Autonomous Robot Teams for Lunar Mining Base Construction and Operation

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Abstract— **There is growing interest in expanding beyond space exploration and pursuing the dream of living and working in space. The next critical step towards living and working in space requires kick-starting a space economy. One important challenge with this space-economy is ensuring the ready supply and low-cost availability of raw materials. The escape delta-v of 11.2 km/s from Earth makes transportation of materials from Earth very costly. Transporting materials from the Moon takes 2.4 km/s and from Mars 5.0 km/s. Based on these factors, the Moon and Mars can become colonies to export material into this space economy. One critical question is what are the resources required to sustain a space economy? Water has been identified as a critical resource both to sustain human-life but also for use in propulsion, attitude-control, power, thermal storage and radiation protection systems. Water may be obtained off-world through In-Situ Resource Utilization (ISRU) in the course of human or robotic space exploration. The Moon is also rich in iron, titanium and silicon. Based upon these important findings, we plan on developing an energy model to determine the feasibility of developing a mining base on the Moon. This mining base mines and principally exports water, titanium and steel. The moon has been selected, as there are significant reserves of water known to exists at the permanently shadowed crater regions and there are significant sources of titanium and iron throughout the Moon's surface.**

Our designs for a mining base utilize renewable energy sources namely photovoltaics and solar-thermal concentrators to provide power to construct the base, keep it operational and export water and other resources using a Mass Driver. However, the site where large quantities of water are present lack sunlight and hence the water needs to be transported using rail from the southern region to base located at mid latitude. Using the energy model developed, we will determine the energy per Earth-day to export 100 tons each of water, titanium and low-grade steel into Lunar escape velocity and to the Earth-Moon Lagrange points. Our study of water and metal mining on the Moon found the key to keeping the mining base efficient is to make it robotic. Teams of robots (consisting of 300 infrastructure robots) would be used to construct the entire base using locally available resources and fully operate the base. This would decrease energy needs by 15-folds. Furthermore, the base can be built 15-times faster using robotics and 3D printing. This shows that automation and robotics is the key to making such a base technologically feasible. The Moon is a lot closer to Earth than Mars and the prospect of having a greater impact on the space economy cannot be stressed. Our study intends to determine the cost-benefit analysis of lunar resource mining.

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TABLE OF CONTENTS

1. INTRODUCTION

A space economy requires critical infrastructure in Cis lunar space and beyond for humans to live, work and vacation in space. The envisioned infrastructure includes communication relay networks, transport networks, fuel depots, repair and spacecraft assembly stations, storage depots, trading stations, entertainment stations, in addition to habitats for human workers to live and hotels for space tourists. The construction material needed to build this infrastructure all need to be produced off-world. Transporting material off Earth is an expensive proposition, requiring a delta-v of more than 11.2 km/s. In comparison transporting materials from the Moon requires 2.4 km/s and Mars 5.0 km/s.

Thanks to the Apollo missions, we have confirmed that the Moon is nearly identical in composition to Earth (except for water). There is a diverse group of construction materials ranging from silica sand, to iron, titanium, aluminum and copper available to mine. These construction materials in turn can be exported into this 'space economy' to enable construction of the various infrastructure instead of launching all that material from Earth.

Importantly, water has also been found on the Moon. Very large deposits of water are estimated to be buried as ice in the permanently shadowed crater regions of the Moon. Water is as a critical resource that is required for processing all of the construction material identified earlier, in addition it essential to sustain human-life and a near-universal chemical solvent. It has important applications for use in propulsion, attitude-control, power, thermal storage and radiation protection systems. Thus, water is a critical resource because of its multi-functionality. Without water, we will need to rely on unfamiliar, higher-risk 'dry' processes to extract most of the construction material known.

The large deposits of water ice suspected at the lunar south pole may be extracted through In-Situ Resource Utilization (ISRU) processes and refined into useable distilled water. Some of the water is believed to have arrived from ancient meteors and comet impacts. The water is unlikely to be pure and will likely have dissolved minerals including carbonates and sulphates. Sulphates in particular are a concern because they can easily poison high-efficiency electrolyzers that split water into hydrogen and oxygen. Furthermore, it should be noted that the lunar south pole is one of most inhospitable cryogenic environments in the solar system.

For these reasons, it makes senses to extract raw materials from the lunar south pole and transport them further north to a mid-latitude location that is relatively temperate for further processing and transport off the Moon. At a temperate location it will be easier to process the raw water ice into liquid distilled water. At the polar permanently shadowed regions, there is a general lack of sunlight and hence the temperature gets below -150 ^{o}C. At such cryogenic temperature, immense resources are required to keep warm and have mechanical systems operating. Very cold temperatures can result in brittle hardware, cold-welding and freezing of components. Current state of the art battery technology including both lithium ion rechargeable batteries and lithium thionyl chloride primary batteries cannot feasibly operate below -50 ^{o}C due to freezing of the electrolyte which can cause irreversible damage to the battery. The permanent eclipse in these craters almost rules out use of renewable energy. However, concept such as "Transformers" from NASA JPL [30] that utilize reflective mirrors positioned on craters rims to reflect sunlight into the crater bottom could be used to power and keep warm open-pit mining vehicles that would dig out the solid water-ice. Previous concepts for operating on the lunar south pole presumed use of radioactive power supplies and RHU (radioactive heating units). Both technologies are limited in supply and cannot use current methods to be scaled up to enable 100s of tons of water ice extraction per day.

The cryogenic temperatures of the lunar south pole are not all bad for technology. At these temperatures it is possible to exploit unique phenomena such as superconductivity to increase efficiency of electrical systems and low-loss power cables, enable next-generation levitated transport (maglev) technology, magnetic steering applications and next-generation particle accelerator technology. Thanks to superconductivity it would be possible to have a high efficiency levitated rail system to transport goods to and from permanently shadowed craters regions. Considering the elements of the levitation system are naturally locked to an 'invisible rail' due to quantum effects, it will be possible to better handle transport over rough terrain, hills, slopes and valleys. Similarly, specialized teams of robotic vehicles operating to excavate water ice in the Permanently Shadowed Regions (PSRs) can exploit the same principle to have critical temperature sensitive components be locked and levitated due to quantum effects. This would shield these components from thermal losses (due to conduction) with the cold ground.

Leading aerospace companies such as United Launch Alliance (ULA), a collaboration between Boeing and Lockheed Martin is willing to buy water from any entity in space (in Low Earth Orbit, Geostationary Orbit and Lunar Orbit). ULA has put forth a plans called "CisLunar 1000" (Fig. 1) [15] an architecture that foresees nearly 1,000 people working and living in cis-lunar space and the development of communication relays [13-14], service depots, and refueling stations at strategic locations between Earth, Moon and Mars. Our proposed lunar base is compatible with the proposed CisLunar 1000 architecture by ULA.

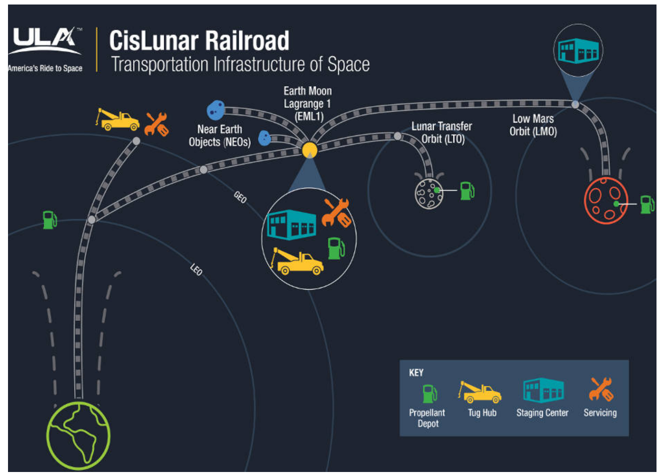

Figure 1. ULA's CisLunar 1000 concept envisions propellant depots, towing centers, staging centers and servicing centers located at strategic location between Earth, the Moon and Mars [15].

In this paper, we present energy models to determine the technological feasibility of developing a base on the Moon that mines and exports water, steel and titanium on a lunar escape trajectory so that a company such as ULA can buy it for its interplanetary transport and service needs. This work is a continuation of our earlier work to develop a Mars Robotic Mining Base to export water [16] and a major update to earlier effort to design a pilot ISRU base from 2008 [5, 6].

The Moon has been selected as water has been found trapped in large quantities at the PSRs of the lunar south pole. In addition, the composition of the Moon is nearly identical to Earth. This indicates there is a diverse source of construction materials and minerals that would be useful for building critical space infrastructure.

Our designs for a mining base (Figure 3) utilize renewable sources of energy from the sun namely photovoltaics and solar-thermal concentrators to provide power to construct the base and keep it operational. This includes power to transport the water (export) at lunar escape velocities using a Mass Driver (electrodynamic railgun) powered using renewable energy. In addition, solar photovoltaics will power a 2000 km superconducting maglev rail system to transport raw, unpurified water ice from the south pole to the main mining base located at the base of a mid-latitude shallow crater region.

Using the energy model developed, we determined that the base requires 1.77×10^7 MJ of energy per day (Earth day) to export 100 tons each of water, low-carbon steel and titanium. 12.1% of the energy obtained from renewable power sources is to power the Mass Driver to export water, titanium and low-carbon steel into a lunar escape velocity. Nearly 78% of the energy is used to power the refineries to process ilmenite into low-grade steel and titanium. Only 9.7 % of the energy is required to excavate resources, transport processed resources and melt the water ice. If the base was occupied by 300 human workers, another 0.43% of the energy would be needed for sustaining life-support, food production and healthy-living.

Our studies found the key to keeping the mining base simple and efficient is make it a robotic base [1-6]. Teams of robots (consisting of 300 infrastructure robots with a mass of 120 kg each) would be used to construct the entire base using locally available resources and operate the base on a daily basis, mining water ice from the lunar south pole, transporting it via Maglev rail transport to the main base, refining it into liquid water and exporting it using a Mass Driver.

Our studies found that a wholly robotic base built using 3D printing using raw natural resources can decrease energy needs by 15-folds compared to a base manned by humans and that uses no 3D printing. Furthermore, the base can be built nearly 15-times faster using robotics and 3D printing. If humans were in the loop, human energy needs overtake nearly-all other energy needs including excavation and surface transport of resources. The only consumers that take up more energy is material refining and transport off the lunar surface. 3D printing and the 'human footprint' is significant when it comes to base construction. The human facilities significantly increase the complexity and negatively impact the overall feasibility of getting a mining base up and running. This shows that automation and robotics is the key to making such a base technologically feasible. The base would benefit from being automated as it would be located in remote off-world locations with daily tasks that are 'dull', 'dangerous' and 'dirty' and so again this is ideal for robotics.

In the following section we present related work, followed by presentation of the base architecture and a representative energy model for both construction and operation of the base in Section 3.0. In Section 4.0, we present simulation results analyzing construction, operation and use of humans on base. In Section 5.0, we present analysis of the results and discussion, followed by Conclusions and Future Work in Section 6.0

2. RELATED WORK

To date significant attempts to design and build an off-world base has relied on carrying significant infrastructure, equipment and supplies from Earth. This includes the "Mars Base Camp" architecture from Lockheed Martin [26]. These base designs are human-centric and ignores use of robots entirely. Such mission require careful design and preplanning to support an exploratory goal. Once an exploratory goal has been achieved, it is unclear how the base will continue to operate. Another is a concept for Mars Polar Research [27]. Here the plan is to build a human base that access the Mars polar region for long term research and data analysis. This is akin to polar research facilities in the Antarctic. The infrastructure, resources and operational supplies all need to be shipped in to sustain the base.

Others have built simulation facilities on Earth to determine how humans adapt and operate in these enclosed and isolated bases. This includes past ambitious efforts such as Biosphere 2 (Figure 2) located in the desert of Southern Arizona and that aimed to have a fully self-sufficient base with miniature support ecosystem to help feed and keep alive a team of human residents for 2 years [24-25]. The experiments produced mixed results, with the ambitious goals of self-sufficiency never being achieved. These results show increased complexity involved in having a base that support humans and living organisms. Similar experiments are being performed at a smaller scale by the Chinese Space Agency (CNSA) by utilizing an enclosed mock Martian base in the inhospitable Gobi Desert [28]. Another ambitious effort is being pursued by the United Arab Emirates Space Agency with the development of a 136-million dollar mock "Mars Science City" being built in the Arabian desert [29].

Figure 2. Biosphere 2 located in Southern Arizona is 3.14-acre indoor (previously sealed) facility designed to operate as a self-sufficient base housing 8 humans for 2 years. Two experiments were conducted in 1991 and 1993, leading to mixed results with self-sufficiency never being achieved [24-25].

The multitude of challenges of sustaining humans and human-centric facilities in space as seen from experiments over the past 20 years has led to consideration of alternate pathways. Exploring and operating in space is both challenging and complex as it is and taking into account petty human considerations particularly for long duration survival further adds to the challenges and complexity of operation. The off-world sites from which these critical resources need to be extracted are inhospitable, the day to day tasks dull, dirty and dangerous making it well suited for robotics. Robotics have meanwhile significantly advanced over the past 20 years, with rapid progress being made in robot dexterity, vision, planning and control. There are a growing list of tasks where these robotic system are human competitive (at the levels of humans) and instances where they exceed even leading human experts. There now exists entire factories that are fully automated with robots. Robots are also making inroads with self-driving cars, trucks and aircraft. Robots have also started to emerge as helpers in the home and workplace taking on dull, dangerous and dirty tasks. One of the biggest challenges faced with robotic systems is their interactions with humans.

Often times, when robots are interacting with humans, they are held to high standards of human decorum, culture and norms which add to operational complexity and chance of failure to adapt/co-exist. In contrast, we envision an all-robot facility or base to be simpler because it can be made to be structured and efficient. Humans in the loop tend to result in a less structured work area. This is akin to a robotic library containing towering high shelves where humans are prevented from directly accessing the book shelves and instead it is an autonomous team of robots that search and retrieve books through a well-structured process. The book shelves can be closely packed together and reach unbounded heights without consideration of humans beings able to access them.

Past literature on lunar and Martian base construction have focused on transporting significant quantities of prefabricated infrastructure and equipment. There has been a fundamental role in construction, particularly in site preparation, open-pit mining and collection of raw materials for construction.

Our past work shows major discrepancies expected with using terrestrial estimates. The low lunar gravity of 1.6 m/s^2 has significant impact on wheeled vehicles. The low gravity results in low cohesion of the lunar regolith. Wheeled vehicles need to drive slow or else risk loss of traction and uncontrolled hops as witnessed from the lunar rovers on the Apollo program. Our earlier work identified bucketwheels to be ideally suited for excavation in low gravity environments, thanks to simplified control and improved excavation efficiency [3]. Other excavation vehicles such as front-loaders and bulldozers were found to be significantly less efficient.

Other studies focus on detailed equipment design [18], and relative comparison of concepts based on trade studies. Some put emphasis on the prime movers and lifting equipment, without analyzing excavation tasks in lunar terrain [19]. A recent trade study by NASA compares excavation equipment based on the expected ability for them to handle the different types of digging tasks faced on the moon [20]. This includes qualitative assessment of criteria

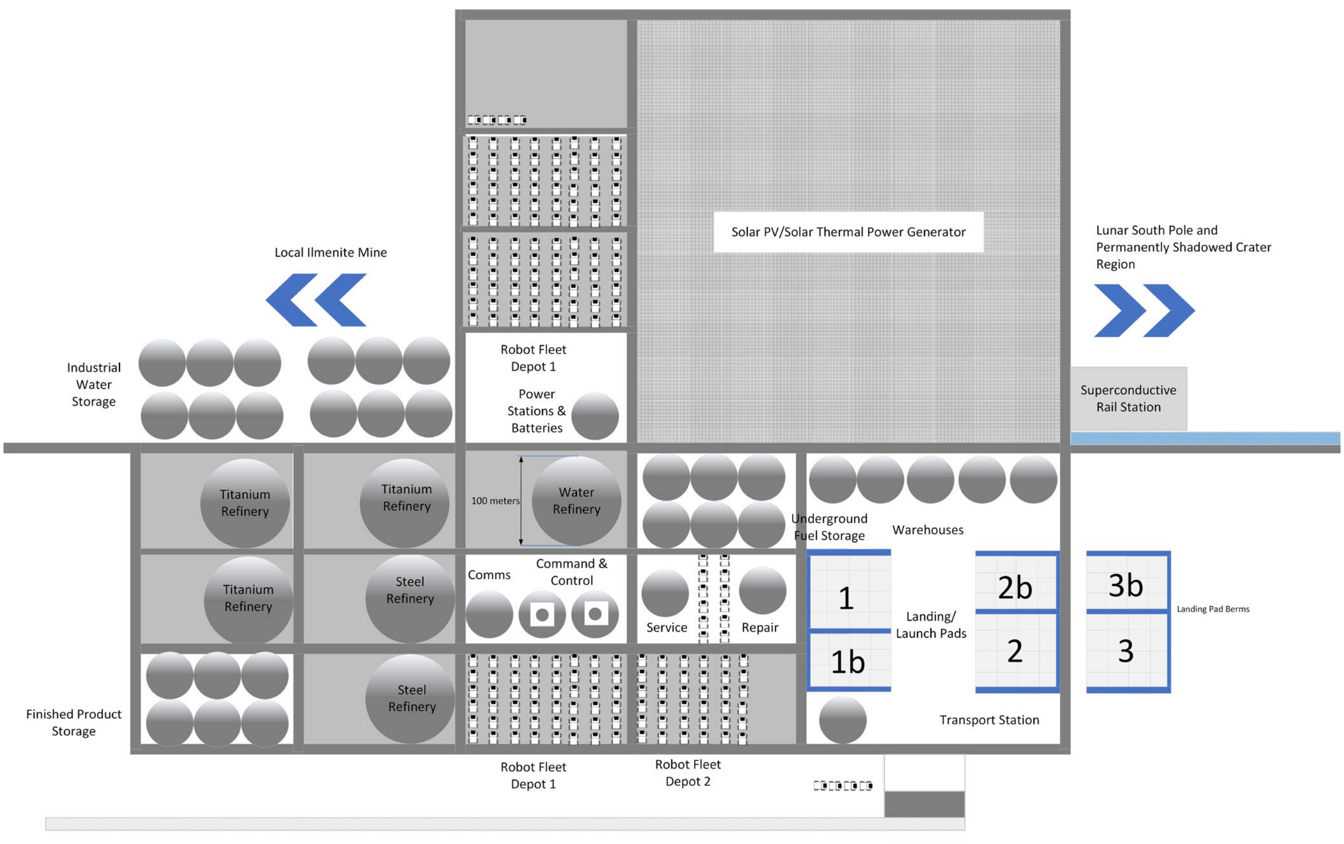

Figure 3. Layout of a Lunar Robotic Mining Base. It occupies over 2 sq. km and would be situated at the base of a crater with known ilmenite deposits. In this concept, there are no humans occupying the base.

a tendency to rely on 'nominal data' obtained from equivalent terrestrial conditions. Shimizu Corp. analyzed excavation tasks from an energy standpoint, but uses terrestrial numbers to determine total requirements [17]. Excavation tasks play such as mining and construction productivity, digging capability, reliability, and maintainability. Although productivity details are highly uncertain, this analysis is useful in that it narrows down the options in a logical manner, paving the way for testing a smaller list of concepts under expected lunar conditions.

Our work in contrast to the other past work envision an era beyond space exploration towards a space economy held up by a network of permanent Off-World Resource Export Centers (OWRECs). These resource exporting centers would exploit advances in robotics, machine learning and artificial intelligence to support human endeavors but will not require humans to be working in them. As we will show with our models and results, there is considerable difference in complexity with and without humans on the base.

We envision that these OWRECs will help to significantly reduce the cost of operation in space and hence allow for rapid expansion of everything else required in the economy.

3. LUNAR MINING BASE

The layout of the Lunar Robotic Mining Base is shown in Figure 3 and covers nearly 2 square kilometers. The mining base would be located at the base of a crater to exploit use of natural incline (slope) for the Mass Driver [11]. Key facilities on the base are interconnected by roadways constructed out of heat-fused silica (as a replacement to concrete). The command and control facilities of the base consist of a 150-meter high control tower to monitor/verify all operations on the base. The command tower will also be a localization beacon and tracking system for the fleet of autonomous robots. In addition, it is equipped with a communication ground station to communicate directly with Earth through the Deep Space Network (DSN). Raw material such as water ice will be transported daily by superconductive Maglev rail from the lunar south pole.

Major facilities on the base including the refinery, service and repair center, command and control buildings, Maglev station and even the warehouses are all 3D-printed spherical domes. The buildings are spherical domes to maximize internal volume with very minimal construction material. The domes would be constructed in one piece, include large glass windows, with an airtight fused silica glass layer in between to optionally maintain a 100 KPa, nitrogen/oxygen atmosphere inside.

A significant portion of the base is covered in solar-thermal and photovoltaic panels to harvest energy from the sun. Furthermore, solar-reflectors will be located on the crater rim to increase net-sunlight beamed to the base, in-addition to raising the temperature of the base surroundings. The base includes a hardened depot to house the 100 robotic vehicles when not in use, in-addition to service and repair facilities. The base houses a refinery to process (crush and bake to 120 ºC) the Martian regolith hydrate into water. An underground facility will be used to store both water and rocket propellant to refuel incoming rockets.

The human habitat and human facilities will be separated from the central operations area of the base by the Solar PV and solar-thermal generators. This is to minimize dust and sand being churned by moving vehicles entering and exiting the base from entering the human habitat regions. In addition, it will keep the human habitat sectors well away from the robotic vehicle traffic.

There are three modes of transport from the base. This includes roadways interlinking, (1) the base to the open pit mine site where ilmenite are located, (2) superconductive rail reaching the lunar south pole and PSRs and (3) a service road for the Mass Driver. The third mode of transport to and from the base is using rockets that can vertically land and take-off from one of six landing pads at the edge of the base. This provides quick access to the base in case of critical maintenance and for transporting repair equipment and other seed-resources to maintain continual operations of the base. Finally, the fourth form of transport is the mass-driver that will propel water, processed titanium and low-carbon steel housed in containers to 2.4 km/s (into a lunar escape trajectory for export).

In our simulation studies we consider four scenarios: Base constructed using (1) 3D printing of fused silica sand, with steel rebar support [7-10] or (2) Steel structure with internal silica-sand blocks. Secondly, we consider the base to be (a) fully autonomous run using up to 300 mobile robots and (b) base run by a human team of 300 workers. The human occupied base as would be expected is much more complex than the robotic base and includes additional buildings shaded in gray (Table 1). Importantly for the human occupied base, there will be O_2 electrolyzers and recyclers. While every effort will be done recycle O_2, some will be lost due to everyday activity at the base and new O_2 will need to be generated from electrolysis of H_2O (water).

The base will also contain 2 large domes as large as the one of the six refineries housing services to take care of the human occupants, including health, banking, pharmaceutical, shopping, restaurants, rest and relaxation centers. The human occupants will live in individual dome-shaped housing with a minimal floor area 120 m^2 or 1,200 sq. feet. The housing areas will be linked via enclosed/pressurized above ground and underground walkways (tubes) spanning 10 km and connecting all the buildings. Several parallel tubes are in place to enable redundant and secure access to key facilities. In addition, there are parallel tunnels leading straight from the living quarters to the launch pad for quick evacuation in case of fire or a major onsite accident.

The Lunar Mining Base contain the following infrastructure:

Table 1. Lunar Mining Base Structures

Structure	Quantity	Dimensions
Road Network [t]	1	Length, L_t = 12,000 m, Width, W_t= 8 m Depth, d_t = 0.2 m Steel Ratio, S_t=0.05
H_2O and Metal Refineries [r]	6	Dome Outer Radius, R_{or} = 50 m Inner Radius, R_{ir} = 49.6 m Base Depth, D_r=0.3 m Steel Ratio, S_r=0.1
Comms. Command, Control, Service and Repair,	6	Dome Outer Radius, R_{os} = 25 m Inner Radius, R_{is} = 24.6 m Base Depth, D_s=0.3 m

Power Ctrl [s]		Steel Ratio, S_s=0.1
Control Tower [CC]	1	Pyramidal Tower Height, H_{cc}=150 Base Length, L_{1cc}=25 Top Length, L_{2cc}=5 Steel Ratio, Scc= 0.1
Warehouses [w]	21	Dome Outer Radius, R_{ow} = 25 m Inner Radius, R_{iw} = 24.8 m Base Depth, D_w=0.3 m Steel Ratio, S_w=0.1
Fuel Storage [f]	6	Cylinder Radius, r_f = 25 m Wall Thickness, D_f=0.1 m Wall Height, $h_f = 2\ m$ Steel Ratio, S_f=0.05
Small Landing Pad [p]	3	Pad and Blast Walls Length, L_p = 100 m Width, W_p = 50 m Depth, D_p = 0.2 m Wall Height, H_p 0.5 m Steel Ratio, S_p=0.05
Large Landing Pad [p]	3	Pad and Blast Walls Length, L_p = 100 m Width, W_p = 100 m Depth, D_p = 0.2 m Wall Height, H_p=0.5 m Steel Ratio, S_p=0.05
Power Generation Pad [g]	1	Pad Length, L_g=1000 m Width, W_g= 1000 m Depth, D_g=0.1 m Steel Ratio, S_g=0.05
Mass Driver [m]	1	Cylinder (Pair) + Support Inner Radius, R_m = 3 m Length, L_m = 10,000 m Thickness, T_m = 0.5 m Slope, $\alpha_m = 5^o$ Post Height= H_m= 5 m Post Width = W_m = 1 m Post Spacing = ε_m = 20 m Post Steel Ratio, S_m=0.05
Superconductive Rail [SR]	1	Cylinder (Pair) + Support Inner Radius, R_{SR} = 3 m Length, L_{SR} = 1000 km Depth-magnet, D_{SR}=0.1m Thickness, T_{SR} = 0.5 m Post Height= H_{SR}= 5 m Post Width = W_{SR} = 1 m Post Spacing = ε_{SR} = 20 m Post Steel Ratio, S_{SR}=0.05
O_2 from H_2O Extract* [O]	18	Cylinder Radius, r_o = 50 m Wall Thickness, D_o=0.2 m Wall Height, h_o=3.0 m
		Steel Ratio, S_o=0.2
Human Services Centers* [SC]	6	Dome Outer Radius, R_{or} = 50 m Inner Radius, R_{ir} = 49.6 m Base Depth, D_r=0.3 m Steel Ratio, S_r=0.1
Human Habitat* [h]	300	Dome Outer Radius, R_{oh} = 6 m Inner Radius, R_{ih} = 5.9 m Base Depth, D_h=0.1 m Steel Ratio, S_h=0.2
Human Walkways (Service Tubes) [ST]	1	Cylinders Length, L_{ST} = 10,000 m, Outer Radius, R_{oST} = 1.1 m Inner Radius, R_{iST} = 1.0 m Steel Ratio, S_{ST}=0.1

The equations for volume of each structure is given below:

$$V_t = L_t W_t D_t \quad (1)$$

$$V_r = \frac{2}{3}\pi\left({R_{or}}^3 - {R_{ir}}^3\right) + \pi D_r {R_{or}}^2 \quad (2)$$

$$V_s = \frac{2}{3}\pi\left({R_{os}}^3 - {R_{is}}^3\right) + \pi D_s {R_{os}}^2 \quad (3)$$

$$V_{CC} = H_{cc}L_{2cc}^2 + H_{cc}(L_{1CC} - L_{2CC})L_{2CC} \quad (4)$$

$$V_w = \frac{2}{3}\pi\left({R_{ow}}^3 - {R_{iw}}^3\right) + \pi D_w {R_{ow}}^2 \quad (5)$$

$$V_f = 2\pi r_f^2 D_f + 2\pi r_f h_f D_f \quad (6)$$

$$V_p = L_p W_p D_p + 2L_p H_p D_p + W_p H_p D_p \quad (7)$$

$$V_g = L_g W_g D_g \quad (8)$$

$$V_O = 2\pi r_O^2 D_O + 2\pi r_O h_O D_O \quad (9)$$

$$V_{SC} = \frac{2}{3}\pi\left({R_{oSC}}^3 - {R_{iSC}}^3\right) + \pi D_{SC} {R_{oSC}}^2 \quad (10)$$

$$V_h = \frac{2}{3}\pi\left({R_{oh}}^3 - {R_{ih}}^3\right) + \pi D_h {R_{oh}}^2 \quad (11)$$

$$V_m = 2\pi L_m (R_m + T_m)^2 - 2\pi L_m (R_m)^2 + \frac{L_m}{\varepsilon_m} 2H_m W_m^2 \quad (12)$$

$$V_{SR} = 2\pi L_{SR}(R_{SR} + T_{SR})^2 - 2\pi L_{SR}(R_{SR})^2 + D_{SR}W_{SR}L_{SR} + \frac{L_{SR}}{\varepsilon_{SR}} 2H_{SR}W_{SR}^2 \quad (13)$$

$$V_{ST} = \pi(R_{oST}^2 - R_{iST}^2)L_{ST} \quad (14)$$

3.1 Energy for Silica Sand 3D Printing + Reinforcement

The energy needed for silica sand 3D printing involves first raising the temperature of the sand to ΔT_{sand} =1,973 ^{o}K followed by melting the sand into a liquid binder. The heat capacity of sand (quartz) is, $C_{p\,sand}$= 0.830 kJ/(kg K). The heat of fusion to melt sand (quartz) is H_{melt}=156 kJ/kg. Therefore, the total energy needed to melt and fuse the sand in-situ is the following:

$$E_{total\,sand} = E_{heat\,sand} + E_{melt\,sand} + E_{trans\,sand} \quad (15)$$

$$E_{total\,sand} = \rho_{sand} V(C_{p\,sand}\Delta T + H_{melt\,sand} + gd) \quad (16)$$

The density of quartz sand is $\rho_{sand} = 1500\ kg/m^3$ and g is the local acceleration due to gravity and d is distance in metres. On the Moon g=1.62 m/s^2. Unless if the sand is transported long distances in the order of 1000s of meters, the energy required simplifies to the following:

$$E_{total\,sand} \approx E_{heat\,sand} + E_{melt\,sand} \quad (17)$$

For steel-bar reinforced structures, the total energy is the following:

$$E_{total\,reinf} = E_{total\,sand} + E_{total\,steel} \quad (18)$$

$$E_{total\,reinf} = \rho_{sand}(1 - S)V(C_{p\,sand}\Delta T_{sand} + H_{m\,sand}) + SV\rho_{steel}(C_{p\,steel}\Delta T_{steel} + H_{m\,steel}) \quad (19)$$

Where S is the volumetric percentage of steel, $\rho_{steel} = 7{,}750\ kg/m^3$, $C_{p\,steel}$ = 0.510 kJ/(kg K) and $H_{m\,steel}$ = 25.23 MJ/kg where the steel is produced from regolith containing 1:1, Magnetite and Hematite with heat of melting 1118 kJ/mol and 824 kJ/mol. Only 70% of Magnetite and Hematite contain Iron, with the remainder being oxygen. ΔT_{steel} =1,640 ^{o}K

3.2 Steel and Sand Block Construction

For the steel and sand-block construction, the structures are all made of a steel support structure and thus the volume of the structure is μ=0.15 of the 3D printed structure. For the road, the volume of the structure is μ=0.05 of the 3D printed structure. Similarly, to form the sand blocks, only μ (percentage volume of the sand) is melted thus energy equation is the following:

$$E_{total} = \rho_{steel} V \mu(C_{p\,steel}\Delta T + H_{m\,steel}) + \rho_{sand} V \mu(C_{p\,sand}\Delta T + H_{m\,sand}) \quad (20)$$

3.3 Water Extraction Energy

We wish to extract liquid water from the ice source found in the lunar south pole. The total energy is the following:

$$E_{total\,water} = m_{water}(C_{p\,water}\Delta T_2 + H_{melt\,ice} + C_{p\,ice}\Delta T_1) \quad (21)$$

Presuming the ice is found at -150 ^{o}C and it is warmed to a liquid at 25 ^{o}C Then ΔT_1=150 and ΔT_1=25. C_{pwater} is the specific heat of water and is 4.200 kJ/kg^{o}C. The specific heat of water ice, $C_{p\,ice}$ =2.108 kJ/kg^{o}C and $H_{melt\,ice}$ is 333.55 kJ/kg and we have a total mass of 100,000 kg of water. The total energy needed to bring it to liquid water at 25 ^{o}C is 7.55 × 10^5 MJ.

3.4 Excavation and Regolith Transport Energy Requirements

We wish to calculate the total excavation energy required to produce 100,000 kg of water during a 24 hour period. First, we calculate the transport energy required to move lunar regolith from a permanently shadowed crater containing water ice 90% by mass, a distance d = 5000 m, with friction coefficient η=0.01, χ= 1.2 and is the vehicle movement ratio.

$$E_{mov\,up} = (100/90)\ mg\eta d\chi \quad (22)$$

Plugging in the values, E_{mov_unp} = 10.7 MJ. Next we calculate the total transport energy required to transport the processed water from refinery to Mass Driver. We presume a maximum d= 1000 m, with friction coefficient η=0.01:

$$E_{mov\,p} = mg\eta d. \quad (23)$$

For hauling the water ice $E_{mov\,p}$ = 8 MJ. Next, we calculate an estimate of the total excavation distance required to cover a flat open pit containing water ice. Knowing that the ρ_{ice} = 1000 kg/m^3, we determine the total volume of the input material. Following this we divide by the total area of the robot vehicle, A_{robot} = 0.42 m^2 and account for picking up and returning with regolith. The expression is then the following:

$$E_{dig} = [\chi F_{dig} + (100/90)mg\eta]\ [(100/90)\ m/\rho_{ice}]\frac{2}{A_{robot}} \quad (24)$$

Where χ= 1.2 is vehicle movement ratio and accounts for inefficiencies in movement. F_{dig} = 3000 N is the force used to dig into the lunar surface and m= 100,000 kg and η=0.1 is the friction coefficient and is applicable for movement in rough terrain. Then $E_{dig\,p}$ = 113 MJ.

Finally, we determine the energy need to transport raw water ice from the permanently shadowed crater region to the mining base for processing using the superconductive rail. We presume d=1,000,000 m. We estimate the rail carriage mass to have a 20% mass overhead of the cargo and thus φ= 1.2 and η=0.005. Therefore, the energy need to haul the mass by rail is the following:

$$E_{train} = \varphi mg\eta d \quad (25)$$

Therefore, the total energy required for train transport is E_{train} = 972 MJ. With this the total energy required for excavation, transport of unprocessed regolith, water extraction and transport of water to Mass Driver is E_{Exc_transp} = 1.64× 10^6 MJ.

3.5 Energy Needed for extracting iron (steel) and titanium

The lunar mining base apart from mining water will also be mining equivalent of 100 tons of low-grade steel and 100 tons of titanium. Both materials can be extracted from ilmenite ($FeTiO_3$) that is located in plentiful supply on the surface of the Moon. Titanium makes up, χ= 31.6% of ilmenite, while iron makes up, χ=37 %. Presuming a 70% extraction efficiency (κ) for each metal. Then the following amount of ilmenite needs to be excavated:

$$m_{ilmenite} = \frac{m_{Ti}}{\kappa\chi_{Ti}} \qquad (26)$$

The total mass of the ilmenite then is $m_{ilmenite}$= 4.53 × 10^5 kg. At an ilmenite deposit (mine), we presume 80% ilmenite by mass and therefore is the following:

$$E_{mov\ up} = (100/80)\ mg\eta d\chi \qquad (27)$$

$E_{mov\ up}$ for the ilmenite is the 55 MJ for every ~100 tons of Ti and Fe. The total Emov p for the titanium and iron(steel) haul is the following:

$$E_{mov\ p} = mg\eta d \qquad (28)$$

Where m=200,000 kg, d= 1000 m, η=0.01 and therefore the total energy for $E_{mov\ p}$ = 3.2 MJ. The digging energy required for the ilmenite is the following:

$$E_{dig} = [\chi F_{dig} + (100/80)mg\eta]\ [(100/80)\ m/\rho_{ilmenite}]\frac{2}{A_{robot}} \qquad (29)$$

Where $\rho_{ilmenite}$ = 4800 kg/m^3. Then the total E_{dig} is 53.5 MJ. Finally, it should be noted the ilmenite mine will be in surrounding region around the mine and hence it doesn't need to be hauled by train. Next, we consider the energy required to produce low-grade steel and iron from the raw ilmenite (Table 2). Terrestrial methods of steel and titanium production also requires plenty of water. Extracting and using clean water for these industrial processes becomes even more energy intensive as for this Lunar Mining Base it takes 16 MJ/kg of water produced. Therefore, a lower energy cost option is to use recycled water for titanium and steel production. Water can be recycled using reverse-osmosis systems, with a minimum energy requirement of 3 kWh/m^3 for brackish water which is 0.0108 MJ/kg. It is more likely the water used contain undissolved particles rather than salts such as NaCl and therefore require closer to the minimal energy for reverse osmosis and passive sand filtration to occur.

Table 2. Resource Processing Energy & Water Needs

Material	Energy Req.	Water Needed	Recycled Water Energy
Low-Grade Steel	25 MJ/kg	23 L/kg	0.25 MJ/kg
Stainless Steel	85 MJ/kg	112 L/kg	1.2 MJ/kg
Titanium	120 MJ/kg	190 L/kg	2.1 MJ/kg
Aluminium	138 MJ/kg	200 L/kg	2.1 MJ/kg
Water*	16 MJ/kg	-	

For 100 tons of low-grade steel, the $E_{process}$ = m$E_{p\ req}$= 2.5 × 10^6 MJ and for titanium, $E_{process}$= 1.21 × 10^7 MJ. The total energy required to process 100 tons of low-grade steel and 100 tons of titanium is 1.46 × 10^7 MJ. This energy includes use and purification of recycled water using reverse-osmosis.

3.6 Mass Driver Energy Needs

For the proposed mining base, a Mass Driver will be used to send the m=100,000 kg of liquid water in a container consisting of M=10,000 kg into a Moon escape velocity. The Escape velocity of the Moon is the following:

$$v_{escape\ moon} = \sqrt{\frac{2GM_{moon}}{r_{moon}}} \qquad (30)$$

Substituting for the estimated mass of the Moon, M_{moon}= 7.34 ×10^{22} kg and r_{moon} = 1,731 km, the Moon escape velocity is the following, v_{escape_moon}=2.44 km/s. The total energy requirement is simply the following as the Moon doesn't have an atmosphere:

$$E_m = \alpha\frac{1}{2}(\varphi m)v^2 \qquad (31)$$

Where $\varphi = 1.2$ and is the container and α is the efficiency of the Mass Driver is presumed to be 0.5. Therefore, the total kinetic energy required to transport the water into lunar escape velocity is then E_m=7.12 × 10^5 MJ. Similarly, the energy required for transporting the 100 tons of low-grade steel and titanium in total is E_m=1.42 × 10^6 MJ. The total energy needed to export all of the resources is then $E_{m\ total}$=2.14 × 10^6 MJ.

3.6 Energy Requirements for Work Crew

Here is a table of daily energy requirements for the 300-member work crew:

Table 3. Life Support Energy Consumption

Item	Energy Required
Oxygen Generation	16,676 MJ
Electricity	16,200 MJ
Water Needs	32,400 MJ
Food	10,062 MJ
Total	75,339 MJ

These figures are based on expected requirements for an average adult human. An average adult is expected to breathe 98.2 moles of O_2 a day. The energy required to recycle O_2 from CO_2 is 566 kJ/mol. Each person is estimated to

consume 15 kWh per sol for personal use which is 16,700 MJ for 300 workers. Each worker is assumed to consume 300 L in water a day. The water is recycled and presumed to consume 1 kWh/L. In terms of food, the following per Table 4 shows kJ energy consumed in terms of food person. Considering 50% of food goes to waste, we presume the total requirements of food per person sol is 16.77 ×2 kJ = 33.54 kJ.

Table 4. Human Daily Food Consumption

Food	Energy Used [kJ/kg]	Consumed [kg]	Total Energy [kJ]
Corn	1.1	0.306	0.336
Milk	2.2	0.18	0.39
Fruits & Vegetables	4.4	0.864	3.80
Eggs	8.36	0.09	0.75
Chicken	8.8	0.09	0.79
Cheese	17.6	0.09	1.58
Goat	30.8	0.09	2.77
Beef	70.4	0.09	6.33
		1.8	16.77

Based on these calculations, the total energy requirements to support the 300 human workers is 75,339 MJ/sol (Table 3).

3.7 Energy Harvested for the Mining Base

The presented base will be using renewable energy to power the entire facility. The base needs to generate 1.77×10^7 MJ/day in terms of electrical and solar thermal energy and where we are counting in terms of Earth days. For this we make some simplifying assumptions. The average daytime solar insolation on Moon is 1360 W/m^2. Solar-thermal systems that use Carbon Nano-Tubes (CNTs) can directly convert solar energy into heat at 99% efficiency [21]. Using CNT, we consider assembly of a solar-thermal plant that capture solar heat. We presume we require generating 1.77×10^7 MJ/day of thermal power and furthermore sunlight hours last 24 hours/day and the average solar insolation, χ=1360 W/m^2. The total size of the solar-thermal power plant required is the following:

$$E_{solar} = \Delta T \chi A_{solar} \quad (32)$$

This requires a total area of 0.15 km^2. Next, we presume the total energy required per day is all electricity. Then equation for the total energy required is the following:

$$E_{PV} = \Delta T \chi \lambda_{PV} A_{PV} \quad (33)$$

Where λ_{PV} is the photovoltaic efficiency. We presume it is 45%. With these parameters, the required Area, A_{PV} is 0.33 km^2.

4. Results and Discussions

Autonomous robotics and 3D printing can have game-changing impact on Lunar Mining Base construction and operation. We developed an energy model that account for construction, operation and maintenance of a Lunar Mining Base. In this study, we also considered the use of 100 human workers vs. 100 infrastructure robots to operate and maintain the base.

4.1 Energy Required for Construction

Our studies compared the potential options for building a Lunar Mining Base (Figure 4). This included use of humans or robots and 3D-printing or no 3D printing. Our studies find that 3D printing and robotics provides the biggest advantage. It can cut time to build by 15-folds and decrease energy consumption by 15-folds (Figure 4,5).

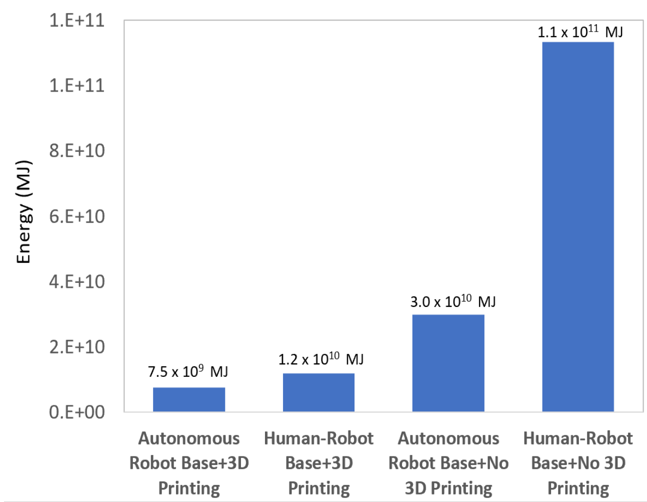

Figure 4. Building a Lunar Mining Base using a human team and without 3D printing requires 15-folds more energy than without. This shows robotic 3D-printing has significant potential to lower cost and make feasible a Lunar Mining Base.

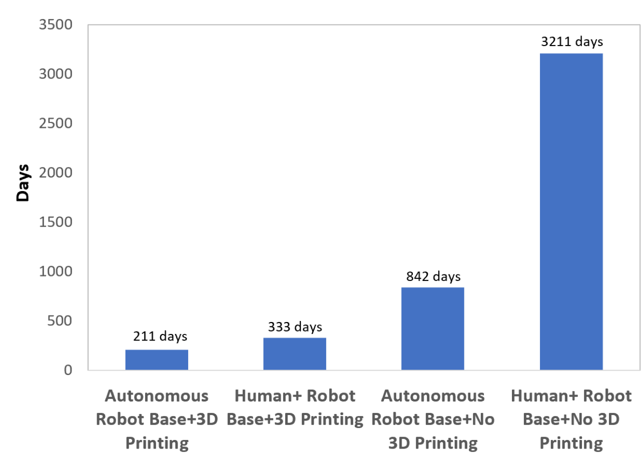

Figure 5. Our model shows that with the available renewable power source it will take 15 folds longer to build a base using a human team without 3D printing than using a wholly robotic team using 3D printing.

Furthermore, we compare base construction to cost of other major infrastructure such as the 1,000 km magnetically levitated rail-line (Figure 6) to haul raw ice from the lunar

PSRs to the base. It would take nearly 50-folds more energy to build this 1000 km rail line than the main base facility. In comparison to the human operated non-3D printed base, it would be 3-folds more energy. For this rail line we only considered the 3D option, as the non 3D printing option would require exorbitantly high energy, making it unfeasible.

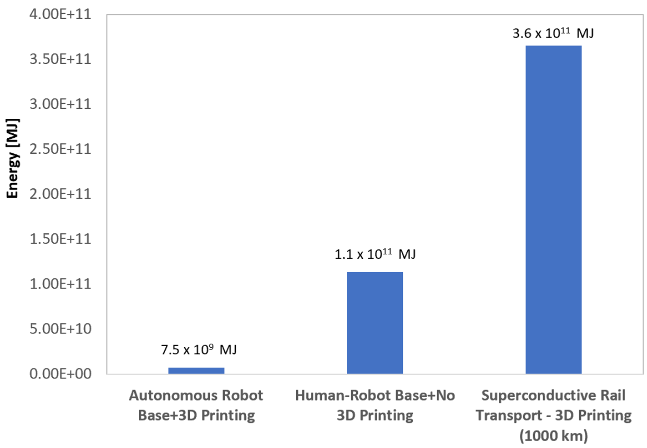

Figure 6. Our models show that building a 1,000 km superconductive rail system would require significantly more energy (50-folds) more than an all robotic 3D printed base and 3-folds more than the human occupied non-3D printed base.

Based on our model, the significant simplifications possible of using an all-robot-team and housing robots is significantly more cost-effective than having humans and providing the significant resources needed to enable healthy living (Figure 7, 8). If the resources needed for the base are obtained locally, that makes significant difference in terms of required transport energy and cost. Hence this study shows the potential game-changing opportunity possible with a construction method that utilizes local resources and doesn't require humans in the loop.

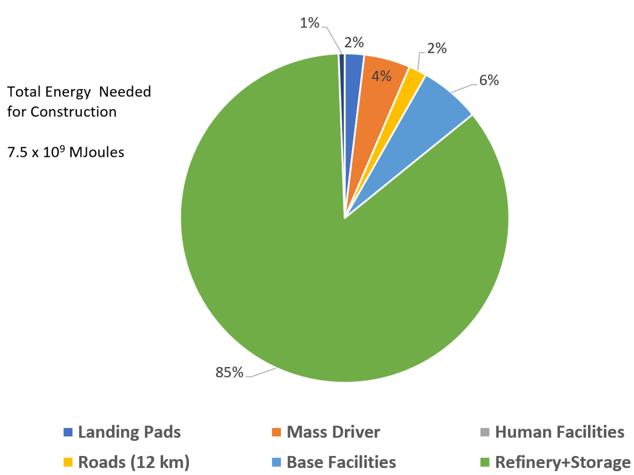

Figure 7. Distribution of energy consumed for building a robotic mining base using 3D printing.

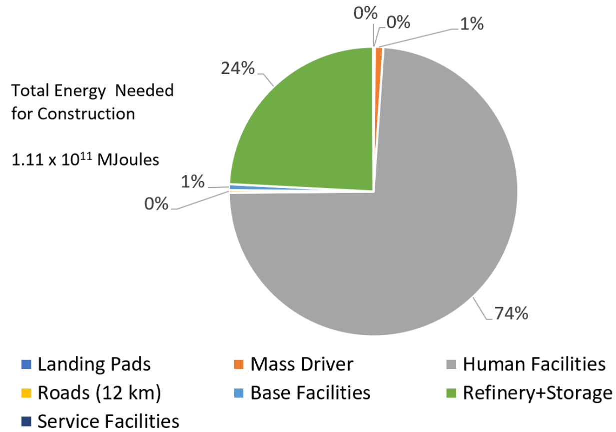

Figure 8. Distribution of energy consumed for building human occupied mining base using conventional construction methods (non-3D printing).

We look into the details of building the Lunar Robotic Mining Base (Figure 7, 8). We presume 12 km of paved roads being built by fused silica-sand with properties similar to concrete. The roads will be reinforced with steel support beams to maximize strength for a 100-year lifetime. These roads will form the transport network for the fleet of 300 robot vehicles which is shown in Section 4.4. Importantly, the roads will connect the open-pit mine to the base and reflector facilities on the crater rim. The remainder will be base facilities including the power station, communication ground station and command and control facilities and 150-meter control tower.

The building structures are all domes that are 3D printed in place using the local silica sand and will be held with a reinforced steel structure that would also be locally produced from the Lunar iron/titanium rich regolith. The refineries will be the biggest dome structures on the base with a diameter of 100 m and hardened further to prevent any spill-over from damage due to accidents. The refinery infrastructure for the all-robot base will take up 85% of the construction energy. This is not surprising as the energy required for refine the metals dominant the daily energy consumption on the base (Figure 7). The remaining 15% of the total energy will be spent on human facilities, landing pads, roads, building the robot facilities including depot, maintenance and repair facilities, together with parts storage.

4.2 Energy Required for Base Maintenance

According to our model, the total energy required for maintaining a Moon Mining base is 1.76×10^7 MJ per day. Of this, 77.74% of the required energy is for processing the 100 tons each of titanium and low-grade steel. The energy needed to transport the 100 tons each of water, titanium and steel into lunar escape trajectory is 12.12% of the total (Figure 9). Remaining 9.71 % would be for mining, processing and maintaining the base facilities, while 0.43 % would be the energy required if there were to be 300 human workers. The significant amount of energy needed to refine and process the metal outweighs all other energy consumption needs include the energy needed to operate the Mass Driver. Building a Mass Driver [11] to transport the 100 tons each of water, titanium and steel will be much easier than to do so from Earth due to low gravity of 1.62 m/s^2.

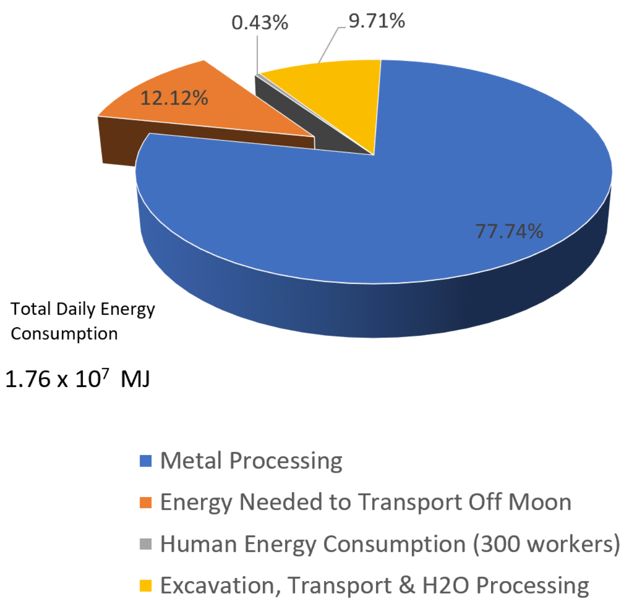

Figure 9. Distribution of energy consumed for operating a humans-occupied Lunar Mining base.

Comparing the energy required for resource extraction, nearly 1.61×10^7 MJ is consumed (Figure 10). The extraction and processing of 100 tons of titanium and 100 tons of low-grade steel from ilmenite surrounding the base consumes 90% of this energy, while 10% of the energy is for extraction and transportation of water ice from the lunar south pole to the base located 1,000 km away via Maglev superconductive rail.

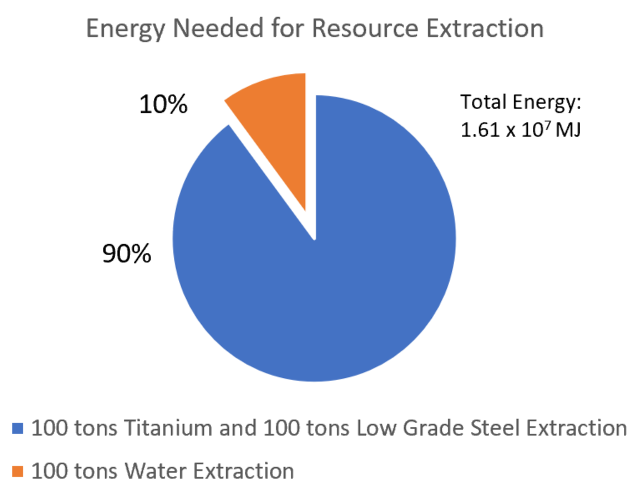

Figure 10. Distribution of energy consumed for extracting titanium and low-grade steel from lunar ilmenite and water-ice from the lunar south pole transported 1000 km.

4.3 Human Impact

Based on our models, the energy consumed per day (Earth day) for operation of the base (excluding Mass Driver transport and refining) is 7.65×10^4 MJ. Our studies show that having humans on the mining base results in significant consumption of energy and facility needs (Figure 11).

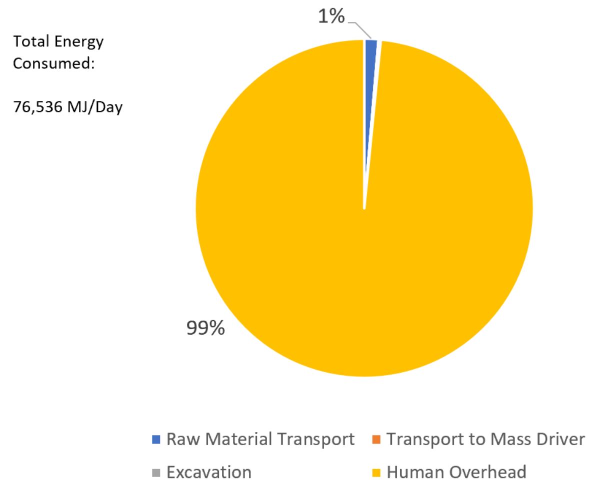

Figure 11. Distribution of energy consumed for operating a humans-occupied Lunar Mining Base (excluding energy for Mass Driver and Refining).

In fact, quite rapidly, human energy needs overtake all other energy needs except Mass Driver transport and refining of the raw material. This in part because Moon in its current form is an unfavorable environment to support Earth life and hence significant increase in energy and resources are required to sustain the life of the 300 human workers. In our energy model, we breakdown human needs into water, oxygen, food and electricity (Figure 12). It is presumed each worker will require about 300 liters of water per day. The highest per capita usage of water is 550 liter per day in the United States. We presume 300 liters as it is attainable and will be possible with improved efficiency expected on a future lunar base.

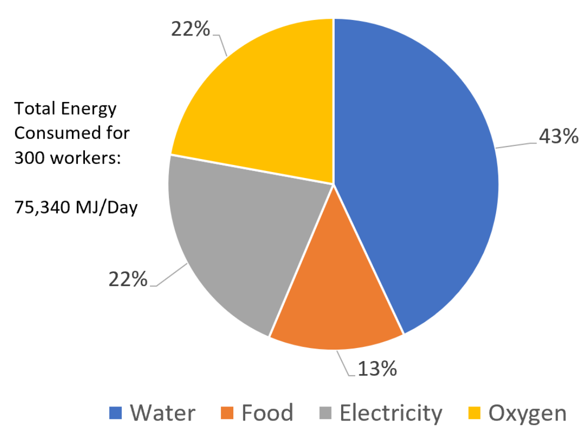

Figure 12. Distribution of energy consumed by 300 human workers on the Lunar Mining Base.

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In addition, each worker is assumed to be consuming 15 kWh of electricity per day and 2,200 liters of oxygen. In terms of food (Fig. 12), each worker is estimated to consume nearly 1.8 kg of food (2,800 calories) per day, with 35% of the food being fats and proteins (including milk, eggs, meats and cheese), 17% being starch (wheat, corn, rice) and 48% (fruits, vegetables). We then accounted for net energy required to produce these foods. Beef is estimated to require 70.4 kJ/kg, while corn for example requires 1.1 kJ/kg. Using this detailed model, we find that the 300 workers consume 75,339 MJ/day. This shows that automation and robotics is the key to making such a base technologically feasible. In the next section we provide a summary of our plans to further develop the 3D printing technology.

4.4 Robotics Vehicles for 3D Printing, Excavation and Maintenance

The proposed robotic vehicles collect regolith and processes them onboard to perform 3D printing (Figure 13, 14, 15). The size of the 3D printed object is not limited by the size of the vehicle. The vehicles are powered entirely on renewable energy, using high-energy fuel cells [22-23] that provide double the energy output of gasoline. The robotic vehicles will also be autonomous operating as a group, with only high-level commands being provided by a human supervisor from Earth or a relay base [1-6] (see Figure 18). Teams of autonomous vehicles under the right conditions can exceed human controllers.

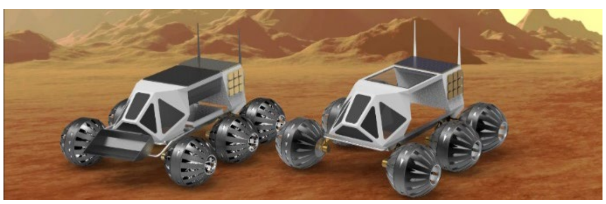

Figure 13. 3D Rendering of a pair of robotics vehicles for excavation and 3D printing.

The vehicles are entirely autonomous and utilizes a combination of onboard sensors, GPS and local beacons to navigate. These vehicles are the template for a family of infrastructure robotic vehicles. On the moon they can be used on everything from digging trenches for underground conduits for water, air, power and data, to the construction and maintenance of pressurized greenhouses. They can be used to build roads, bridges, and more advanced infrastructures for human settlement including radiation-shielded architectures. Gravity being 16% that of Earth, smaller units can be effective at moving large volumes.

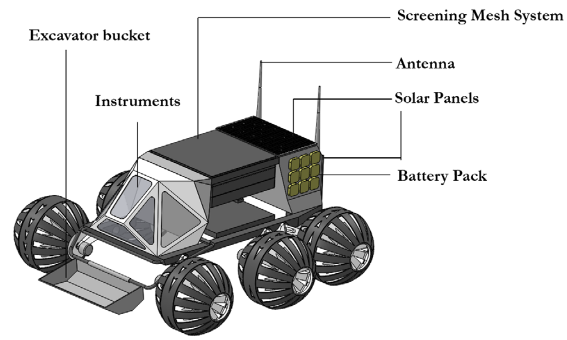

Figure 14. 3D Rendering of an autonomous robotic vehicle for excavation.

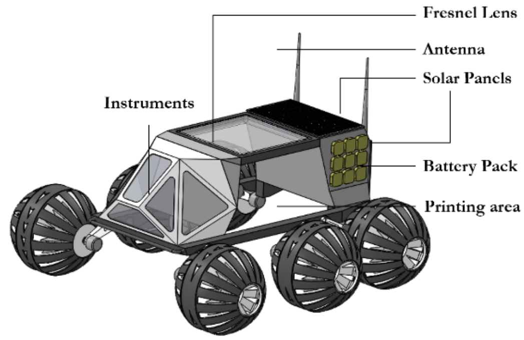

Figure 15. 3D Rendering of an autonomous robotic vehicle for 3D printing.

Here we present advanced laboratory prototypes of the vehicles that we expect to build to test end-to-end automated design, excavation and 3D printing capability in a controlled setting on Earth as part of the next phase of this research program (Figure 16).

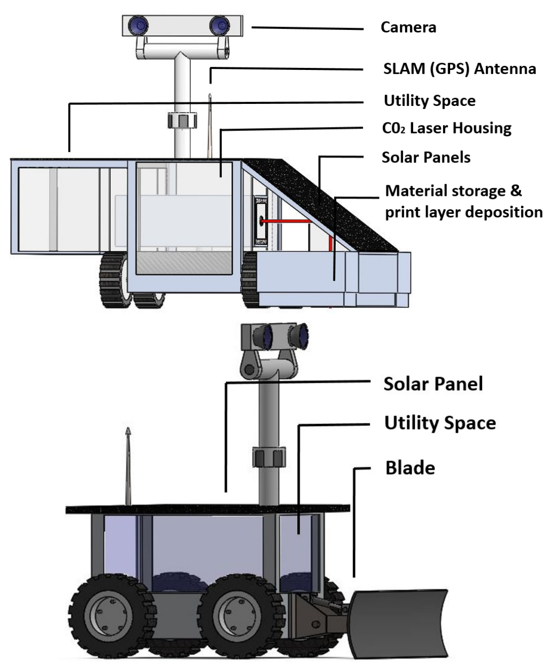

Figure 16. An advanced lab prototype of a 3D Printing Rover (top) and Excavating Rover (bottom).

4.5 Macroscopic Factors in Energy Consumption

Based on these simulations, it is clear that base construction is significantly impacted by human occupation and lack of 3D printing. This has 15-fold increase in energy needed for based construction. The key factor is being able to perform site preparation, obtain raw material and perform 3D printing efficiently. Our work builds upon earlier work where we have used machine learning methods to evolve near-optimal controllers for multirobot systems to perform excavation, base preparation and open-pit resource mining (see Fig. 18) [1-6]. This shows promise and importance of efficient multirobot operation to cut-down on the energy needed for base construction which is key, defining variable.

In comparison, other infrastructure elements such as the superconductive rail line consumes even more energy for construction. This is based on the presumption that large water reserves are only found in the south pole and where the temperatures not conducive for a large mining/processing base. Thus, an efficient means of construction of the rail line is critical to making this entire enterprise feasible.

A separate issue is daily consumption of energy. It is dominated by processing of ilmenite into titanium and steel which takes up 78% of the energy (Figure 17). This is quite surprising as it takes more energy for metal refinement than even transporting the finished products into a lunar escape velocity. Another option includes transporting ilmenite ($FeTiO_3$) into lunar escape trajectory as opposed to the finished titanium or steel. This has advantage of transporting three elements that are important for the space economy, namely iron, titanium and oxygen.

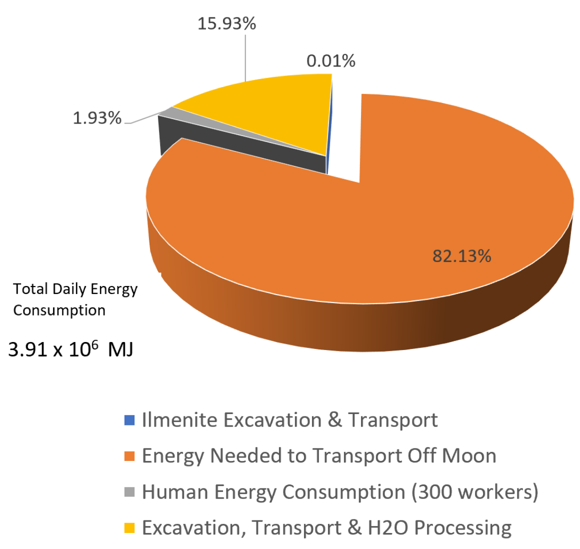

Figure 17. Distribution of energy consumed for operating a humans-occupied Lunar Mining Base that exports 100 tons of water and 350 tons of ilmenite per day.

It would be up to the consumer to then refine the ilmenite accordingly. This has significant impact on daily energy consumption and reduces down to 3.93 x 10^6 MJ which is 4.5-fold decrease from the scenario from Figure 9. For this new scenario, 15.4% of the energy goes to extracting, transporting the water ice 1,000 km to the base followed by melting it into liquid water. Meanwhile 82% of the energy goes to powering the Mass Driver to transport the raw ilmenite and water into lunar escape velocity. The energy expenditure shown is unavoidable. However, with the biggest expenditure of energy being the Mass Driver, potential methods to improve its efficiency will have significant return. Our simulations estimated the Mass Driver has a 50% operational efficiency. The use of superconductive magnets could potentially lead to further increased efficiency of the mass drive but requires operation below -150 ºC. The Mass Driver system could achieve game-changing performance improvement using superconductive magnets, but they need to operate in cold temperatures. Multirobot systems (Figure 18) may have a role in operating a large facility such as the Mass Driver with a length of 10 km to maintain precise temperatures below -150 ºC when the surrounding daytime temperature is 120 ºC. This will have significant impact on the capability of the mining base and how much resources can be efficiently exported into the space economy.

4.6 Base Scalability

Utilizing our earlier simulations and results, we considering scaling up and scaling down the base in terms of the resources produced (Figure 18). Our intention is to determine growth factors in terms of energy required for constructing the base and compare this to the various construction and base operations techniques considered. When considering scaling up the mining base, we presume the productivity of human and robot workers are identical and for the baseline scenario consisting of export of 400 tons of resources a day, where require 300 human or robot workers. Using these assumptions, we then scale up resource production up to 10 times resulting in daily production of 4,000 tons, consisting of 1,000 tons each of water, low-grade steel, aluminum and titanium. In addition, we also scale down by 10 times to consider resource output of 40 tons/day.

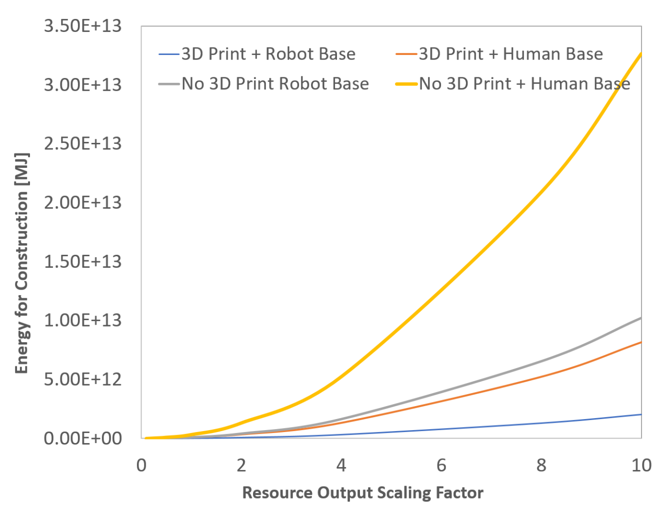

Figure 18. Energy required for constructing mining base when scaling resource output.

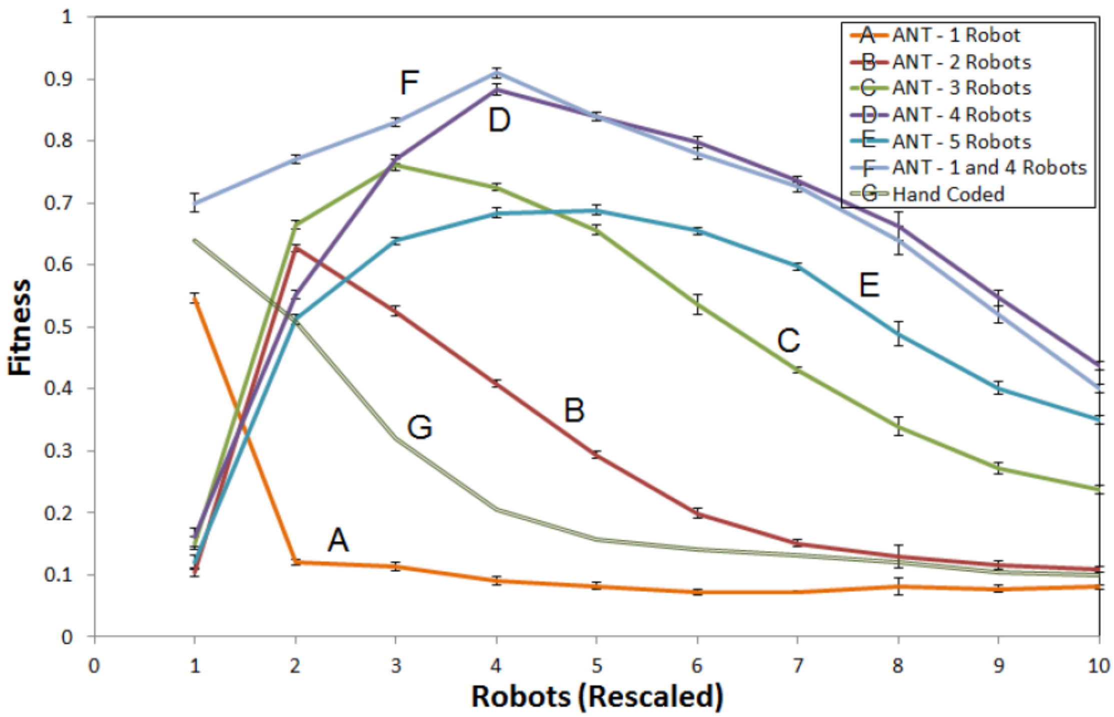

Figure 19. Our earlier work shows that teams of robots for excavating task can be more effectively controlled using autonomous decentralized neuromorphic controllers than human-coded program [2, 12].

The results show that except for 3D printing a robot base, all other options show substantial increase in energy needed for construction. The growth rate in fact is not linear but is exponential! This is expected for conventional construction methods due to high proportion of steel and glass needed for construction. 3D printing using in-situ raw material is significantly more efficient and thus energy needs are comparable to a linear increase with production. These factors highlight the critical importance of implementing 3D printing (construction) of the base and to make the base a wholly robotic mining base thus limiting overall construction and operational complexity.

In Figure 19, we show the potential for scalability in terms of number of robot workers for base preparation tasks such as excavation. Importantly, it shows scalability is possible and it is possible for us to find optimal robot density ratio to maximize productivity. With too few robot workers there won't be enough time to complete the task as there is enough labor. In comparison, too many robots will cause saturation and result in a drop-in performance. However, using algorithms such as ANT [2, 12], we can find optimal ratio of robots for a given task and see a smooth drop-off with an increased number of robots (beyond optimal). Having additional robots in reserve is important to deal with individual robot losses and repairs.

5. CONCLUSION

In this feasibility study we analyzed the application of multirobot systems towards development of a Lunar Robotic Mining base. We analyzed the potential feasibility of setting up a mining base to export water, titanium and iron/steel. The biggest energy consumer is the construction of the mining base and critical infrastructure such as a rail line to the lunar south pole. Ensuring the mining base is operated by robots results in a significant simplification, with energy needs dropping by 15-folds. Use of multiple robots to perform dull, dirty and dangerous construction tasks is an excellent match. The potential for an all-robotic system to construct and operate a mining base has clear advantage from the point of view construction.

Processing of the raw materials remains the biggest source of energy consumption for daily operations. Efforts to improve the efficiency of the refinement process could have significant impact here but it is outside the scope of using robotics. It is the chemical processes that need to be improved in terms of efficiency. Furthermore, efforts to improve efficiency of transport of raw materials and water into lunar escape velocity using mass-driver technology has significant implications. Multi-robot systems may have a role in operating a large facility such as the Mass Driver with a length of 10 km to maintain precise temperatures below -150 ºC when the surrounding daytime temperature is 120 ºC.

Our studies show that a precursor to a Moon Robotic Mining Base is technologically feasible within the next 10 years. The critical technologies, namely autonomous multirobot systems [1-6] and 3D printing have undergone significant advancement and are being prepared for rugged-field use. Multi-robot systems can have greatest impact in simplifying and minimizing energy use in construction. A secondary role is for the multi-robot systems to operate large facilities and maintain precise but cold temperatures to enable operation of mass-drivers. Successful demonstration of these integrated technologies will bring us one step closer towards realizing the vision of off-world colonization, mining and resource processing.

ACKNOWLEDGEMENTS

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BIOGRAPHY

Jekanthan Thangavelautham *has a background in aerospace engineering from the University of Toronto. He worked on Canadarm, Canadarm 2 and the DARPA Orbital Express missions at MDA Space Missions. Jekan obtained his Ph.D. in space robotics at the University of Toronto Institute for Aerospace Studies (UTIAS) and did his postdoctoral training at MIT's Field and Space Robotics Laboratory (FSRL). Jekan is an assistant professor and heads the Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory at the University of Arizona. He has co-authored 103 peer-reviewed publications and he is the Engineering Principal Investigator on the AOSAT I CubeSat Centrifuge mission.*

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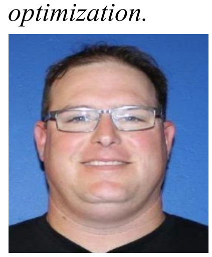

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