Comparative analysis of human settlements on the Moon and Mars

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Summary

Both the Moon and Mars have been on spacefaring nations' radars for the past several decades, with NASA shifting back-and-forth between the two destinations, it seems, almost every time Washington leadership changes. But what *are* the differences between the two worlds with respect to long-term human settlement? Is one superior to the other? SpaceVault invited Emerging Futures to answer this question quantitatively, considering multiple aspects of human life support and the needs of a self-sufficient technological society in space. Results are summarized in a companion infographic at http://spaceeconomy.spacevault.world/moonvsmars, and presented in detail below.

We find that the Moon could sustain a human surface population of 50,000, and provide exports of inorganic materials (metals, glass, solar photovoltaics, etc.) sufficient for 173 million people living in space or on other solar system bodies. For Mars, we find that its much larger water resource could sustain a human population of 25 million, along with exports of inorganic materials for 77 million people, and organic materials (water, air, food, hydrocarbons) sufficient for 250 million people. We place stringent limits on land areas that would be covered by solar photovoltaics, and require the limited water resource on the Moon to last at least 8,000 years. (For Mars, with a water resource ~1 million times larger, the limiting factor is power, not water.) Limited carbon and nitrogen resources also severely limited the Moon's ability to provide exports of organic materials, so these were instead provided entirely from Mars. The energy requirements to power surface settlements and export manufacturing on the Moon and Mars were 1.3 TW and 4.0 TW, respectively, equivalent to 11% and 32% of current power consumption on Earth. We estimate that with these levels of power generation and resulting industrial capacity, the annual Gross Interplanetary Product (GIP) of the Moon and Mars could be $8 trillion and $24 trillion, respectively, with an additional $51 trillion from in-space activities. By comparison, Earth's Gross World Product was $76 trillion in 2015 (CIA, 2015).

Physical characteristics

Both the Moon and Mars are smaller than the Earth, but the Moon is about half the diameter of Mars, which itself is 53% of Earth's diameter. Therefore, given that oceans cover 71% of Earth's surface, the area of Mars is about equal to the land surface of Earth, while the Moon's surface area is about a quarter that of Earth's land surface. Both are rocky worlds with similar elemental compositions of surface regolith, though there are some differences, such as Mars having relatively more iron, sodium, sulfur, carbon and nitrogen, whereas the Moon has more calcium, aluminum and titanium. Both have plentiful amounts of silicon, oxygen and magnesium. Mars also has much more water than the Moon. The surface gravity of the Moon is 0.165 times that of the Earth, whereas it is about twice as large (0.376 times Earth) on Mars. These differences mean that less energy is required to leave the surface, and less material is required to build strong structures.

The Moon's rotation is tidally locked to the Earth, so its "day" and "year" are the same: about 27.3 Earth days. This will make things challenging for people living on the Moon, but they will likely be tied to Earth's schedule, and mainly living underground with artificial lighting anyway, so it may not make as much of a difference to human rhythms as expected. Mars, by contrast, has a rotation rate of 24.66 hours, so its "day" is almost the same as Earth's, but the Martian "year" is 1.88 Earth years. People living on Mars would likely adapt to the local rhythm, slowly slipping out of sync with people on Earth (Earth and Mars clocks would line up every ~37 Earth days).

The Moon also lacks any substantial atmosphere, whereas Mars has a thin atmosphere (~1% of Earth's) that is 96% CO_2, and ~2% each nitrogen and argon. The Martian atmosphere offers little protection from ultraviolet or cosmic rays, however, and both worlds experience a steady bombardment from micrometeorites, so protection of people and surface structures is important. Also, neither world has a magnetic field, so solar charged particles are free to impinge upon the surface, causing damage (but also embedding light molecules in the surface over geologic time, which is why the Moon has any carbon or nitrogen at all).

Because both worlds are basically airless, they will require pressurized buildings and vehicles for all human activities, as well as protection from both solar ultraviolet rays, space radiation and micrometeorites. The Moon and Mars endure similar levels of micrometeorites, and a significant fraction of 60 to 1200-μm diameter particles probably survive entry into Mars' atmosphere (Flynn and McKay, 1990). While the vast majority of micrometeorite threats are from very small particles, necessitating protective layers on clothing, equipment and habitats, there is a finite risk of impact from larger particles capable of causing significant destruction. According to a recent study of the lunar surface (Speyerer et al., 2016), the risk of a 1 m^2 disturbance from a micrometeorite impact is 1 in 25,000 years, so a 1,000 m^2 facility would on average incur one such impact every 25 years.

Because it is so near the Earth, the Moon receives the same amount of solar energy as the Earth—more, even, since there is no atmosphere to block it. By comparison, Mars is an average of 1.52 times as far away from the Sun and therefore receives less than half as much solar energy as Earth. See Table 1.

Table 1. Physical characteristics of the Moon and Mars

	Moon	Mars
Area	37,936,695 km^2	144,371,391 km^2
Fraction of Earth's land mass	26%	97%

Period of rotation (length of day)	27.3 days	24.66 hours
Period of revolution (length of year)	27.3 days	1.88 years
Axial tilt	5°	25°
Gravity (relative to Earth)	0.165	0.376
Average distance from Earth	384,400 km	227,950,000 km
Average one-way light travel time	1.3 s	3 to 22 min
Average one-way rocket travel time	~3 to ~7 days	~3 to ~9 months
Atmosphere	Negligible	~1% of Earth, mainly CO_2 with some N_2, Ar
Regolith	Rich in O, Si, Al, Fe, Ca, Mg, Ti (all >1%)	Rich in O, Si, Al, Fe, Ca, Mg, Na, S (all >1%)
Sunlight in space (relative to Earth)	100%	43%
Micrometeorite environment	Similar conditions on both worlds	

Getting there and back

Light takes ~1.3 seconds to travel from Earth to the Moon, whereas it can take anywhere from 3 to 22 minutes from Earth to Mars, depending on planetary alignment. Rocket travel times from Earth to the Moon is ~3 to ~7 days, versus ~3 to ~9 months to Mars, depending on planetary alignment and departure velocity. SpaceX hopes to send cargo and, eventually, people to Mars with a 3-4 month travel time (SpaceX, 2017), so we use this as our estimate.

Getting from Earth's surface to low Earth orbit (LEO) requires a powerful rocket (e.g., SpaceX Falcon 9, Falcon Heavy, or ITS booster), a high-thrust velocity change (delta-v) of ~9.5 km/s, and is the departure point for virtually any other Solar System destination. Starting from LEO, reaching the Moon's surface requires an additional delta-v of ~5.7 km/s. Likewise, reaching the surface of Mars requires a delta-v of ~6.0 km/s (assuming a 3-4 month trajectory per SpaceX's announced plans, capture and braking using Mars' atmosphere, and a propulsive landing). The much longer duration of a trip to Mars, however, would require more supplies for a human crew, reducing the non-consumable payload size relative to a trip to the Moon. For Mars, a heat shield would also be required that increases its total mass, but returning to Earth from either destination would require a similar heat shield, so this may not be a significant differentiator. In principle, therefore, the same spacecraft could be used to reach either destination.

The required delta-v to return from the Moon to Earth would be ~2.6 km/s, assuming Earth's atmosphere is used for braking, and parachutes for landing. For Mars, getting into an Earth transfer orbit would require ~5.9 km/s (assuming minimum-energy transfer orbit and average Earth-Mars alignment conditions), with almost no additional delta-v to land on Earth. So while the propellant requirements of reaching the two destinations are about the same, the return requirements are quite different. See Table 2.

Table 2. Approximate delta-v budgets for Moon and Mars (km/s)

	Moon	**Mars**
Outbound		
Earth surface to LEO	9.5	
LEO to transfer orbit	3.1	4.8 (3-4 month trajectory)
Transfer orbit to low orbit	0.9	1.2 (atmospheric capture, braking; propulsive landing)
Low orbit to surface	1.7	
Total from LEO	5.7	6.0
Return		
Surface to low orbit	1.7	3.8 (with atmospheric drag)
Low orbit to transfer orbit	0.9	2.1
Transfer orbit to Earth	0.0 (atmospheric braking; parachute landing)	0.0 (atmospheric capture, braking; parachute landing)
Total to Earth	2.6	5.9
Surface to Lagrange point*	**2.55**	**5.1**

* For Moon, assume Earth-Moon L1/L2; for Mars, assume Sun-Mars L1/L2.
Sources: Greenblatt (2016); SpaceX (2017), Wikipedia (2017).

In our analysis, we focus on export of large amounts of material from both worlds into space, so use different delta-v requirements. For the Moon, we assume a delta-v of 2.55 km/s to reach the Earth-Moon L1/L2 Lagrange points, convenient destinations for aggregation and utilization of space resources from many locations, and almost the same delta-v as returning to Earth. For Mars, without a large satellite like the Moon and with potential commercial domain of the entire asteroid belt as well as cislunar space, a more useful destination are the Sun-Mars L1/L2 Lagrange points with delta-v requirements of ~5.1 km/s, approximately the same as Mars escape velocity, or slightly lower than entering an Earth transfer orbit from Mars' surface.

Chemical rocket propellants include liquid hydrogen/oxygen (H_2/O_2) and "subcooled" (nearly frozen) liquid methane/oxygen (CH_4/O_2). To make both propellants requires water, and, for

CH_4/O_2, CO_2. While H_2/O_2 has superior mass efficiency (expressed by a specific impulse or I_{sp} of ~450 s) to CH_4/O_2 (I_{sp} = 381 s in vacuum), there are storage and other advantages to the latter, which why both SpaceX and Blue Origin have chosen that propellant for their next generation engines (SpaceX, 2016; Ferster, 2014). The ample CO_2 in Mars' atmosphere allows CH_4/O_2 to be made fairly easily, but the lack of much carbon (in any form) on the Moon makes H_2/O_2 a far easier prospect. While both the Moon and Mars appear to have large reserves of water, the amount on the Moon (~2.9 billion tons; Crawford, 2015) is dwarfed by much larger estimates for Mars (~2.4 million billion tons; Smith et al., 1999).

We have done calculations for a number of lunar scenarios, and have concluded that there is not enough water to sustain long-term export of material in appreciable amounts using H_2/O_2 propellant. Therefore, for the Moon, we embraced an alternative: laser ablation of regolith (surface rock). A number of researchers have pointed out that heating rock to its vaporization temperature using concentrated laser light can result in significant ejection of material and hence thrust. This concept has been explored in the context of redirecting asteroids using remote lasers on Earth or in orbit for planetary defense. But the concept can also be used to launch material into orbit from the surface. Using estimates provided by Lubin et al. (2014), we estimate that for each kg of payload launched from the Moon's surface, about 21 kg of regolith is needed plus ~100 MJ of electricity (assuming it is carried on a spacecraft based on the SpaceX ITS, with the same dry and gross rocket masses as for a CH_4/O_2-based spacecraft). By comparison, to produce CH_4/O_2 propellant from water and CO_2 requires ~85 MJ per kg payload. See Table 3 for a summary of these assumptions.

Table 3. Propellant requirements (based on SpaceX ITS parameters)

	Moon	**Mars**	**Units**
Propellant type	Laser ablation of regolith	CH_4/O_2	
Delta-v (including contingency)	2.71	5.26	km/s
Specific impulse (I_{sp})*	122	375	s
Dry rocket mass	150,000	150,000	kg
Propellant mass	2,149,000	1,826,000	kg
Cargo mass	101,000	424,000	kg
Gross rocket mass	2,400,000	2,400,000	kg
Propellant needed per kg cargo	21.3	4.30	kg
Energy needed per kg propellant	4.8	19.7	MJ
Energy needed per kg cargo	102	84.7	MJ

* For regolith ablation, derived from effective enthalpy of vaporization of SiO_2 (2.4 MJ/kg) and ablative thrust coefficient (500 μN/W) at 10 MW/m^2 (Lubin et al. 2014). For CH_4/O_2, derived from the average of three sea level (361 s) and six vacuum (382 s) Raptor engines (SpaceX, 2017).

Permissible areas and solar power

Nothing in space is possible without power. While we assume a very large scale human and industrial presence on the Moon and Mars, we limit these activities by the area allowed to be covered with solar photovoltaic (PV) panels to 0.1% of the total area. (Nuclear power is another possibility, but would require extraction of uranium from practically all mined regolith, along with large-scale refining, which we felt was beyond the scope of currently envisioned capabilities.) For the Moon, whose visibility from Earth has immeasurable cultural and historic significance, we assume that the entire near-side is off-limits to development (except, perhaps, for some Earth communications or observation equipment that would be invisible to the naked eye and probably most telescopes as well). Thus, the effective solar PV area is limited to 0.05% of the lunar surface, or ~19,000 km^2 (roughly the size of Slovenia). For Mars, we allow 0.1% of the entire surface to be covered, for a total of ~144,000 km^2 (roughly the size of Greece).

As mentioned earlier, solar energy in the vicinity of the Moon (1,368 W/m^2) is much higher than near Mars (592 W/m^2) due to the distance from the Sun. Corrections to these values due to sun angle, diurnal cycle, and dust bring the average surface energy intensity down to 332 W/m^2 on the Moon and 130 W/m^2 on Mars. Including PV cell efficiency and other losses means that total average power available from the permitted areas is ~1,340 GW on the Moon and ~4,000 GW on Mars, as compared to ~11,900 GW of global final energy consumption on Earth in 2012 and ~11 GW of average solar PV output (IEA, 2014); these are projected to grow to ~14,400 GW and ~110 GW, respectively, by 2025 (IEA, 2014; Hill, 2016). See Table 4 for more information.

Table 4. Solar power assumptions

	Moon	Mars	Units
Total surface area	37,936,695	144,371,391	km^2
Fraction of surface covered by solar PV	0.05%	0.1%	
Solar PV area	18,968	144,371	km^2
Solar constant	1,368	592	W/m^2
Cosine losses	50%	50%	
Diurnal cycle	50%	50%	
Dust derating	3%	12%	
Average solar flux	332	130	W/m^2

Efficiency[a]	33%	33%	
Age derating	8%	8%	
Storage losses[b]	30%	30%	
Available power	1,337	3,996	GW

[a] "Power" is treated generically in this analysis and is comprised of a combination of both electrical and thermal energy. Ample waste heat is generated in solar PV cells, some of which can be utilized for thermal applications. Here we assume 20% electrical plus 13% thermal efficiency from incoming sunlight.

[b] Given the assumption of continuous operation, energy stored during the day for nighttime use incurs a ~46% round-trip efficiency loss. Therefore, for every 100 J of energy produced, 35 J are used directly and 65 J are stored, of which 35 J are recovered, resulting in 70 J overall and hence a 30% loss.

Concentrations of materials

We assembled a list of useful elements and their concentrations in lunar and Martian regolith from several sources (Colaprete et al., 2010; Crawford, 2015; NASA, 2012; Neal-Jones and Steigerwald, 2015; Permanent, 2002). See Table 5. Note that concentrations do not necessarily sum to 100% because these represent highest and lowest concentrations found anywhere on the surface. We used these concentrations to estimate the amount of regolith required to produce all desired materials.

Table 5. Concentrations of materials in surface regolith and Mars atmosphere by percentage of total mass

	Moon regolith		**Mars regolith**	
	Low	**High**	**Low**	**High**
Iron (Fe)	4.0%	17.0%	10.88%	17.10%
Calcium (Ca)	7.5%	11.3%	4.29%	5.29%
Silicon (Si)	19.8%	21.6%	20.10%	21.97%
Aluminum (Al)	7.3%	18.0%	4.60%	5.77%
Magnesium (Mg)	3.5%	6.0%	3.98%	5.49%
Titanium (Ti)	0.3%	8.0%	0.42%	0.96%
Oxygen (O)	41.6%	44.6%	51.26%	36.03%
Nickel (Ni)	0.020%	0.020%	0.032%	0.060%

Platinum (Pt) group metals	0.00003%	0.00003%	N/A	N/A
Sulfur (S)	0.050%	0.200%	1.88%	3.04%
Carbon (C)	0.008%	0.017%	N/A	N/A
Hydrogen (H)	0.003%	0.006%	N/A	N/A
Nitrogen (N)	0.004%	0.012%	0.000%	0.025%
Phosphorus (P)	0.05%	0.44%	0.22%	0.52%
Chlorine (Cl)	0.001%	0.005%	0.60%	0.80%
Potassium (K)	0.08%	0.83%	0.25%	0.50%
Sodium (Na)	0.29%	0.31%	1.48%	2.45%
Fluorine (F)	0.0023%	0.0117%	N/A*	N/A*
Helium-3 (^{3}He)	8.00E-10	7.60E-09	N/A	N/A
Uranium (U - all isotopes)	0.0002%	0.002%	N/A	N/A
Water (H_2O)	0.15%	~100%	1.5%	85%
			Mars atmosphere	
Carbon dioxide (CO_2)			96.5%	95.4%
Nitrogen (N_2)			1.90%	2.70%
Argon (Ar)			1.60%	1.90%

*Concentrations of 0.8-2.4% F by mass have been observed in certain surface rocks on Mars (Forni et al., 2015), but estimates of typical global F concentrations have not been established.

The concentrations of water are the most uncertain of all parameters. For the Moon, it varies from 0.15% ubiquitously as solar wind-deposited molecules trapped in regolith (Crawford, 2015) to possibly up to ~100% in permanently-shadowed craters. Other measurements (e.g., by LCROSS) in the southern polar regions indicate concentrations of 2.7-8.5% (Colaprete et al., 2010). The total water resource inferred from LCROSS is estimated to be up to 2.9 Gt in the first 1 m of regolith (Crawford, 2015), which we use as our estimate of the global total, though it could be a large underestimate (or overestimate). For Mars, the Curiosity rover has measured 1.5-3.0% water in regolith, and up to 85% in Utopia Planitia, a region in the northern midlatitudes with an estimated 14,300 Gt (Stuurman et al., 2016). Across the entire planet, there is perhaps 2.4-3.4 million Gt (Smith et al., 1999). We use the lower end of this range as our estimate for the global resource.

Both worlds also have comparatively little nitrogen, though as noted above, Mars contains ~2% in its atmosphere, and while there is also some in Martian regolith (Neal-Jones and Steigerwald, 2015), the atmosphere is probably the easiest source to extract it because large amounts of CO_2 will also be needed. The Moon, by comparison, contains only 40-120 ppm N (as NH_3) in regolith. Recycling of air, food and fertilizer helps to stretch these precious resources, but they are still quite limited.

While ample O_2 would be available on both worlds from the reduction of metal oxides to various metals, perchlorate (ClO_4^-) on Mars, which may be ubiquitous in surface regolith, could also provide O_2 and Cl^- (Davila et al., 2013) with subsequent conversion into Cl_2 for industrial use (see below). Large areas of regolith could be treated this way, removing a significant surface hazard to humans.

Demand for materials

In developing our estimates of material demands, we relied heavily on data from Earth (see sources in Table below). For the most part, we utilized global production or consumption data, but observed that China, with ~20% of the world's population, produces ~50% of the cement, steel, aluminum, glass, chlorine gas, and caustic soda, among other commodities. As a fast-growing economy, China is a good analogy to a space settlement that would grow quickly for several decades to fuel both its own expansion and the export of considerable amounts of material to support space activities. Therefore, we used global per capita production rates scaled to China's population (e.g., multiplied by 5.34, the ratio of world to Chinese population in 2015) to estimate per capita production of basic commodities on the Moon and Mars, and then doubled these to represent the potentially higher growth needed by the harsher conditions of space that could considerably shorten material lifetimes.

For materials more tied to human sustenance, e.g., food, fertilizer, water and air, we relied on different estimates. For food, we used global estimates and did not scale them to China's population; the resulting mass flow (1.33 kg/person/day) is consistent with estimates of dry food requirements (~1.0 kg/day) (Powell et al., 2001; Zubrin and Wagner, 2011), with some extra to be used for animal feed, etc. Fertilizer use was based on global demands for nitrogen, phosphorus and potassium for all purposes, which were then normalized by global food consumption to arrive at scaling ratios of 3.3%, 1.3% and 0.9%, respectively, of food mass consumed. For water, we relied on estimates of water consumption for all uses in water-scarce California (Greenblatt, 2016a), scaled down to reflect greater assumed efficiencies of urban (50%) and agricultural (75%) water use, arriving at 1,100 kg/person/day. (We also assumed a very high recycling rate for water; more on that below). For water exported to space, we assumed a much lower water use of 30 kg/person/day, roughly twice the demand on the International Space Station (NASA, 2000). Air was assumed to be 20% oxygen and 80% inert (nitrogen, argon or some combination) and consumption was 5 kg/person/day, slightly higher than assumed in Powell et al. (2001).

For propellant demands, see Energy section below.

Table 6 shows our assumptions for each basic commodity material along with assumed compositions. Note that concrete, comprised of cement, crushed rock, and water, can also be made with sulfur (Ponnada and Singuru, 2014). However, while water is comparatively scarce on the Moon, we assume so much regolith is mined for exporting materials that only a tiny fraction of the available water is needed for concrete. The same is true on Mars, but in this case, sulfur is under-utilized so we assume 10% sulfur-based concrete there simply to make use of this material.

Table 6. Base demand for commodity materials

Material	**Raw global demand (Mt/yr)**	**Reference demand for Moon/Mars (kg/person/yr)**	**Assumed composition**
Concrete	4,193 (as cement)	20,320	Water-based: 5% water, 15% cement (35.8% Ca, 11.4% Si, 5.5% Al, 3.0% Mg, 44.4% O), 80% raw regolith Sulfur-based: 20.0% S, 12.5% cement, 67.5% raw regolith
Steel	1,615	1,174	99% Fe, 1% C
Regolith for shielding	N/A	20,320 (equal to concrete demand)	Raw regolith
Glass	70.4	51.2	3.6% Ca, 28.5% Si, 5.6% Al, 7.8% Mg, 54.5% O
Aluminum	58.3	42.4	99.97% Al, 0.07% F (lost)
Plastic	322	234	85.6% C, 14.4% H
Gypsum (wallboard)	84.0	61.1	23.3% Ca, 37.2% O, 18.6% S
Solar PV	~8	Based on energy needs (see below): 303,500 (Moon) 4,550 (Mars)	Moon (no plastics): 8.9% Fe, 2.3% Ca, 24.5% Si, 23.6% Al, 5.1% Mg, 35.4% O, 0.1% C Mars (some Mg for Al): 9.1% Fe, 2.2% Ca, 23.5% Si, 11% Al, 10.9% Mg, 33.2% O, 8.8% C, 1.4% H
Wood	1,040	756	50.0% C, 6.0% H, 42.0% O, 0.2% Fe, 0.2% Ca, 0.2% Mg,

			1% N, 0.2% K, 0.2% K
Chlorine gas	70.0	50.9	100% Cl
Sulfuric acid	258	187	2.0% H, 32.7% S, 65.3% O
Caustic soda	79.0	57.4	40.3% Na, 56.2% O, 3.5% H
Nitrogen	151	20.6	100% N
Phosphorus (as P_2O_5)	50.6	6.9	43.6% P, 56.4% O
Potassium (as K_2O)	35.8	4.9	83% K, 17% O
Breathing air	N/A	1,825	Moon: 20% O, 80% N Mars: 20% O, 47% N, 33% Ar
Potable water	N/A	400,000 (surface) 11,000 (space)	100% H_2O
Food	3,510	486	40.0% C, 6.7% H, 52.3% O
Surface transport propellant (as crude oil)	4,583	2,978	Moon (H_2/O_2): 11% H, 89% O Mars (CH_4/O_2): 15% C, 5% H, 80% O

Sources: Bray, 2016; Delvin, 2016; FAO, 2015, 2017; Freedonia, 2017; Grand View Research, 2016; IHS Markit, 2014; Johnston, 2017; Merchant Research & Consulting Ltd., 2013; Portland Cement Association, 2013; Statista, no date; World Steel Association, 2017 and others.

Building from these demands, we then applied several correction factors. Structural materials (concrete, steel, aluminum, wood) were scaled downward based on the lower gravities on the Moon and Mars. Not all structural materials are load-bearing, so we were conservative and used a 75% reduction for the Moon and 50% for Mars, instead of scaling based solely on gravity.

Solar PV: The total demand for surface solar PV was governed by available land area, given that we optimized our model for ~100% utilization. Therefore, the mass of solar PV panels was found from the maximum PV area times the mass per m^2 estimated from life-cycle analysis (Fthenakis et al., 2011) of ~20 kg/m^2. The elemental breakdown was also obtained from this study, which is comprised of 6% Si, the rest being structural (aluminum, glass, plastic) or used in processing (e.g., steel wire for cutting). With these inputs, plus an assumed 25-year panel lifetime, the demand was estimated at 303,500 kg/person-year on the Moon (due to exports comprising >99.9% of total manufacturing) and 4,550 kg/person-year on Mars (where exports are ~75% of total production).

Recycling was another important consideration. Particularly for precious commodities such as water, carbon and nitrogen, we assumed high recycling rates to conserve materials. While state-of-the-art water recycling today is >98%, we assumed that the need to conserve as much water as possible, at least on the Moon, would drive the use of technology with 99.5% recovery eventually. Recycling of elements in food (e.g., solid waste) and breathing air was assumed to be 97%. For surface transport on the Moon using H_2/O_2, a 90% recovery rate was assumed using storage tanks to capture the product water, but on Mars with CH_4/O_2, where both water and CO_2 products are plentiful, no such recycling was assumed.

Aluminum (Al) production requires aluminum trifluoride (AlF_3) for processing, but fluorine (F) is a rare element in lunar regolith (≤0.01% by mass). Concentrations in Martian regolith have not yet been established (see Table 5 footnote) but are probably also low. Terrestrial Al production typically loses ~14 g F per kg Al produced through reaction with sodium oxide (Na_2O) impurities and volatilization as hydrofluoric acid (HF) and sodium aluminum tetrafluoride ($NaAlF_4$) gases, 98% of which are recycled (Kvande and Drabløs, 2014). If such loss rates were incurred on the Moon, consumption of F would dominate surface mining requirements. Therefore, we assume significant improvements in the F recycling rate (99.9%), sufficient to replenish F losses with lunar regolith concentrations found along with Al.

Terrestrial Al production currently uses carbon (C), another rare element in lunar regolith (0.01-0.02% by mass) as consumable anodes, with 0.4 kg C lost (as CO_2) per kg Al produced. However, driven by economics as well as the desire to reduce CO_2 emissions, terrestrial companies are developing inert anodes based on cermets (metal oxide/metal composites) that are made from iron (Fe), nickel (Ni), copper (Cu) and possibly silver (Ag) (Davis et al., 2010; Kvande and Drabløs, 2014). While Fe is abundant on both the Moon and Mars, and Ni is present at modest concentrations (0.02% on Moon, 0.03-0.06% on Mars), Cu and Ag are less so; however, the existence of platinum (Pt)-group metals on the Moon at abundances of 0.3 ppm (Crawford, 2015) suggests that other elements, with much higher abundances on Earth, would be present also. For instance, Cu has a terrestrial crustal abundance of 0.007%, just below that of Ni (0.009%) and ~1,800 times higher than that of Pt, while Ag's terrestrial abundance is ~2x that of Pt (http://periodictable.com/Properties/A/CrustAbundance.html). We expect inert anodes would be used on the Moon and probably also Mars, though the abundance of CO_2 in its atmosphere does not foreclose the use of carbon anodes there.

For all other materials, a 10% recycling rate was assumed, given that the large growth rates would require little need for recycled materials, except to replace worn-out components. See Table 7.

Table 7. Recycling rates assumed for materials

	Moon	**Mars**
Potable water	99.5%	99.5%
Food, fertilizers and breathing air	97%	97%

Surface transport propellant	90%	0%
Fluorine in aluminum production	99.9%	99.9%
All others	10%	10%

A waste factor of 10% was also applied to all materials, acknowledging imperfect processing.

Finally, because of the very limited amounts of C on the Moon, steel (which requires Fe with ~1% C to manufacture) was largely replaced by Al and magnesium (Mg), two metals plentiful in regolith whose lower strengths could be compensated for with larger volumes of material, as regolith abundances permitted. (In practice, alloys of these metals would probably be used to improve their mechanical properties, but we have not explored these.) The ratios of masses of material required to achieve similar performance in bending can be found with the following simple relationship, derived from standard engineering equations (Engineering Toolbox, 2017):

$$M_a/M_b = (\rho_a/\rho_b)(Y_a/Y_b)^{-0.5}$$

Here M_i = mass of material (kg), ρ_i = density of material (kg/m^3), Y_a = Young's modulus of elasticity (GPa), and i = material (a or b). We calculated these ratios for steel, aluminum, magnesium, concrete, wood, and carbon fiber, though not all were used in the current model configuration. Table 8 summarizes the assumptions used in our analysis.

Table 8. Scaling relationships for structural materials

Material	**Density (kg/m^3)**	**Young's modulus (GPa)**	**Mass ratio relative to wood**
Steel	7,800	200	3.5
Aluminum	2,700	70	2.0
Magnesium	1,700	45	1.6
Concrete	2,400	17-30	2.8-3.7 (used 3.0)
Wood	500	10	1.0
Carbon fiber	1,550	100-200	0.7-1.0 (used 0.8)

Source: Engineering Toolbox (2017)

<u>Exported materials</u>

We assumed exports of many materials to support activities in space. For the Moon, we assumed exports of structural materials in great excess (3,500x) compared with surface needs, and sufficient solar PV to provide ample energy (see energy estimates below). However, life support materials (air, water, food and fertilizer) as well as plastic were severely limited by supplies of nitrogen, carbon and water, so none was exported.

To compensate for these deficits, exports of these materials from Mars were higher to ensure that supplies in space were adequate when summed between the two worlds. Exports of structural materials from Mars were also in excess of the surface need, but only by ~3x. Exports of raw regolith for shielding was much lower (5%) than its use on the surface, due to the bulky nature of this material, probable availability in space, and the unknown amounts actually needed. Exported CH_4/O_2 propellant was equal to the mass of all other exports, enough to transfer all material with a delta-v of ~2.3 km/s, sufficient to reach the Earth-Moon system with ample propellant to spare for transport of humans, (empty) spacecraft return, etc.

Energy

Energy use was broken into six basic categories: human buildings, solar PV, other industry, potable water, surface transportation, and propellant production. While very crude, it forms the starting point for a more sophisticated energy analysis that could be undertaken in the future.

Human buildings: Because both the Moon and Mars represent much harsher environments than found on Earth, the energy per person required to maintain human comfort is expected to be much higher. We examined several sources, including energy use at scientific bases in Antarctica (Baring-Gould, et al. 2005) and on board the International Space Station (Taranovich, 2014), and determined that a reasonable estimate of energy use on either the Moon or Mars would be about ten times the average U.S. demand, or ~13 kW/person electrical equivalent (note this includes a mix of electricity and heating).

Solar PV: We assumed a manufacturing energy of 150 MJ/kg based on Ecoinvent (2012) and our assumed 20 kg/m^2. We converted to W-yr/kg based on an assumed 25-year lifetime. Note that for exported PV, the same energy intensity was assumed per m^2 but the panel mass was assumed 50% that of surface PV, due to lightweighting and the fact that not all materials (e.g., steel) used in processing were exported, so energy intensity per kg exported was doubled.

Other industry: We began with China’s industrial energy use per person (EIA, 2016) and doubled it to allow for harsher conditions in space. We then divided this energy use by the total materials production on the Moon, not including solar PV, water, propellant or raw regolith (the latter of which was assumed to require negligible energy to mine), to arrive at an energy intensity per kg. This same metric was assumed to scale for Martian industrial manufacturing.

Water melting was estimated from earlier work (Greenblatt, 2016b) separately for the Moon (816 kJ/kg) and Mars (751 kJ/kg) due to different assumed initial temperatures (35 and 120 K, respectively), and treatment from average desalination energy estimates of 4000 kWh/acre-foot

(11.7 kJ/kg). To arrive at a total energy value per kg, the desalination energy was divided by the recycling rate to represent the number of times the water was reused before discarding.

Energy use for surface transportation was based on the U.S. demand for petroleum, which is ~20% of global demand, because it represents a minimum level of affluence expected for space settlement. It is also close to the demand in China if it consumed half the world's petroleum (it currently consumes 13%). This number was normalized by the U.S. population and then multiplied by 5 to include the much greater amount of energy needed to maintain environmental controls inside vehicles, much the same as would be needed inside buildings. The required energy was then converted into an equivalent mass of propellant, assuming H_2/O_2 on the Moon and CH_4/O_2 on Mars. Note that unlike fuels on Earth, oxygen, which dominates overall propellant mass, must be carried along with fuel on airless worlds for combustion to occur.

Energy needed to make chemical propellant is based on the energy required to melt water ice, convert it electrochemically into H_2/O_2 or (along with CO_2) CH_4/O_2, and liquefy it for optimal storage and transport. We assumed efficiencies of 67% for electrochemical conversion and 50% for liquefaction, based on estimates developed in earlier work (Greenblatt, 2016b). For surface propellant on the Moon, the energy estimate includes recycling, so the energy use per kg of propellant is higher. See Table 9 for energy assumptions.

Table 9. Energy use assumptions

	Moon	Mars	Units
Human buildings	13.3	13.3	kW/person
Solar PV (surface)	150 4.76	150 4.76	MJ/kg W-yr/kg
Solar PV (space)	300 9.52	300 9.52	MJ/kg W-yr/kg
Other industry	25.7 0.816	25.7 0.816	MJ/kg W-yr/kg
Potable water:			
Virgin production	0.0262	0.0262	W-yr/kg
Waste treatment per cycle	0.000370	0.000370	W-yr/kg
Total surface use	0.1003	0.1003	W-yr/kg
Surface propellant[a]	28.63 (virgin) 9.08 (with recycling)	18.97 (virgin) 0.601 (no recycling)	MJ/kg W-yr/kg

Rocket propellant[b]	4.80 0.152	19.68 0.624	MJ/kg W-yr/kg

[a] Propellant is H_2/O_2 for Moon and CH_4/O_2 for Mars, assuming stoichiometric O_2:fuel mass ratios.
[b] Propellant is regolith for Moon and CH_4/O_2 for Mars. O_2:fuel mass ratio is 3.8 per SpaceX.

Results

Our model adjusted both the surface and exported human populations to optimize material and energy resources on both worlds. We enforced a water resource depletion rate of <0.02%/yr (e.g., >5,000 year lifetime) as a reasonable sustainability metric. As a result, the surface population on the Moon was limited to 50,000 people, but the number of people supported in space through material exports was limited only by available power, since no water was exported from the Moon. Because of the ample energy resources available from even 0.05% of the Moon's surface, we calculated that it was possible to support ~170 million people.

On Mars, a much higher surface population was permissible (25 million) due to much larger water resources, along with a large space population supported by exports (~80 million). Included in these exports were "organic" materials not available for export from the Moon, so enough air, water, food, plastics and propellant for 250 million people total were exported from Mars. The water depletion rate on Mars was much lower than on the Moon: <0.0001%/yr, or a lifetime of 1.1 million years. Other combinations of surface and space populations were also possible: up to ~50 million people could be supported on the surface (and fewer in space), or ~160 million in space (and fewer on the surface), plus 250 million in organic exports.

The resulting consumption of water, regolith and (on Mars) atmosphere is shown in Table 10, assuming optimistic (maximum) concentrations of all resources. (We made this assumption because we expect detailed prospecting to reveal locations with the highest concentrations for feasible extraction; it is therefore likely that our estimates could be low.) Consumption of key elements is shown in Table 11. Note that consumption of ^{3}He and U are shown merely to illustrate the potential quantities available "for free" along with other elements extracted; they are not currently used in our model. The consumption by material, along with breakdown between surface use and exports, is shown in Table 12 for the Moon and Table 13 for Mars.

Table 10. Supported human populations and consumption of resources

	Moon	**Mars**	**Units**
Human population			
Supported on surface	50,000	25,000,000	people
Supported in space	173,000,000	77,000,000	people
Water			

Direct use on surface	110,000	55,000,000	t/yr
Other surface uses (includes materials produced for export)	254,400	833,900,000	t/yr
Exported directly to space	0	121,500,000	t/yr
Used for propellant	0	1,150,000,000	t/yr
Total	364,400	2,160,000,000	t/yr
Supply lifetime	7,958	1,111,000[a]	years
Regolith			
Surface use (includes materials produced for export)	149,600,000	5,935,000,000	t/yr
Exported directly to space	174,000,000	77,440,000	t/yr
Used for propellant	7,195,000,000	0	t/yr
Total	7,519,000,000	6,012,000,000	t/yr
Surface depth loss	0.239	0.0274	m/yr
Atmosphere (Mars only)	N/A	2,805,000,000	t/yr

[a] Water supply lifetime for Utopia Planitia alone (14,300 Gt) is 6,619 years.

Table 11. Consumption rate of key elements and fraction of resource consumed

	Consumption rate (t/yr)		**Fraction consumed**	
Element	**Moon**	**Mars**	**Moon**	**Mars**
Fe	6,362,000	80,050,000	7.5%	96.8%
Ca	844,200	16,940,000	1.49%	66.3%
Si	7,961,000	37,040,000	7.3%	34.9%
Al	90,000,000	27,900,000	99.5%	100.0%
Mg	30,140,000	26,480,000	100.0%	99.8%
O	12,680,000	1,619,000,000	5.7%	27.8%
S	3,593	7,780,000	0.4%	52.9%
C	79,180	730,300,000	93.3%	100.0%

N	2,537	7,861,000	4.28%	10.4%
Ar	N/A	5,631,000	N/A	10.6%
Cl	2,519	1,259,000	10.0%	32.6%
F	57,180	7,390	97.3%	N/A
Pt group metals	106	N/A	100.0%	N/A
^{3}He	3.82	N/A	100.0%	N/A
U - all isotopes	10,050	N/A	100.0%	N/A

Table 12. Consumption of materials on the Moon (t/yr)

	Surface use	**Exported**	**Total**
Concrete	251,400	0	251,400
Steel	320	4,424,000	4,424,000
Aluminum	6,087	84,250,000	84,250,000
Magnesium	2,046	28,310,000	28,320,000
Regolith for shielding	1,006,000	174,000,000	175,000,000
Glass	2,533	8,764,000	8,767,000
Plastic	11,590	0	11,590
Solar PV	15,020,000	7,221,000	22,240,000
Wood	9,354	0	9,354
Fertilizers (N, P, K)	53	0	53
Breathing air	3,011	0	3,011
Potable water	110,000	0	110,000
Food	802	0	802
Exported propellant	0	0	0
Surface transport propellant	218,200	0	218,200
Propellant for	7,195,000,000	0	7,195,000,000

exporting materials			
Other materials	17,650	0	17,650
Total	7,212,000,000	307,000,000	7,519,000,000

Table 13. Consumption of materials on Mars (t/yr)

	Surface use	Exported	Total
Concrete	256,200,000	0	256,200,000
Steel	9,590,000	59,070,000	68,660,000
Aluminum	1,521,000	9,368,000	10,890,000
Magnesium	1,461,000	9,002,000	10,460,000
Regolith for shielding	502,900,000	77,440,000	580,300,000
Glass	1,266,000	3,901,000	5,167,000
Plastic	5,793,000	57,930,000	63,720,000
Solar PV	125,100,000	8,129,000	133,300,000
Wood	9,354,000	0	9,354,000
Fertilizers (N, P, K)	26,700	220,500*	247,200
Breathing air	1,506,000	15,060,000	16,560,000
Potable water	55,000,000	15,060,000	70,060,000
Food	400,900	4,009,000	4,410,000
Exported propellant	0	259,200,000	259,200,000
Surface transport propellant	1,553,000,000	0	1,553,000,000
Propellant for exporting materials	2,452,000,000	0	2,452,000,000
Other materials	8,826,000	0	8,826,000
Total	4,984,000,000	518,400,000	5,503,000,000

*Not exported, but used in growing food for export

Gross Interplanetary Product (GIP) estimation

Based on the ratio of final energy consumption on the Moon and Mars of 11% and 32% of Earth, respectively, estimated 2015 global energy production of 12.4 TW (IEA, 2014), and a current annual Gross World Product of $76 trillion (CIA, 2015) on Earth, we estimate the annual GIPs of the Moon and Mars would be $8 trillion and $24 trillion, respectively. However, this does not include the additional energy that would be produced in space from exported PV, which adds another 8.3 TW or $51 trillion.

Considering only surface operations (e.g., excluding exported materials), the energy used on the Moon and Mars is 61 and 69 kW/person, respectively, which translates into GIP/capita of $370,000 and $420,000. Combining the energy used for exports from both the Moon and Mars (including the propellant needed for transport), in-space populations require 14.5 kW/person, and exported solar PV capacity adds another 33 kW/person, bringing the total to 48 kW/person. Therefore, in-space GIP/capita is estimated at $290,000. Total average GIP/capita is $303,000.

Note that ULA (2016) recently shared their vision of a partially self-sustaining economy, with 1000 people living and working in cis-lunar space in 30 years. They estimate a “gross space product” of such an economy at $2.7 trillion, several orders of magnitude larger per person than we estimate here. Therefore, our numbers may likely be large underestimates.

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