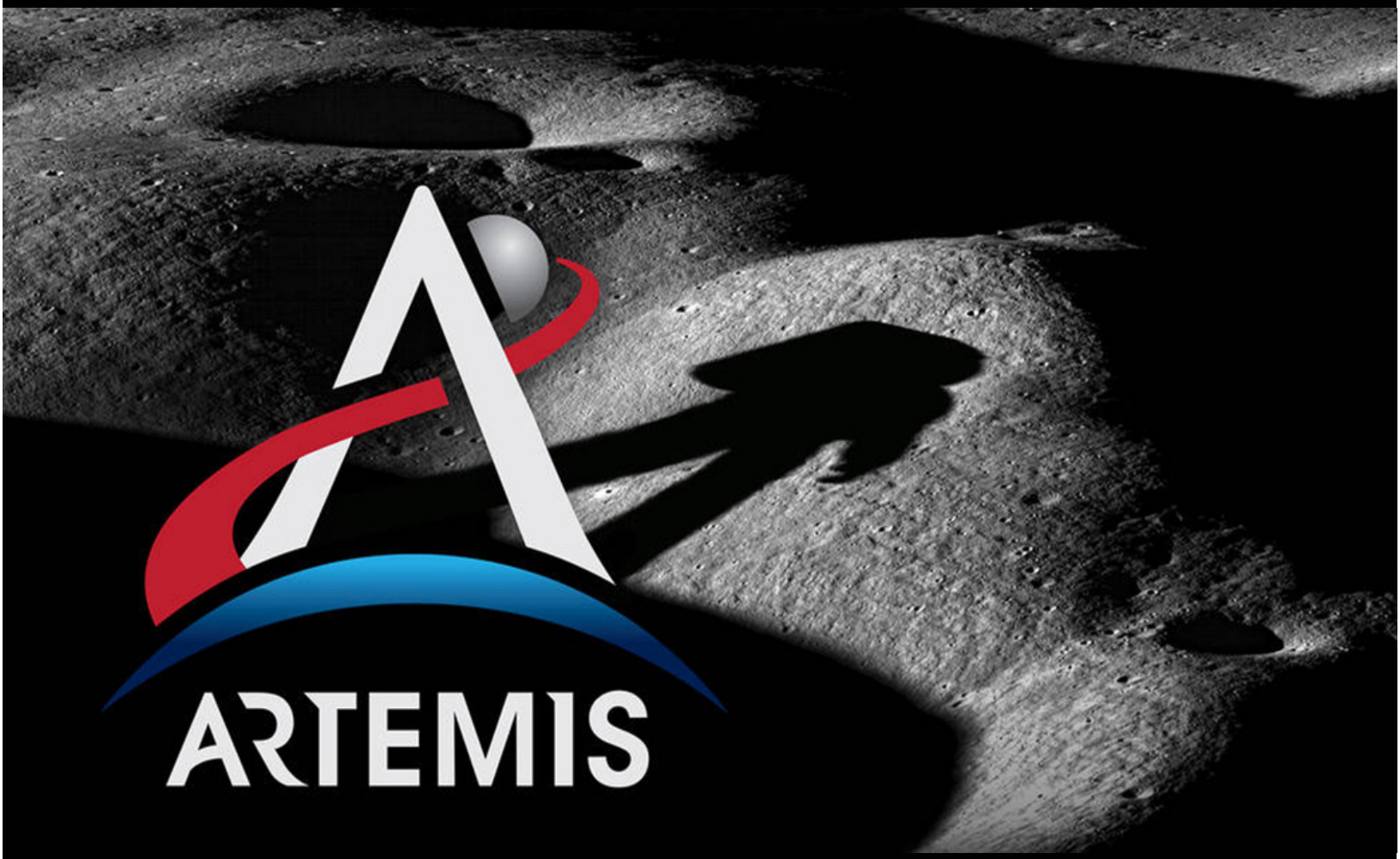
Economic Growth and National Competitiveness Impacts of the Artemis Program



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Economic Growth and National Competitiveness Impacts of Artemis

NASA's Artemis Program will return humans to the lunar surface in the 2020s, create a sustainable American presence for years to come, and provide the experience and technology to conduct the first human missions to Mars. While providing scientific returns, geopolitical leadership, and the enduring value of human and robotic space exploration, the program also offers the prospect of substantial economic growth and enhanced U.S. national competitiveness.

NASA funds commercial lunar initiatives that follow in the footsteps of the successful Commercial Orbital Transportation Services (COTS), Commercial Resupply Services (CRS), and Commercial Crew (CCrew) programs that revolutionized space transportation, cargo supply to low-Earth orbit, and human spaceflight. The Commercial Lunar Payload Services (CLPS) program, Human Landing System (HLS) program, and NextSTEP Broad Agency Announcement (BAA) lunar initiatives seek to fund commercial and private companies to deliver payloads, services, and astronauts to the lunar surface.[i] Much like earlier commercial programs, the intention is to grow U.S. commercial technical capability, broaden the space sector, and provide the impetus for innovation.

This study summarizes the economic and national competitiveness benefits of the Artemis program to complement its inherent values of scientific discovery, technology development, space exploration and global leadership. It includes a brief background on the success of NASA's historical commercial space initiatives and how Artemis program is an extension of COTS and Commercial Crew. It also examines how the Artemis program may benefit the U.S. economy by driving innovation and new capabilities, lowering the cost of access to space, improving market competition and expanding the potential customer base. Finally, it provides an assessment of the Artemis program's role in helping U.S. firms compete in the global marketplace and the role of government in funding early-stage technology development. This study primarily focuses on the economic and national competitiveness impacts of the commercial elements of the program, and suggests they represent an evolution of the COTS/CCrew programs. Additional perspective on the significant impacts of all Moon to Mars programs (including ISS, SLS, Orion, Gateway, HLS, CLPS, etc) is referenced in the appendix.

Key Highlights:

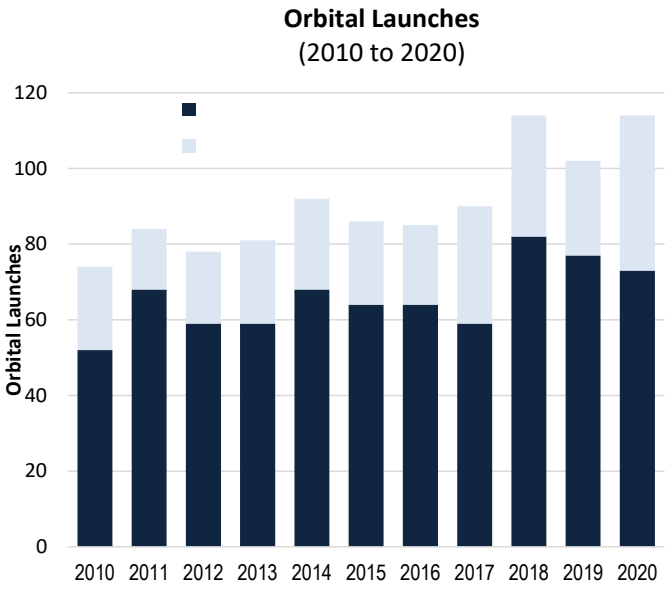
- NASA's selection of the SpaceX Starship vehicle for a human lunar landing mission helps build a new commercial launch capability. Due to its size, this vehicle may lower launch costs to orbit significantly, expand the potential customer base for launch services, and increase U.S. market share.
- The CLPS program provides service contracts to companies building robotic lunar landers with a lower cost and shorter development schedule than previous missions. These companies also offer payload delivery services to commercial and international customers. CLPS supports the development of a new, multibillion-dollar space subsector in lunar surface operations.
- Artemis drives innovation with challenging program requirements and its "mission-driven" approach. Potential solutions for lunar surface missions include technologies in compact power

systems, synthetic biology, additive manufacturing, on-orbit fuel transfer, lunar surface mobility, and materials science.

- Economic activity from "Moon to Mars" programs across the U.S. includes:
  - More than 69,000 jobs
  - Spending that supports more than $14 billion in total economic output
  - An estimated $1.5 billion in federal, state, and local tax revenues nationwide
- National competitiveness impacts include the diffusion of new space technology more broadly across U.S. space enterprise, expansion of the U.S. technical workforce and STEM talent pipeline, enhancement of U.S. soft power, and stronger capacity of U.S. space firms to compete globally.

Commercial Space Programs in Perspective

The COTS program enabled U.S. private industry to develop space transportation capabilities with the goal of safe, reliable, and cost-effective access to low-Earth orbit. Ultimately, this program delivered two new low-cost U.S. launch vehicles carrying cargo to and from the ISS: SpaceX Falcon 9 and Orbital Antares. The vehicles can also be used at a cost-savings advantage for small and mid-sized NASA Science missions (e.g., Transiting Exoplanet Survey Satellite, Jason-3, Sentinel-6 Michael Freilich). Riding on the success of the Falcon 9, SpaceX grew its share of the global commercial launch market from 0% in 2011 to 78% in 2020 (and over 50% of overall launch market worldwide in 2021, excluding China). SpaceX also jumpstarted the nanosatellite and CubeSat markets.



Commercial launches include internationally competed launches, any launch in which the primary spacecraft and launch vehicle are commercially owned or operated, and test launches of commercial launch vehicles. Launches procured under COTS, CRS, or CCrew are commercial.

Source: BryceTech

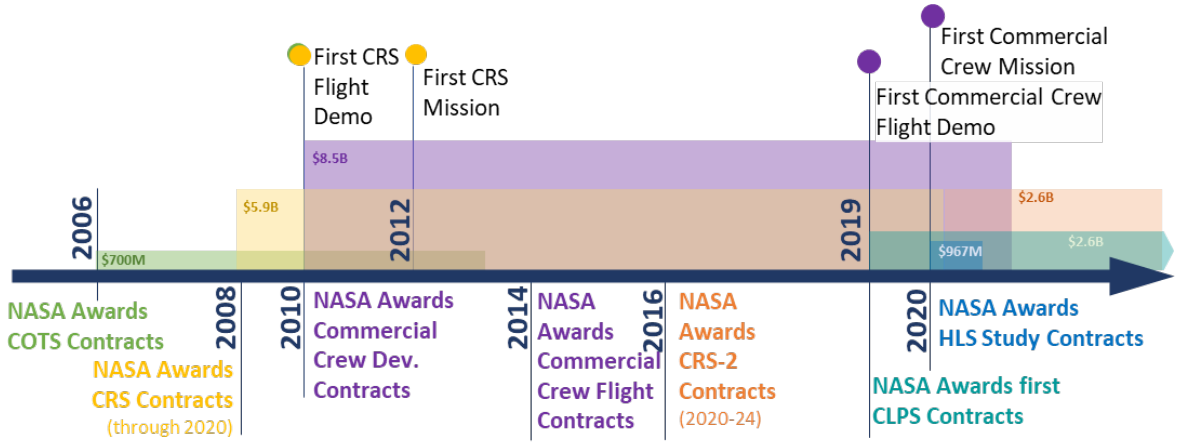
With the success of the launch vehicles, NASA entered into major multibillion-dollar commercial cargo resupply services (CRS) contracts with the two firms, creating future robustness for ISS cargo transportation. Building further upon these programs, NASA initiated the CCrew program for private sector firms to carry U.S. astronauts into orbit. To date, SpaceX has launched four crewed missions to the ISS (with several additional missions planned). A second competitor, Boeing's Starliner vehicle, is under development and slated for a crewed demonstration mission in 2022.

Economic Impacts of the Artemis Program

It's important to note that the Artemis program rebuilds capabilities not present in the U.S. space enterprise since the Apollo era. In many cases, a capability has not existed for decades, the production knowledge has disappeared, and new technology must be invented.

Artemis offers the chance to reconstitute the American moon program, which includes super-heavy launch vehicles (SLS, Starship); Earth-return-capable crewed spacecraft (Orion); lunar orbit docking; lunar landing system (Starship HLS); and lunar surface EVA suits. In addition, sustainable human presence requires wholly new elements, including the Gateway, on-orbit fuel transfers, and lunar surface habitation and expanded mobility capabilities. One prominent commercial example central to Artemis is the SpaceX Starship HLS. Another is the Gateway Logistics Services.

NASA intends the initial Human Landing System contract ($2.9 billion) to procure payload delivery of multiple tons of cargo and astronauts to the surface of the moon in the 2020s. The selection of the in-development Starship rocket and HLS crew lander to deliver U.S. astronauts to the lunar surface can have far-reaching impacts. The following sections describe how Artemis can expand economic growth similarly to previous commercial space programs (COTS, CRS, CCrew).



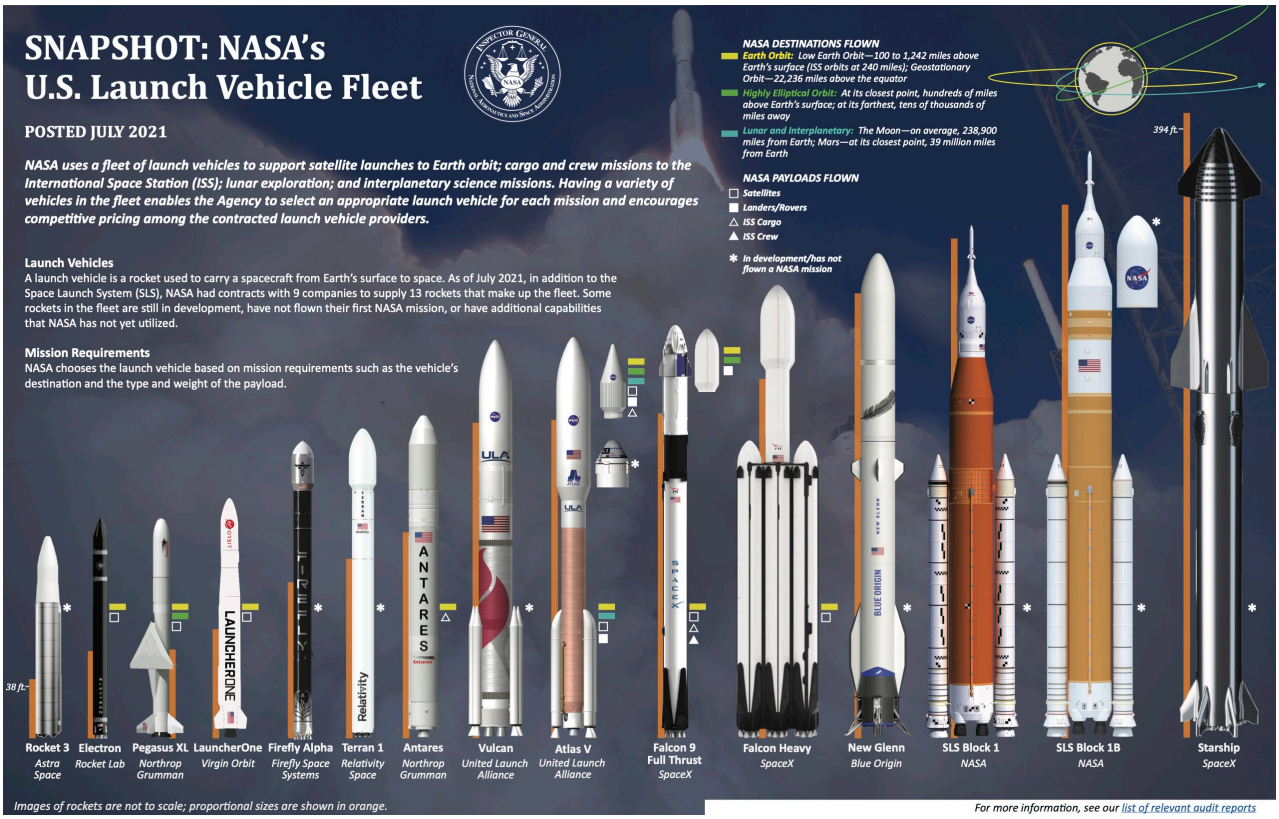
Timeline of major NASA Human Exploration Commercial Contracts

Source: NASA OIG Report data

New capabilities and lower cost access to space

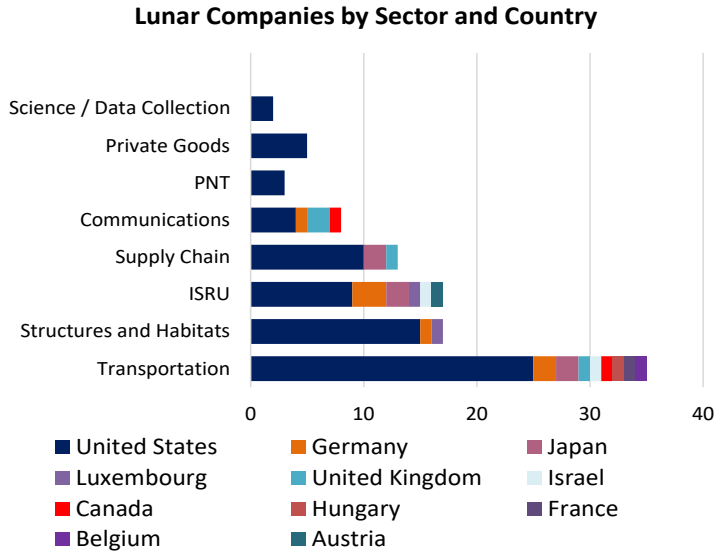
- Starship HLS is to provide a cargo delivery and astronaut landing capability for NASA. Other potential revenues in the future include lunar tourism and payload delivery (estimates are highly variable and range from several million to over a billion dollars).[ii] The ability to deliver tons of cargo, which may include scientific and commercial payloads, concurrently with astronaut landings offers a major rideshare opportunity to advance scientific, diplomatic, and economic development aims. In addition, broader strategic government interests in cislunar space may become possible with this new capability.
- Just as with the ISS, the regular provision of cargo and payload delivery underpins the future long-term establishment of a robust anchor tenet. The anchor for Artemis is infrastructure on the surface of the moon and in lunar orbit (Gateway). Due to the expense and complexity involved in these missions, NASA and international partners will be the first customers, but the customer base may eventually evolve towards stronger commercial and private sector participation. The initial steady stream of government contracts can ensure new capabilities and services are maintained until they reach commercial profitability.
- Starship's lift capability (>100t to LEO) is significantly greater than existing commercial launch vehicles (SLS Blk 2 will have a similar capability). As larger vehicles have come on line, the

cost/per kg to orbit has dropped for many applications.[iii] Lowering the cost of access to space has historically opened up new space sectors, including nanosatellites, CubeSats, Earth Observation, and communications satellite constellations, as well as the development of larger, more sophisticated satellites.



Source: NASA OIG

- Low-cost access to space has inverted the historical supply-demand curve in the space launch market. Where once high-cost suppliers had trouble fulfilling demand, today demand outstrips available low-cost launch supply. Consequently, entirely new customers and architectures in orbit become possible: from universities and private citizens to Earth observation CubeSats and LEO-based internet constellations. While commercial demand drivers for cislunar and lunar surface appear nascent now, as costs decrease and opportunities increase, the demand is likely to change. The figure (*right*) shows the proliferation of



Source: STPI

lunar companies worldwide across multiple subsectors, including entirely new commercial interests such as ISRU.

Market competition and improved value to government

- The initial procurements for CLPS, HLS, and other NextSTEP BAA awards were broadly competed, with selections based on technical, cost, and management factors.[iv] There are fourteen eligible vendors for CLPS contracts, with major task order awards to four lunar payload service companies. Similarly, while a single firm received an HLS contract, multiple firms competed and are eligible to compete for follow-on missions. Market competition supports the broadening of expertise across the industry and generally drives per-mission costs down. Robotic lunar payload services and crewed astronaut landing support are now multibillion-dollar space subsectors.

Improving Value to the Government Through Innovative Contracting

By awarding a firm-fixed price contract, NASA departed from traditional fee-plus contracts that have seen program costs spiral. Elements of the cislunar Gateway platform have also followed this new contract model. If successful, the new model may lead to procurement reforms to improve government efficiency, enabling better distribution of resources to other elements of the Artemis program.

- Firm competition showcases a strength of the American economy and system of government, drawing a notable contrast to the space programs of military-controlled and state capitalist systems.

Program Characteristics	Traditional Approach	Commercial-Oriented Approach
Owner	NASA	Industry
Contract type	Cost-plus	Fixed price
Contract management	Prime contractor	Public-private partnership
Customers	NASA	Government and nongovernment
Funding for capability development	NASA procures capability	NASA provides "milestone" payments as agreed goals are reached
NASA's role in capability development	NASA defines "what" and "how"	Industry defines "how" and NASA approves
Requirements definition	NASA defines detailed requirements	NASA defines only higher-level requirements
Cost structure	NASA incurs total cost	NASA and industry share costs

Source: NASA Space Operations Mission Directorate / Exploration Systems Development Mission Directorate

Expansion of customer base for lunar flights, services, and payload delivery

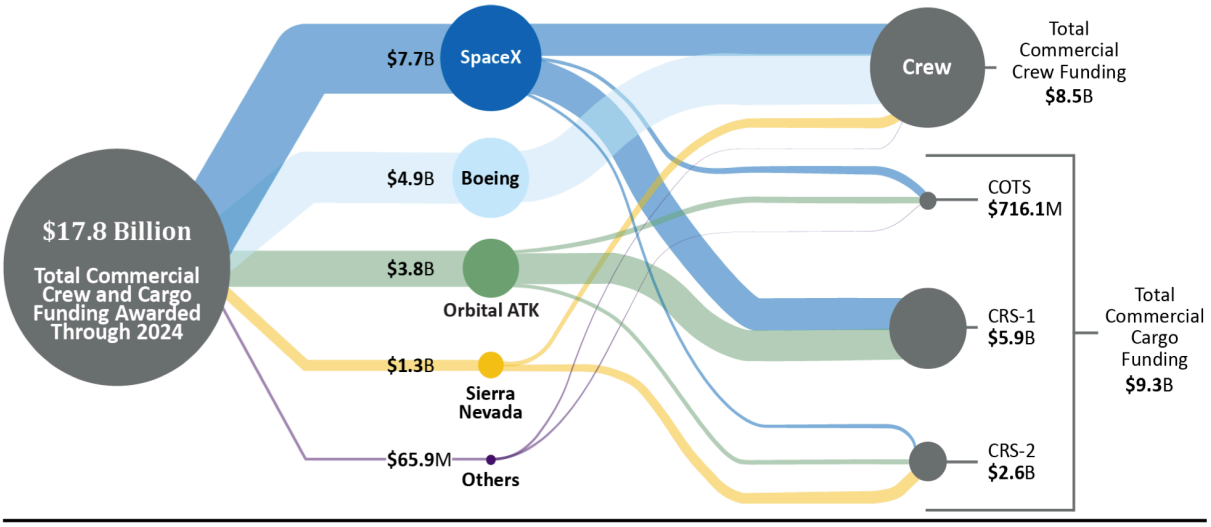
- The U.S. Department of Defense (DOD) expressed interest in procuring payload services for upcoming commercial flights to and around the moon. Given the utility of this domain and the funding capacity of the customer, DOD may eventually be an important source of revenue.
- In the last few years, the roster of countries interested in fielding robotic missions to the moon grew to include UAE, Israel, S. Korea, and India. Countries interested in providing instruments

for upcoming lunar missions include Germany, France, Saudi Arabia, and others. Astrobotic and other companies have acknowledged they maintain significant pending contracts for lunar payload delivery services from over a dozen countries (although for many customers there may be an uncertain ability to fulfill these commitments). A greater revenue base for American lunar companies provides financial robustness and market certainty, allowing them to grow their operations and create more high-paying U.S. jobs.

Commercial human spaceflight

- The CCrew program and successful demonstration of carrying astronauts to the ISS paved the way for the recent all-civilian Inspiration4 mission to orbit.[v] Using the Dragon crew capsule (reused from Crew-1 mission to the ISS) and the Falcon 9 rocket, the Inspiration4 mission was commercially procured by a private citizen and featured a charity fundraising element. After years of apparent stagnation, private astronaut missions are quite literally taking off. In addition to Inspiration4, Space Adventures flew a Japanese billionaire to the ISS in late 2021; one mission chartered by Axiom brought private citizens to the ISS in April 2022; Russia's Roscosmos lofted a filmmaker and leading actor to the station to film a movie production in October 2021; Blue Origin has flown three commercial missions; and Virgin Galactic has flown one mission to the edge of space. The estimated per-flight cost of these missions varies from several hundred thousand dollars to over $70 million, depending on the vehicle, destination, and duration.

NASA's Awards for Commercial Cargo and Crew Activities Through 2024 (2018 est.)



Source: NASA OIG analysis of Agency commercial activities and awards.

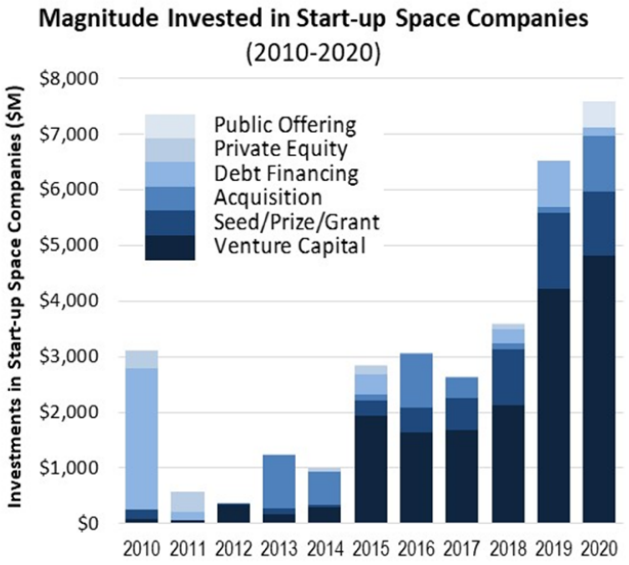
Driver of innovation

- NASA's lunar programs are largely based on the model, processes, and contractual agreements pioneered by commercial space programs.[1] Such investments in private sector R&D have historically yielded significant advances in launch technology, avionics, and spacecraft design not foreseen or planned by the government (such as reusable rockets). The complexity of the human landing system and lunar surface operations is likely to generate advances in technology similar

[1] NASA estimates that the development of Falcon 9 cost $400 million, or roughly ten times less than if built under traditional government contracting.

to how the Apollo missions advanced state-of-the-art in materials science, microelectronics, life support systems, and other areas. The figure (*right)* illustrates significant momentum of corporate and private sector investment in new space companies. This financing enables companies to develop innovative new hardware/software, generate revenue, become profitable and contribute to national economic growth. It may also help companies broaden their customer base beyond government to encourage greater stability and financial robustness.

- In a "moonshot" approach to innovation, high-technology R&D historically has greater economic impacts than many other areas of public sector investment.[vi]
- Technology spinoffs have historically been a significant benefit of government investment in basic and applied R&D, broadly diffused to U.S. companies.
    - Currently, the need for power on the surface of the moon is generating interest and investment in small, modular reactors. If established as a viable technology, these reactors would have tremendous variety of terrestrial applications and could provide for populations presently underserved. (See, for example, a startup developing this technology.)[vii]



Space start-up ventures are any space firm that has received and reported seed funding or venture capital.
Source: BryceTech

    - Food for space explorers may be developed using synthetic biology, given the absence of traditional organic ingredients and agricultural methods in space.[viii] NASA's SynBio project aims to find a pathway to convert carbon dioxide into organic compounds and enable biomanufacturing in space. Such technologies could lead to the development of long shelf-life foods, new and more sustainable techniques for creating medicines and plastics, and more efficient and less wasteful global agricultural practices.
    - Additive manufacturing in space, including 3D-printed solar panels on the lunar surface, may yield manufacturing advances that can both accelerate the creation of space infrastructure and be utilized on Earth. The establishment of infrastructure is crucial to expanding human presence in Earth orbit, cislunar space, and the lunar surface. In-space manufacturing may enable platforms and satellites at much larger scales than what can be launched into orbit.[ix] Already, in-space manufacturing on the ISS yields ultra-high-fidelity fiber optics (e.g., ZBLAN) and protein crystal growth in microgravity that surpasses the quality produced in terrestrial labs. Using regolith on the moon to build structures, including protective shields against solar radiation, may ultimately enable long-term presence on the moon. Such a foundational technology also has terrestrial applications, as remote populations and resource exploration platforms can benefit greatly from the ability to manufacture on-demand tools, parts, and other items.
    - The ISS is an important testbed and demonstration platform for Artemis missions. Over its roughly 20-year lifetime, it has yielded a number of significant breakthroughs with applications in medicine, physics, chemistry, materials science, and other areas.[x]

Broad economic impacts

- The broad Moon to Mars effort employs thousands of highly skilled professionals, and the U.S. Government channels billions of dollars into states through its contracts.
- M2M's economic impact goes beyond its immediate employment of NASA civil servants. The program creates wide-ranging benefits for local and state economies, as well as the U.S. economy, as NASA's contracting boosts economic activity elsewhere in the country:[xi]
    - Economic activity across the U.S. supports more than 69,000 jobs.
    - Spending supports more than $14 billion in total economic output across the country.
    - M2M programs generate an estimated $1.5 billion in federal, state, and local tax revenues nationwide.
    - The supplier base for major programs, such as SLS, is spread out over all 50 U.S. states, supporting initiatives such as "Buy American" and strengthening our domestic supply chain.

National Competitiveness Impacts of the Artemis Program

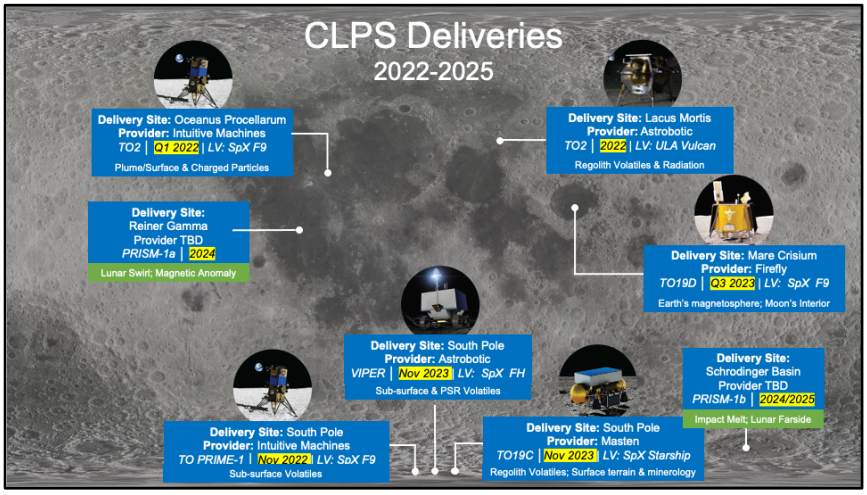
National competitiveness is a measure of a nation's firms' ability to compete in the global marketplace. Competitiveness depends on the ability of firms to innovate and upgrade, and claim greater market share. Different factors contribute to this ability. For commercial lunar firms and the Artemis program, the most important factors are technology development, workforce, market conditions, and government role. U.S. economic growth has slowed in recent decades, largely due to globalization, as technology-based economic competitors take ever greater shares of high value-added markets at the expense of U.S. domestic industries.[xii] To remain competitive, U.S. firms need to maintain a world-class technical workforce and sustain robust investment in technology.

CLPS companies such as Astrobotic and Intuitive Machines and HLS companies such as SpaceX develop technologies that do not currently exist commercially, including advances in low-cost manufacturing and spacecraft design. These technologies may ultimately diffuse to other space companies. NASA's recent missions to lunar orbit (LRO, LADEE) cost ~$250 to $583 million and did not feature a lander, generally a more costly and complex element. In contrast, cost estimates for the first CLPS lander missions are ~$80 million, and ~$200 million for the VIPER surface rover mission. The diffusion and rapid maturation

of technology is at the core of the commercial lunar effort, as NASA seeks to harness private sector innovation to speed up mission development and lower costs. Furthermore, supporting entrepreneurship and incorporating new companies into high-tech supply chains broadens areas for innovation and can make supply chains more resilient and robust.

A strong technical workforce is critical to U.S. industries, requiring a robust pipeline of talent from students to institutional academia to eventual STEM careers. The Artemis missions represent humanity's first return to the moon in nearly 50 years, and the majority of student-age and early-career STEM professionals have no direct memory of the moon landings or their far-reaching cultural and social impacts. As such, Artemis is a once-in-a-generation opportunity to recruit scientific and engineering talent into U.S. academic, government, and private industries. The ability of U.S. firms, especially those involved in high-technology areas, to attract and retain top talent both domestically and abroad is a cornerstone of our national competitiveness.

Commercial Lunar Payload Services – Destinations and Payloads



Market conditions suggest a firm's success may be predicated on having robust revenue and investment strategy and a sophisticated and deep customer base. The influx of private equity, angel or venture capital, and SPAC-supported and other corporate investment into the private sector is currently at an apex (approaching $9 billion in 2020), with the U.S. accounting for over 64% of all investment worldwide.[xiii] Although the market for lunar payloads and services is not as strong now as in other space subsectors (e.g., launch, sat com), the U.S. market is more robust than any in the world. This robustness is in part due to multi-year government contracts for lunar services, which currently represent up to $5 billion, by far the most significant funding for private sector lunar missions globally. Early government support in the form of services contracts and R&D funds has historically been critical for companies to mature past the high-risk phase of development until private and corporate financing is willing to step in.

Finally, as noted above, the government's role can be critical in early stage technology development. NASA has taken a strong position supporting a broad array of competitive firms and funding service contracts to enable mission development. Artemis is mission-oriented innovation, with government proposing a strategic mission and American firms stepping up to deliver. NASA creates missions (and the enabling policy and regulatory environment) but does not create or fix markets. The "moonshot" approach to innovation, pioneered by the Apollo program, suggests that strong government support for radical technology development to tackle unsolvable problems can yield major change. As a driver for economic growth, few levers are more powerful than creating new high-technology sectors of the economy in which firms can flourish. Government missions as varied as spaceflight, weapon systems, and energy storage led to the miniaturization of hard drives, microprocessors, improved lithium battery storage, HTTP/HTML code, and capacitive screens. Adopted by Apple and smartphone makers, these innovations revolutionized communications and IT industries, generating trillions in market value.[xiv]

One first step in establishing the legal and policy grounds for ownership of space resources will take place in the early 2020's. In August 2021, as part of an agreement between NASA and the firm Lunar Outpost to provide 4G communications as part of the Artemis program, Lunar Outpost also agreed to scoop up a sample of lunar regolith, take a picture, send it back to Earth and transfer ownership of the dust to NASA. The goal is to conduct the first sale of resources in space. For the most part, major commercial prospects for such endeavors currently remain in the well into the future. Speculating out to the 2030's and beyond, we might envision entirely new markets emerging. Once companies have established a toehold on the lunar surface and in cislunar orbit, they may provide services such as transportation to destinations in the Earth-Moon system, electrical power, rocket fuel depots, water extraction, and resource mining.

A recent surge in startups and financing support is tempered by forecasts suggesting significant commercial revenue may be beyond a 15-year window in most cases.[xv] Yet other nations are pursuing expansive plans for long-term lunar exploration and research bases, bringing the moon and cislunar space into Earth's economic sphere. A U.S. national exploration strategy should be no less visionary. Future systems of governance around the moon and in Earth orbit are likely to be modeled after those nations with a commanding presence. Ideals that the U.S. champions on Earth today, including the expansion of liberal free market democracy, may help set the stage for humanity's future in space.

Conclusion

The Artemis program is likely to generate significant economic impacts, improve innovation and technology development in the space sector, and contribute to the growth of the U.S. STEM pipeline. The market environments of the COTS, CRS, and CCrew programs may be different from those encountered by the lunar commercial programs. However, the lunar programs are expected to mature over a longer time horizon. The most important demand drivers in the near term are likely to be NASA and other government agencies. Significant non-government revenues are likely to be realized from upgraded launch capabilities and demonstrated lunar crew landing capabilities developed as part of the early Artemis missions.

References

[i] https://www.nasa.gov/content/commercial-lunar-payload-services-overview; https://www.nasa.gov/nextstep/humanlander2; https://www.nasa.gov/content/nextstep-overview

[ii] https://www.ida.org/research-and-publications/publications/all/d/de/demand-drivers-of-the-lunar-and-cislunar-economy

[iii] Falcon Heavy currently offers approximately ~$1,400-2,300 to LEO, the lowest in the world by a factor of two to three times. Source: https://www.spacex.com/media/Capabilities&Services.pdf

[iv] https://www.nasa.gov/sites/default/files/atoms/files/option-a-source-selection-statement-final.pdf

[v] https://inspiration4.com

[vi] (2018) Tassey, Greg. "The Economic Rationales and Impacts of Technology-Based Economic Development Policies". https://www.nist.gov/system/files/documents/2021/01/15/DOMESTIC%20TBED%20Programs__Policy%20Targets%20and%20Impacts.pdf

[vii] For example, Radiant startup founded by former SpaceX engineers: https://www.powermag.com/former-spacex-engineers-tout-new-microreactor/

[viii] https://www.nasa.gov/directorates/spacetech/game_changing_development/projects/SynBio

[ix] https://madeinspace.us/blog/2020/06/22/how-in-space-manufacturing-will-impact-the-global-space-economy/

[x] https://www.nasa.gov/mission_pages/station/research/news/iss-20-years-20-breakthroughs

[xi] https://www.nasa.gov/sites/default/files/atoms/files/2020_nasa_eir_brochure_for_fy19.pdf

[xii] Tassey, Greg (2018). https://www.nist.gov/system/files/documents/2021/01/15/DOMESTIC%20TBED%20Programs__Policy%20Targets%20and%20Impacts.pdf

[xiii] https://www.cnbc.com/2021/01/25/investing-in-space-companies-hits-record-8point9-billion-in-2020-report.html

[xiv] https://www.oecd.org/naec/NAEC_Mazzucato.pdf

[xv] https://www.technologyreview.com/2019/06/26/134510/asteroid-mining-bubble-burst-history/