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SpaceX, Economies of Scale, and a Revolution in Space Access

On the afternoon of February 6, 2018, Space Exploration Technologies' (SpaceX) Falcon Heavy launched from the historic Kennedy Space Center in Cape Canaveral, Florida. At an altitude of 115 km, the rocket fairing separated from the main stage and deployed a cherry red Tesla Roadster into orbit with a dummy dubbed "Starman" in the driver's seat and David Bowie's "Space Oddity" on the radio. The launch was a spectacle: some 100,000 people had traveled to Cape Canaveral to watch alongside SpaceX's founder and CEO, Elon Musk, and 2.3 million viewers tuned into the livestream on YouTube, making it the second most-viewed livestream in the platform's history.[1]

In the mission control room of SpaceX's headquarters in Hawthorne, California, President and COO Gwynne Shotwell pumped her fists in the air as she celebrated, knowing the SpaceX team was one step closer to their ultimate goal: putting humans on the surface of Mars. Seven years earlier, Falcon Heavy had been only a model rocket, carried around largely empty conference rooms in Washington D.C. by Musk as he shared his dream of "making human life multiplanetary". Believing that the settlement of Mars would be a "positive, constructive, inspirational goal [capable of] uniting humanity at a critical time", he had proposed a $20 million "Mars Oasis" project that would launch a robotic lander to Mars by 2005 with a mini-greenhouse onboard.[2] But Musk's Mars Oasis plan failed. The limiting factor? The astronomical cost of launching a rocket to orbit. And thus was born SpaceX, as Musk saw an opportunity to shake up the launch industry and build his own ride to space.

With Elon Musk's vision and Gwynne Shotwell's deft leadership, SpaceX had transformed the commercial space industry in a single decade. It developed a line of rockets that cut costs to orbit by a factor of 18 and captured 30% of the commercial launch market. Falcon Heavy, capable of delivering 63,500 kg to low Earth orbit (LEO) or 17,000 kg to Mars, was the most powerful operational rocket in the world and larger than any launched from U.S. soil since the Saturn V in 1973.[3] Moreover, prices for a Falcon Heavy launch started as low as $90 million, less than a third of the price of its closest competitor.[4]

Professor Matthew C. Weinzierl, Kylie Lucas (MBA 2018), and Research Associate Alissa Haddaji prepared the original version of this case, " SpaceX, Economies of Scale, and a Revolution in Access to Space," HBS No. 719-071, which is being replaced by this version prepared by Professor Matthew C. Weinzierl, Kylie Lucas (MBA 2018), and Research Associate Mehak Sarang. This case was developed from published sources. Funding for the development of this case was provided by Harvard Business School and not by the company. HBS cases are developed solely as the basis for class discussion. Cases are not intended to serve as endorsements, sources of primary data, or illustrations of effective or ineffective management.

In 2019, after SpaceX's remarkable decade, Musk's original goal to reach Mars seemed both within reach and impossibly optimistic. Falcon Heavy's launch proved that SpaceX possessed heavy-lift capabilities, a technology that would be critical in supporting a crewed mission to Mars. But a 2014 NASA study put the cost of a human mission to Mars at $220 billion, while SpaceX's revenues from launch were just $2 billion in 2018. Where would the funding for a Mars Mission come from? As Musk mused in 2008, "[reaching orbit] is normally a country thing, not a company thing."[5] Would there be enough demand for launch services to make Elon Musk's vision a possibility, or would SpaceX have to find other ways to get there?

History of the U.S. Commercial Launch Industry

The Soviet Union's launch of the first orbital satellite, Sputnik 1, in 1957, called into question U.S. technological capabilities, and the business of launching rockets was born as part of the Space Race. In response to Sputnik, Senate Majority Leader (and future President) Lyndon B. Johnson chaired a series of congressional hearings which found that a substantial reorganization of the U.S. space program was needed to ensure American competitiveness. President Dwight D. Eisenhower suggested forming a civilian space program, the National Aeronautics and Space Administration (NASA) from the existing National Advisory Committee on Aeronautics (NACA). Congress passed the National Aeronautics and Space Act to establish NASA with the stated purpose of "provid[ing] for research into the problems of flight within and outside the Earth's atmosphere, and for other purposes." The act was signed into law by President Eisenhower on July 29, 1958.[6]

NASA and the Soviet Union soon competed to achieve human spaceflight. Yuri Gagarin, a Soviet cosmonaut, became the first human in space on April 12, 1961 just weeks before Alan Shepard completed a suborbital flight as part of NASA's Project Mercury.[7] NASA accelerated its efforts in the following years with Project Gemini and the Apollo Program, developing capabilities in a crescendo that culminated with astronauts Neil Armstrong and Buzz Aldrin becoming the first humans to land on the Moon in 1969. While a remarkable feat of engineering and policy, the Moon landing was in some ways an end rather than a starting point for the space program, as demand for lunar launches was short lived, and the last manned lunar flight took place in 1972.[8]

After Apollo, in a decision fateful for the nascent launch industry, NASA chose the partially reusable Space Transportation System (or Space Shuttle) as its next mission priority. In the 1970s, companies had built Expendable Launch Vehicles (ELV) that, under contract with NASA and the Department of Defense (DOD), provided launch services for commercial and national security satellites. But the DOD and National Reconnaissance Organization (NRO) were instructed that, once the Shuttle began launching, defense payloads would be flown solely on it, and by the late 1970s the ELVs were completely phased out. Granting a monopoly on launch to the Shuttle was meant to spread its high fixed costs across enough missions to make it cost-effective,[9] but this decision was widely criticized for disadvantaging commercial players.

While the Shuttle loomed large over the next two decades, policymakers sought ways sustain a commercial launch industry that could supply the rapidly growing market of commercial communication and national security reconnaissance satellites. President Ronald Reagan bolstered the ELV market with NSDD 94 in May 16, 1983, stating that the "U.S. Government fully endorses and will facilitate the commercialization of U.S. Expendable Launch Vehicles". Congress affirmed and expanded these actions through the Commercial Space Launch Act in October 30, 1984.[10] A decade later, the DOD announced the Evolved Expendable Launch Vehicle (EELV) program to encourage development of new launch capabilities and establish a system for procurement of launch services.

In response, the industry demonstrated remarkable achievements. In 1989, Space Service, Inc. became the first U.S.-licensed commercial launch with a suborbital mission, and McDonnell Douglas used a Delta I launch vehicle to become the first U.S.-licensed commercial orbital launch later that year. Over these decades, four ELVs would be available from private manufacturers: Titan, built by Martin Marietta; Atlas, built by General Dynamics; Delta, built by McDonnell Douglas (now Boeing); and Scout, built by LTV Aerospace Corporation.[11]

In 2003, a second shuttle disaster (Columbia) pushed policymakers and NASA to consider a broader mandate for commercial launch providers. The shuttle program would be cancelled in 2010, after which the U.S. would be unable to transport astronauts to the ISS from U.S. territory, instead relying on Russian Soyuz rockets. The Commercial Space Transportation Act was passed in 2004, declaring:

> The United States Government is committed to encouraging and facilitating a viable U.S. commercial space transportation industry that supports U.S. space transportation goals, benefits the U.S. economy, and is internationally competitive. Toward that end, United States Government departments and agencies shall: … d) Refrain from conducting activities with commercial applications that preclude, deter, or compete with U.S. commercial space transportation activities, unless required by national security; e) Involve the U.S. private sector in the design and development of space transportation capabilities to meet United States Government needs.[12]

At the time, the U.S. launch industry had become a duopoly (or monopoly), led by Boeing and Lockheed Martin's joint venture United Launch Alliance (ULA). The two companies had vied for EELV dominance for years; Boeing with the Delta IV, and Lockheed Martin with the Atlas V. The fierce competition between the two came to a head in 2006, when Boeing was found to be in possession of confidential Lockheed Martin documents. Rather than pursue litigation, the competitors agreed to establish a 50-50 joint venture to serve the market. Thus, United Launch Alliance (ULA) was formed and enjoyed a monopoly on national security launches for more than a decade.[13] From 2006 to 2013, ULA held fixed contracts with the U.S. military that totaled roughly $1 billion a year, regardless of how many rockets it launched. ULA had a stellar record, never losing a single payload, but costs began to soar. By 2014, the average cost of each launch offered by ULA had risen to roughly $420 million, and there were few other options for accessing space from U.S. soil.[14] Meanwhile, countries such as Russia, India, China, and France had developed their own launch vehicles and were offering regular launch opportunities at much lower prices than ULA. In its fiscal year 2019 budget proposal, the Department of Defense asked for $2.4 billion in launch services spending alone.[15]

Attempts to start new American rocket companies to challenge ULA had been largely unsuccessful. An early entrant to the arena in the early 2000s, Beal Aerospace Technologies, shut down operations just two years after entering. According to Andrew Beal, the CEO, "there will never be a private launch industry as long as NASA and the U.S. government choose and subsidize launch systems."[16]

But in an experiment that would prove important, in 2006 NASA had launched the Commercial Orbital Transportation System (COTS) program to subsidize the development of private launch vehicles for resupply missions to the ISS. COTS proved to be a dramatic success. In particular, it provided essential early financing for several nascent launch companies, including SpaceX.[17] NASA projected its FY19 Space Transportation and Commercial LEO Development spending to be $2.1 billion and $150 million respectively (**Exhibit 1**).[18]

Space Exploration Technologies (SpaceX)

Elon Musk was born in Pretoria, South Africa in 1972, and was inspired at an early age by science fiction novels of Isaac Asimov to "try to take the set of actions that are likely to prolong civilization, minimize the probability of a dark age and reduce the length of a dark age if there is one." He moved to the U.S. to complete his studies in economics and physics at the University of Pennsylvania. While Musk enrolled for a PhD in energy physics from Stanford, he dropped out of the program after only two days. Eventually, he went on to found X.Com, an online financial services and payment company, which later became PayPal. Due to disagreements with other PayPal executives, Musk was ousted as CEO in October of 2000. In 2002, eBay purchased PayPal for $1.5 billion, of which Musk received $180 million for his 11.7% stake. [19]

After a near-death experience with a rare form of malaria in December 2000, Musk began to seriously pursue his interests in space. His first idea was the "Mars Oasis" plan, following what Musk thought of as the path to Mars: "[getting] the public enthusiastic about the possibility, then translat[ing] that into legislative pressure so that Congress hands us a Mars mandate."[20] To that end, Musk intended on using a Russian R-36 ICBM for the mission. But after meeting with Kosmotras, the commercial manufacturer of the rockets, he was laughed off when he was unable to procure the expected $21 million for each rocket. On the flight home from the failed negotiations in Russia, Musk turned to his business partner, Jim Cantrell, and said, "I think we can build a rocket ourselves."[21] From there, the idea for SpaceX was born.

Gwynne Shotwell, unlike Musk, had both little interest in space growing up and substantial experience in the space industry. Her first job out of college was in Chrysler Corporation's new graduate training program, and she earned her master's degrees in Mechanical Engineering and Applied Mathematics from Northwestern University in 1987. But then Shotwell spent a decade at The Aerospace Corporation (a federally funded research and development center) in space systems engineering and project management, and then became Director of Space Systems at Microcosm, a manufacturer of affordable, small launch vehicles. Just after SpaceX's founding in 2002, Shotwell was introduced to Musk by a former Microcosm employee. Shotwell joined SpaceX and became VP of Business Development that September. Her oversight of government relations helped SpaceX clinch a key contract under the COTS program to develop and deliver transportation to the ISS in 2006. In 2008, Shotwell was promoted to President and COO.

Challenging the Stronghold on Commercial Launch

Breaking into the U.S. commercial launch market would be no easy feat, but Musk believed that the entrenched duopoly which relied on government contracts to survive had stifled innovation in the industry, leading to unnecessarily high launch costs. He identified three areas where cost-savings could be achieved.

Reusability Following the end of the Space Shuttle and the beginning of the EELV program, designing reusable rockets was no longer a priority. Musk reasoned that "throwing away multimillion-dollar rocket stages after every flight makes no more sense than chucking away a 747 after every flight."[22] To Musk, reusability would be a key lever in generating commercial activity in the industry since, "the reason there is low demand for spaceflight is because it's ridiculously expensive…the problem is that rockets are not reusable."[23]

Reliability without over-engineering Launch vehicles tended to be intentionally over-engineered, in part because reliability was a much greater priority than cost for defense payloads. "What the EELV program does is launch national reconnaissance satellites that cost billions of dollars a pop," explained former NASA associate administrator Alan Stern. "[Defense department customers] don't care whether [the launch cost] is $100 million or $300 million; it's in the noise. What they want is a guarantee it's going to work."[24] Musk believed the assumption that cost was tied to reliability was false, "Many times we've been asked, if you reduce the cost, don't you reduce reliability? This is completely ridiculous. A Ferrari is a very expensive car. It is not reliable. But I would bet you 1,000-to-1 that if you bought a Honda Civic that that sucker will not break down in the first year of operation. You can have a cheap car that's reliable, and the same applies to rockets."[25]

Vertical Integration According to Harry Jones, a research analyst at NASA, ULA had "hundreds of subcontractors that have dozens of facilities spread all over the country, which [was] a political necessity for a government funded jobs program."[26] ULA's Atlas V used three different kinds of rockets tailored to a specific phase of flight. While the use of three rockets in the same vehicle could optimize performance, as Musk remarked, such a system was highly costly, "to a first-order approximation, you've just tripled your factory costs and all your operational costs."[27]

Musk was convinced that by pursuing reusability, reusability without over-engineering, and vertical integration "SpaceX has the potential of saving the U.S. government $1 billion a year. We are opposed to creating an entrenched monopoly with no realistic means for anyone to compete."[28] In a series of lawsuits against the DOD, Musk argued that defense contracts didn't allow for fair competition, and he attempted to halt the formation of the ULA joint venture. However, he knew his best argument would be to achieve the cost savings that he promised.

SpaceX's Solutions and Product Development

Falcon 1

SpaceX's first launch vehicle was the Falcon 1, a reference to the Star Wars franchise's Millennium Falcon. SpaceX designed and built the Merlin 1A kerosene liquid oxygen engine for the vehicle's first stage. With a single Merlin engine, the vehicle was able to launch small satellites up to 470 kg into LEO (**Exhibit 3**). The first stage was intended to be reusable if recovered after a successful launch.

SpaceX experienced its share of failures and setbacks early on with the Falcon 1. The vehicle's first launch took place in March 2006 from the Marshall Islands and was intended to place a U.S. Air Force Academy payload into LEO, but the rocket crashed into a reef less than a minute after launch due to a first stage plumbing failure. The second launch attempt was in March 2007. While the Falcon 1's first stage performed as expected, a problem during the rocket's first and second stage separation led to the mission's failure. SpaceX would state that "although short of complete success, a significant majority of mission objectives were met from both a programmatic and technical perspectives." After these two failures, SpaceX would upgrade the Falcon 1's first stage engine to the improved Merlin 1C. The third Falcon 1 launch, in August 2008, again ended in failure after the first stage effectively rear-ended the second stage. After three consecutive failures, Falcon 1 at last successfully launched a dummy payload to orbit in September 2008.

At this point, competitors were highly skeptical of the bold claims made by the company as it struggled to successfully reach orbit. The "big players" dismissed SpaceX, with the head of communications for Boeing remarking that, "for SpaceX to be considered a potential competitor they need to have a launch."[29] In those early days, SpaceX was entirely expected to fail. John Pike, a space policy analyst noted that it was the nature of the business, "this is an enormously difficult business to make money in. The best way to make a small fortune in space is to start out with a large one. New rocket science has a high mortality rate, and we don't know what [Musk's] got his hands on until he's flown it a half-dozen times."[30]

Internally, SpaceX employees and executives were less concerned. Senior design engineer at SpaceX, Kevin Brogan, noted, "There's a silly notion that failure's not an option at NASA. Failure is an option here. If things are not failing, you are not innovating enough. The first time we had a major engine failure Elon was kind of excited. It gave him some street cred." Told this story later, Musk replied, "If I had the option of not having it blow up, I'd rather not," he says. "But it was pretty cool."[31]

On the Falcon 1's fifth and final launch in July 2009, SpaceX placed the Malaysian RazakSAT imaging satellite into LEO – its first successful launch of a commercial satellite. If that launch had failed, Musk had intended to shut the company down, but, as he later remarked, "fate liked us that day."[32] SpaceX was able to begin work on upgraded versions of the vehicle, the Falcon 1e and the Falcon 5, but would ultimately never complete them as the company focused its efforts on development of its new rocket, the Falcon 9. The Falcon 1 reportedly cost SpaceX $90 million to develop.[33]

Falcon 9 and NASA's Commercial Crew and Cargo Programs

Circumstances four years after SpaceX's founding helped finance its progress. In January 2006, NASA announced the advent of the COTS program, challenging commercial partners to develop means for transporting crew and cargo to the ISS. COTS was designed as a cost-sharing program between NASA and commercial partners in which the partners were not paid a margin over reported costs, as in standard contracts, but rather received fixed amounts for achieving certain milestones. The Commercial Resupply Services (CRS) and Commercial Crew Development (CCDev) programs which followed COTS included ongoing cost-sharing elements as well as fixed price contracts meant to incentivize commercial partners to reduce costs while decreasing the risks from large upfront R&D investments. SpaceX would compete and win contracts with NASA under nearly every phase of COTS, CRS, and CCDev—collectively known as the Commercial Crew and Cargo Programs—from 2006 to 2018, receiving over $5.2 billion from NASA (**Exhibit 4**).

The first COTS contract was awarded to SpaceX in 2006, largely due to Gwynne Shotwell's success in lobbying NASA. On winning the initial contract, Koenigsmann, SpaceX's vice president for mission assurance later reflected, "[Gwynne] was selling stuff to NASA at a time when we had a little rocket on an island. That takes bravery and vision."[34]

SpaceX used this initial funding to begin work on the Falcon 9. The Falcon 9 would rely and improve on technology developed and tested for Falcon 1. This included the Merlin 1C engine, of which Falcon 9 used nine, to enable medium and heavy payload launches. SpaceX stated that the Falcon 9 cost $300 million to develop, but some argued that the Falcon 9 development costs should be considered closer to $390 million to include the investments made in creating Falcon 1.

Falcon 9 became SpaceX's workhorse vehicle, completing over 60 launches from 2010 through 2018, but not without setbacks. While the first stage of this first iteration, Falcon 9 v1.0, was potentially reusable, no reuses were attempted in the subsequent four Falcon 9 v1.0 launches. The Falcon 9 v1.1, featuring upgraded Merlin 1D engines, first launched in September 2013. This version reached geostationary transfer orbit (GTO), an orbit typically used as an intermediate orbit in placing larger satellites in GEO. Falcon 9 v1.1 also was used for more extensive testing of component recovery and for SpaceX's first attempts to land a first stage on a drone ship in the Atlantic Ocean. In June 2015, the penultimate launch of the v1.1 (which was meant to carry cargo to the ISS as part of SpaceX's 7th CRS mission) failed two minutes into the launch, when the rocket broke apart due to a defective strut. In an industry that valued mission assurance, the failure called into question whether SpaceX could be relied on as a launch provider for expensive cargo and ultimately humans.

With its December 2015 launch of the next iteration of the Falcon 9 (v1.2, also known as Falcon 9 Full Throttle), SpaceX became the first group to successfully land an orbital class rocket, a major step toward reusability. Two years later, on March 30, 2017, the Falcon 9 v1.2 core number B1021.2 would become the first rocket to reach orbit twice. Again, with these successes came setbacks. In September 2016, during pre-launch preparations, a rocket exploded on the launch pad. As a result, SpaceX delayed launches for several months, while it investigated the cause of the explosion (which was determined to have originated in an oxygen tank of the upper stage). Once again, industry members wondered whether SpaceX was pushing too hard, too fast.

SpaceX would continue to make upgrades to the Falcon v1.2 in versions internally referred to as Block 4 and later Block 5, which had its maiden launch in May 2018. By this time, the Falcon 9 was capable of launching 22,800 kg to LEO or 5,300 kg to GTO and returning to Earth for reuse.

Dragon

SpaceX's Dragon spacecraft was its first attempt at addressing the human spaceflight market. Through the Commercial Crew and Cargo Programs, SpaceX received $2.5 billion to develop the spacecraft for delivery of cargo and (later) crew to the ISS. The Dragon 1.0 was designed to carry up to 6,000 kg of cargo to the ISS, while the Dragon Crew could accommodate up to seven astronauts. Both models would be reusable and fly atop the Falcon 9 rocket. The Dragon 1.0 had flown over fifteen times since its first flight in 2010. Dragon Crew, which SpaceX had initially hoped to have certified by NASA to fly humans in 2017, was expected to be certified sometime in 2019. Along with Dragon Crew, Boeing's CST-100 Starliner spacecraft was being developed in parallel through the Commercial Crew Program, and it faced similar delays. SpaceX had also marketed Dragon for commercial use as a microgravity laboratory for companies interested in conducting experiments in space, though in early 2019 SpaceX had yet to make public any sales of this Dragon Lab configuration.

Falcon Heavy

SpaceX would rely on learnings from Falcon 9 in developing its next rocket, the Falcon Heavy. Falcon Heavy used three cores from the Falcon 9's first stage to create significantly larger launch capabilities, up to 63,800 kg to LEO or 8,000 kg to GTO when planned for reuse. SpaceX wrote of the Falcon Heavy's development that it "was designed from the outset to carry humans into space and [restore] the possibility of flying missions with crew to the Moon or Mars".[35] Falcon Heavy launched for the first time on February 6, 2018. Though this launch carried only a dummy payload, Falcon Heavy's potential implications for the heavy launch market became clear as commercial customers gradually signed on to the world's most powerful rocket's ride to space. Industry journalist Eric Berger also noted "the significance of this larger rocket, powered in part by reused Falcon 9 cores, is that it can hit all nine of the Department of Defense's reference orbits for missions. This effectively means that there are now no military missions that a 'reusable rocket' cannot reach."[36]

Starship

Initially dubbed the B.F.R., Starship was designed to be a "Mars Colonial Transporter" or, more formally, the "Interplanetary Transport System". The largest rocket in the fleet with a diameter of nearly 30 feet, the vehicle would have the ability to carry crew and cargo to Earth orbit, the Moon, Mars and beyond on a fully reusable transportation system. On those missions, it would be capable of carrying more than 100 metric tons to Earth orbit or 100 people to Mars. Although still in development by mid-2019, Musk laid out an ambitious timeline for launching the vehicle, targeting a crewed launch by 2020.[37]

SpaceX's Success and Economies of Scale

As SpaceX's launch capabilities grew, so too did its market share. In 2013, SpaceX captured just under 10% of the global commercial launch market share. By 2018, that reached over 60%.[38] SpaceX effectively displaced all but two commercial launch competitors, ILS (based in Russia) and Arianespace (Europe) from the market, and it was gradually eroding their market share as well. By 2018, SpaceX had attained nearly two thirds of the global commercial launch market. It was able to achieve this impressive market share not only by developing reliable launch capabilities, but also by offering significantly lower prices than the competition (**Exhibit 5a**). A chart of launch costs per kg over time showed, in fact, how SpaceX had succeeded in reducing launch costs by an order of magnitude in just over a decade, thereby playing a key role in driving costs down by two orders of magnitude since the early days of the shuttle. (**Exhibit 5b**)

Several factors contributed to SpaceX's ability to undercut its competitors' launch prices, but most came back to its achieving economies of scale, a persistent feature of the launch market.

Economies (and diseconomies) of scale The phrase "economies of scale" refers, roughly, to the idea that a producer can gain an (average) cost advantage over competitors by increasing the amount it produces. Average costs of production equal the sum of fixed costs (which do not rely on the amount of production) and variable costs (or "marginal" costs of actual production). If variable costs are declining, constant, or rising slowly enough with output, average costs may fall with the amount of output: that is, production may exhibit economies of scale.

This seemingly straightforward idea is in fact complicated by a number of factors. The separation of costs into fixed and variable requires an assignment of upfront costs to particular products, when in reality most fixed costs in firms support the production of multiple products (especially over time). Related, the bucketing of products can matter substantially for the calculation of economies of scale: a suite of products may enjoy scale economies unobtainable by any one component product, but how are the boundaries of such a suite defined? Perhaps most complicated, the economies of scale that apply to a given product at a given point in time—using a given state of technology—may be of limited relevance to an industry in which innovation rapidly changes the competitive landscape.

Despite the theoretical complications involved in defining and identifying economies of scale, in practice they are a powerful force in markets. Most important, economies of scale naturally lead to market power, as the producer or producers who reach greater levels of production will enjoy lower costs and, therefore, entrench their competitive positions. The same economies of scale can substantially benefit purchasers, as the lower costs they bring make way for lower prices, but regulation is often used to ensure that the producers "at scale" do not claim all of the potential benefit. A particularly clear case of this interaction is with so-called "natural monopolies" such as utilities, where economies of scale are so dominant a force that the most efficient—that is, the lowest cost-of-production—market structure is a monopoly. Typically, as in the case of local water or power provision, governments oversee public utilities that produce these products at low marginal (and average) cost for all customers and face substantial limits on their pricing decisions.

Scale does not always bring benefits, however. Economists use the term "diseconomies of scale" to identify factors that cause increases in the amount of production to raise average costs. Typically, these diseconomies do not include the standard rising cost of inputs that scale often produces. Rather, the idea behind diseconomies of scale is that increased production requires investment in new supportive infrastructure, introduces costly complexity, and stretches scarce resources (such as management talent) so far as to detract from efficiency. A striking example of such diseconomies is the dysfunction of centrally planned economies such as the Soviet Union in the latter half of the twentieth century. There, the burden and complexity of managing an entire nation eventually led to declining competitiveness and standards of living. More prosaically, large corporations were often criticized for spreading themselves too thin, as in a 2018 *New York Times* piece, "In 2018, then, mergers, demergers and partnerships have continued to remix the world of business. And, for the first time in a while, there were also early glimmers that corporate America is realizing that bigger isn't always better.[39]"

SpaceX's path to scale SpaceX's key strategy to achieve economies of scale was its embrace of reusability. While the notion of rocket reusability was not new to the industry, SpaceX took the concept to new levels and put it at the center of its business model. According to SpaceX, the fuel costs of a Falcon 9 launch were only $200,000, while the majority of total launch costs were due to the costs of building the vehicle.[40] Musk estimated 60% of the Falcon 9's marginal cost came from the first stage, 20% from the second stage, and 20% from the fairing and costs associated with launch.[41] Therefore, starting with the first stage, and ultimately developing a fully reusable launch vehicle, SpaceX could dramatically cut down on the cost of producing new rockets. On the other hand, reusability imposed new costs: R&D to establish vertical landing capabilities, operating expenses to recover spacecraft and fairings, and refurbishment efforts between launches. To make reusability profitable, SpaceX had to have enough demand to spread these new costs – and of course the fixed costs of building the vehicle - across enough customers and launches. Developing vehicles like Falcon Heavy allowed the company to pack a large number of payloads into a single rocket.

SpaceX, like all firms in the launch market, sought to take advantage of a virtuous cycle in which growth led to cost reductions and, thus, more growth through lower prices. Such a cycle could operate for multiple companies, if lower costs drove increased demand, or—if market size remained limited—for only those companies that gained market share. Shotwell noted that the launch market appeared to be closer to the latter case than the former, at least in 2018 and likely until human spaceflight became routine: "So obviously, the market has to grow a bit. We launched 18 times in 2017, served the market. As I said, in 2018 we'll launch just under 30, serving the market. And we're doing probably 60% of the launches across the globe, so in order to launch every day you have to have a lot more launches. And I think once we're flying people that could actually be realized."[42]

To take advantage of this virtuous cycle, SpaceX generated an initial cost advantage by leveraging the change in government contracting that came with the COTS program. ULA, Boeing, Lockheed Martin and other legacy contractors had argued that the pre-COTS cost-plus contracts were appropriate in a sector that required firms to make upfront R&D expenditures on products with limited, or at best uncertain, commercial viability. However valid that argument was, cost-plus contracts also diminished companies' incentives to lower costs and improve efficiency. As budget pressure and dissatisfaction with the Shuttle mounted in the 2000s, NASA experimented with fixed price contracts under COTS, rewarding companies that were able to lower their costs and thus bid for lower fixed fees and nevertheless sustain profit margins.

The switch in contracting was viewed as a key component in the remarkable cost savings achieved under COTS and its successors. As expert Edgar Zapata explained in "An Assessment of Cost Improvements in the NASA COTS/CRS Program and Implications for Future NASA Missions"[43], NASA's estimates were that the SpaceX ISS resupply missions cost one-third what a conventional program would have cost. Similarly, when NASA investigated SpaceX's 2010 estimates that Falcon 9 development costs would be $300 million, it verified that the company was fundamentally changing the economics of launch. NASA's initial study determined that if NASA had attempted to develop the Falcon 9, it would have cost $4 billion.[44] Even when NASA assumed a more commercial scenario, it estimated a cost of $1.7 billion.[45] Unable to account for the remaining $1.4 billion cost reduction, NASA visited SpaceX's facilities to gather more information and revise its inputs to the cost estimation model. Following its visit to SpaceX, NASA estimated the Falcon 9 would have cost $1.4 billion in a cost-plus contract model and $443 million in a firm fixed price model.[46]

Several factors contributed to SpaceX's cost efficiency, including the focus on reliability without over-engineering and vertical integration that had been part of Musk's initial strategy of disruption. NASA's analysis highlighted the importance of reducing redundant elements of vehicle design and learning from previous vehicles (e.g, Falcon 9 and Falcon 1). SpaceX itself emphasized its use of off-the-shelf components and previously used, proven technologies wherever possible rather than developing new, custom built technology.[47] At the same time, SpaceX was highly vertically integrated, unlike many other launch competitors, allowing them to eliminate transaction costs throughout the supply chain. SpaceX designed its Falcon rockets with commonality in mind. Both of Falcon 9's stages are powered by RP1 and liquid oxygen, so only one type of engine is required. Both are the same diameter and are constructed from the same aluminum-lithium alloy, reducing the amount of tooling and the number of processes and resulting in what Musk calls "huge cost savings." SpaceX estimated that subcontractor overhead and profits could result in a 3 to 5x increase in costs for every dollar sent out of the company.[48]

Three additional factors were cited as helping to drive SpaceX's cost containment: an intense work environment, organizational simplicity, and lean infrastructure.[49] SpaceX's workforce was smaller than its larger competitors, and both former employees and outsiders described it as a high-intensity workplace. SpaceX had a relatively flat organization with little overhead, and it used less infrastructure and higher machine utilization than competitors to lower its fixed costs. In short, SpaceX tried to do (and often seemed to succeed in doing) more with less, though critics warned that SpaceX's demands on its employees "might blow up a team or set impossible expectations."[50] Nevertheless, as of early 2019 SpaceX enjoyed a high employee rating on glassdoor.com (an online platform on which employees rate their employers) relative to competitors such as Blue Origin and ULA.

Perhaps surprisingly, reusability did not play a large role in SpaceX's cost competitiveness over these early years, as only a single Falcon 9 booster had been reused four times by 2019, far too little reuse to see significant cost savings. According to some sources, any projected cost savings from the reusable first stage of Falcon 9 would remain in the future and depend on a high cadence of launch.

Funding a Mars Mission

SpaceX hoped to continue building on its many successes--both technological and financial--in developing Starship. Shotwell remarked that funding Starship would rely on SpaceX "plowing our entire revenue stream back into our technology,"[51] with Musk agreeing that, "if we can build a system (Starship) that cannibalizes our own products, makes our own products redundant, then all the resources I used for Falcon 1, 9, Heavy and Dragon can be applied to one system." Musk estimated that the cost of development for Starship alone could reach two or three billion dollars.[52]

Once Starship was developed, SpaceX would also have to fund the potential Mars mission. NASA estimated a crewed mission to Mars would cost no less than $200 billion (see **Exhibit 6a,b**), assuming the agency's Space Launch System (SLS) and Orion module would be utilized. The non-profit Mars One, which "[aimed] to establish a permanent human settlement on Mars" brought the estimate closer to $6 billion.[53] Developing a budget for such a feat appeared, in other words, to be a difficult task.

Regardless, SpaceX would have to find a way to pay for its mission while sustaining operations. When financial difficulties caused the company to cut 10% of its workforce in January 2019, Musk noted that projects like Starship "have bankrupted other organizations."[54]

Small Satellite Launch

SpaceX's main revenue source came from launching satellites into Earth orbit, the activity which not coincidentally made up the vast majority of global space revenues.[55] Just over a decade after entering the market, SpaceX had become the leading launch provider, with revenues of $2 billion, and it had changed the economics of the satellite market.[56] Notably, by packaging various payloads of different sizes together to send to space in "rideshares", SpaceX was able to efficiently spread fixed costs across its product lines and multiple launches.

As a result of SpaceX's dramatic reduction in cost to low-Earth orbit, demand for launch increased, most significantly among small satellite owners and operators. These satellites were small enough (less than 500 kg) that once the majority of the Falcon 9 (with a capacity of 22,800 kg) had been filled with larger payloads, they could "piggyback" on a launch, filling up remaining space and enjoying low costs to orbit.

Shortly after Falcon 9 became operational, the small satellite market saw a major boom, with a 23% compounded annual growth rate in 2009 to 2018. In 2017, these payloads made up 69% of total launches while only accounting for 4% of total mass.

The greatest source of growth was the launch of large "constellations" or groups of small satellites. When operated in concert, small satellites achieved greater functionality, allowing for increased revisit times over areas on Earth or increased spatial resolution. Constellations for earth-imaging (such as Planet's Dove) and satellite broadband (such as SpaceX's Starlink) accounted for much of the demand in launch, as they included hundreds or even thousands of satellites.

As the market for small satellites and constellations grew, the launch industry saw new entrants to the market, competing for SpaceX's market share. Companies such as Vector and RocketLab began developing small launchers (with payload capacity under 1,000 kg), offering "dedicated" rides for small payloads. While SpaceX remained the most competitive in terms of price per kilogram to orbit (**Exhibit 7**), these dedicated small satellite launchers offered increased responsiveness.[57] When purchasing a "rideshare" on a larger rocket, small satellite operators were beholden to the interests of the primary payload, often dealing with unpredictable schedules or compromising on desired orbit destinations. Small launchers could offer dedicated, predictable, bespoke orbit access. By 2019, there were an estimated 100 small launcher companies in development, some founded by former SpaceX employees.

Some believed that the market for small launchers was overblown, jeopardizing the fate of new companies. Bryan Baldwin of the innovations department of Northrop Grumman reasoned that with the bulk of demand coming from constellations, "if you look at the number of satellites that they are putting up in these constellations, we see that as a market for the larger launch vehicles. Just by economies of scale, to put that many spacecraft up, it doesn't fit well in the small launcher arena. I think you can do satellite replenishment and those types of things, but you are talking about a lot of satellites that — it's just going to take bigger rockets to do that."[58] In the past, small satellites relied on medium (up to 7,000 kg to LEO) to light-lift (up to 1,500 kg to LEO) vehicles (**Exhibit 8**). The question was whether the demand could be met by existing vehicles like Falcon 9, or if small launchers would ultimately become a viable, or even preferable, option.

SpaceX took note of the competition offered by new launch companies, with Gwynne Shotwell remarking, "one should always be aware of competition…Boeing and Lockheed dismissed the competition that we could provide a decade or so ago because they thought we would never make it…and to their misfortune, actually." SpaceX's response was to begin the "SmallSat Rideshare Program" in 2019, offering dedicated launches for small satellites below 200 kg on a regular cadence for $1 million a mission. According to Darrell Etherington from TechCrunch, "this is a clever way to drum up more business for SpaceX. Based on all the conversations I've had with space tech startups and people working in the industry, the main cap right now on activities is securing launch services. By addressing this bottleneck, and doing so in a way that offers as much flexibility as you can when dealing with rocket launches, the company could potentially capture a lot more of the commercial space business revenue it's currently leaving on the table."[59]

Clearly, for SpaceX, guarding its position in the small satellite launch market was a priority. Even without worrying about the threat from potential competitors, however, SpaceX would also have to rely on the sustained health of the satellite market. The current boom in launch could prove limited, as many constellations were projected to be fully deployed by the mid-2020s. EuroConsult predicted, for example, that market growth would peak in 2024 at 48%.[60] Moreover, SpaceX had previously overestimated launch demand. In 2017, it forecast operating 30 to 40 launches per year in 2018. By the end of 2018, SpaceX had only launched 21 times, reaching a similar number towards the close of 2019. Looking back on those projections, Shotwell remarked, "We thought the commercial market might expand to that, I think we probably wished it had."[61]

Starlink and the Promise of Satellite Broadband

In May of 2019, SpaceX launched 60 satellites into LEO, the first of the planned 12,000 that would make up its own megaconstellation, Starlink. Intended to be fully operational by 2027, Starlink would provide low latency, high bandwidth global broadband internet, targeting rural communities and populations with low connectivity. With Falcon 9 making launch affordable, developing a satellite constellation seemed to be the next logical, and potentially lucrative, step for Musk. By SpaceX's own estimations, Starlink could eventually bring in revenues of $30 billion by 2025, far surpassing revenues from launch (**Exhibit 9**).

By 2019, three other companies (Telesat, OneWeb, and Amazon's Project Kuiper) had drawn up proposals for similar satellite broadband constellations, aiming to bring online the remaining four billion people without internet access and reduce lag times between distant locations. By using satellites for internet provision, these companies would avoid expensive ground-based infrastructure such as fiber-optic cables. Furthermore, bypassing physical infrastructure could significantly reduce lag, especially with satellites orbiting close to Earth in LEO utilizing laser communication, beaming data at nearly the speed of light.

Even with all the fervor around satellite broadband, it was still unclear whether these new services would be as affordable or useful as expected. While not as complex as laying down fiber optic cables, developing ground stations to service the thousands of satellites that would encircle the globe could still end up costing customers more than traditional internet options. Beyond that, the benefits of these types of services were only dramatic for long-distance connections, while fiber optic cables would still provide higher speeds for short distances.[62]

Furthermore, the demand for satellite internet was still unclear, with existing terrestrial broadband offering stiff competition. Matt Desch, CEO of Iridium, a satellite communication company that focuses on voice and data wondered, "is there enough demand in the world for all that capacity coming online over the next 10 years? No one really knows. The investment markets are clearly concerned, which is why these new markets are being slow to be funded, at least by the public equity and debt markets."[63]

Human Transportation

Another potential target market for SpaceX was human spaceflight, as Musk believed that—at the right price—there would be a viable market for travel to Mars:

> If you can reduce the cost of moving to Mars to around the cost of a middle-class home in California—maybe to around half a million dollars—then I think enough people would buy a ticket and move to Mars. You obviously have to have quite an appetite for risk and adventure. But there are seven billion people on Earth now, and there'll be probably eight billion by the midpoint of the century. So even if one in a million people decided to do that, that's still eight thousand people. And I think probably more than one in a million people will decide to do that.[64]

UBS reports estimated space tourism could be worth about $3 billion by 2030 and eventually grow to an annual market of $20 billion, even competing with long-distance airline flights for point-to-point travel.[65] Virgin Orbit and Blue Origin both intended to exploit this market with suborbital offerings, in addition to shuttling people to LEO or the moon, while Musk seemed singularly focused on reaching Mars. Shotwell shared his optimism on human spaceflight, remarking, "in [our] lifetime it is going to be commonplace for people to go to space…the economics we have to get right on that, doing it is different than doing it affordably."[66]

If not humans, perhaps Starship could be used to transport cargo, but Musk admitted, "that's where things get a little dodgy, we're not quite sure how to pay for the vehicle…the DOD might have some ideas for putting some big things in space,". To make Starship cost-effective and exploit economies of scale in the way Falcon 9 had, SpaceX would have to build up a regular launch cadence, transporting something, or, ideally, someone, to space.

At the end of the day, Musk made it quite clear that he would not stop until he had developed the capability to put humans in Mars, believing that:

> Fundamentally, the future is vastly more exciting and interesting if we are a spacefaring species and a multiplanetary species than if we are not. You want to wake up in the morning and think the future's going to be great. And that's what being a spacefaring civilization is all about. It's about believing in the future.[67]

Exhibit 1 Summary of NASA's FY19 Budget Request

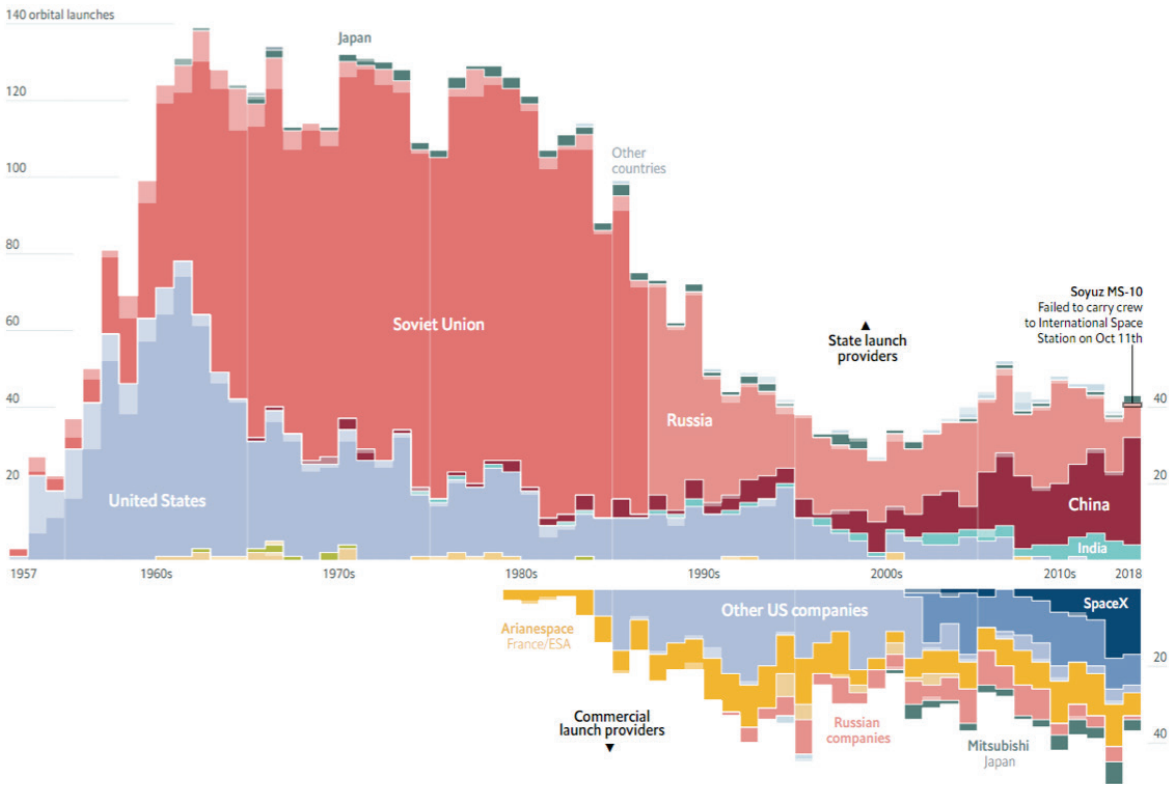
National Aeronautics and Space Administration

FY 2019 PRESIDENT'S BUDGET REQUEST SUMMARY

Budget Authority ($ in millions)	Operating Plan 2017	CR 2018	PBR 2019	Notional 2020	Notional 2021	Notional 2022	Notional 2023
NASA Total	19,653.3	19,519.8	19,892.2	19,592.2	19,592.2	19,592.2	19,592.2
Deep Space Exploration Systems	4,184.0	4,222.6	4,558.8	4,859.1	4,764.5	4,752.5	4,769.8
Exploration Systems Development	3,929.0	--	3,669.8	3,790.5	3,820.2	3,707.5	3,845.6
Advanced Exploration Systems	97.8	--	889.0	1,068.6	944.3	1,045.0	924.1
Exploration Research and Development	157.2	--	--	--	--	--	--
Exploration Research and Technology	826.5	820.8	1,002.7	912.7	912.7	912.7	912.7
LEO and Spaceflight Operations	4,942.5	4,850.1	4,624.6	4,273.7	4,393.3	4,430.3	4,438.0
International Space Station	1,450.9	--	1,462.2	1,453.2	1,471.2	1,466.2	1,451.2
Space Transportation	2,589.0	--	2,108.7	1,829.1	1,858.9	1,829.2	1,807.3
Space and Flight Support (SFS)	902.6	--	903.7	841.4	888.2	934.9	954.6
Commercial LEO Development	--	--	150.0	150.0	175.0	200.0	225.0
Science	5,762.2	5,725.8	5,895.0	5,859.9	5,841.1	5,822.4	5,803.6
Earth Science	1,907.7	--	1,784.2	1,784.2	1,784.2	1,784.2	1,784.2
Planetary Science	1,827.5	--	2,234.7	2,199.6	2,180.8	2,162.1	2,143.3
Astrophysics	1,352.3	--	1,185.4	1,185.4	1,185.4	1,185.4	1,185.4
Heliophysics	674.7	--	690.7	690.7	690.7	690.7	690.7
Aeronautics	656.0	655.5	633.9	608.9	608.9	608.9	608.9
Education	100.0	99.3	--	--	--	--	--
Safety, Security, and Mission Services	2,768.6	2,749.8	2,749.7	2,744.8	2,738.6	2,732.3	2,726.1
Center Management and Operations	1,986.5	--	1,949.6	1,945.4	1,939.8	1,934.1	1,928.5
Agency Management and Operations	782.1	--	800.1	799.4	798.8	798.2	797.6
Construction and Environmental Compliance and Restoration	375.6	358.3	388.2	293.8	293.8	293.8	293.8
Construction of Facilities	305.4	--	305.3	210.9	210.9	210.9	210.9
Environmental Compliance and Restoration	70.2	--	82.9	82.9	82.9	82.9	82.9
Inspector General	37.9	37.6	39.3	39.3	39.3	39.3	39.3
NASA Total	19,653.3	19,519.8	19,892.2	19,592.2	19,592.2	19,592.2	19,592.2

Source: NASA. "FY 2019 Budget Estimates." Accessed December 12, 2018. https://www.nasa.gov/sites/default/files/atoms/files/fy19_nasa_budget_estimates.pdf

Exhibit 2 Global launch market by nation and company



Source: "The Space Race is Dominated by New Contenders." The Economist. October 18, 2018. Accessed December 12, 2018. https://www.economist.com/graphic-detail/2018/10/18/the-space-race-is-dominated-by-new-contenders.

Exhibit 3 Launch capabilities of SpaceX's Falcon vehicle family iterations.

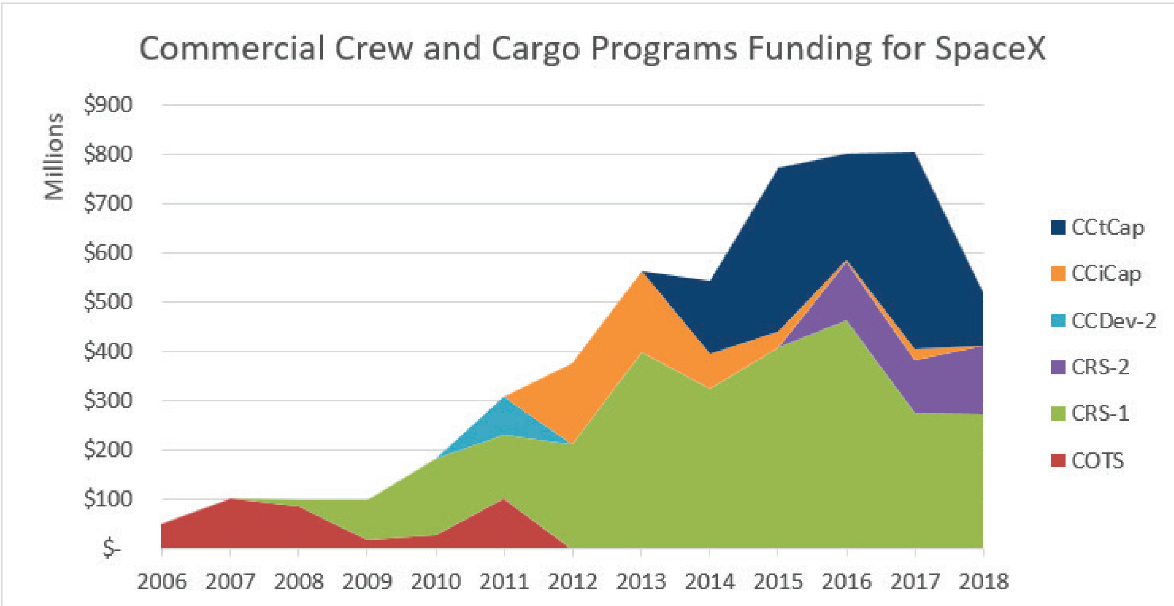
Payload Capability (kg)	Reusable or Expendable Configuration	Low Earth Orbit	Low Polar Earth Orbit	Sun Synchronous Orbit	Geostationary Transfer Orbit	Geostationary Orbit	Interplanetary Trajectory
Falcon-1 (dev)	Expendable	420	-	-	-	-	-
Falcon-1	Expendable	470	290	-	-	-	-
Falcon-1e	Expendable	-	1,010	-	-	-	-
Falcon 9 v1.0	Expendable	9,900	-	-	4,050	-	
Falcon 9 v1.1	Expendable	10,450	9,000	8,159	4,850	-	2,473
Falcon 9 v1.1	Reusable	-	-	-	-	-	-
Falcon 9 v1.2	Expendable	-	-	-	6,700	-	-
Falcon 9 v1.2	Reusable	22,800	-	-	5,300	-	4,020
Falcon Heavy	Expendable	63,800	-	-	26,700	-	16,800
Falcon Heavy	Reusable	-	-	-	8,000	-	-
Starship	Expendable	250,000	-	-	-	-	-
Starship	Reusable	150,000	-	-	-	-	-

Source: Compiled from "Launch Vehicles - USA," Gunter's Space Page, Accessed April 13, 2020. https://space.skyrocket.de/directories/launcher_usa.htm.

Exhibit 4a SpaceX's funding from the Commercial Crew and Cargo Program.

Year	COTS	CRS-1	CRS-2	CCDev-2	CCiCap	CCtCap
2006	$52,488,000	-	-	-	-	-
2007	$102,146,000	-	-	-	-	-
2008	$88,085,231	$9,739,760	-	-	-	-
2009	$20,280,767	$78,449,400	-	-	-	-
2010	$29,576,473	$154,345,638	-	-	-	-
2011	$103,423,527	$129,130,677	-	$75,000,000	-	-
2012	-	$211,622,746	-	-	$165,000,000	-
2013	-	$399,486,844	-	-	$165,000,000	-
2014	-	$324,347,423	-	-	$70,000,000	$148,800,000
2015	-	$408,173,112	-	-	$33,500,000	$330,200,000
2016	-	$463,522,216	$117,631,181	-	$3,500,000	$216,406,611
2017	-	$275,203,932	$106,420,800	-	$23,000,000	$400,680,228
2018	-	$273,532,292	$137,098,047	-	-	$110,859,256
Total	$395,999,998	$2,727,554,039	$361,150,028	$75,000,000	$460,000,000	$1,206,946,095

Exhibit 4b SpaceX's funding from the Commercial Crew and Cargo Program



Source: Federal Procurement Data Systems. "'SPACE EXPLORATION TECHNOLOGIES CORPORATION'." Accessed December 12, 2018. https://www.fpds.gov/ezsearch/fpdsportal?indexName=awardfull&templateName=1.5.1&s=FPDS.GOV&q=NNJ06TA26S+VENDOR_FULL_NAME%3A%22SPACE+EXPLORATION+TECHNOLOGIES+CORPORATION%22&x=0&y=0

Exhibit 5a Comparison of SpaceX's launch vehicle costs to similar vehicles.

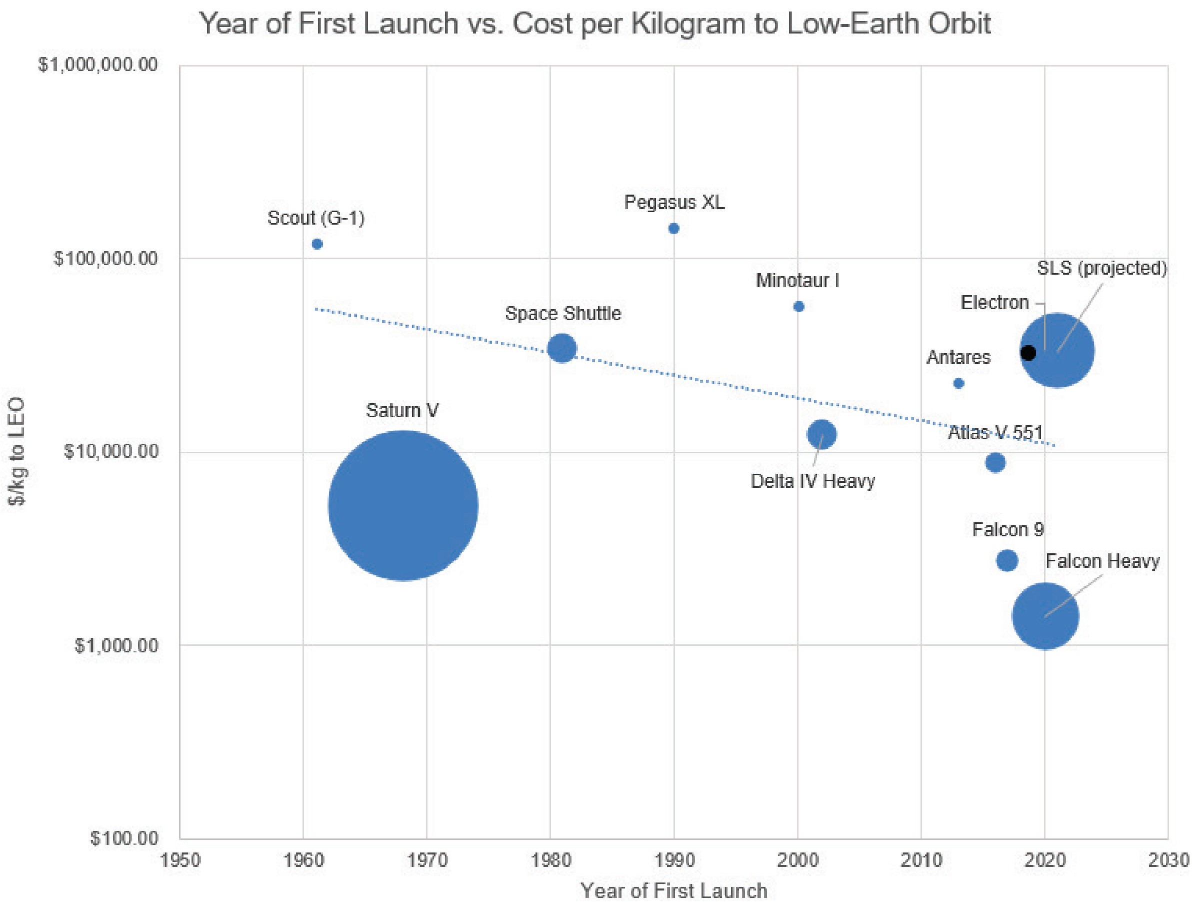
	Unit Costs	Comparable Unit Costs	Non-Recurring Engineering Costs	Comparable Development Costs
Falcon 1	$7.8 million[a,68]	$4.9 million per flight Rocket Lab Electron[69]	$90 million[70]	$100 million Rocket Lab Electron[71]
Falcon 9	$62 million[72]	Starting at $109 million per flight ULA Atlas V[73]	$300 million[74]	$443 million to $1,383 million NAFCOM estimate[75]
Falcon Heavy	$90 million to $150 million (fully expendable)[76]	$350 million to $600 million per flight ULA Delta IV Heavy[77]	$500 million[78]	$2,000 million ULA Vulcan[79]
Starship	Unknown	$1,100 million per flight for NASA Saturn V ($650 million to produce)[80]	$5,000 million to $10,000 million[81]	$35,000 million NASA Saturn V[b,82]
Dragon 1[83]	$98 million	$174 million Cygnus/ Northrop Grumman	$659 million	$596 million Cygnus/ Northrop Grumman
Dragon 2[84]	$308 million	$418 million CST-100/Boeing	$2,201 million	$3,271 million CST-100/Boeing

Source: Casewriter compiled from various sources.

[a] $5.9 million as of 2005. $7.8 million represent 2018-dollar value.

[b] Estimated from total Saturn V appropriation funding less $1,100 million for thirteen Saturn V launches. The $1,100 million-unit cost and $35,000 development cost have been converted to 2018 dollars.

Exhibit 5b Launch vehicle costs over time. Marker size indicates relative payload capability of launch vehicle in kilograms. Logarithmic scale.



Source: Zapata, Edgar. "The State of Play US Space Systems Competitiveness: Prices, Productivity, and Other Measures of Launchers & Spacecraft." presented at the Future In-Space Operations Seminar, NASA Kennedy Space Center, October 11, 2017. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170012517.pdf.

Exhibit 6a Cost Estimates (in billions of FY17 dollars for Orbital Mars Mission)

System		Costs through FY 2018	Projected System Costs (2019 onward)	Total System Costs
SLS		15.9	17.8	33.6
Exploration Ground Systems		3.0	2.7	5.7
Orion		14.9	10.7	25.6
Gateway		6.6		6.6
DST		29.2		29.2
Exploration Ground Systems Operations		16.2		16.2
Suborbital Mission to Mars through 2037	**33.7**	**83.2**		**116.9**
Cost associated with Mars Orbital Mission 2038-2040		3.7		3.7
Orbital Mission to Mars Total	**33.7**	**86.9**		**120.6**

Source: Linck et al. "Evaluation of a Human Mission to Mars by 2033." IDA Science & Technology Policy Institute, February 2019. https://www.ida.org/-/media/feature/publications/e/ev/evaluation-of-a-human-mission-to-mars-by-2033/d-10510.ashx.

Exhibit 6b Cost Estimates (in billions of FY 2017 dollars) for Exploration Systems through 2037

System	Costs through FY 2018	Projected System Costs (2019 onward)	Total System Costs
Orbital Mission to Mars Costs through 2037	33.7	83.2	116.9
Lunar landings		20.0	20.0
Mars Surface Systems		24.6	24.6
Other Human Spaceflight		55.9	55.9
Human Spaceflight Total	**33.7**	**183.6**	**217.4**

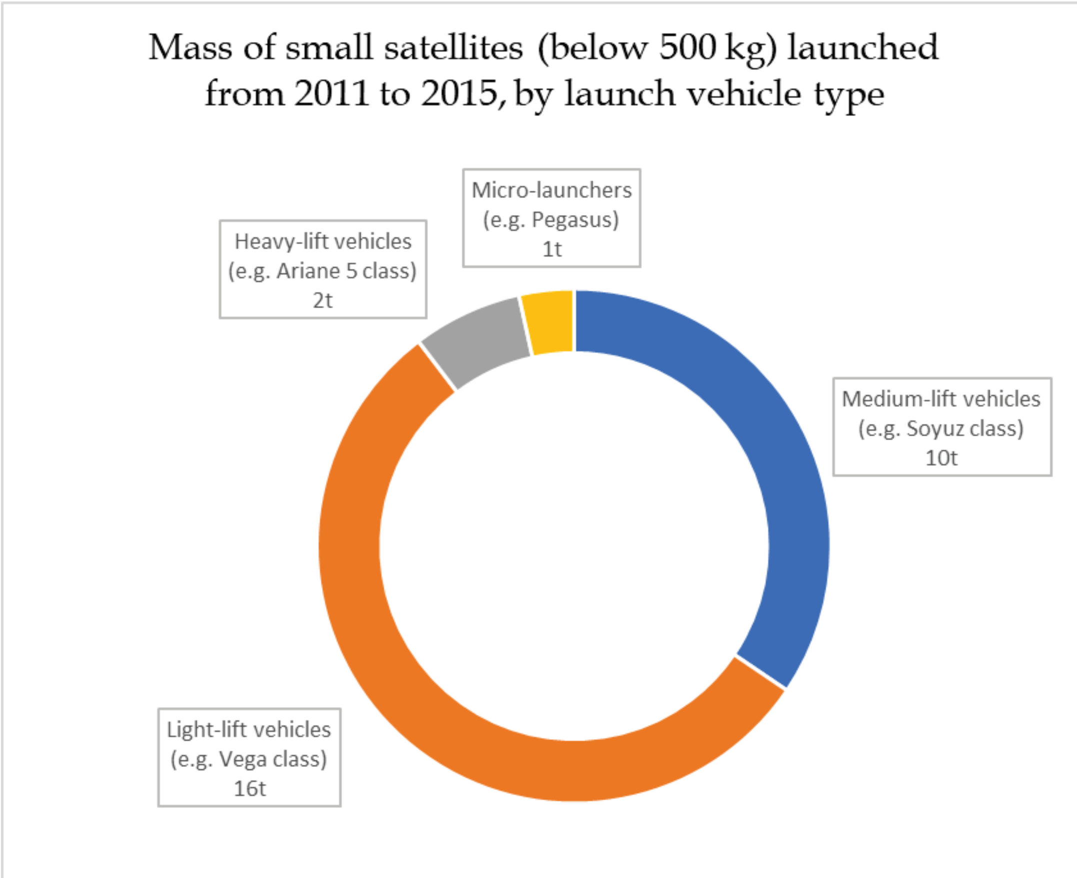
Source: Linck et al. "Evaluation of a Human Mission to Mars by 2033." IDA Science & Technology Policy Institute, February 2019. https://www.ida.org/-/media/feature/publications/e/ev/evaluation-of-a-human-mission-to-mars-by-2033/d-10510.ashx.

Exhibit 7 Comparison of current U.S. launch vehicles with SpaceX's Falcon 9

Vehicle	Electron	Minotaur IV	Minotaur C	Antares	Atlas V	Vector-R (Proposed)	Falcon 9
Manufacturer	Rocket Lab	Northrup Grumman	Northrup Grumman	Orbital ATK	ULA	Vector	SpaceX
2017 Total Launches	1	1	1	1	6	0	18
Total Launches in Last 10 years	1	4	10	7	74	0	46
Launch Reliability (Last 10 Years)	0/1 (0%)	4/4 (100%)	10/10 (100%)	6/7 (86%)	74/74 (100%)		45/46 (98%)
Year of First Launch	2017	2010	1994	2013	2002		2010
Payload to LEO (kg)	150	1,600	1,458	6,200-6,600	8,123-18,814	60	22,800
Cost	$5.7 million	-	-	-	$150 million	$3 million	$62 million
Cost/kg to LEO	$38,000	-	-	-	$8,800	$50,000	$2,700

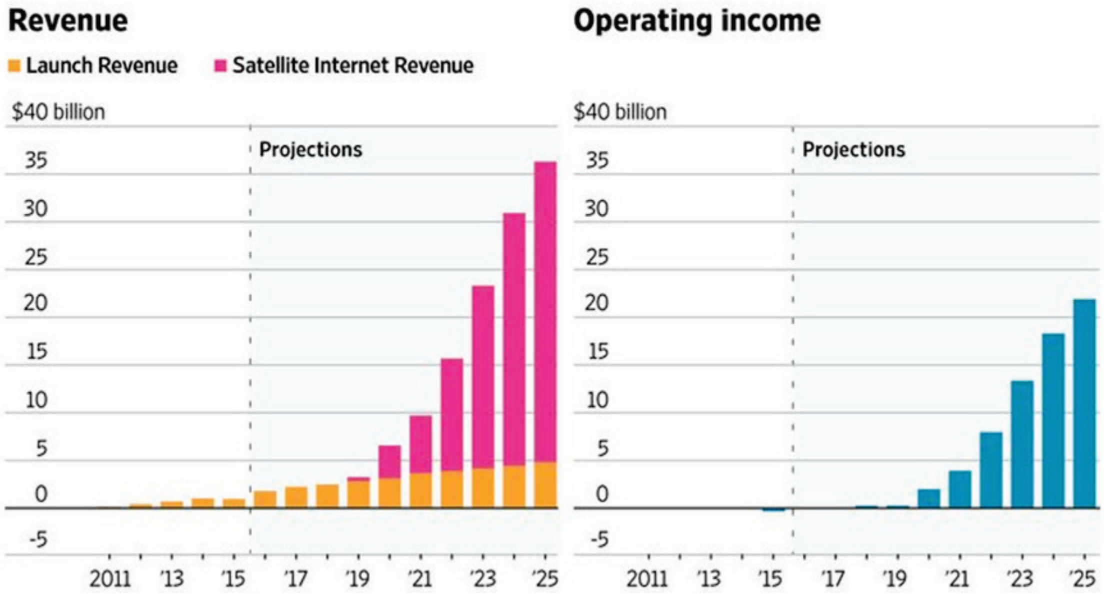
Source: "The Annual Compendium of Commercial Space Transportation: 2018," Federal Aviation Administration, January 2018. https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2018_ast_compendium.pdf.

Exhibit 8 Mass of small satellites (below 500 kg) launched from 2011 to 2015



Source: "Micro-Launchers: What Is the Market?" Thought Leadership on the Space Sector. PWC, February 2017. https://www.pwc.fr/fr/assets/files/pdf/2018/11/space/pwc-micro-launchers-what-is-the-market.pdf

Exhibit 9 SpaceX revenue and operating income, historical and projected



Source: Pasztor, Rolfe Winkler and Andy. "Exclusive Peek at SpaceX Data Shows Loss in 2015, Heavy Expectations or Nascent Internet Service." *Wall Street Journal*, January 13, 2017, sec. Tech. https://www.wsj.com/articles/exclusive-peek-at-spacex-data-shows-loss-in-2015-heavy-expectations-for-nascent-internet-service-1484316455.

Appendix A: SpaceX Financing Fact Sheet

Fundraising

In February 2020, SpaceX announced it was looking to raise an additional $250 million, bringing the total amount raised in 2020 to $3 billion and the total valuation of the company to $36 billion.[85] In 2019, it closed three rounds of funding, raising $1.33 billion.

Revenue Streams

The company has two main areas of business: 1) launch of payloads and people; 2) the satellite internet constellation Starlink.

Commercial Launch: Currently, SpaceX offers launches onboard two vehicles: Falcon 9, at $61.2 million per launch, or about $2,000/kg; and Falcon Heavy, with a payload capacity of 64 metric tons and an estimated price per launch of $90-120 million. The recent astronaut launches to the ISS are estimated to have cost $55 million/seat onboard the Falcon 9 to NASA.[86]

Table A.1 SpaceX Launch Revenues + Contract Awards from NASA

	SpaceX Revenues from Commercial Launch[a]	NASA ISS Commercial Crew Contracts (development)[b]	NASA ISS Commercial Resupply Contracts[c]	
2011		$0.1 b		
2012		$0.5 b	$3 b	
2013		$2.6 b	$3 b	
2014	$1.1 b			
2015	$0.9 b			
2016	$1.0 b			
2017	$1.3 b			
2018	$2.0 b			
2019	$0.9 b			
2020	$1.2 b			**TOTAL**
Total	$8.4 b	$3.14 b	$6.04 b	**$17.5 b**

Source: Compiled by Casewriter

[a] Trefis. "What Is Driving SpaceX's Revenue & Valuation?" Accessed May 14, 20121. https://dashboards.trefis.com/data/companies/SPACEX/no-login-required/yaQTBXoY/What-Is-Driving-SpaceX-s-Revenues-Valuation-.

[b] Heiney, Anna. "Commercial Crew Program." Text. NASA, August 14, 2019. http://www.nasa.gov/content/commercial-crew-program-the-essentials.

[c] Clark, Stephen. "SpaceX to Begin Flights under New Cargo Resupply Contract next Year." Spaceflight Now. Accessed May 14, 2021. https://spaceflightnow.com/2019/08/02/spacex-to-begin-flights-under-new-cargo-resupply-contract-next-year/.

Table A.2 SpaceX Launch Price Analysis

	Falcon 9	Falcon Heavy
Price per launch ($ million) *from SpaceX*	61.2	90.0
Estimate of Current Gross Margin *from Jefferies International LLC*	40%	40%
Direct Costs ($ million) *calculated*	36.7	54.0
First stage as % of total direct costs *from SpaceX*	75%	75%
First stage costs ($m) *calculated*	27.5	40.5
Other costs ($m) *calculated*	9.2	13.5

Source: Selding, Peter de. "SpaceX's Reusable Falcon 9: What Are the Real Cost Savings for Customers?" SpaceNews, April 25, 2016. https://spacenews.com/spacexs-reusable-falcon-9-what-are-the-real-cost-savings-for-customers/.

Figure A.1 Falcon 9 Costs

Fairing Cost: $5-6 million
recovered: 11
reflown: 8

The **First Stage** *accounts for 70-75% of the costs for each Falcon 9 launch (~$27 million)*
# of boosters landed: 68
# of boosters reflown: 47
# of times first stage can be reflown without hardware changes: 10
# of times first stage can be reflown with moderate refurbishment: 100

Refueling costs for the First Stage: $200,000-300,000

Sources: Selding, Peter de. "SpaceX's Reusable Falcon 9: What Are the Real Cost Savings for Customers?" SpaceNews, April 25, 2016. https://spacenews.com/spacexs-reusable-falcon-9-what-are-the-real-cost-savings-for-customers/.

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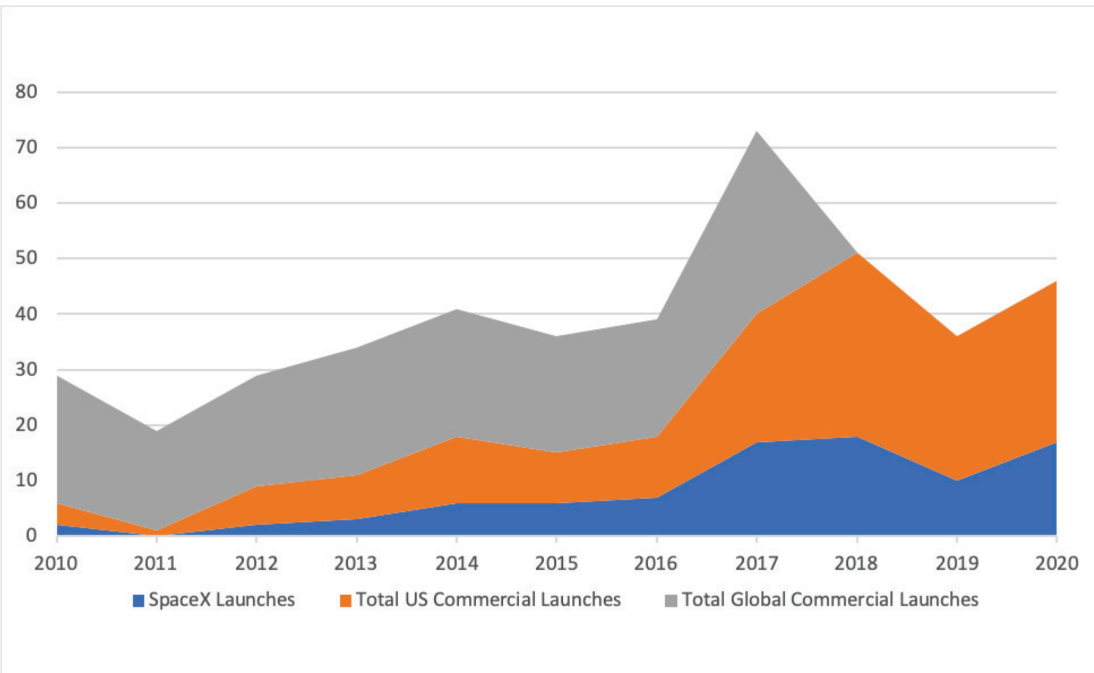
Starlink is a proposed constellation in low-Earth orbit aiming to provide satellite internet to terrestrial users. The beta rollout began in 2020, offering users access to Starlink for $99/month, with an upfront cost of $499 for hardware. Initial data speeds ranged from 50Mb/s to 150 Mb/s, with latency around 20ms-40ms. The cost of building and launching the constellation of satellites is estimated to be around $10 billion to achieve global coverage, requiring 1,400 satellites (as of 2020, there were 240 satellites in orbit).[87]

In December 2020, the FCC announced SpaceX would be one of 180 companies awarded a subsidy to bring Internet to rural areas in the U.S. with the Starlink constellation – the award was for $900 million (the second highest award), to be distributed over ten years. [88]

Forbes provides a market sizing for Starlink.[89]

- Estimated population by 2025 = 8 billion, internet penetration estimated at 72% (5.8 billion)
- Assume Starlink garners 0.1% of all new Internet users by 2021, rising to 2.3% by 2025
- New subscribers = 0.2 million in 2021 to 5.6 million by 2025
- User base = 14.4 million by 2025, implies revenues of $10 billion @ monthly ARPU of $60
- SpaceX annual revenues = $30 billion/year by 2025

Figure A.2 Global Commercial Launches



Source: FAA, "Licensed Launches," April 19, 2021, https://www.faa.gov/data_research/commercial_space_data/launches/

Note: Incomplete data for total global commercial launches in 2019-2020

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