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Mining of Helium-3 on the Moon: Resource, Technology, and Commerciality—A Business Perspective

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ABSTRACT

Lunar helium-3 is considered one of the potential resources for utilization as a fuel source for future Earth-based nuclear fusion plants. With a potential start-up of a commercial fusion power plant by the year 2050, the author describes technology and commercial aspects for a lunar helium-3 mining operation that could fuel such a power plant. Barriers for development are mostly inferred to exist in the fusion part of the helium-3 value chain. Commercially, a helium-3 operation would have to compete with other energy supply sources that might become available in the future and that could be developed in a stepwise function instead of in an all-encompassing effort. The author suggests that space technology research, development, and demonstration and fusion research should be pursued separately and should only form a symbiosis once a common fit caused by separately achieved scientific and/or technical progress justifies a joint commitment of financial resources. Research, development, and demonstration costs for these programs will be several hundred billion dollars, which will mostly be provided by public investments. The private sector, however, is emerging in space technology and could play a significant function in such a value chain, as outlined in the suggested business model. The author does not suggest such an operation as of yet, but instead that only a high-value resource—such as helium-3—could justify such endeavor. However, even then, other difficult-to-extract resources on Earth, such as gas hydrates, most likely would be preferred as an investment opportunity over a lunar mining development.

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BACKGROUND

Introduction: Recent Lunar Missions and Resource Interest

Reports of a large resource base of helium-3 and its potential mining have been published during the past decade (Duke et al., 2006; Schmitt, 2006a). Kulcinski (2001) reported of at least 1 million tons of indicated resources based mostly on an early assessment of rock samples returned by the Apollo 11 to 17 missions by the economic geologist Eugene Cameron in the mid-1980s. Cameron estimated that Mare Tranquillitatis alone (location of Apollo 11 and 17 landings) could yield a total of 2500 t (Schmitt, 2006b) of highest grade helium-3. In 2007, Slyuta et al. (2007) estimated total lunar helium-3 probable reserves to be 2,469,158 t. (For economic evaluation purposes, such tonnage could at best be referred to as a probable resource, but not a probable reserve.)

Interest in lunar energy resources increased noticeably during the past one-half decade. Expressions of interest in these resources have been made—among others—by China, Russia, and India. China launched Chang'e 1 into lunar orbit in October 2007 loaded with equipment to search for potential landing sites to help plans to have taikonauts on the lunar surface by 2020—after having sent China's her first taikonaut into space in 2003 for 14 orbits around Earth; two taikonauts in 2005 for 5 days of earth orbits; and in September 2008, three taikonauts including a spacewalk. Chang'e 2 followed in 2009; a rover mission for 2012 and a robotic sample return mission for 2017 are planned (Kluger, 2008).

On October 22, 2008, India launched the Chandrayaan-1 lunar orbiter. A Chandrayaan-2 rover mission is planned for 2011. Japan sent Selene into the Moon's orbit. Europe sent SMART-1 into lunar orbit in 2003 and plans to be back to build a global robotic village by 2016 and a permanent manned base by 2024 (Kluger, 2008).

In January 2004, former United States President George W. Bush authorized the National Aeronautics and Space Administration (NASA) to lay out a plan for human exploration for revisiting the moon by 2020, establishing a permanent base by 2024, and then to visit Mars. These plans were reviewed by a blue-ribbon panel (established by President Barack Obama) that concluded in a final report in October 2009 that these goals were not achievable with the current budget and given time frame (Review of U.S. Human Spaceflight Plans Committee, 2009).

The private industry awarded the US $10 million Ansari X Prize in 2004 to fly a manned vehicle to suborbital space of 100 km (62 mi) altitude twice in one week. In December 2007, Google sponsored a US $30 million Lunar X Prize with the objective to have a private rover covering a 500 m (1640 ft) distance on the lunar surface and sending back video before the end of 2012. Privately funded Bigelow Aerospace announced a $50 million prize to anyone building an orbital spacecraft, but the prize was never claimed before its expiry in January 2010 (Chang, 2010a). These prizes are indications of the beginning of space commercialization.

The international interest is a resource-driven motivation to discover and potentially extract valuable resources—foremost helium-3. The existence of water, confirmed by the Lunar CRater Observation and Sensing Satellite (LCROSS) (Chang, 2009) mission in November 2009, could greatly reduce the difficulty of any lunar mineral extraction operation. Lunar ice could serve as drinking water and, furthermore, as propellant once oxygen and hydrogen are broken apart, and oxygen could serve as air to breathe.

Lunar Helium-3: Utility in Perspective

During the past several decades, a total of 73 lunar missions (Lunar and Planetary Institute, 2012) have been conducted by various space agencies, including six lunar landings by NASA's Apollo program, and a total of 2196 individual rocks with a total mass of 381.6 kg (840 lbs) were returned to Earth (Allen and Lofgren, 2008). Studies of these rocks indicated that the isotope helium-3 had its highest abundance at the landing site of Apollo 11 in Mare Tranquillitatis (15.1 ppb) (Slyuta et al., 2007). The value of mining this isotope, when fused with deuterium, is attributed to its extremely high British terminal unit (Btu) value of 5.6E+11/kg (Schmitt, 2006a) as compared with petroleum of 42,000 Btu/kg—a ratio of 13,333,333:1! For comparison, the total United States energy consumption expressed in Btu is shown in Table 1.

This total United States Btu value of about 100,000 trillion Btu could be delivered by 178,571 kg (~180 tons) of helium-3 fused with deuterium for nuclear fusion. A 2500 t helium-3 resource base in Mare Tranquillitatis alone would be the equivalent of 1400 quadrillion Btu once fused with deuterium. In terms of Btu value, proven world oil reserves of 1.258 trillion bbl (BP Statistical Review of World Energy, 2009) hold the equivalent of 7422 quadrillion Btu. By definition, proven reserves are technically, economically, and legally extractable under current conditions;

Table 1. **The United States energy consumption (trillion Btu) and percent share of total energy.***

2007 Actual, 2008 Estimate, 2009 Forecast						
	2007	*2008*	*2009*	*2007*	*2008*	*2009*
Oil	39,772	37,505	36,090	39.2	37.7	36.7
Gas	23,637	23,780	24,018	23.3	23.9	24.5
Coal	22,776	22,800	22,550	22.4	22.9	23.0
Nuclear	8415	8400	8400	8.3	8.4	8.6
Hydro, other	6968	7100	7150	6.9	7.1	7.3
Total	101,568	99,585	98,208	100.0	100.0	100.0

**Radler and Bell, 2009.*

hence, currently, the lunar-based helium-3 Btu values are resources at best but cannot be classified as reserves!

Solar wind, blowing for the last 3.8 b.y. across the lunar surface, is responsible for the deposition of volatiles, including helium-3. On Earth, it is extremely rare, as the magnetosphere is shielding the Earth from solar wind. These volatiles are concentrated in the upper layer of the lunar surface, called regolith, a debris layer created by continuous meteor impact on the underlying rock. The very top of this layer would reach a depth of up to 3 m (10 ft), creating a substantial resource base. Being deposited in the top layer of the lunar surface would make such geography suitable for a surface mining-type operation (Duke et al., 2006; Schmitt, 2006a). Schmitt (2006c) stated that 100 kg (220 lbs) of helium-3 fused with deuterium could fuel a 1000 MW nuclear fusion power plant for 1 yr. As of March 2010, 437 nuclear fission power plants are in operation worldwide plus 55 reactors under construction (European Nuclear Society, 2012). If these approximately 500 plants were being fueled by helium-3 and deuterium instead of uranium, then the entire world fleet of nuclear reactors could be fueled by Mare Tranquillitatis for 50 yr.

Mining lunar helium-3 would be driven by its strategic or commercial utility value. Its utility is defined by its use as fuel source for potential future nuclear fusion power plants. Several fusion concepts have been researched during the last five decades; however, to date, no continuous fusion process has been developed that creates more energy as output than it consumes as input. A concept of using lunar helium-3 for such earthbound utilization would face technically and scientifically the threefold complexity of (1) conquering high-energy physics, (2) developing a space transportation and delivery system, and (3) developing robotics for lunar operations. Commercially, the technical solution must be (1) cost competitive with alternative investments; (2) deliver on schedule relative to the other components of the value chain; and (3) perform on quality, environmental impact, and safety standards. Economically, the project must be palatable to attract lenders to provide project financing. Legal rights for any lunar mineral extraction need to be cleared before any investment will be possible. Resolving issues of jurisdiction, ownership, cleanup of debris, and political implications can create formidable hurdles, as demonstrated by the negotiation of the Law of the Sea Treaty, the Antarctic Minerals Regime, and the Kyoto Protocol. Sophisticated management talent will be needed to handle the enormous multitude of complexities of such venture from concept development through planning and execution followed by the actual operations.

CURRENT STATE OF TECHNOLOGY

Neither fusion technology nor lunar mining and space transportation logistics are currently available for such a project.

Fusion Power

Fusion technology is still in the scientific experimental reactor phase—decades away from any practical commercially operating power plant, and none is expected to be built before 2050 at the earliest (Maissonnier et al., 2005; Smith and Ward, 2007; ITER Organization, 2012). The Electric Power Research Institute, an electric utility funded research organization in the United States, presently sees only limited private funding for Generation III+-type nuclear fission power plants and even less for Generation IV-type fission reactors (see Table 2). Several Generation IV nuclear reactor designs are in various stages of development; however, these are not expected to

Table 2. Generation of nuclear fission reactors by decade.

Generation I: 1945–1965	Early prototype reactors
Generation II: 1965–1995	Commercial power reactors
Generation III: 1995–2010	Advanced light water reactors
Generation III+: 2010–2030	Near-term deployment with improved economics
Generation IV: 2030–?	

be commercially viable until the 2030s or even not before 2050 (Electric Power Research Institute, 2008). Eventually, privately funded nuclear fusion research might occur through Generation IV-type budgeting; however, not in the near future.

To advance nuclear fusion into commercial reality, an international government-funded joint venture of seven nations started construction of buildings for the International Thermonuclear Experimental Reactor (ITER) in southern France in 2010. The project's road map envisions an operational demonstration power plant after a 10-year construction and a 20-year operational research phase. Original cost estimates in 2001 assumed 10 billion euros (US $13 billion) for the entire 30-year period, including operating costs. However, this figure was upgraded to 16.1 billion euros (US $21.5 billion) (Harrison, 2010) in 2010. For comparison, at the time of ITER's original cost estimate, research, development, and demonstration (RD&D) budgets in International Energy Agency (IEA) countries between 1974 and 1986 totaled US $158.240 billion and, between 1987 and 2002, US $132.781 billion, totaling US $291.021 billion, of which nuclear fusion received approximately 10.5%, that is, US $30.5 billion (International Energy Agency, 2004).

Historically, the first fusion experiments were conducted at the University of Cambridge, United Kingdom, in the 1930s, followed by the Zero-Energy Thermonuclear Assembly at the Harwell Laboratory in the 1950s. In 1951, Igor Tamm and Andrei Sakharov designed the tokamak concept (a toroidal donut-shaped structure), which led to the successful operation of the T3 machine at the Kurchatov Institute in the former Soviet Union in 1968. In the 1970s, approvals were granted for large fusion reactors based on the tokamak design, the largest facilities being the Japanese reactor JT-60 (1985–present); the Princeton, New Jersey, U.S.A., Tokamak Fusion Test Reactor (TFTR) (1982–1997); and the European Joint European Torus (JET) (1984–present). In the 1980s, then Soviet General Secretary Mikhail Gorbachev proposed to then United States President Ronald Reagan that the superpowers should invest in ITER. After an initial lack of interest in funding large energy research and development (R&D) projects during the 1990s (because of low oil prices), an ITER plan was agreed to by a seven-member international consortia in November 2006 (Nuttall, 2008).

In terms of technical success, the highest electricity output ever achieved by one of these reactors was by JET in 1997, generating fusion power of 16 MW, based on a Q value of 0.64 (i.e., 64% of the input energy was achieved; hence, more energy consumed than produced), during a period less than a second (Smith and Ward, 2007; Nuttall, 2008; Moyer, 2010). In practical reality, only at a Q value greater than 5 is the internal heating power greater than the supplied power (Nuttall, 2008). In a commercial power station, Q values must be far greater (e.g., $Q = 50$) because energy output must be far greater than energy input and the size of output in itself must be much larger (e.g., 1000 MW), and production must be a continuous process and must last longer than mere seconds! The planned experimental ITER is a magnetic confinement fusion reactor based on the deuterium-tritium (D-T) reaction using superconducting magnets (to confine the plasma) and the heat of 150 million °C (25,000 times hotter than the Sun's surface) to fuse hydrogen isotopes. It is aiming to reach a Q value of 10 and generating 500 MW during a period of tens of seconds (Nuttall, 2008).

Nuclear fusion's scientific concept is based on fusing atomic nuclei together, unlike fission, which splits them apart. The D-T reaction is the simplest fusion process, whereby a D-T gas is heated to more than 100 million °C to create a plasma. A heavier helium-4 nucleus is being formed, and energy is released. The D-T reaction has a very low Coulomb barrier, which is the energy barrier that two nuclei need to overcome so they can get close enough to undergo nuclear fusion. This energy barrier is given by the electrostatic potential energy. The low Coulomb barrier is advantageous for the D-T reaction as compared with a much higher barrier for a D-He-3 reaction. However, a D-He-3 reaction creates slightly more electricity per kilogram (14.7 MeV proton and 3.6 MeV alpha particle plus a higher conversion efficiency) as compared with a D-T fusion (17.6 MeV) (Kulcinski, 2001).

In a fusion reactor, such process will liberate neutrons, which then bombard a so-called blanket made of yet to be developed advanced materials that surrounds the magnetically confined plasma. The blanket will then transfer the neutron energy into heat. This heat then will be removed by a coolant fluid (like molten salt) and will be transported to steam generators to produce energy in the conventional way. Simultaneously, breeding of tritium to maintain the D-T reaction will be needed. Tritium will be generated by a complex series of reactions where lithium in the blanket will capture some of the energetic neutrons to create helium and tritium. Such a complex blanket has never been built. Some estimate that it would take between 30 and 75 years to understand the issues sufficiently to begin construction of an operational plant (Moyer, 2010), and others doubt the practicality of the fusion of helium-3 (Close, 2007). Such pessimistic view, however, is not unilateral. Optimistic on fusion science in general are, for example, Smith and Ward (2007) and Hazeltine et al. (2010) and, on power plant technology, a European Union study on commercial fusion power plants (Maisonnier et al., 2005). Schmitt et al. (2009) are very optimistic on lunar D-He-3 fusion in particular.

Building commercially viable D-T fusion power plants requires very large reactors, which would have to be even larger for the more challenging D-He-3 fusion reaction, which requires even higher plasma temperatures. Challenges for technology breakthrough focus on scientific, engineering, construction, operational, and commercial solutions. In general, heating, confinement, and the related structural and reliability issues are the central challenges before any practical fusion power can be harnessed. Structural materials must have the ability to sustain very large and continuous neutron bombardment for years at extreme temperatures to prevent phenomena like irradiation creep (slow deformation of a structural component under stress at high temperature), metal fatigue, and embrittlement (Nuttall, 2008). For ITER, a special research facility called International Fusion Material Irradiation Facility (IFMIF) is dedicated to focus on the complex and diverse design requirements of materials to prevent early degradation and limited lifetime of components.

Commercial power plants require an operating availability of greater than 90% (normal for fission power plants). Maintaining a fusion reaction over time, controlling its long-term behavior, and containing it successfully are a major reliability challenge. In addition, commercial fusion power plants must fit into existing regulations for electricity production; that is, licensing regulations will include documentation on, for example, demonstrated availability, maintainability, and reparability. A U.S. Department of Energy workshop (U.S. Department of Energy, Office of Fusion Energy Sciences, 2009) concluded that sufficient progress had been made in plasma confinement with respect to control of its instability and amelioration of turbulent transport. The report further stated that the present demonstrated level of confinement is sufficient to impart confidence in the future of magnetic fusion energy.

In 1979, Kulcinski et al. (1979) developed a road map for fusion commercialization, which assumed three generations of reactors predating commercialization, experimental power reactors (producing 10–100 MW), prototype demonstration reactors (250–500 MW), and semicommercial reactors (1000–1500 MW), each requiring successively higher performance characteristics. Concurrently, several smaller facilities would need to be developed to test various aspects of physics, engineering, materials, and safety issues. The anticipated time frame for such commercialization effort was 35 years, beginning with scientific work from 1980 to 1985, at which point funds for an engineering test facility would be approved with start-up of such a facility in 1992, followed by appropriations of funds for an experimental power reactor in 1997 with start-up of operations in 2004, followed by appropriations of funds for a demonstration power reactor in 2005 and its start-up of operations in 2015, which then would be followed by commercialization. In 2010, construction on the experimental reactor ITER had barely begun, and funding—because of increased costs—had still not been secured, pointing to a commercial phase not to start before 2050 at the earliest.

Space Transport and/or Delivery System

The year 2050, as the earliest target date for commercial fusion power plant operations, postpones the development of suitable lunar mining technology into the future. Even a first post-Apollo human landing on the moon by 2020 was questioned by the members of the 2009 review panel of NASA's Constellation program (Review of U.S. Human Spaceflight Plans Committee, 2009, p. 16), who concluded that "no plan compatible with the FY 2010 budget profile allows for human exploration to continue in any meaningful way" given various scenarios, such as one-time landing would cost a minimum of US $130 billion, far in excess of the planned US $100 billion budget. Instead, the panel suggested (among other alternatives) a flexible path option, which would delay landing on the moon until approximately 2030 and fund the development of enabling technologies and incentivize commercial launch operations to low Earth orbit (LEO).

A human space exploration strategy that is flexible and enabled by technical capacity over time and simultaneously guided by new discoveries could engage with an ITER fusion development program by the mid-2030s. By that time, lunar landings and lunar exploration activity could provide a much advanced knowledge base of lunar helium-3 development potential and ITER would have delivered the first results of its almost finished operating phase. Hence, both research efforts would focus on their specific objectives without diverting funds for a not-assured symbiosis. Thus, they would be conducted independently from each other but could focus on a common goal once program-specific breakthroughs have been achieved.

Following the panel's concept of commercialization of launching privately funded rockets to LEO would free government funding for deep space R&D and solar system capabilities, that is, the development of heavy lift rockets and space infrastructure. Already, the emerging space market is beginning to transform into an interplay of the private and public sectors. In 2009, the commercial and governmental market for satellites and other space infrastructure grew to US $261 billion—up 40% during the previous 5 yr (Tabuchi, 2010). This is an indication that the Apollo era space policy paradigm, ''a singular crash program response to a perceived threat in a specific time in history to achieve and demonstrate technological superiority'' (Wilford, 2010), is being transformed into a commercial application policy. Such merging of national and commercial goals is a stepwise process that is actively pursued using inventive nontraditional arrangements (Broad and Chang, 2010) such as the commercialization of launching astronauts to LEO.

Two examples highlight such anticipation of private funding initiatives. On June 4, 2010, a privately funded rocket was sent into orbit, with a second planned for midsummer, and a third for March 2011, with the objective to send a fourth rocket carrying cargo to the International Space Station (ISS). The company Space Exploration Technologies Corporation (SpaceX) claims that it could send astronauts to the ISS within a three-year time window after having received a contract from NASA (Chang, 2010b).

Similarly, another private company, Bigelow Aerospace, expects that its first private space station will be launched into orbit in 2014, followed by a larger version in 2016, providing combined slots for 36 individuals at any given time (Chang, 2010a). The concept is centered on an inflatable airtight bladder surrounded by Vectran, a bullet-resistant material to protect from micrometeoroids. Such inflatable concept can be packed tightly as payload. It is based on NASA's 1960 and 1964 Echo I and Echo II mylar balloons. Boeing and Bigelow Aerospace, received US $18 million in federal funding for preliminary development and testing of a crew module for seven individuals (four astronauts, three space tourists) ready to fly to the ISS by 2015 (Chang, 2010c). By 2017, 15 to 20 rocket launches are planned to the Bigelow Aerospace inflatable space station (Chang, 2010a). Such time frame would confirm the Constellation panel's assumption that commercial crew transport service to the ISS could become available in the mid- to late 2010s (Review of U.S. Human Spaceflight Plans Committee, 2009).

The propulsion stage to LEO is the most energy-intensive stage in space exploration, typically counting for 80% fuel by mass, that is, leaving only a relatively small percentage for payload mass. Therefore, high launch costs to LEO are mostly caused by the transportation of propellant needed to reach LEO. To incentivize commercial transport to LEO, launch rates would have to increase substantially to reduce costs, which the panel (Review of U.S. Human Spaceflight Plans Committee, 2009) expected not to decline significantly in the short term.

Currently, NASA's launch costs are about US $10,400/kg for the space shuttle (Futron Corporation, 2002), down from US $59,400/kg for Saturn V of the Apollo era and once targeted to decrease to US $2200/kg (Futron Corporation, 2002) by NASA's Space Launch Initiative (canceled in 2004). For their Falcon 9 rocket, SpaceX priced a payload to LEO at about US $50 million at a mass transport of 10,450 kg, hence, bringing the price per kilogram to about US $5000/kg. At that price, a 600 mt payload per annum—the envisioned Constellation program tonnage to be lifted to LEO—would create a market value of US $3 billion per year. For comparison, 250 mt per year were lifted during the Apollo program between 1969 and 1972; and during the past decade, the 350 mt ISS was transported via the shuttle into orbit (Review of U.S. Human Spaceflight Plans Committee, 2009). With a mass of about 105 mt, the shuttle has an actual payload mass of 25 mt, which would be about equal to the Constellation program's Ares I payload mass but only about 16% of the 160 mt payload mass of the planned Ares V heavy lift rocket. The National Aeronautics and Space Administration expects that strategic investment in mass reduction technologies could significantly reduce operating costs, such that a tenfold mass reduction from a mass eight times the ISS to a mass equal to the ISS would be achievable for future Mars expeditions (Review of U.S. Human Spaceflight Plans Committee, 2009). Such technical development would be needed for transporting heavy mining equipment from Earth to the lunar surface.

Such mass reduction concept in conjunction with a commercial LEO transport delivery system would enable a successive development of space technology according to the flexible path exploration strategy. A stepwise increase in operational experience in space could greatly improve logistics over time, that is, by increasing long-duration flights (from weeks to years) and moving from near-Earth targets (like asteroids) to Mars and beyond. At several points along this flexible path, the off-ramp to a Moon exploration program could be taken, for example, because of new discoveries while accomplishing new technological firsts (Review of U.S. Human Spaceflight Plans Committee, 2009). A lunar helium-3 mining operation could be integrated over time into such a phased human space exploration program that focuses on development of enabling technologies, as listed in the following:

- Visiting near-Earth targets would extend human experience with living and working in space, practicing landing and ascending from small bodies, and gaining experience with robotic exercises. First experience has been gained by the Japanese spacecraft Hayabusa, launched in 2003, which landed on the 535 m (1755 ft)-wide asteroid Itokawa in 2005, and returning asteroid samples to earth on June 14, 2010 (Matson, 2010). Such repeated exercise would allow for developing systems for lunar payload logistics.
- The National Aeronautics and Space Administration and industry experts consider propellant storage and transfer in space technologies as ground tested and ready for flight demonstration in a microgravity environment but do not yet consider these as options for system design (Review of U.S. Human Spaceflight Plans Committee, 2009). In-space refueling has been demonstrated by Russia (for its space station using Progress vehicles) and the United States military (by refueling of a satellite with its Orbital Express mission in 2007) (Cass and Sauser, 2009). The European Space Agency's automated transfer vehicle Jules Verne demonstrated automated docking of delivery tankers with the ISS. In one step, 811 kg (1787 lbs) of refueling propellant was transferred to the ISS in less than 30 min while the two vehicles orbited Earth at 28,000 km/hr. Jules Verne became the first Western spaceship to succeed in refueling another space infrastructure in orbit (European Space Agency, 2008). Technologies such as cryogenic in-space propulsion, cryogenic storage and fluid transfer with near-zero boil-off, and high-performance in-space restartable engines will be integral parts of the logistics chain for lunar mining.
- Enabling technologies would also focus on improved regenerative life-support systems and technologies for operational autonomy systems for deep space crews, such that telerobotic systems could be operated by a crew to remotely maneuver, for example, lunar surface robots. This would allow for remotely gathering data and samples without having first to develop expensive technologies for lunar landing and surface systems. Advancement in operating rovers and orbiters has been demonstrated with Mars expeditions. As of May 20, 2010, the NASA rover Opportunity set a new record of 2307 Earth days operating on the Mars surface—surpassing the previous record by the Viking 1 lander that operated on Mars from July 20, 1976, until November 1982. The National Aeronautics and Space Administration's Global Surveyor orbited Mars for more than nine years (falling silent in 2006), and Odyssey is orbiting Mars since 2001 and expected to surpass that record (Chang, 2010d).
- Experience with varied levels in space orbit also needs to be developed, particularly with the Earth-Moon and Earth-Sun Lagrange points (L1–L5). In this triangular system, precisely at these points, a gravitational equilibrium can be maintained as the effective forces are canceling each other; that is, L1 will always be the same distance from the Moon. This fact makes these locations important for parking of scientific observatories and servicing of spacecraft, and extremely important for future space transportation infrastructure and interplanetary travel. The Earth-Moon Lagrange point L1 is about 85% of the way to the Moon. Earth-Sun Lagrange points are about four times as far from the Earth as the Moon. Hence, objects
  a) have previously been stationed at various Lagrange points (e.g., the Genesis probe collecting solar wind from December 2001 to April 2004 at Sun-Earth L1);

b) are currently stationed at such locations (e.g., Wilkinson Microwave Anisotropy Probe (WMAP) launched in June 2001 to Sun-Earth L2 to measure differences in temperature of the Big Bang's remnant radiant heat);

c) will be stationed there in the near future (e.g., the James Webb Space Telescope to replace the Hubble Space Telescope in 2014 at Sun-Earth L2);

d) are planned to be stationed throughout the solar system. The Earth-Moon L4 and L5 were investigated for dust accumulation by the Japanese probe Hiten (1990–1993).

COMMERCIAL RISKS

Project Investment: Schedule and Cost

The schedule and cost for such value chain could be based on the above descriptions and are shown in Tables 3 and 4. Accordingly, the period from 2010 to 2020 would focus on the construction of ITER and the development of enabling space technologies such as cryogenics and fuel storage and refueling, plus restartable engine design, that is, the government-funded development of deep space systems technology leading beyond LEO while supporting the private sector in the development of commercial transport to LEO. The period 2020 to 2030 would focus on operational testing of the fusion reactor, and space technology would focus on the development of a heavy lift rocket and mission operation without landing on the Moon or Mars, that is, operating the deep space systems and developing planetary systems. The period 2030 to 2040 would focus on developing operating results for ITER and operating the planetary systems. First landing on the lunar surface could occur at the beginning of that decade and would be a reccurring event to the middle of that decade to establish lunar habitat and research and exploration facilities. The ITER's fusion reactor would reach the end of its planned lifetime near the end of the decade. Both programs could have significant new information concerning their research efforts by the middle of the decade. The period 2040 to 2050 would focus on the construction and operation of the Demonstration Fusion Power Plant, with a focus on commercial operations, whereas space technology development would concentrate on advanced systems for lunar and Mars human habitat operating logistics.

The provided cost estimate yields a total investment of US $252.6 billion. This would include the R&D, testing, and demonstration of all systems and operational viability. The individual subcategories would require (1) US $146.6 billion for the space delivery transportation infrastructure based on the Constellation program; (2) US $62.6 billion for the lunar industrial park, including the lunar outpost base, surface facilities, mining equipment, refining, processing, and liquefaction facilities; (3) US $4.4 billion for the transportation and storage logistics consisting of Earth-Moon L1 and LEO facilities plus orbital transfer vehicle (OTV) transportation; (4) US $39 billion for the fusion power plant development based on ITER. However, these estimates would not include actual ongoing operations. Note, for example, that only one single fusion power plant is included. No operation would be planned to focus solely on one such plant.

Project Risk: Cost Overrun and Schedule Delay

Cost overruns and schedule delays are common for large-scale publicly funded scientific projects and privately funded industry programs. As stated in *Nature* (Editorials, 2008, p. 824), "quoting a price for a major new scientific instrument is notoriously tricky. Researchers have to estimate costs for equipment that has never been built, forecast expenditures years in advance, allow for unknown contingencies, and win approval from skeptical politicians who always want the project to cost less."

In 1979, a United States fusion research program was expected to cost about US $20 to US $25 billion to get through the demonstration reactor phase, with an additional US $5 to US $10 billion to progress through the commercialization phase (Kulcinski et al., 1979). These 1979 figures are surpassed by the March 2010 ITER cost estimates of 16.1 billion euros (US $21.5 billion) just for the experimental power reactor phase alone, signaling at least a 60% increase in costs since its initial forecast in 2001 (European Commission, 2010; Harrison, 2010).

A further recent example in cost overruns and schedule delay is the National Ignition Facility (NIF), a fusion research facility at Lawrence Livermore National Laboratories, dedicated on May 29, 2009, after a seven-year delay. The 1994 original cost estimate of US $1.2 billion resulted in a final cost of US $3.5 billion, that is, a cost overrun of 292%—tripling the original estimate. Annual operating costs will be US $140 million for the next 30 years. The complexity of building such a facility is illustrated by the fact that it took 7000 construction workers and 3000 contractors one decade to build. The facility is the largest laser system ever built, with 192 lasers and 97 km (60 mi) of mirrors optimized by 60,000 points of control (30 times

Table 3. Schedule for lunar helium-3 mining development (excluding construction of power plant post-2050).*

	2010–2015	***2016–2020***	***2021–2025***	***2026–2030***	***2031–2035***	***2036–2040***	***2041–2045***	***2046–2050***
ITER**	Construction	Construction	Low D-T** operation; checkout	High duty D-T operations	2nd D-T operation phase	2nd D-T operation phase		
IFMIF**	Construction	Construction	Materials testing	Materials testing	Materials testing	Materials testing		
DEMO**		Conceptual design	Engineering design	Construction phase 1, blanket design phase 1	Blanket construction and installation	Operation phase 1, blanket design phase 2	Blanket construction phase 2 and installation	Operation phase 2
Power plant							Conceptual design	Engineering design
Flexible Path	Technology development phase 1	Commercial crew transport to LEO,** technology development phase 2	Heavy lift rocket development	Unpiloted lunar test, lunar flyby and Earth-Moon L1 test, near-Earth visits	Light lunar lander and surface systems testing and lunar landing	Intensify Lagrange point utilization, additional lunar landings	Advanced systems for lunar and Mars human habitat operating logistics	Lunar mining operating systems development

**Adapted from Review of U.S. Human Spaceflight Plans Committee, 2009; ITER Organization, 2012.*

***ITER = International Thermonuclear Experimental Reactor; D-T = deuterium-tritium; IFMIF = International Fusion Material Irradiation Facility; LEO = low Earth orbit; DEMO = demonstration fusion power plant.*

Table 4. Capital investment for development.*

Total	**252.6**	
Space Delivery Infrastructure	**146.6**	Source: 70
Advanced capabilities	9.6	Flexible path-type technology developments
Orion	14.4	Crew capsule
Ares I	17.6	Lift rocket to LEO** for Orion
Ares V	20.8	Heavy lift rocket for equipment
Reserves	22.4	This is a 15% contingency
Program integration, operations, other	25.6	
Altair	11.2	Lunar lander module
Lunar surface systems	16.0	
Pre-2010 investment	9.0	NASA** investments on Constellation before its cancellation
Lunar Industrial Park	**62.6**	Based on Congressional Budget Office, 2004; Sabathier et al., 2009
Lunar outpost	35	
Universal lander module	2	
Lunar base (habitation and support modules)	29	CSIS** estimate includes US $12 billion for Altair; however, Altair is already included in space delivery infrastructure, hence, US $12 billion was included here for a larger base needed for industrial operations versus a purely basic scientific station, i.e., US $29 billion versus US $17 billion
2 Ares V launches for base modules	2	
Orion safety margin	2	
Regolith mining and processing, refining	2.7	Adjusted from H. Schmitt, 2005a (US $2.5 billion–2005) includes design and development of equipment and supporting facilities for excavation of minerals for helium-3 and by-products plus oxygen
Oxygen, propellant, and helium-3 liquefaction plant	24.9	Adjusted from Congressional Budget Office, 2004; Lindroos, 1999; Joosten and Guerra, 1993; US $7.3 billion (1993) for production costs (launch vehicle production US $3.5 billion, lunar lander production US $1.0 billion, cargo spacecraft production US $2.8 billion) were discounted by author as they already are included in space delivery infrastructure, and a 40% management fee was added; all numbers were adjusted for 2009 value
LUNOX systems and liquefaction	10.9	Originally US $3.9 billion, however, because this is an industrial application and includes some liquefaction, a larger investment is needed than for a small scientific base; hence, planned capex** for a separate lander for this plant (US $3.5 billion) plus separate launch vehicle development (US $1.2 billion) were reassigned by author to LUNOX systems because lander and launch vehicle development costs are already part of space delivery infrastructure and universal lander module under lunar outpost
Lunar Surface Systems	5.9	Includes storage
Science payloads	1.3	
Project support and management	6.9	40%
Transportation and Storage Logistics	**4.4**	
L1 storage and propellant production	1.2	
LEO** storage and propellant production	1.2	
OTV**	2	
Power Plant	**39**	
ITER**	22	
DEMO plant	5	
Commercial plant	12	

**in billions 2009 US $.*

***LEO = low Earth orbit; NASA = National Aeronautics and Space Administration; CSIS = Center for Strategic and International Studies; OTV = orbital transfer vehicle; ITER = International Thermonuclear Experimental Reactor; capex = capital expenditure; DEMO = demonstration fusion power plant.*

as many as on the space shuttle) to hit pellets of frozen hydrogen. Eventually, temperatures of 180 million degrees Fahrenheit will be reached (Broad, 2009; Data Points, 2009).

In the aerospace sector, the proposed budget for NASA's Constellation program for the period from 2005 through 2020 was estimated to be US $63.8 billion (2005 dollars) (Butts and Linton, 2009), yet, NASA's separate Exploration Systems Architecture Study (2005) determined the cost to be US $124 billion (Butts and Linton, 2009) (through the first lunar landing, FY06-FY18). The National Aeronautics and Space Administration estimated costs for Constellation in 2009 dollars were US $98.4 billion (Review of U.S. Human Spaceflight Plans Committee, 2009). This compares with US $165 billion for NASA's Apollo effort through the first human landing (1961–1969) on the Moon (Butts and Linton, 2009). The Apollo lunar program (1962–1973) had a total program cost of about US $170 billion (2005 dollars) comprising 17 missions. This included all R&D costs; expense of procuring 15 Saturn V rockets, 16 command/service modules (C/SMs), 12 lunar modules, program support and management costs; construction expenses for facilities and their upgrading; and costs for flight operations (Butts and Linton, 2009).

Apollo's first cost and schedule estimate (made by the U.S. Air Force in 1958) was US $1.5 billion with a schedule to land on the Moon in 1965. In 1961, NASA estimated a total cost of US $7 billion with a lunar landing in 1967. This estimate was formally changed to US $20 billion and submitted to Congress by Jim Webb, then NASA's administrator. The real cost of Apollo was submitted to Congress in 1973, with a cost of US $25.4 billion. The real schedule was achieved in 1969, with landing a man on the Moon. This means Apollo had a 263% cost overrun and a 40% schedule slip (Butts and Linton, 2009).

In a wider NASA study, in September 2004, the Congressional Budget Office (CBO) analyzed cost growth for 72 of NASA's programs (Congressional Budget Office, 2004), which were drawn from a general cross section of projects that included most of NASA's research enterprises since 1977. Growth in budgeted costs for the 72 programs ranged from minus 25% to 274%, with more complex programs generally having more dramatic cost increases. Using these programs' experiences, the CBO derived a cost growth risk (CGR) factor that represented an average ratio of actual costs to initial estimates for NASA's programs, yielding an average CGR factor of 1.45 for NASA's past programs—once the effects of inflation had been removed.

Such cost increases are not unique to the public science and space exploration sector.

Examples of the aerospace industry include (among others) developments such as the Boeing 787 Dreamliner and the United States military's F-35 Joint Strike Fighter jet, and the Airbus A400M military transport plane. The Boeing 787 Dreamliner had board approval in late 2003, with a first delivery scheduled for 2008, but was rescheduled for first delivery to 2011—its sixth delay (Drew and Clark, 2010). Originally, Boeing had estimated to invest between US $8 and US $10 billion, but stock analysts now believe that the investment could increase to US $20 billion (including penalties) (Drew, 2009). In case of the United States military's F-35 Joint Strike Fighter program, the United States military's most expensive program, projected costs increased by 64% to US $382 billion (real terms since 2001) for 2457 planes, with recent Pentagon estimates for a single F-35 to be US $112 million (Austen and Drew, 2010; Drew, 2010). The Airbus military transport plane A400 M is about four years behind schedule and more than US 7 billion over budget (Clark, 2010).

Such delays will not only cause canceling of orders but also trigger penalties and compensation payments to airlines. Managing the supply of components is a very complex procedure. In case of the Dreamliner, delays were caused by a shortage of bolts, faulty designs, engine problems, and factory strikes (Reuters, 2010). In the case of the Airbus 380, delays were caused by installing more than 483 km (>300 mi) of wiring in the airplane and minor structural redesign of the wings. Cost overruns and delays commonly lead to write-downs by companies, which, if significantly high, could lead to a downgrade in their credit rating, hence negatively impacting the cost of borrowing capital for investments. Both Boeing and Airbus have chosen write-downs, for example, in the case of the Airbus A400M by 1.8 billion (US $2.5 billion) and in the case of Boeing's redesign of the Boeing 747 as a freighter jet (US $1 billion) (Associated Press, 2009).

Systemic existence of cost overruns was also found for the transportation infrastructure sector. A 2002 study (Flyvbjerg et al., 2002) had sampled 258 projects from 20 countries on five continents, valued US $90 billion and covering the time span from 1927 to 1998. The results determined that nine of ten projects had cost overruns—commonly between 50 and 100%. Causes were of technical nature (imperfect forecasting system), psychological (optimism bias), and political-economic (strategic misrepresentation of scope and budgets). Poor practices of establishing proper contingencies and a mismatch between scope of work and budget were the main drivers for cost overruns.

These experiences from the private and public sectors indicate that cost overruns and schedule delays could be very much expected in the case of a lunar mining operation. At a minimum, a 45% cost overrun should be considered, given the NASA-specific study, resulting in an estimate of US $366.27 billion. If a 75% cost overrun is assumed (based on the worldwide transportation infrastructure study), then the estimate would result in US $442.05 billion. An Apollo program-type cost overrun of 263% would result in US $664.34 billion, and an NIF-type cost overrun of 292% would result in a US $737.59 billion estimate.

All of these outcomes should be considered possible given the complexity and long time horizon of such a planning exercise. A tripling of costs should not be ruled out—as wisely foreseen by Jim Webb, NASA's administrator at the time of the Apollo program—particularly when no trade-off exists between performance, schedule, and cost. "If a major project is truly innovative, you cannot possibly know its exact cost and its exact schedule at the beginning. And if in fact you do know the exact cost and the exact schedule, chances are that the technology is obsolete" (Gavin, 1994, p. 62).

Project Valuation: Private Sector Investment Versus Government Funding

A project proposal of mining lunar helium-3 for fusion power plant operations would be compared with other options for energy development and would be evaluated via established evaluation criteria as part of a portfolio to achieve overall investment objectives. Hence, in a portfolio, long-term strategic objectives will be mixed with the near-term economically viable opportunities. The perceived time frame for commercial viability is the dividing line between private and government sponsorship. Possibilities for private investments decrease with increased time requirements for commercialization and higher anticipated costs.

Theoretically, an investment in Mare Tranquillitatis could be considered a strategic investment by a company, that is, resulting in a lower than acceptable rate of return with the perspective of long-term gains. In the future, such an asset could be sold without reaching production, hence, creating an option value. However, a noncore asset could tie up a large percentage of annual capital expenditure. This, in turn, could undervalue the stock market value of the investing company while being the most expensive asset to be developed. Overall company production, hence, revenue generation, could decline as other opportunities are not being pursued in the short term. Investors mostly reward near-term profits and discount future projected success, as aptly described by Gavin (1994), leader of the Apollo lunar lander project at Grumman Aerospace Corp., when recalling that Grumman's stock dropped 10% within two days after a stock analyst was told of a successful technical development, costing US $120 million, whose commercial time might not arrive within the next 20 years.

A Mare Tranquillitatis mining proposition to shareholders will be evaluated in terms of its percentage of the company's equity market, its percent contribution of energy reserves, and as percent of its contribution to production in terms of time. Contribution to these factors would be very far into the future. The stock market valuation of resource companies would not allow spending large amounts of shareholder's money on a Mare Tranquillitatis investment. Instead, the stock market will focus on reserve replacement (i.e., future longevity of a company measured by the reserve-to-production [R/P] ratio) and the shortest amount of time required to develop these reserves (i.e., the concept of time value of money).

Because of the long time horizon and uncertainties about future market conditions, government-funded investment would be needed for basic scientific research, engineering, development, testing, and technology demonstration. Such funding typically needs a driver, for example, the energy crisis in 1973 and 1979. In January 1975, then United States President Gerald Ford proposed, among other major investments, to build 20 major synthetic fuel plants, and Vice President Nelson Rockefeller championed a US $100 billion program to subsidize synthetic fuels and other high-cost energy projects that commercial markets would not support (Yergin, 1991). As a result, one of the historically dramatic examples of United States energy policy was the creation of the Synfuels Corporation in 1980 with an initial funding of US $20 billion by the United States Congress for four years and an additional US $68 billion to follow for an additional eight years. However, no commercially profitable operating plant was ever built.

Absent an urgent driver, governmental initiatives typically focus on incentive programs for technology development by the private industry, for example, the offshore Gulf of Mexico deep-water development. Over time, the Gulf of Mexico incentives translated into significant federal and state income in the form of lease payments and royalties. During the 50-year period from 1954 through 2004, the United States federal government received US $64 billion in bonuses, US $3 billion in rentals, and US $89 billion in royalties. In addition, since 2000, some of the royalty on outer continental shelf (OCS) oil, valued at about US $3.2 billion, has been taken in kind for delivery to the U.S. Strategic Petroleum Reserve (U.S. Minerals Management Service, 2009).

For a lunar helium-3 mining operation with the indicated cost and schedule, public funding would be needed for the fusion research and space research programs until the mid-2030s. Only then, if both programs provide promising first results, is private funding conceivable. This could be in the form of a conceptual commercial prototype helium-3 fusion power plant design and participation in drafting a licensing round concept for lunar mining, similar to offshore hydrocarbon licensing rounds. This would be part of the negotiations for a Moon mineral's regime, which should have started in the early 2020s, before gaining any new knowledge on lunar helium-3 deposits.

The assumed high concentration of helium-3 provides Mare Tranquillitatis with a high premium. However, such resource would be considered stranded. Because of the expected high development costs and lack of development technology, no value would be assigned to these helium-3 resources in a marketplace. Stranded resources are common and are best exemplified by the vast worldwide known natural gas resources that were not extracted, but instead flared, as an unwanted associated by-product of crude oil development. Then, as a market slowly developed, the supply source was commonly too remote from the market, leaving it stranded again with no available commercial transportation mechanism. It was not until liquefied natural gas (LNG) was first commercially shipped in 1964, even costly, to use such resources and turn them into reserves, although LNG itself was first scientifically demonstrated in 1877. Hence, it took 87 years before the process was commercialized. In 2008, worldwide LNG trade reached 226.51 bcm (BP Statistical Review of World Energy, 2009). Such time frame in technology development is common; it typically has been stepwise and rarely revolutionary.

A US $252.6 billion investment (without contingencies) for simply developing the technology but without investment into actual operations would not attract private investment. However, the actual amount in itself would not necessarily be a hindrance. The energy industry is familiar with large-scale capital investments. A 2007 study by Ernst & Young LLP (2007) concluded that during the period from 1992 to 2006, the five major oil companies (BP, Chevron, ConocoPhillips, ExxonMobil, and Shell) had US $765 billion in new investment, net income of US $662 billion, and cash flow from operations of US $1.19 trillion. A larger grouping of the 57 largest United States oil and gas companies had new investments of US $1.25 trillion, a net income of US $900 billion, and cash flow of US $1.77 trillion. The five major companies accounted for 61% of the larger group's investment. The absolute amount of new investment was defined as capital expenditures on property, plant, and equipment plus exploration expenses and R&D expenditures.

For the year 2010 alone, investments in United States oil and gas projects will be US $220 billion (US $196 billion for upstream exploration and production, US $25 billion for downstream investments), investments in Canadian hydrocarbon projects will be US $44 billion (upstream and downstream), and Mexico's upstream investments will be US $19 billion. Outside North America, upstream spending will be US $337 billion. This leads to a total upstream investment of more than US $550 billion (Radler, 2010)! On a project-specific basis, one of the largest projects, Kashagan, is a US $136-billion (Nurshayeva, 2008) investment in the Caspian Sea. These figures show that the private industry is not afraid of large capital investments and will take the associated risk, but the industry is highly afraid of uncertainty, which will hinder most investments.

Business Model: Concept, Logistics, and Operations

The business concept could be modeled after the existing LNG value chain (see Figure 1). The technology will be based on the previous description and its cost and time horizon. The original LNG model was based on a creditworthy buyer (power plant) that provided a strong market with existing sales agreements. The buyer signed a long-term (20-year) take or pay contract with the upstream gas developer. Simplified, this meant that even if the buyer could not take delivery, payment still had to be made. Only after such agreements were in place, would the upstream party invest in producing, liquefying, and shipping its gas and delivering it to a regasification terminal that was owned by the buyer. Today, this business model is far more diverse, where drilling and production is one component, the liquefaction facility a second value driver, shipping partially performed by independent transporters and regasification terminals that are independent of sales contracts, yet ready to deliver into

Not acceptable for one part of value chain to subsidize another

UPSTREAM	**LIQUEFACTION**	**SHIPPING**	**RECEIVING AND REGASIFICATION**	**PIPELINING AND GAS MARKETING**
Gas Development Exploration Development Production	Processing Gas Trains Utilities Offsites	Transportation Tankers	Terminal Gas Vaporization	Sales Monetization of Gas
Responsible for specified gas quality and gas volume	Enabler for whole value chain: 1. Most significant investment; 2. limiting capacity	Dedicated fleet, purpose-built for the project concerned	Terminals have varying ranges of gas specs that they can receive	Limited gain in market share by product differentiation; no price differentiation (i.e., commodity price)

Opportunity: Multitude of contract arrangements - - - double – digit US$ billions - - - Uncertain future market conditions

Alignment of purpose throughout whole value chain needed
Alignment Issues:
different perceptions of risk
different perception of value
different view where to generate value
different view on commercialization criteria
different view on risk tolerances

Competitiveness
Long-term plant reliability
Quality of construction
Lowest cost of production
Customer service: destination flexibility
Flexibility w/ feed gas suppliers

Limitations
Long-term commitments
Long time until payout

FIGURE 1. The liquefied natural gas (LNG) value chain.

an existing pipeline grid. The value of the gas is measured against an agreed-upon market gas hub, and pricing is according to a determined netback pricing formula based on such a market hub, for example, Henry Hub in the United States or the National Balancing Point (NBP) price in the United Kingdom.

Lunar helium-3 could be provided in a similar fashion (Figure 2). A nuclear Future Fusion Power Plant Co. would be the anchor of the value chain by selling electricity into an existing market. Sufficient market share of such plant would then incentivize investors to create the Lunar Industrial Park and Helium-3 Mining Company. This company would mine, process, and liquefy helium-3 and would also manufacture propellant (LOX, LH2) for space transportation as a by-product from regolith mining. A third company, Space Transport and Logistics, would operate a storage and refueling depot at the Earth-Moon Lagrange point L1. This would be a commercially operated trading company that will sell the liquid helium-3 to fusion power plants on earth and propellant to governments for space transport. The same company would maintain a second storage and refueling station closer to Earth in LEO. This facility would also have a small processing unit for propellant production, ready for sale to commercial LEO transport companies. Also, this company would provide for all product handling, distribution, and shipping on Earth.

Operationally, such a venture could start with a surface-mining step using a bucket-wheel excavator integrated with a beneficiation and processing unit followed by a refining step, as described by Schmitt (2006a). An annual shipment of 100 kg of helium-3 per 1000 MW fusion power plant would require mining of 2 km^2 (0.8 mi^2) of the lunar regolith to a depth of 3 m (10 ft), that is, mining and processing of 10 million tons of regolith (Schmitt, 2006d). For propellant production, as envisioned by Duke (Blair et al., 2002; Duke et al., 2003), water could be extracted from the mined regolith, then electrolyzed to produce gaseous hydrogen and oxygen, which then will be liquefied for propellant use. The liquefied products would be stored in a small facility, powered by solar arrays.

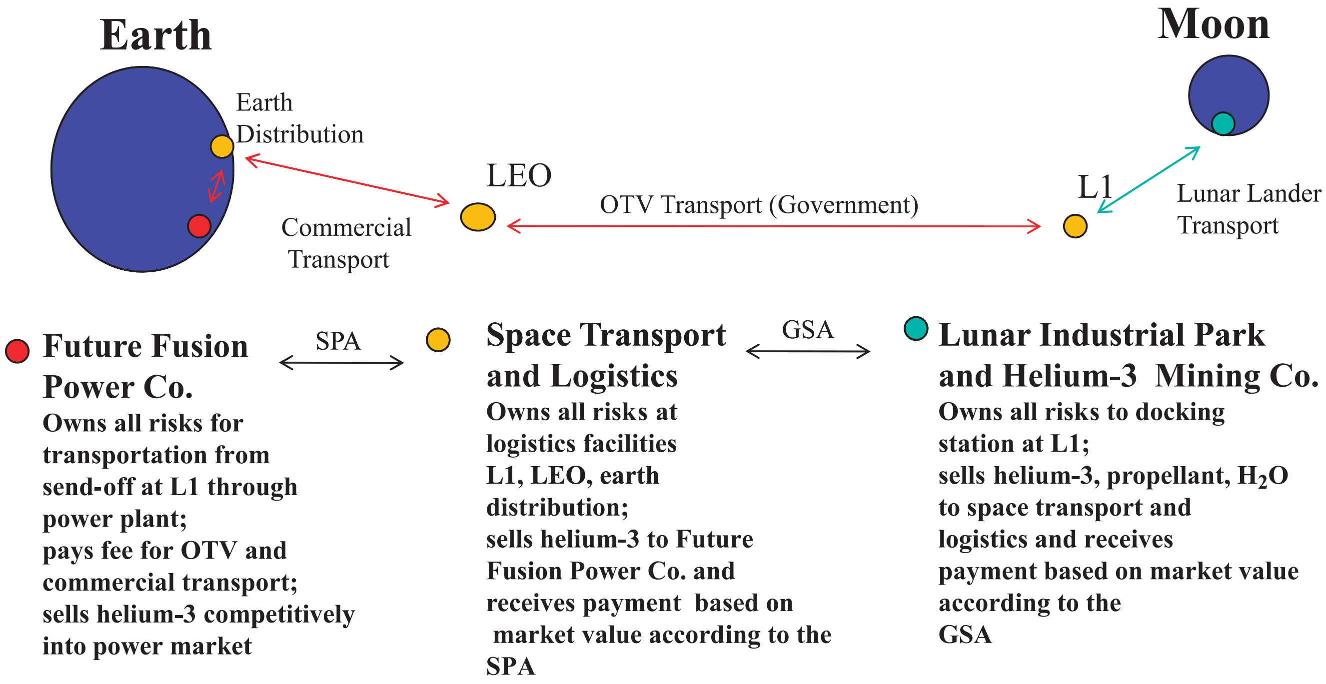


FIGURE 2. Business concept, logistics, contracts, risk distribution, and netback pricing of helium-3 value chain. LEO = low Earth orbit; OTV = orbital transfer vehicle; SPA = sales and purchasing agreement; GSA = gas sales agreement.

The payload water, propellants (LOX, LH2), and helium-3 would be transferred via a Constellation Altair-type lunar lander to L1, which would serve as a distribution center in space. All payload would be stored here in small quantities and then delivered to LEO or to other Lagrange point locations in space. The development of in-space cryogenic refueling and transfer technology would greatly enable such a facility. If water and propellants could be produced in large quantities on the lunar surface, then their distribution to LEO could significantly lower lifting costs for propellant from Earth's surface to LEO. Because the Moon has only one-sixth of Earth's gravity, such a propellant processing facility would have a competitive advantage in lifting costs, hence, could also serve other locations in space.

Transportation of payload (helium-3, propellant, water) between L1 and LEO would be in an OTV. Such a vehicle could be part of a larger government-owned fleet of transporters that serve also other points in space (e.g., L2 or Earth-Sun Lagrange points or farther destinations, e.g., Mars). Such OTV transport would greatly benefit from the development of in-space restartable engine development. Commercial vehicles will provide transportation service for helium-3 from LEO to a distribution terminal on Earth.

The legal ownership of helium-3 would transfer from the mining company to the trading company at the docking facility of the storage facility at L1. Any buyer would purchase helium-3 at this station. The delivery of liquid helium-3 would be free on board (f.o.b.). The ownership would then transfer at the send-out station of L1 to the buyer. The buyer would charter the government-owned OTV for transport to LEO and would charter a commercial transporter from LEO to Earth. The buyer would pay a user fee for the L1–LEO and LEO–Earth transport. Although the mining company will bear all risks to the docking station at L1, the trading company would bear the risks for all operations at L1, LEO, and the Earth-based distribution center. The buyer would bear all risks for transportation from L1 to the end-user facility.

Pricing of the helium-3 would be based on a netback price scenario, whereby the fusion power plant would sell its electricity on a competitive basis into the market and the trading company and then the mining company would share in the market-driven price volatility via a predetermined pricing formula.

Legal entities would be established such that Joint Ventures would be formed to operate the Lunar Industrial Park and Helium-3 Mining Company and the Future Fusion Power Plant Co. This would require complex negotiations of a shareholder agreement (SHA) for both of these joint ventures before a final investment decision (FID) can be made and a contractor has been selected to manage the engineering, procurement, and construction (EPC) stage for these two phases. Simultaneously, the sales and purchasing agreement between the power plant and the trading company needs to be finalized, and a gas sales agreement must be in place between the trading company and the mining company.

Arriving at binding contractual arrangements along the value chain will be a lengthy process. The potential for project delay is high because of the immense project complexity, the high degree of technical innovation, political involvement regarding jurisdiction, ownership and potential misuse of lunar access and mining rights, possible lack of precise project definitions that might lead to change orders, faulty executions, and type and multitude of ownership that could lead to misalignment of shareholders and even diplomatic incidents.

Hence, development of an integrated master schedule for the entire value chain would be immensely difficult because different types of industries would have to align their production processes. Actual manufacturing of individual components at various international locations could lead to execution problems of the schedule. Cost growth and schedule delays are linked because solving technical obstacles could lead to increased resource needs, that is, increasing costs and, in reverse, higher costs for labor and materials can lead to a schedule delay because schedules will be slowed down to match approved budgets. Hence, managing cost, schedule, and quality of performance will be a very challenging task.

Resource Pyramid: Perspective of an Energy Transformation

The oil age is now 150 years old, beginning with its discovery in Pennsylvania in 1859. It took a century to surpass coal as the world's largest energy source and nearly another 50 years for natural gas to have a sizable function in the world's energy mix.

Now, petroleum is the benchmark for all forms of energy. It is the measure in terms of versatility, cost, ease of transport, storage, and development of backstop technology. Unconventional energy solutions are being measured against this energy paradigm, facing acceptance barriers in terms of performance, cost, safety, and environmental and social concerns. Complexities of new technologies, the enormous scale of the global energy market, and governmental policies result in long time horizons for energy transformation.

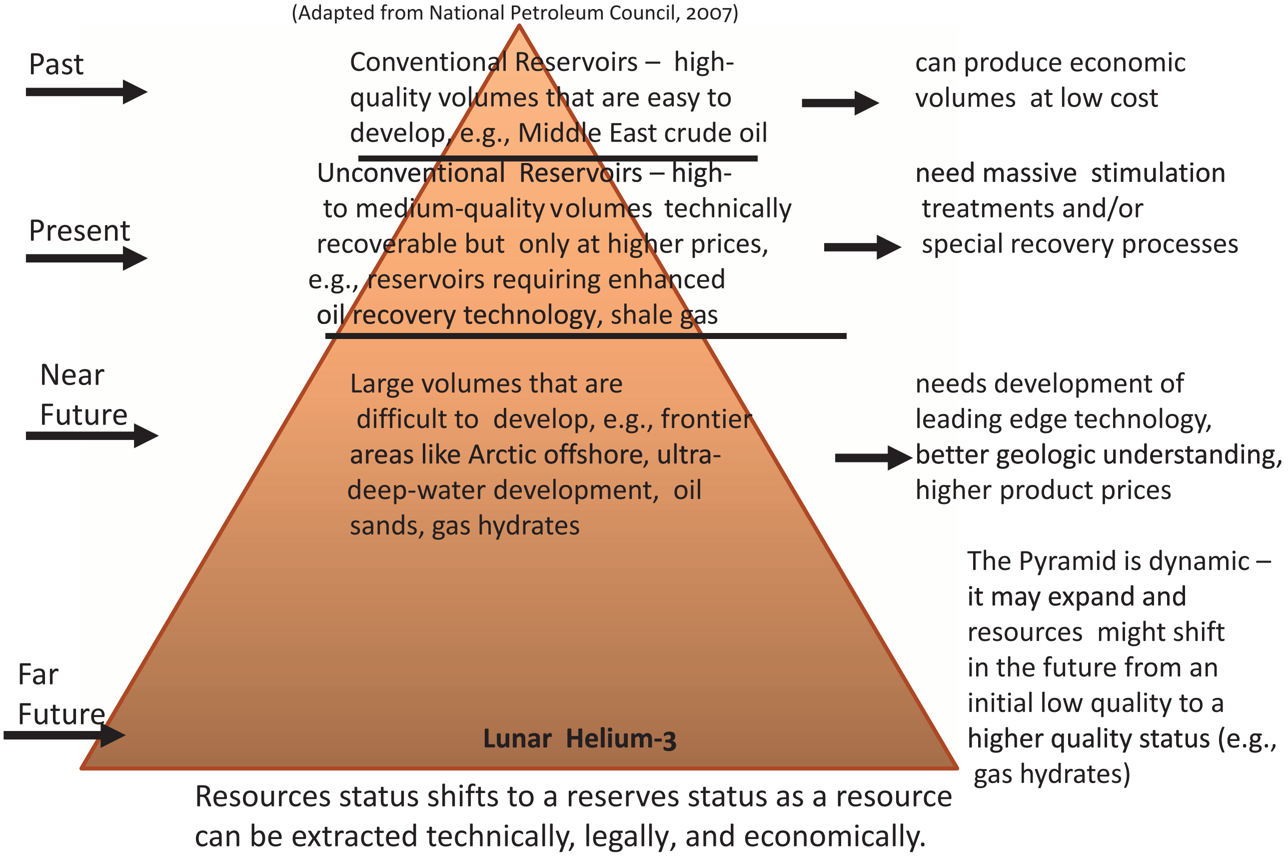
The sheer existence of a vast resource, like Mare Tranquillitatis, does not ensure its development. To translate such resource into an actual reserve base, that is, its legal, technical, and economically feasible development, requires that a market for such a resource exists that can pay for its extraction. The relative value of such a resource can be illustrated by means of the resource pyramid (Figure 3), where resources at the very top are valued much higher (because of higher quality and lesser costs) than resources farther down the slope or even at the very broad base.

Technology developments and economic attractiveness shift the dynamic momentum within the pyramid over time; hence, previously uneconomic and technically challenged resources become reserves. In 1860, oil in Titusville, Pennsylvania, was at the top of the resource pyramid, followed by Spindletop, East Texas in 1901, whereas at that time, the Middle East, the world's current most prolific oil region, would be ranked at the bottom. Now, this picture is reversed because the Middle East is at the top and Titusville and Spindletop are lower in the pyramid.

Resource companies are investing in reserve potential near the top of the pyramid and invest in technology development for relative near-term production. Hence, energy companies are not afraid to invest, for example, US $136 billion in the technically and geopolitically challenged Kashagan oil field in Kazakhstan. In terms of Btu value, this field would yield 1054 containers, each filled with 100 kg of helium-3 (assuming 10 billion bbl of recoverable reserves out of 38 billion bbl of oil in place). This would be equal to a two-year supply of supply of helium-3 for 500 nuclear fusion power plants, that is, one twenty-fifth of a Mare Tranquillitatis development.

Ranked at the bottom of the resource pyramid, like lunar helium-3, are unconventional gas hydrates. Simple CH_4 hydrates concentrate methane volumetrically at a factor of 164:1 in comparison with standard temperature and/or pressure conditions (Moridis et al., 2008). The estimated worldwide resource potential ranges from 0.9 to 40 $\times$ 10^{17} scf and could possibly be two orders of magnitude larger than conventional gas reserves (Sloan et al., 2009). This would, at maximum, yield almost 73 million containers, each filled with 100 kg of helium-3 or, at minimum, 1.6 million containers of 100 kg helium-3. This shows the enormous resource potential for gas hydrates, yet, they are not considered reserves mostly because of significant technological challenges. A Mare Tranquillitatis development would result in 25,000 containers of 100 kg helium-3.

Aside hydrocarbon developments, lunar helium-3 would also have to compete with alternative technology developments because governments are reprioritizing



(Adapted from National Petroleum Council, 2007)

FIGURE 3. Resource pyramid.

their energy supply. Portugal already has embarked on a US $22 billion program to develop alternative renewable energy that now provides 45% of the energy supply (up from 17% in 2004). All costs will be carried by the private industry but fueled by lucrative government incentives (Rosenthal, 2010). Such a US $22 billion investment represents just 56% of the US $39 billion investment in technical RD&D, as estimated for nuclear fusion development.

Portugal's restructuring was driven by the dearth of domestic resources and the related high costs for imports. For comparison, in 2008, the United States imported 9,756,000 bbl of oil/day at an average estimated landed cost of crude imports of 93.30 per bbl (Radler and Bell, 2009), which translates into a value of US $332 billion for 2008 crude imports alone. This value is more than twice the estimate for the Constellation program and 30% higher than the suggested unrisked US $252.6 billion RD&D costs for a lunar mining operation.

Such data show that the industry's interest in a lunar mining operation would be delayed with successful technology development for more easily extractable hydrocarbon resources and alternative technology development. The time value of money would clearly favor such investments that provide earlier returns than a lunar venture.

CONCLUSIONS

The value of such a lunar helium-3 mining project would reside in the business assumption of the need for adequate long-term energy supply for increasing energy needs. The IEA estimates that by 2050 (International Energy Agency, 2008), US $21.9 trillion will be needed on energy investments, of which 24% will be on oil, 19% on gas, 3% on coal, 1% on biofuels, and 53% on electricity. To what extent lunar helium-3 could be funded (privately or publicly) would mostly depend on the success of an ITER-type exercise. Without a comfortable understanding of the scientific concept of continuously controlling and confining a nuclear fusion reaction and finding accompanying engineering solutions, no funding could be expected for a lunar helium-3 mining operation and the related needed space technology.

A workshop on research needs for magnetic fusion (U.S. Department of Energy, Office of Fusion Energy

Sciences, 2009, p. 5) concluded that "the worldwide fusion community broadly agrees that the science has advanced to the point where an aggressive action plan, aimed at the remaining barriers to practical fusion energy, is warranted. At the same time, and largely because of its scientific advance, the program faces new challenges; above all, it is challenged to demonstrate the timeliness of its promised benefits." Demonstrating such benefits will take time, and it is the time value of money, as the resource pyramid demonstrates, that might favor the development of other alternatives.

The pursuit of space infrastructure development based on the flexible path strategy would not be affected by lack of progress in fusion technology. The development of enabling technologies such as cryogenic refueling in space restartable engines and the development of Lagrange point infrastructure would progress independently from any lunar mining endeavor.

Energy resource development would also be independent from any potentially targeted year for fusion technology commercialization (e.g., year 2050). At the end of 2008, BP (BP Statistical Review of World Energy, 2009) estimated that the proved R/P for coal was 122 yr (826,001 million tons); for natural gas, 60 yr (6534 tcf); and for oil, 42 yr (1258 billion bbl, excluding Canadian oil sands). Such numbers do not include technology developments in each individual resource like the recent shale-gas development breakthrough that will considerably increase the R/P for natural gas.

Furthermore, large geographic areas have yet to be opened up for mineral extraction, but resource companies are barred from any exploration/extraction activity by legal means, such as mining and hydrocarbon development in the Antarctic (Beike, 1990, 1993) or ocean mineral resources. In both of these cases, even after lengthy negotiations concerning their mineral resource development, no binding mineral's regime was negotiated and no active mineral extraction regime was agreed to by the international community. Instead, in case of the Antarctic, a moratorium on mining entered into effect in 1998 that bans all mining activities in Antarctica until 2048. In case of the use of the world's oceans, rights and obligations were addressed during the Law of the Sea negotiations of the third United Nations conference (UNCLOS III), lasting from 1973 until 1982. The regulations established guidelines for businesses, environment, and management of marine natural resources. The UNCLOS III came into force in 1994 (after the 60th nation ratification). Most of the nations have ratified this convention; however, some (among them the United States) have signed, but not yet ratified, and others have not signed at all. However, it remains unclear to what extent the convention codifies customary international law, particularly with part XI of the convention, which provides for a regime relating to seabed minerals outside the exclusive economic zone of any country, as it provides for exploration and mining and royalty collection.

The Moon, if considered common heritage of mankind, faces similar ramifications concerning resource extraction. As these two examples demonstrate, negotiations on the legal framework for a lunar mineral regime should start early before any significant minerals will be detected on the Moon. It took 21 years for the Law of the Sea to be ratified, and no Antarctic mineral regime is in place, pointing to a lengthy negotiation phase between nations for a lunar mineral's regime.

In summary, before a clear business case for mining helium-3 on the Moon for terrestrial use in fusion nuclear reactors can be made, mankind will need to take very many small steps to overcome the enormous risks and uncertainties to achieve the ultimate reward.

ABBREVIATIONS

JET = Joint European Torus
TFTR = Tokamak Fusion Test Reactor
NIF = National Ignition Facility
ITER = International Thermonuclear Fusion Experimental Reactor
LNG = liquefied natural gas
FID = final investment decision
OTV = orbital transfer vehicle
LEO = Low Earth orbit
ISS = International Space Station
R/P = reserve-to-production ratio
RD&D = research, development, and demonstration
IFMIF = International Fusion Material Irradiation Facility
NBP = National Balancing Point
f.o.b. = free on board
SHA = shareholder agreement
EPC = engineering, procurement, construction
OCS = outer continental shelf
CGR = cost growth risk
EPRI = Electric Power Research Institute
D-T = deuterium-tritium
He-3 = helium-3
CBO = Congressional Budget Office
C/SMs = command/service module
DEMO = demonstration fusion power plant

IEA = International Energy Agency
LCROSS = Lunar CRater Observation and Sensing Satellite
NASA = National Aeronautics and Space Administration
R&D = research and development
UNCLOSS III = Third United Nations Convention on the Law of the Sea
WMAP = Wilkinson Microwave Anisotropy Probe

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