large container vessels (ULCVs) being able to carry more than 20,000 standard shipping containers.[1] But in commercial aviation, Airbus learned the hard way that the A380 jumbo jet's massive size did *not* lead to greater profits.[2] Instead, it introduced higher costs and operational constraints, as the hub and spoke air transport system Airbus envisioned ultimately gave way to smaller but more fuel-efficient aircraft flying point-to-point routes. In a similar way, the development of SHL rockets is an example of how the space sector is maturing and striving to achieve economies of scale, but the question is whether SHL will be as economically successful as the ULCVs or an economic failure like the A380. In this respect, the SHL rocket's story is still unfolding and its future is still uncertain.

This examination of the commercial economic potential of SHL launch vehicles begins with an overview of SHL programs past and present, focusing on the two leading commercial competitors of today—SpaceX and Blue Origin—and the differences in their engineering and commercialization strategies. It then dives into the interdependent technical and economic factors that are likely to impact their market success. Finally, it concludes with a discussion of the potential future markets that could be enabled by SHL and serve as their main source of demand.

Battle of the Titans—Two Competing Commercial SHLs

SHL is a space launch vehicle category, defined by NASA as those vehicles that can lift greater than 50,000 kg, or 50 metric tons, to low Earth Orbit (LEO) as seen in Table 1. The following section discusses historical SHL LVs and providers that were developed in previous decades and the new vehicles and providers that have emerged in the last decade. See *Appendix A* for LV combinations for various missions and LV types.

Table 1: Launch Vehicles Carrying 50,000 kg (50 Metric Tons) or More to LEO

Rocket (Country) *Inaugural Flight Date*	**Reusability** Expendable (E) Partially Reusable (PR) Fully Reusable (FR)	**Approx. $ per Launch** *(2025 Dollars)*	**$/kg to LEO** *(a)*	**Payload** Metric Tons [t]	**Fairing Diameter, Volume**[*] [m: m^3] *(b)*
SpaceX—Falcon Heavy *(c)* (USA) *February 6, 2018*	PR—Booster + core	$90 million (PR) $150 million (E)	$1,400 (PR) $2,350 (E)	64 (LEO)	5.2: 170
NASA—SLS Block 1 *(d)* (USA) *November 16, 2022*	E (with some elements of reuse from the Space Shuttle Program)	$2 billion	$28,500	70 (LEO)	8.4: 230
Blue Origin—New Glenn 9x4 *(f)* (USA)	PR—First stage only			70 (LEO)	8.7: 821
SpaceX—Starship (USA) *(e)* *April 20, 2023 (2 stage)*	FR	$10-$100 million	$67-$900 *(h)*	150 (LEO FR) 250 (LEO PR)	9: 1,000
NASA—SLS Block 1b	E (with reuse elements from the Space Shuttle Program)		$19,000	105 (LEO)	8.4: 621
NASA—SLS Block 2	E (with reuse elements from the Space Shuttle Program)		$15,400	130 (LEO)	8.4: 988
Long March 9 (China) *(g)* *First flight TBD*	Plans for PR			150	10.6
Long March 10 (China) *First flight TBD*	Exploring PR			70	5
Yenisei (Russia) *First flight TBD*	Unknown			103	4.1
Saturn V (USA) *November 9, 1967*	E	$1.5 billion	$10,714	140	
Energia (Russia) *(j)* *May 15, 1987*	PR			100	
N1 (Russia) *1969-1972 (4 test failures)*	E			95	

Operational	*Demo/Testing*	*Under Development*	*Historical or Retired*

a) Cost per kg ($/kg) calculated for fully loaded fairing. Implies that this is the lowest cost point to be achieved.
b) Carrying capacity volume is estimated using fairing drawing to scale or based on launch provider specifications.
c) Cost figures from 2018 Elon Musk tweet, payload information from SpaceX website.
d) Figures from various NASA SLS Fact Sheets or from GAO reports.
e) Cost figures are from Elon Musk statements in 2022, $/kg calculated based on that information.
f) Payload capacities and size from Blue Origin webpages.
g) China Aerospace Science and Technology Corporation, March 4, 2023.
h) Starship costs per kg varies widely depending upon first use, marginal cost.
i) Competitor's estimate for the cost of a New Glenn launch; $/kg derived from cost estimate and Blue Origin website.
j) Designed for HSF and reusability as a counter to the space shuttle. Retired after only two non-crewed flights.

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[*] Volume to LEO.

SHL rockets have existed since 1967, when NASA's Apollo Program introduced the massive Saturn V rocket, which at the time set the record for the largest payload capacity (140,000 kg) to LEO.[3] During this time, Russia also developed the N-1 rocket for its own lunar program, although it faced funding and schedule challenges. After the N-1's four failed launch attempts, the Saturn V became the only operational SHL rocket, achieving 13 orbital launches between 1967 and 1973. But after launching Skylab, the first American space station, the Saturn V stopped flying and there were no SHL launches for 50 years.

In 2018, the SHL renaissance began with an unforgettable inaugural flight of SpaceX's Falcon Heavy, dispatching a cherry-red Tesla Roadster into heliocentric orbit (see *Appendix B—What Happened to the Falcon Heavy?*). Within the next seven years, the launches of three new U.S. SHL vehicles—SpaceX's Starship, NASA's SLS, and Blue Origin's New Glenn—followed. In China, the Long March 10 is a new SHL rocket designed to meet immediate needs, while the Long March 9 is intended to be the future SHL workhorse. Like earlier SHLs from the Apollo days, the SLS and Long March 9 and 10 mirror traditional government-funded programs to achieve national goals. By comparison, Starship and New Glenn represent private sector investments that heavily depend upon a combination of commercial and government demand. The rest of this examination focuses on Starship and New Glenn, their competing strategies, and pathways to commercialization.

***Two Competing Commercial SHL Strategies*.** While both SpaceX and Blue Origin (see Table 2) seek to leverage Silicon Valley technology and an

Table 2: Commercial SHL: Two Companies and Two Visions

	SpaceX—Starship	Blue Origin—New Glenn 9 x 4†
Innovation Approach	Rapid, iterative, high-risk innovation and experimentation	Careful "measure twice, cut once" and emphasis on reliability
Funding	Private capital, funded primarily by venture and private equity capital.	Private capital, funded primarily by founder, Jeff Bezos
Roll Out	SpaceX's Starship and smaller LV, Falcon 9, are intended to serve various markets concurrently	Blue Origin's New Glenn 9 x 4 and smaller LV, 7 x 2, are intended to serve various markets concurrently
Payload	~150 – 200 metric tons (est.) to LEO	~70 metric tons (est.) to LEO
Material	Relatively heavy, strong, and thermally resilient stainless steel	Lighter materials, including aluminum and carbon fiber composites
Reusability	**Full** reusability (booster + upper stage)	**Partial** reusability—**first-stage-only** reuse, designed to land on an ocean platform after boosting the second stage to space
Recovery—Stage 1	Return to launch tower—catch with "chop sticks" or mechanical arms	Downrange sea landing on recovery vessel or drone ship; uses 4 "fins" for attitude adjustment during first-stage descent and landing
Fuel	First and second stage—Methalox (liquid methane and liquid oxygen)	First stage—Methalox; second stage—Hydrolox (liquified hydrogen and oxygen)
Vertical Integration	**Very High**—backward integration to parts, components and systems; forward integration to Starlink	**High**—backward integration to systems and components—Blue Origin is a separate aerospace company; therefore, forward integration is indirect to Amazon Leo, a division within Amazon

† New Glenn 9x4 includes nine BE-4 engines on the first stage and four BE-3U engines on the second stage.

intense "risk capital" culture to their SHL programs, such as applying digital age simulation tools, rapid prototyping, and high-risk, long-term visions—the two companies also have different strategies and designs.

The dueling efforts between SpaceX and Blue Origin could bring competitive market forces to bear on SHL launch vehicles. According to one space economist, "At last there is pressure on price as the introduction of Blue Origin's New Glenn launch vehicle will reshuffle the cards and drive down launch prices."[4]

The design strategies of New Glenn and Starship are influenced by their founders' aspirations. Since 2002, Elon Musk's primary goal was to transform humans into a multiplanetary species by colonizing Mars. More recently, Musk cited several reasons for emphasizing lunar ambitions, including a shorter development timeline, faster transit times, and more regular launch windows.[5, 6] By contrast, Jeff Bezos's vision includes a "future where millions of people will live and work in space with a single-minded purpose: to restore and sustain Earth, our blue origin".[7] Yet despite different visions, both founders share common interests in lunar missions and LEO destinations and have incorporated modern design principles with manufacturability and launch cadence in mind.

Starship and New Glenn have demonstrated different development and engineering strategies to meet these aspirations. SpaceX utilizes a "hardware-rich" approach, similar to the "fail fast, fail often" philosophy of the Agile software development community. In contrast to SpaceX's rapid design iteration and test flight experimentation, Blue Origin has chosen methodical engineering, and a more deliberate process.[8] Moreover, both companies have two fundamentally different approaches to achieve a rapidly reusable rocket booster evidenced by different materials and reentry landing mechanisms.

- ***Launch Vehicle Materials***—Driven largely by their approach to reusability, SpaceX's **fully reusable** Starship and Blue Origin's **partially reusable** New Glenn have selected different materials. Starship is designed for multiple launches and uses heavier stainless steel to harness its advantages in terms of cost, strength, thermal properties, and manufacturability.[9] By contrast, New Glenn is designed to reduce weight to orbit by using an aluminum alloy for its first stage.

- ***Landings***—SpaceX relies on a tower-based mechanical catch system, referred to as "chopsticks" or "Mechazilla," to minimize booster weight and refurbishment time, while Blue Origin utilizes four onboard aerodynamic controlled actuated fins and traditional landing legs to land on a downrange ship.

Notably, both Starship and New Glenn launch vehicles have shifted away from fuels that can release significant amounts of exhaust products that can negatively impact the atmosphere. Instead, both commercial SHLs have turned to cleaner burning rocket propellants.[10] Starship uses Methalox for both stages, while New Glenn's second stage uses liquid hydrogen (Hydrolox) and liquid oxygen (LOX).

The other notable characteristic of both programs is their degree of vertical integration. In business, vertical integration is a consolidation strategy wherein a firm integrates backward with suppliers or integrates forward with distributors or service providers. Both SpaceX and Blue Origin have demonstrated a strong commitment to vertical integration (see Figure 1), including:

- ***Backward Integration***—Launch vehicle providers make many of the subsystems in-house to reduce reliance on external suppliers to lower costs and speed up development. Both SpaceX and Blue Origin are committed to building their

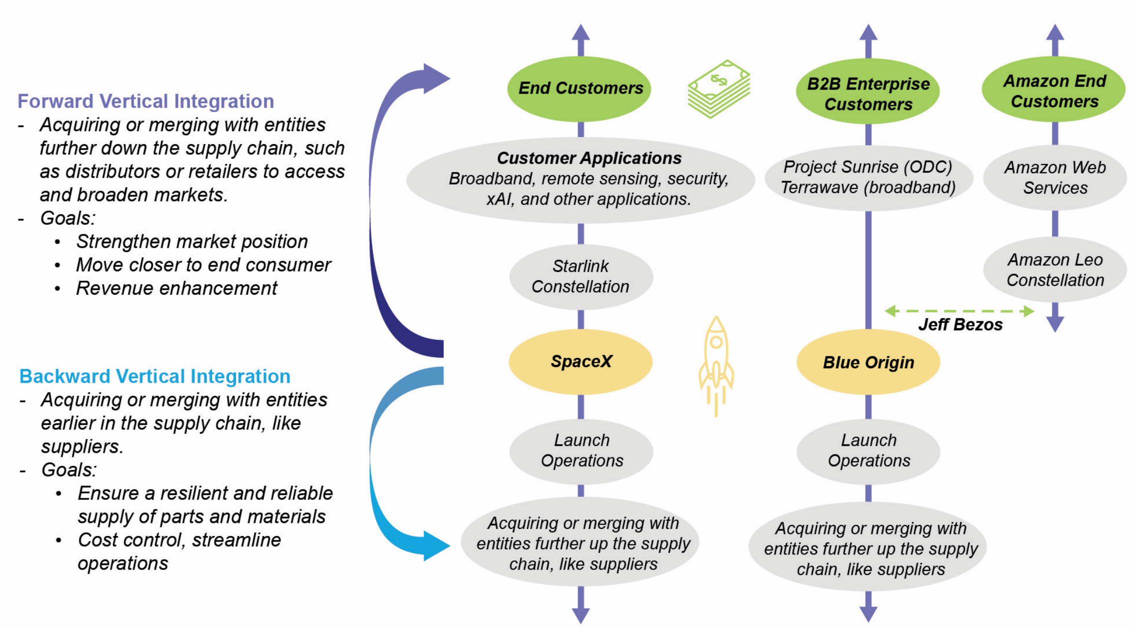


Figure 1: Forward and backward vertical integration within commercial SHL providers.
Source: The Aerospace Corporation.

own rocket engines as well as other components and systems. SpaceX's backward vertical integration even extends to microelectronics, as it currently operates the largest printed circuit board (PCB) factory in the United States.[11]

◆ ***Forward Integration***—Among rocket companies, SpaceX has a uniquely high degree of forward integration with its broadband constellation. SpaceX's Starlink has more than 10,000 satellites in orbit to date, serves a growing population of customers across land, air, and sea in more than 155 countries, and generated approximately $11.8 billion in revenues during 2025.[12, 13] Importantly, through Starlink services, SpaceX moves closer to the end user and the revenue generation side of the business. In brief, SpaceX self-funds its Starlink constellation deployment, which in turn generates revenues via Starlink subscriber fees. Blue Origin could also have a degree of forward vertical integration between Blue Origin's rockets and Amazon Leo's broadband constellation through their shared origin with Bezos, but they are currently separate companies.

Despite significant innovation by both SpaceX and Blue Origin and general excitement about the return of SHL rockets, the market is still in an early stage that some technologists refer to as a "fluid phase," wherein companies are focused on fostering innovation, generating new ideas, and borrowing design ideas from others. A future commercially viable SHL will depend on whether new technical approaches can drive down costs, whether those lower costs will meet expected profit margin thresholds, and whether there will be an enduring SHL market at those margins. The following sections explore each of these issues.

Techno-economic Overview—Tradeoffs, Payload Volumes, and Reusability

The economics of a single rocket with a given reach (delta V) for a given payload mass can change based upon key capabilities, including cargo volume, reusability, and refuelability. But even if technologically successful, a larger rocket or one that can carry the most payload is not guaranteed to be economically successful. Both positive and negative examples of efforts to maximize transportation efficiency can be found in maritime and aviation sectors. They are useful examples for understanding SHL market dynamics, which will also be shaped by customer expectations, logistical networks, cost models, and operational tempo.

In the maritime sector, since the 1960s there has been a long trend toward increased size and carrying capacity of cargo-carrying ships. The rapid adoption of the twenty-foot equivalent unit (TEU) as the standard intermodal shipping container size in the early 1970s enabled strong synergies between ships and land vehicles.[14] Shipping capacity grew to reach the so-called "Panamax standard," the largest size that could fit in the Panama Canal, of about 4,000 to 4,500 TEUs in the 1980s. By the late 1990s, global shipping demand for routes other than through the Panama Canal had grown enough to incent the creation of post-Panamax ships of 8,000 TEUs, which opened the door to even more growth, even after the Panama Canal was widened. Today, the largest class of ships, ULCVs, can carry upward of 24,000 TEUs, approaching the limits of what the Suez Canal can accommodate.[15] Since their emergence, ULCVs have demonstrated significant economies of scale for container ship operators. This works for the maritime transport industry because it typically operates with a predictable, high-volume, and continuous intermodal container logistics system across land, rail, and sea, where larger size directly reduces the cargo transportation costs. But that same predictability does not apply to the space industry, wherein launch cadence is more volatile due to a range of technical, operational, regulatory, and environmental factors. And unlike intermodal transportation, the space industry is far from having standardized payloads that can easily be loaded and unloaded from launch vehicles and integrated into other transportation chains.

By contrast to maritime transport, the commercial passenger airline industry has not seen the same success with larger jumbo jets. This is mainly due to the rise of point-to-point air travel, which partially replaced the hub-and-spoke model that was the main driver for ever-larger planes to transport passengers between hubs. This shift to smaller and more fuel-efficient aircraft significantly reduced the Airbus A380's market for high-volume routes.[16] And unlike the 747, which was able to transition to cargo freight due to its swinging nose door design, the A380 was left with few options to pivot toward.

The success or failure of these maritime and aviation transportation options were heavily influenced by core economic principles, such as increasing marginal costs and diminishing returns. While these principles are not exact analogies to the space sector, it is still worthwhile to see how the same or similar dynamics could play out in the space launch sector.

Increasing Marginal Costs and Diseconomies of Scale. As examples from the maritime and aviation sector show, having massive cargo capacity does not guarantee a commercially viable transportation option. The laws of diminishing returns apply to transportation logistics everywhere, whether on land, sea, or in space. For rockets, this means that increasing the size beyond a certain point could involve diminishing returns. Economies of scale is a principle in microeconomics that refers to reduced costs per unit that arise from increased total output of a product.

Figure 2 illustrates the optimal design point. "Q_2" is the sweet spot, wherein launch size is optimized for the lowest average cost. However, beyond this design point, some products see increasing marginal costs, or diseconomies of scale. In the aviation analogy, Airbus struggled with escalating marginal costs for refueling the A380, compared to the typical fuel-efficient twin-engine passenger jet. Other operational complexities and costs also emerged due to the large plane size.[17]

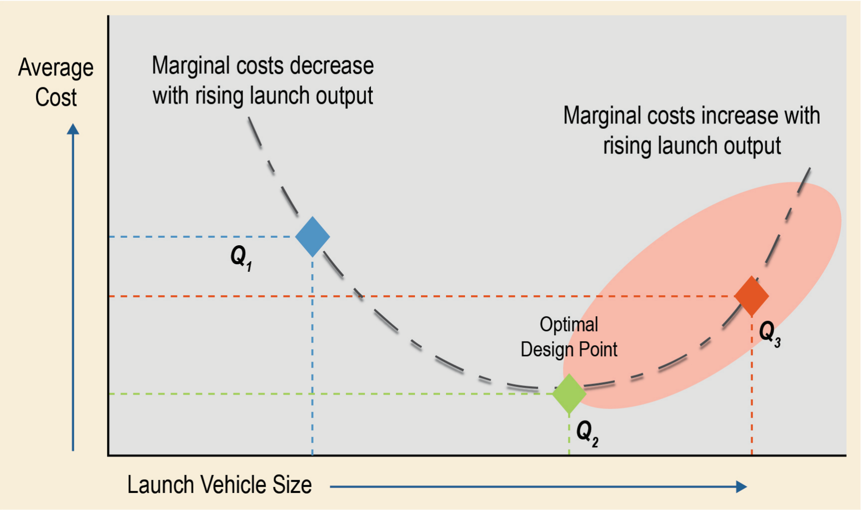


Figure 2: Launch vehicle diseconomies of scale. *Source: The Aerospace Corporation*

It is worth noting that the orbital destination can sometimes outweigh goals to achieve the optimal design point from a marginal cost perspective. Often, launching payloads into orbit involves a multi-objective trade space wherein there are more considerations than just launch vehicle (LV) size and marginal costs for that launch output. Instead, a complex trade space can guide decisionmakers to optimize rocket utilization, cargo capacity, and orbital reach (see *Appendix C*).

For a larger LV, marginal costs could involve increased LV preparation, larger "keep out" zones surrounding the launch pad, other operational costs, and complexities due to an increase in size. Some space economists have postulated that SpaceX's Falcon 9 rocket appears to be near an optimal design point.[18] Launch providers will need to ask themselves, what is the optimal design point beyond which a large rocket will yield diminishing returns? Also, an SHL rocket's flexible mass requirements can sometimes allow for simpler and heavier materials. As one expert at NASA's Jet Propulsion Laboratory notes, "The availability of greater mass and volume capability, at lower cost, enlarges the design space" for a range of space missions.[19]

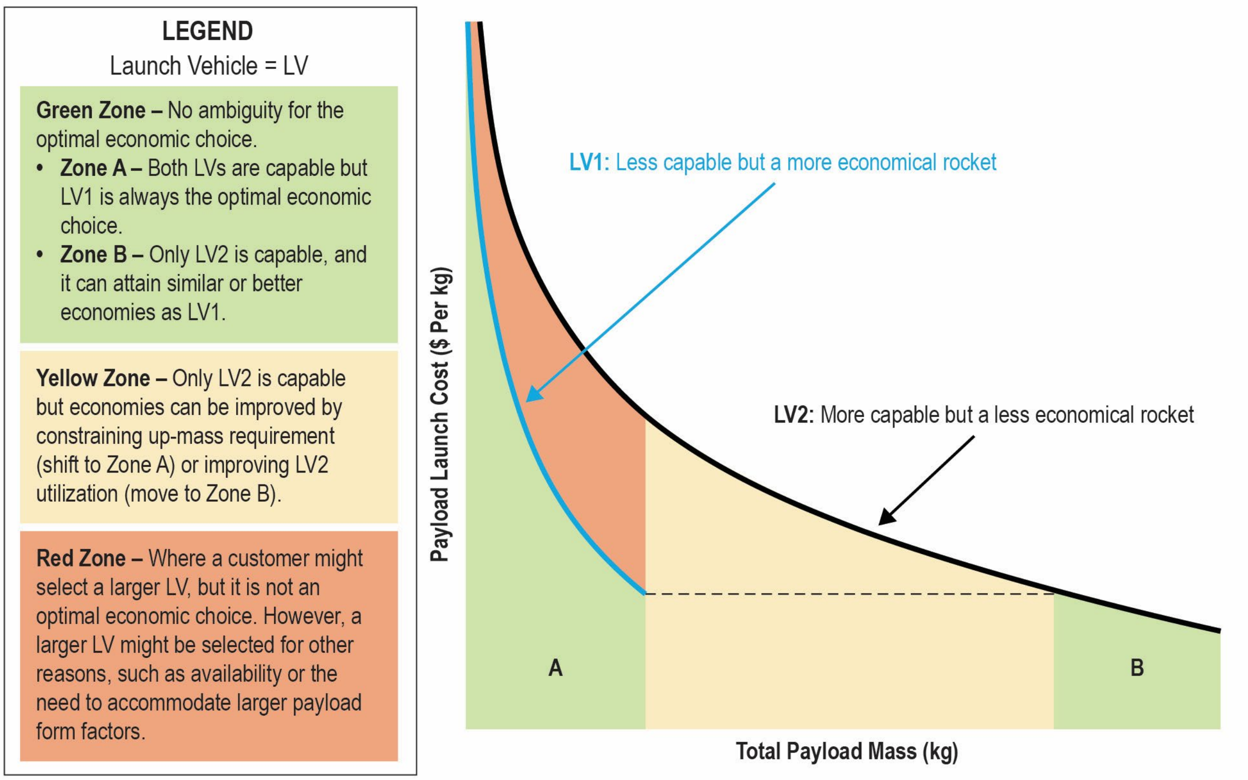
Tradeoffs Between Smaller and Larger Rockets. Larger and more expensive SHL rockets will also face competition from smaller and cheaper rockets with significantly more flight heritage. For SHL to be commercially viable, one must optimize use of SHL's greater capacity fairing and lift capacity to achieve lower cost per kg for the payload. Although the cost per launch is a fixed amount for a given launch, the cost per kg can be reduced by maximizing the mass to space (e,g., full payload capacity).

Figure 3 shows theoretical tradeoffs between selecting a more economical LV with less capable lift capacity (blue line) versus a less economical LV with more lift capacity (gray line). For example, these two lines might represent medium- and super-heavy lift vehicles, respectively. The cost per unit mass lifted falls as overall LV payload mass increases. Depending upon LV choice and payload mass, a customer might find itself in the green, yellow, or red zones.

In Figure 3, Green Zone A shows that both LVs are capable of carrying the total payload mass (x-axis), but the smaller and less capable rocket is the optimal economic choice in terms of $/kg (y-axis) for lower total payload mass. Green Zone B shows that only a larger LV2 can carry a higher payload mass, and can achieve similar or better economies of scale, depending upon the degree of fairing utilization. From a transport economics perspective, rocket operators, airline carriers, or maritime logistics operators would all agree that fully utilizing a high-volume rocket fairing, plane cabin, or ship hull allows operators to spread high fixed costs over more cargo or passengers to achieve maximum economic efficiency. But sometimes, on low-demand routes, smaller and more efficient transport vehicles can minimize trip costs to minimize overall costs.

Figure 3 also illustrates conceptually that while payload mass is the limiting factor for a rocket, volume is also an operational constraint. It is possible that some payload form factors could push the cargo capacity limits of a LV before maximum payload mass is reached.

Large Cargo Volumes. A separate but related efficiency consideration is the enormous cargo volume offered by a SHL rocket's wider fairing, which introduces a host of additional mission possibilities for lofting a single, very large payload to space. Eight years ago, then-chief engineer for the James Webb Space Telescope, Jonathan Arenberg, described the industry's launch limitations as "the tyranny of the fairing"—referring to technical limitations of the width of existing rocket fairings, which cannot carry large enough payloads to accomplish certain milestones.[20]


LEGEND

Launch Vehicle = LV

🟩 **Green Zone –** No ambiguity for the optimal economic choice.
- **Zone A –** Both LVs are capable but LV1 is always the optimal economic choice.
- **Zone B –** Only LV2 is capable, and it can attain similar or better economies as LV1.

🟨 **Yellow Zone –** Only LV2 is capable but economies can be improved by constraining up-mass requirement (shift to Zone A) or improving LV2 utilization (move to Zone B).

🟥 **Red Zone –** Where a customer might select a larger LV, but it is not an optimal economic choice. However, a larger LV might be selected for other reasons, such as availability or the need to accommodate larger payload form factors.

Figure 3: Theoretical tradeoffs between smaller and larger LVs. Economizing a customer's payload to orbit is not strictly about constraining mass but optimizing the chosen LV's utilization of lift capacity.
Source: The Aerospace Corporation

It is worth noting that, while vehicles with very large payload volumes for one or a few large cargo pieces are also seen in the maritime and aviation sectors, they are often used sparingly to serve government customers and other niche markets. Aviation examples include NASA's Super Guppy Oversight Cargo Transport and the U.S. Air Force's C-5 Super Galaxy, which are used to transport oversized loads such as satellites and tanks.[21, 22] Maritime examples include the *Mighty Servant 1* and *MV Black Marlin*, which are used commercially to transport other ships and oil platforms.[23, 24]

SHL launch vehicles could also offer more spacious cargo volume for transporting future large payloads, perhaps allowing for less complex folding requirements as compared to smaller rockets. Payloads could include infrastructure for lunar operations such as power systems, habitation, rovers, and in-situ resource utilization (ISRU) technology. Spacious payloads could also include commercial space stations in LEO for tourism and research. However, it remains to be seen how much demand there will be for such services and whether it will come from the public or private sector. Additionally, faring volume alone does not ensure the ability to deliver large payloads as the rocket must also have an appropriate deployment mechanism.

A final element of the large cargo volume is the ability for SHL to allow additional smaller payloads to "rideshare" alongside one or two larger ones. Rideshare uses these additional payloads to help maximize the utilization of cargo. Rideshares have existed in the space world for decades but have become more commonplace recently with missions such as the SpaceX Transporter rideshare program, which created reliable and consistent rideshare availability for small satellites.[25]

Expendability, Reusability, and Refuelability. The ability to refuel and reuse transportation vehicles is accepted as commonplace in almost every transportation sector (land, air, and sea), but is still relatively rare in the space sector. For decades, the space industry used only expendable rockets. Refuelable rockets were viewed as practically impossible due to several technical factors such as the difficulties of achieving a controlled landing, the viability of reusing engines despite their exposure to extreme thermal and mechanical stress, general structural fatigue, and potentially overcoming significant refurbishment requirements.

Space X's Falcon 9 brought about a revolution by demonstrating the durability of reuse and the ability to withstand structural stresses endured across the life of a booster. For instance, booster B1067 successfully returned from space for the thirty-fifth time on June 8, 2026, demonstrating a durability that contributes to the competitiveness of the Falcon 9 line of launch vehicles and the "bedrock of SpaceX's success."[26] It remains to be proven whether SpaceX's Starship or Blue Origin's New Glenn will see similar success with reusability, as both are significantly larger structures than the Falcon 9. One of the main challenges with reusing rockets is returning them to Earth for a soft landing, which requires the extra mass of both stronger components and thermal protection that an expendable rocket would not need to carry.[27, 28]

A reuseable rocket is, by definition, refuelable on the ground in between launches, but refueling rocket **upper stages** and satellites in space has not yet been fully operationalized. In-space refueling technology is being actively developed as a key part of the Artemis Program's architecture for returning humans to the Moon, which envisions the Human Landing System being refueled multiple times.[29] Additionally, U.S. Space Command has signaled a desire for in-space refueling.[30]

However, there is a complex set of tradeoffs between the mass utilization, expendability, and refuelability of a rocket, as discussed in detail in *Appendix C*. A rocket that can be refueled in space is sometimes (but not always) more efficient than one that is fully expendable. The optimal tradeoff depends on the specific objective being sought and impacts for both payload capacity and reach. Visualizing this multi-objective trade space can help decisionmakers optimize rocket utilization, cargo capacity, and orbital reach.

Cost Scenarios, Early Mover Advantage, and Payload Integration

The preceding discussion of technical and economic realities reveals the simple truth that a partially utilized large rocket (whether by volume, mass, or both) may not deliver economies of scale and could end up being more expensive than a fully filled smaller rocket. However, if the larger volume can be realized, hypothetical cost scenarios show it is plausible SHLs could be economically competitive.

Launch costs and capacity have a disproportionate impact on space systems due to the historically enormous cost to orbit and the constraints placed on the size and mass of payloads that can be accommodated.[31] To illustrate how these considerations change, the following three hypothetical scenarios use Starship with various assumptions. Launch *cost* refers to the depreciated cost of launch vehicle based upon usage (e.g., number of times launched), which declines with each use, plus the fixed **marginal** cost at cadence. Price refers to the fee charged by the launch provider to a launch customer, which could include a profit margin or the difference between price and cost.

Hypothetical Cost Scenarios of Starship. To illustrate various future costs for Starship, three scenarios are provided (see Figure 4). Hypothetical cost scenarios apply a 10x reuse of Starship, a far-from-trivial feat for the launch vehicle, but within the realm of the possible given the demonstrated success with Falcon 9 reusability.[32] The cost scenarios are based on the following considerations:

- Assume a fully loaded fairing of 150,000 kg where both super heavy lift booster and the second-stage Starship are returned to the launch site and reused ten times.

- Apply (as a percentage of initial LV value) constant marginal costs per use for LV maintenance, propellant/fuel replenishment, maintenance and refurbishment, logistics and ground support, and payload integration.

- Use a *unit of production* method to calculate depreciation based on the SHL's number of launches rather than number of years in use, and add the depreciated value of Starship to each launch cost, which significantly increases the cost-per-kg estimate. This nonstandard method to calculate launch cost raises the overall cost-per-kg estimate and incorporates a self-insurance mechanism to cover the potential loss of the launch vehicle itself. However, as the launch vehicle ages and depreciates, lower costs are achieved.

- Finally, Scenario 1 assumes 35 percent fixed marginal costs; however, Scenarios 2 and 3 assume a decline to 20 percent fixed marginal costs due to streamlined operations over time.[33]

Using this methodology, three hypothetical scenarios for Starship costs are described:

- ***Scenario 1*** applies $100 million for the initial rocket and 35 percent marginal costs. A fully loaded Starship at full cost would yield $900 per kg and would be reduced to $233 per kg after ten reuse cycles. This cost scenario is lower than a reusable Falcon 9's price per kg based on a maximum 17.5 metric ton capacity ~ $4,000 per kg.[34]

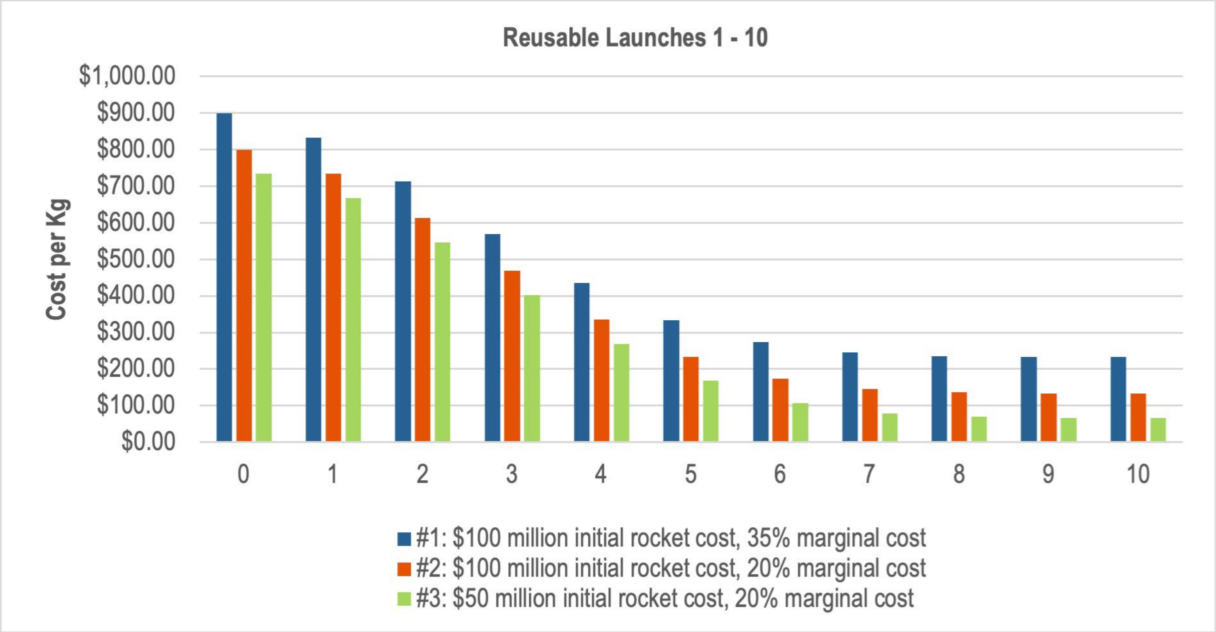


Figure 4: Three scenarios for reusable launch for starship. *Source: The Aerospace Corporation*

- ***Scenario 2*** applies a $100 million initial rocket cost and a lower 20 percent marginal cost‡ due to improved efficiencies gained through repeatable relaunch. A fully loaded Starship at full cost would yield $800 per kg, which would be reduced to $133 per kg after ten reuse cycles.

- ***Scenario 3*****,** the most optimistic, assumes a lower rocket manufacturing cost of $50 million, due to a steep manufacturing learning curve *and* low marginal cost reduced to 20 percent. A fully loaded Starship at full cost would yield $733 per kg, which would be reduced to $67 per kg after nine use cycles. Under this scenario, $67 per kg is the same as Musk's estimate in 2022.[35] Such a high level of reuse is not outside the realm of reason. In fact, a Falcon 9 rocket reached the thirty-fourth flight milestone on March 30, 2026.[36]

These example scenarios indicate the plausibility that SHLs can yield lower costs to launch providers and offer a greater likelihood of lower prices to launch customers through a combination of manufacturing and operational learning curves, lower marginal costs, a fully laden rocket, and adequate reuse.

Vertical Integration and Payload Integration.

The previous two sections emphasize the economics of SHL's dependence on utilizing the larger volume. SpaceX appears to have a significant advantage in trying to commercialize Starship through its successful Starlink business. Starlink's continued expansion depends on deploying hefty V.3 satellites weighing up to 2,000 kg, compared to the current smaller V2 Mini models that weigh approximately 575 kg each. These larger size V.3 Starlink satellites have close to 60-m wingspans and fold up to approximately 7-8 m. The SHL rocket fairing is

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‡ During the Mars Society's 2020 Virtual Convention, Elon Musk mentioned the goal of reducing Starship's marginal launch cost to as low as $2 million. If he assumed, as indicated by *Payload Research* in 2024, that the eventual cost of Starship would be $10 million, then Musk was using a 20 percent marginal cost metric.

currently the only rocket class that can efficiently accommodate the larger size V.3 satellites.[37,38] Starlink's early market capture of approximately 10 million global satellite broadband subscribers also provides the basis for recurring revenue that helps fund the development costs of Starship.[39]

Using Starship to deploy future Starlinks depends heavily on finding more efficient payload integration and deployment methods that can make the most efficient use of its capacity. In 2023, *Financial Times* pointed out that Musk's "bold bet" for Starship may share a similar fate as the world's largest passenger airliner, the A380, unless SpaceX can fill the launch vehicle's enormous capacity.[40] To address this, in 2024 SpaceX introduced a payload deployment system to tightly pack and stack a new, flatter version of Starlink satellites into Starship's capacious fairing and dispense them one by one through a slot (similar to that in the iconic "Pez" candy dispenser) from the side of the ship's cargo bay.[41]

This strong link between Starlink and Starship may offer yet another advantage over other SHL vehicles in moving the space world toward its own version of containerized standard payloads. Like the global uniformity of the intermodal shipping container, which established size compatibility and simplified logistics coordination, Starship's Pez dispenser could set a new standard in terms of deployment compatibility and space optimization between launch vehicle and payload. But it is still unclear if other satellite manufacturers can develop standardized satellites at the same scale and reliability as SpaceX has demonstrated, and whether other mission areas can make use of large numbers of identical satellites.

However, this high degree of vertical integration and "first-mover" advantage could also be a hindrance for SpaceX, particularly if it creates high barriers to competition that raise concerns with regulators. A custom payload deployment system that works *only* for Starlink spacecraft could spark such concerns. Yet if the past is an indicator, SpaceX accommodated a broad range of dispenser systems on Falcon 9, including multi-payload systems and mission-unique adapters as a nonstandard service for launch customers. Perhaps the same will be true for Starship.[42] Still, SpaceX could enjoy a first-mover advantage for its own satellite broadband constellation and still allow rivals (that either adapt their satellites to a Starlink form factor or invest in a dispenser system) a means to access Starship's capabilities. Such efficient and broadly available utilization of SHL's volume offers the greatest promise for its economic viability.

Potential Commercial Markets for SHL

Logically, lower costs to orbit addressed in the previous section could provide a boost for a range of space applications, including large constellations for space-based broadband, even larger-scale, capital-intensive space projects such as orbital data centers (ODCs), and space-based solar power generation. But cost is not the only factor in determining the SHL rocket's commercial viability. Future demand, from commercial or government customers, is also a critical factor to realize revenues and growth, driven in part by competitive market pricing and potential demand.

The space sector has continued to expand over the past 50 years. According to the Department of Commerce's Bureau of Economic Analysis, the U.S. space sector grew by 6.3 percent in 2023[§] and the average 10-year annual growth rate (between 2012 and 2023) was 2.4 percent.[43] Other forecasts have concluded that the space sector could reach $1 trillion or more within the next ten years, driven

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[§] While current-dollar growth in GDP was 6.3 percent in 2023, real growth was only 0.6 percent, primarily reflecting the impact of inflation on current-dollar estimates.

by new capabilities and activities. While traditional space applications (e.g., satellite communications, positioning, navigation, and timing, and remote sensing) continue to grow, it is these future and speculative commercial uses for space that could spur demand for SHL rockets and prompt more frequent launch demand.

For any new technology or capability such as commercial SHL, future demand is difficult to predict at this stage of development. Nonetheless, there are many companies and innovators in the growing space sector that see the future availability of SHL launch vehicles as key enablers for new business opportunities and space capabilities, if the price is right. Some of these markets are unproven (e.g., space-based solar power and ODCs) and will require a high level of upfront capital investment and risk, and it is doubtful that they can be established without strong government commitment, private sector innovation, and stakeholder risk tolerance.

The following analysis categorizes market segments for SHL, starting with existing customers and large constellations, as well as future potential markets.

Large Constellations. A "killer application" can drive market adoption rates to new levels. The growing demand for satellite-enabled broadband and connectivity services may become that compelling SHL use case, as satellite operators continue to deploy and replenish their large constellations with increasingly large satellites.

Over the past ten years, the number of satellites on orbit has grown tenfold—from about 1,400 satellites on orbit in 2016 to more than 14,000 today.[44] Over the same period, the annual global launch rate increased roughly threefold. This disparity is due to rockets deploying multiple satellites per launch, significantly reducing the cost per kg of payload. While Starlink has accounted for most of the deployed broadband constellation satellites, emerging competitors include the following large constellations: Amazon *Leo* (USA), formerly known as *Project Kuiper*; Amazon *Terawave*; Eutelsat *OneWeb* (France); Telesat *Lightspeed* (Canada); *Qianfan* or *Thousand Sails* (China); and *Guowang* (China).

Amazon *Leo* has already contracted the New Glenn rocket for as many as 27 launches and SpaceX has repeatedly said that the next-generation V3 Starlink satellites are intended to be launched on Starship.[45, 46] SpaceX's V3 satellites are much larger and heavier than their predecessors and are designed to offer a whopping 1,000 Gbps, a tenfold improvement over the V2 Mini models (96 Gbps).[47] The reusable SHL vehicles promise faster and more affordable constellation deployment as well as an opportunity to launch more voluminous—and capable—satellites. The SHL market's **near-term** fate hinges on its ability to deploy and replenish these large broadband constellations at competitive price levels ($/kg), including an ability to launch large-volume satellites.

Orbital Data Centers. One category of large constellations that have seen a very recent surge in interest and investment are orbital data centers (ODCs), which aim to reduce reliance on ground-based infrastructure, enable fast and secure storage and processing of satellite data, and greatly increase the amount of computation and artificial intelligence (AI) processing done in space. A primary driver for ODCs is their ability to use solar energy to power electricity-hungry clusters of central processing units (CPUs) and graphics processing units (GPUs). Thus, ODCs can be thought of as large, solar-power-generating satellites that fully leverage the intense solar radiation in space to conduct energy-intensive data processing.

At present, technology investors are backing multiple ODC concepts, such as Nvidia's *Starcloud*. Likewise, Google, in partnership with Planet, is examining a new venture called *Project Suncatcher*, which plans to scale machine learning in space using Google's Tensor Processing Unit (TPU) AI chips. Finally, SpaceX acquired xAI in an all-stock deal valued at more than $100 billion and proposed an ODC constellation of up to one million satellites in LEO.[48] Musk acknowledged that the scale of the xAI constellation would be a "forcing function" for the Starship launch.[49] However, others in the space sector are skeptical that a "super-constellation of one million satellites" is practical and believe it would attract opposition from a range of space operators, as well as diplomatic and regulatory pressures from other countries.[50]

Despite "super-constellation" regulatory hurdles and concerns, ODCs are potential game changers and their success will depend upon affordable and reliable access to space, likely enabled by SHL rockets. But it is not yet clear how ODCs will compete economically against terrestrial-based data centers, which are rapidly improving their efficiencies** through system optimization. According to the International Energy Agency, these measures typically deliver a 5 to 40 percent energy savings in commercial facilities.[51] Beyond the economics, ODC technical challenges loom large, including: protecting integrated circuits from radiation exposure; effecting expensive in-space assembly, repair, and maintenance; and (above all) overcoming thermal management challenges in the vacuum of space. While there are significant potential benefits to moving additional compute to space, there are many technical, economic, and regulatory challenges that still need to be worked through for this market to fully emerge.

New Commercial Space Stations. While the International Space Station (ISS) was constructed gradually over 42 assembly fights, newer concepts may leverage SHL high-volume capabilities for faster deployments.[52] According to SpaceX, just "one single Starship has a pressurized habitable volume of more than 600 cubic meters, which is roughly two-thirds the pressurized volume of the entire International Space Station."[53]

With the planned retirement of the ISS drawing nearer, commercial companies were expecting to fill the void. However, the market demand for commercial space stations is "highly speculative without continued government interest," and the onus is on the U.S. government to "create opportunities and an environment to thrive."[54] Recently, NASA has deemphasized the Commercial LEO Destinations (CLD) program and has pivoted to a "core module" concept, allowing commercial modules to attach to a standardized infrastructure hub in orbit to form a mini-ISS.[55] The debate continues as NASA representatives have underscored that the CLD program, including space tourism and commercial research, has *not* materialized. In return, commercial representatives have responded by pointing out the significant amount of private capital already raised for the CLD program.[56]

***Sustained Lunar Presence*.** In addition to NASA's near-term goal to return humans to the Moon, various nations and private actors have expressed interest in leveraging the Moon for resource extraction, meaning materials are either returned to Earth or used in-situ, requiring the construction of mining and facilities for processing and transport. Blue Origin's founder, Jeff Bezos, cited his investment in heavy-lifting infrastructure as a key to his vision of the industrialization of space, including the Moon.[57] Other organizations have shared similar visions for lunar habitation, manufacturing, and large-resource extraction. [58] To achieve the scale necessary for these projects, access to regular and reliable SHL will be essential.

** Improved IT device efficiencies, advanced controls, automation and virtualization software, efficient cooling systems.

Space Tourism. A limited space tourism market currently exists for suborbital flights such as Blue Origin's New Shepard spacecraft, which offers a short period of weightlessness after crossing the Karman line. Additionally, SpaceX's Crew Dragon spacecraft is designed to transport astronauts to the ISS and could be in a position to take civilian tourists on orbital journeys. Perhaps a future tourist destination in orbit would require a larger rocket. While smaller rockets could serve shorter stays on small commercial stations, in the distant future a tourist destination might require the capacity offered by an SHL launch vehicle to transport tourists and supplies into orbit with a regular tempo to support many humans and the required cargo for their survival.

Space-based Solar Power. This concept involves orbiting satellites with large solar arrays that collect uninterrupted sunlight, convert it to microwaves or lasers, and transmit it to ground-based receiving stations that receive and convert it into electricity. In addition to supporting missions such as China's International Lunar Research Station and future deep space missions, China intends to use the Long March 9 SHL rocket to carry parts of a 1-km-long solar array into space. When complete, this space-based solar power station is expected to beam continuous clean energy back to Earth from GEO.[59] A private venture-backed company, Space Solar (United Kingdom), also has ambitious plans to generate multi-gigawatt systems of space-based solar energy,[60] an endeavor that will require significant investment and upmass. Overview Energy (United States), another space-based solar power startup, announced an agreement to provide up to one gigawatt of power for data centers operated by Meta—with commercial service to begin as soon as 2030.[61]

A 2025 "technoeconomic analysis" led by the California Institute of Technology pointed out that Starship could deliver 559 solar modules using only 11 Starship launches, while a Falcon 9 would require 280 launches to deliver the same cargo. Ultimately, greater launch mass efficiencies result in a much lower levelized cost of energy (LCOE) per kilowatt hour for this type of large infrastructure project.[62]

Mars Colonization. Beyond the Moon, Elon Musk has his sights set on long-term Mars colonization. This aspirational goal will depend on SHL capabilities at nearly every turn, along with the ability to meet Musk's oft-stated goal to maximize the cargo of the spaceship and increase the reuse of the booster and the tanker as much as possible. This potential market, like other speculative ventures such as asteroid mining, will require enormous capital commitment over decades to realize. Although the Martian frontier is perhaps generations removed from a self-sustaining economy, it is worth studying lessons from history on how to establish a new territory as a modern state, with courts and a functional bureaucracy and rules for a functional stewardship. For now, however, any commercial Mars venture is conjectural and private-sector investors or publicly traded companies would need to see a reasonable path to profits before committing capital.

Point-to-Point Space Transportation. The point-to-point space transportation concept aims to use reusable super heavy lift vehicles for rapid global transportation, potentially reducing travel times to under an hour.[63] Near-term, Air Force Research Laboratory is moving forward with its "Rocket Cargo" transport program to deliver military freight to various points around the globe using smaller rockets such as Rocket Lab's Neutron, a medium-lift reusable launch vehicle.[64] While such a system could provide benefits for international logistics (mainly due to its speed), it faces limited market impact and ultimately may capture only a very small fraction of the global air freight. There are also significant technical and logistical risks related to reusability and rapid-turnaround operations, substantial regulatory hurdles, and unproven market demand. Nevertheless, some space industry advocates believe point-to-point space transportation could be a game changer for national security and economic competitiveness.[65]

Near-term and Evolutionary Commercial Paths. Outside of large constellations, none of these markets fully exist yet. Many rely on a circular dependency; the markets are not practicable without SHL, but SHL may not be sustainable without the market. The key question is, *at what point will these markets emerge and drive enough demand for the launch costs SHL might generate?* Furthermore, can commercial SHLs ever achieve success as a sustainable and profitable business model? This analysis finds that the initial path to profitability likely depends upon the ability to provide reliable and economical rides to space for deployment and replenishment of large communication and broadband constellations. Here, vertical integration between a SHL rocket (the supply) and a large constellation (the demand) could be the critical factor to get it over the commercialization hump. Beyond this near-term opportunity, there is also an evolutionary path toward SHL enabling the development of large space infrastructure projects that will serve as future sources of demand.

> ***"Obviously, it is going to be a challenge to fund this whole endeavor. We expect to generate a pretty decent net cash flow from launching lots of satellites and servicing the space station for NASA, transferring cargo to and from the space station."***
>
> —Elon Musk,
> *Making Humans a Multi-Planetary Species,* 2017

Conclusion

In looking at the potential future of SHL and the space launch industry in general, it is useful to examine how mature transport industries in the aviation and maritime sectors sought and gained greater scale and economy. Jumbo jets carrying more passengers per route and increasingly massive container ships transporting more cargo per voyage provide useful examples of both success and struggles. Those other sectors show that bigger is not always better, as excessive scale sometimes leads to complexity, reduced agility, and often reduced payload utilization; sometimes there are broader market factors and externalities that determine economic success.

It is too early to tell if the SHL launch vehicle will result in a boom for an audacious space race or a bust for a space economy where existing and more agile rockets succeed. For now, the market maturation path will most likely involve serving megaconstellations with a regular launch cadence. Such an *ordinary* effort will define the SHL not as just an engineering marvel but a proven commercial success and the necessary foundation for unlocking and building the *extraordinary*.

Acknowledgments

The authors acknowledge the many experts and colleagues who informed the research and provided meaningful feedback. Special thanks to: Brian Weeden for several extensive reviews; Jamie Morin and Russell Rumbaugh who provided constructive advice and edits; and Denise Betts, Jacob Bain, and Richard Reed for their professional editorial and graphics support.

APPENDIX A: Definitions

Launch Vehicle Combinations for Various Missions

The SHL rocket landscape includes historical launch vehicles as well as those that are under development, testing, and fully operational. Various combinations of rocket stages are possible and are optimized for mission goals. Terminology is sometimes confusing and includes:

- **Strap-on Booster**—Attached to the side of a rocket to provide extra thrust during liftoff and initial ascent.
- **Core Stage**—For rockets with strap-on boosters, the "core" provides thrust from lift-off and is the main source of thrust after separation from strap-on boosters. The core is the structural backbone of the rocket with essential systems such as flight computers and avionics.
- **First Stage**—For rockets with only vertically stacked stages, the initial section of a rocket that provides the main thrust for liftoff and early ascent, before it falls off to be expended or recovered and reused. For such configurations, this is sometimes referred to as "the booster."
- **Second Stage**—The subsequent stage after either the first stage (in a stacked configuration) or the core stage (in a modular configuration) separation. Performs orbital insertion in a two-stage rocket.

Launch Vehicle Types

Expendable Launch Vehicle (ELV)—designed to launch only once. The Saturn V rocket is an example of an ELV. During reentry or after impact, the ELV and its components are destroyed. An ELV can also be discarded in space. ELVs remain vital for missions where launches are infrequent and maximizing mass to deep space is critical.

Partially Reusable Launch Vehicle—allows for one or more stages of the launch system to be reusable. SpaceX's fully operational Falcon 9, for instance, is a two-stage-to-orbit partially reusable launch vehicle. Blue Origin's New Glenn is also designed to be partially reusable.

Fully Reusable Launch Vehicle—designed to be relaunched multiple times and must be recovered and refurbished before launching again. SpaceX's Starship is designed as a fully reusable launch vehicle.

Refuelable Launch Vehicle—allows for refueling in space, to extend mission range or payload capacity. Though both fuel and oxidizer are replenished, the term "refuelable" borrows from familiar, colloquial use.

Appendix B: What Happened to the Falcon Heavy?

Falcon 9 and Falcon Heavy share the same fairing, with a diameter of about 5 m and a height of 13.3 m, and a total useful volume of up to 200 cubic meters. Falcon Heavy comprises three core boosters, with two side boosters typically recovered and reused, while the center core can also be recovered. SpaceX can provide an extended fairing as a nonstandard service.[66]

To date, the Falcon Heavy has completed 12 successful launches with zero failures, most recently to transport the massive ViaSat-3 F3 communications satellite into geosynchronous transfer orbit.[67, 68] And yet, the smaller SpaceX Falcon 9 rocket still dominates the launch market, despite the Falcon Heavy's greater lift capacity as an SHL-class rocket. This raises the question, *does the Falcon Heavy's relatively low usage presage low market demand for future SHL rockets with even greater lift capacity?* One potential reason is the limitation of Falcon Heavy's payload volume. Despite its power, the Falcon Heavy's fairing size is the same as Falcon 9, meaning it cannot carry significantly larger or more satellites (only heavier ones) or undertake missions to higher energy orbits, limiting its advantage for serving large LEO constellations or unique science missions. Another possibility is that this specific SHL design is not a market disruptor as it has not found the optimal balance between agility, reliability, volume, and mass to orbit. Instead, the Falcon Heavy could be a "gateway" rocket for other SHL rockets such as SpaceX's Starship and Blue Origin's New Glenn—both launch vehicles could provide the volume and power to serve the growing large LEO constellation market. Finally, the reason could be that the markets which could benefit most from SHL have not yet emerged and *won't* until SHL is fully developed (in the sense of "If you build it, they will come.").

APPENDIX C: Expendability and Refuelability Tradeoffs

Understanding the performance envelope is crucial for mission planning to ensure that the launch vehicle meets requirements of different payloads and destinations, whether they're going to low Earth orbit (LEO), geostationary transfer orbit (GTO), or beyond. Because launch vehicles need to effectively perform within a range of conditions and capabilities, the performance envelope defines the limits within which the vehicle can deliver payloads to various orbits. It is influenced by factors like mass, delta V (Δv), insertion orbit geometry and accuracy, fuel reserve for recovery operations, aerodynamic properties, and structural limits. Especially during the development of the broader operational system context for any launch program, there are two factors that can drastically reshape the physical and economic possibilities of a launch vehicle—*expendability* and *refuelability*.

- **Expendability** maximizes the capability of a given launch vehicle to inject higher mass payloads into a given orbit. Historically, expendable launch vehicles[††] (ELVs) have been the only option for reaching orbit, their propulsive stages are flown only once.[69]
- **Refuelability** allows for new possibilities that include broadening the performance envelope for new missions as well as increasing mission lifespan and payload capabilities. Reusability enables affordable refuelability.

The impacts of both expendability and refuelability are illustrated in Figure 5. Each circle represents a potential launch scenario. The optimum cost per kilogram of a launch, represented by the smallest circle (m_0, Δv_0), occurs where payload mass is at capacity and Δv[‡‡] is at its highest point given the mass. If customers have needs beyond the vehicle's optimal capabilities, they have three options (all of which increase the cost per kg):

1. **Reduce launch mass to increase achievable Δv.** Though the total cost of launch does not change, this option increases incremental cost per kg because of the need to trade away payload mass to reach higher orbits. This option is represented by the circles along the *Performance Envelope* to the left of the *Optimum Cost per kg* point.
2. **Refuel to increase reach but maintain payload mass.** Refueling increases the cost of a given mission due to operational costs of in-space replenishment. Though refueling does not increase the payload mass that can be lifted to the refueling orbit, it extends the ability of a given launch vehicle to reach higher orbits with that payload mass. This option is represented by the larger circles directly above the optimum point.
3. **Expend fuel to increase mass to orbit.** After separation, reusable stages require fuel on board to be used in recovery maneuvers. However, mass to orbit can be increased by trading away this landing fuel reserve. This naturally raises the cost of launch as future revenue from the expended stage is lost. This option is shown by the horizontal shift from m_0 to m_1 and can be combined with separate refueling operations.

[††] At the other end of the scale, a reusable launch vehicle (RLV) is designed to return to Earth intact and can be launched more than one time. RLV stages are designed for recovery and reuse.

[‡‡] Δv refers to required velocity change for a spacecraft to perform a maneuver, such as launching from or landing on a planet or moon, or escaping from the gravitational pull of a celestial body.

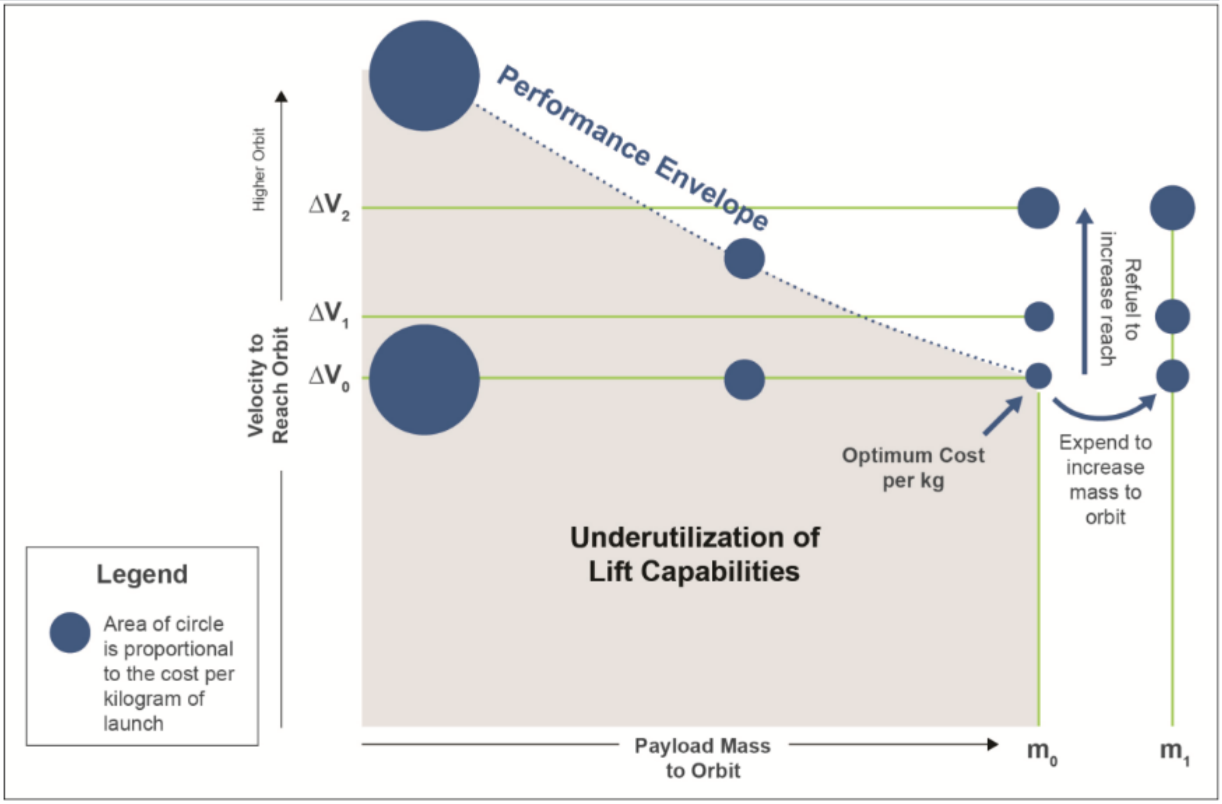

Figure 5: Impact of the degree of mass utilization, expendability and refuelability. The Pareto frontier plot demonstrates the impacts of expendable and refuelable LVs on payload capacity and reach. The size of each circle is roughly proportional to the cost per kilogram of payload delivered. This multi-objective trade space visualization can help decisionmakers optimize rocket utilization, cargo capacity, and orbital reach. *Source: The Aerospace Corporation*

Points in the gray, shaded region represent launch parameters that underutilize a vehicle's capabilities. Sometimes this can happen with oddly shaped cargo or light materials that do not fill the payload bay but also do not require the highest Δv possible in order to reach the intended orbit. Although beyond the scope of this analysis, underutilization of cargo space is often a concern for mission operators. This is where space logistics design models and mission planning optimization frameworks can sometimes help.

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