A Trade Study of Lunar Power Plant Technology

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Abstract

With future plans to return to the Moon in the next few years over the course of the NASA Artemis missions, as well as other government and private ventures, it is critical to assess different power sources for a permanent lunar base. Here, we detail a power source with the lowest upfront and per-unit cost while remaining safe and reliable, assuming a lunar base on the rim of the Shackleton Crater on the South Pole, with a capacity of 8 astronauts, and a mission duration of ten years. Here, power sources are analytically assessed by assigning rankings for each power source based on these metrics, a common technique referred to as a design matrix [1]. Ranked on a 0 to 10 scale for each power source, the five metrics used in this paper are: (1) total cost, (2) safety, (3) reliability, (4) technological readiness, and (5) miscellaneous factors like scalability. Analyzed power sources include conventional options such as solar panels with batteries or a nuclear fission reactor, developing solutions such as nuclear fusion, and unorthodox solutions such as laser beaming. Using this design matrix, mirrors in high, polar lunar orbit constantly reflecting sunlight onto a collector system below was found to be the best solution out of the analyzed power sources.

1 Introduction

This decade, NASA aims to start a sustained lunar presence in the form of a base camp using their SLS super-heavy-lift rocket. During the Apollo missions only fuel cells were necessary to power the lander as it was only going to stay on the moon for about a week. However, temporary power solutions like fuel cells are not feasible for a lunar base as they require large amounts of consumables. Solar power is more enticing for longer stays, as continually shipping consumables to the habitat is expensive. However, so-called peaks of eternal light, where light illuminates a spot for the vast majority of a year, have not been discovered yet on Shackelton [2]. Therefore, solutions like batteries, towers, or orbital mirrors must be used to provide continuous power. Nuclear fission also provides continuous power and only requires small amounts of consumables from Earth, but is expensive and complex. Developing technologies such as nuclear fusion may also be used in the far future.

One promising development for powering a long-term lunar habitat is in-situ resource utilization (ISRU). The moon has many rich resources that can be used to create solar panels [3] or maybe even nuclear power plants. This is an appealing option considering costs to send material to the moon are estimated to be about $100,000/kg. In the short term, it might be better to send the power plant materials directly, but an ISRU plant can continue to produce power-generating units as well as other structures for the habitat itself, making it a more viable option long–term. However, due to a current lack of cost estimates, power options are assumed to not use any ISRU.

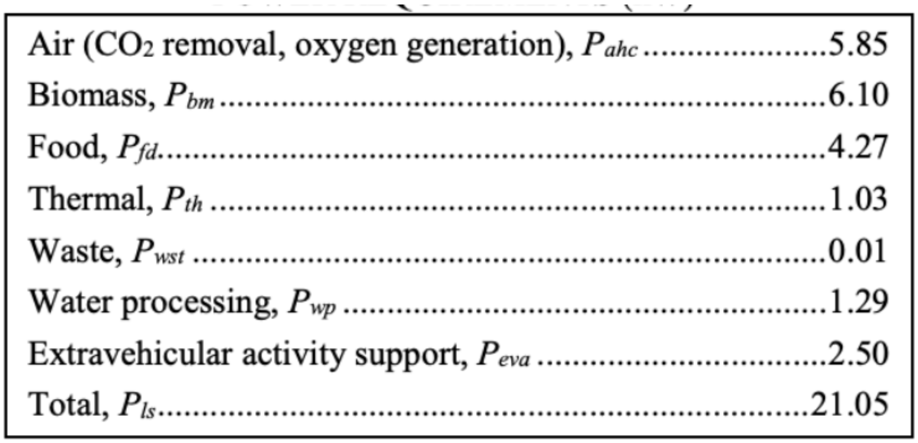
Table-1 lists symbols and acronyms used throughout the paper. The systems and components referenced as "x" are defined as follows:
soltow: the whole solar tower system, assuming 4 towers
solbatt: the whole solar battery system, assuming 3 reflectors
nucfis: the whole nuclear fission system
nucfus: the whole nuclear fusion system
beam: the whole beaming system
spacemirr: the whole space mirror system
pfuelcell: the whole primary fuel cell system

List of Symbols		List of Acronyms	
g_{moon}	Gravitational Acceleration on Moon's Surface [1.62 m/s^2]	Mirror	in solar concentrator designs, one mirror capable of powering the full lunar base at full efficiency and sunlight
g_{earth}	Gravitational Acceleration on Earth's Surface [9.81 m/s^2]	Collector	in solar concentrator or beaming designs, the light collector system
δ	Specific cost to the lunar surface [$100,000/kg]	Panels	in solar designs, all the panels needed to power the base
P_x	Total power generated by component 'x' [kW]	Batteries	in solar battery designs, mass of the total amount of batteries needed to keep the base running during dark periods
P_{tot}	Total power requirements [103 kW]	Tower+mirr	in solar tower designs, one tower and mirror construction
$h_{tower\ seg}$	The height of a tower segment [15.25 m]	Hydrolox	in fuel cell designs, the hydrolox fuel needed for 1 refill of the fuel cell system.
$C_{manufac,\ x}$	Manufacturing cost of component 'x' [$]	Laser	in beaming power designs, an Earth-based laser that beams power to the lunar power receiver.
$C_{initial,\ x}$	Total initial system cost, including transport, of component x [$]	Earthfis	in beaming power designs, the Earth-based nuclear power system that powers the laser. FSPS: in nuclear fission designs, 1 Fission Surface Power System, as described by [4]
$C_{annual,\ x}$	Total annual cost of component x [$]	TBC	To be calculated
C_x	Total cumulative cost of component 'x' [$]		
M_x	Mass of component 'x' [kg]		
μ_x	Power-to-mass ratio of component 'x' [kW/kg]		
ß_x	Specific manufacturing cost of component 'x' [$/kg]		
$M_{transport,\ x}$	Annual transport mass required for component 'x' [kg]		
t_{tot}	Total duration of lunar base [10 years]		

Table 1: List of Symbols and Acronyms

2 List of Power Requirements

In order to maintain an 8 person settlement on Shackleton Crater, power requirements will include both essential systems and scientific experiments. Similar to the International Space Station (ISS), the primary purpose of a habitat on the moon would be for scientific discovery. The estimated power requirements to run these experiments on the moon is roughly 50-100 kW [5].



Air (CO_2 removal, oxygen generation), P_{ahc}	5.85
Biomass, P_{bm}	6.10
Food, P_{fd}	4.27
Thermal, P_{th}	1.03
Waste, P_{wst}	0.01
Water processing, P_{wp}	1.29
Extravehicular activity support, P_{eva}	2.50
Total, P_{ls}	21.05

Table 2: Power requirements for a 6-person habitat (kW) [6]

Table 2 summarizes essential, non-scientific power needs: life support, communication, and other basic systems. Life support systems include the ability to keep the habitat warm and cold in the required climates, produce oxygen for the astronauts, and remove CO2. Communication with the Earth and future spacecraft in the lunar region is a necessity for a habitat on the moon for mission, scientific, and personal use.

Assuming the essential, non-scientific needs for an 8-person crew are proportionally larger than those for a 6-person crew, and scientific experiments take about 75 kW,

$$P_{tot} = (21.05\ kW) * \frac{8\ people}{6\ people} + 75\ kW = 103\ kW$$

This estimate of 103 kW is used to estimate the total cost of power sources in section 4.1.

3 List of Power Sources

This section introduces the power sources analyzed in section 4.

3.1 Solar Power

Solar installations are a promising candidate for powering a lunar base. Since the settlement will be on Shackleton Crater, so-called “peaks of eternal light” [7] may exist. Such peaks never receive darkness due to the Moon’s low axial tilt of 1.54˚ [7]. However, no such peaks are confirmed to exist, only providing power 85% of the time with one reflector, improved to 92.5% with three reflectors [8] . To address the lack of continuity provided by a system set up on the surface, there are many variations of this concept.

Disadvantages to solar panels include high susceptibility to cosmic and solar radiation which is amplified by the Moon’s lack of a magnetic field and atmosphere. Even using modern multijunction PV solar cells, a strong solar proton event may permanently reduce their power output by 5–10%. Similarly, they degrade by 2-3% each year from galactic cosmic rays. Not only does one likely need an additional 40% more panels to compensate for this degradation, they would need to be replaced every few years, which would be inconvenient in the long term [2].

3.1.1 Solar Power with Batteries

The simplest option is to send batteries as well as solar panels from Earth and install them in the lunar base. Solar power could provide power most of the time, the rest covered by lithium-ion batteries. The power-to-mass ratio of such a system is approximately 130 W/kg, excluding batteries. This figure is relatively high when compared to other power sources such as nuclear power with 5 W/kg and when compared to the values seen in flight, such as on the Apollo Telescope Mount (ATM), which only realized 10-15 W/kg [9]. Degradation of batteries will occur, but they only go through a few cycles per year, so it is unlikely to majorly affect the amount required.

3.1.2 Solar Power with Towers

Towers can be used in place of batteries to ensure constant power[10]. If reflectors are placed at the top of sufficiently high towers, they can achieve almost total solar illumination. As modeled in section 4.1.2, the tower mass is an exponential function of the tower height.

Towers may be difficult to construct and take up valuable parts of the base inhabitant’s time. They may also be dangerous, as falling off one could cause serious damage to one’s spacesuit and lead to a pressure leak. However, they are relatively simple, and lunar dust is likely not as big of a problem as it would be on the surface.

3.2 Nuclear power

3.2.1 Fission

Nuclear fission power, the use of radioactive heat for power from materials such as uranium, is another popular option. NASA issued a Request for Proposal in 2021 for a demonstration within a decade, for example [11]. These solutions are reliable and able to work continuously for years, without requiring solar radiation or an extensive energy storage system [2]. Their compactness also likely makes them easy to shield from micrometeorite impacts.

Potential downsides include the requirement of fissile material to be shipped to the lunar surface, which may present a significant safety risk to both Earth and lunar inhabitants. This transfer will also be costly with the purchasing of the material and the safety protocols associated with transporting, handling, and launching it.

3.2.2 Fusion

Fusion power utilizes the power of hydrogen atoms fusing in extreme conditions to create helium, releasing energy in the process. One cannot deny the advantages of fusion power; it is safe, with the risk of a runaway reaction low due to the low amount of fuel in the reactor at any given time [12]. Helium 3, a suitable fuel for reactors, is known to be present in the lunar surface due to the Moon’s high exposure to solar wind.

Of course, the current technological state of fusion power makes it quite unfeasible to use as a power source on Earth, let alone on the Moon. It is jokingly said to be ‘always ten years away’. The technological level needed to put a fusion plant on the moon will likely require many more decades to achieve. The high minimum mass of a fusion plant also makes this concept unviable; see section 4.1.5.

3.3 Miscellaneous Power

3.3.1 Beaming power

A power system has been proposed where power from the Moon is beamed back to Earth as a source of energy [13]. If there is a point on Shackleton that always has Earth's line-of-sight, power from Earth could be beamed to the Moon. Stations can be placed 120 degrees apart south of the Earth’s equator to ensure constant line-of-sight to Shacketon. This has the benefit of avoiding the need for large power generation systems equipment on the lunar surface, which might be more costly given the $100,000/kg price for transporting such generation to the Moon.

However, the total efficiency of the system is quite low. About 29% is lost in the Earth’s atmosphere[4.1.5], and about 90% is lost in inefficiencies with the laser and collector.

Infrastructure on the Earth, most likely a nuclear power plant (as continuous power is needed on the dark side of Earth) independent from the grid, needs to be set up in three remote locations to ensure the collector system on the Moon has line of sight of it while also not losing too much power to the atmosphere.

3.3.2 Space Mirrors

One concept is to position 12 adjustable mirrors in high lunar orbit to provide constant brightness to a specific spot on the moon, the power from which could be collected by a solar panel on that spot. This offers many advantages over the costly method of sending solar panels to the Moon. For one, it costs significantly less to put mirrors in orbit around the Moon rather than solar panels to the Moon's surface due to the lowered delta-v requirements and the lack of large batteries or towers. Such lunar mirrors also reflect more light due to the absence of lunar dust.

This system, however, is somewhat complex; it requires that mirrors have adjustable focal lengths to compensate for the changing distance between the mirrors and the base, and it requires precise aiming of the mirror to ensure the light hits only the collector.

3.3.3 Non-Regenerative(Primary) Fuel Cells

One interesting idea would be to set up a simple fuel cell not unlike the ones used on the Apollo missions. Hydrogen and oxygen, also known as hydrolox, would be shipped from Earth every six months as the crew would be rotated. However, the mass of the tankage to sustain 130 kW for a year is prohibitively large, as well as the mass of the tankage and hydrolox that would need to be shipped a total of 20 times over the 10-year mission duration; this is shown in section 4.1.8.

4 Design Matrix

4.1 Cost Estimates

Table 3 defines the cost ratings used in Table 18. A logarithmic scale is used due to the high variance of the options.

Cost Rating	Minimum Cost (US Dollars)	Maximum Cost (US Dollars)
10	10^{7}	$4*10^{7}$
9	$4*10^{7}$	10^{8}
8	10^{8}	$4*10^{8}$
7	$4*10^{8}$	10^{9}
6	10^{9}	$4*10^{9}$
5	$4*10^{9}$	10^{10}
4	$10*10^{10}$	$4*10^{10}$
3	$4*10^{10}$	10^{11}
2	10^{11}	$4*10^{11}$
1	$4*10^{11}$	10^{12}
0	10^{12}	$4*10^{12}$

Table 3: Cost Ratings

4.1.1 Assumptions

Many assumptions were made in the cost calculations outlined in sections 4.1.2–4.1.8. Most notably, ISRU was neglected in the construction of any power system. ISRU has the potential to revolutionize lunar power production by eliminating the large launch cost. However, because of a lack of cost estimates for constructing the different power options using ISRU, this paper cannot accurately factor these in. Other major assumptions are listed here:

- Inflation was not adjusted for, so reliance on old papers may have resulted in decreased cost estimates.

- The cost of construction of components was sometimes deemed insignificant compared to the launch cost, and thus not accounted for.
- The specific cost δ of sending something to the lunar surface was assumed to be \$100,000/kg. Reusability, apparent in the SpaceX Starship and other developing rockets, may have the potential to dramatically lower this over the next few years. However, the \$100,000/kg figure is used because these concepts likely have a long way to go until they reach maturity and can reliably send cargo to the moon; for example, Starship still needs to perfect orbital refueling.
- Research and development costs for unestablished solutions have not been discussed. However, the technological readiness estimates in section 4.4 should compensate for that.

4.1.2 Solar Panel Tower

Additional symbols are used for the following cost calculations:

Symbol	Value	Description	Source
h_{tower}	300 m	Required height for 3 reflectors to achieve 99% sunlight availability to a lunar base.	Table 5.
h_{seg}	30-70 ft → 50 ft = 18.3 m	The height for which a tower can be made with the same mass as the mass on top of it, on Earth	[14]
$M_{tot}(n)$	N/A	Used to demonstrate tower modeling, represents the total mass of a tower and mirror construction after n segments are added.	N/A
h	N/A	Used to demonstrate tower modeling, represents the total height of a tower and mirror construction.	N/A
M_{mirror}	487.16 kg	The mass of one of the mirrors, accounting for α_{cont}.	See section 4.1.3.
α_{cont}	1.4	A contingency factor for the possibility of solar proton events, as well as background radiation, damaging the solar cells. Value approximated assuming 2 solar proton events and background radiation.	[2]
$M_{collector}$	162.39 kg	The mass of one of the collectors, accounting for α_{cont}. This assumes it is the same as in solar concentrator designs.	See Section 4.1.3 of this paper

Table 4: Additional Symbols

Table 5 lists required height for n reflectors placed on rim of Shackleton Crater to achieve 99% annual sunlight availability [15]

Number of Reflectors	Reflector Height [m]
1	775
2	450
3	300
4	300

Table 5: Required height for n reflectors placed on rim of Shackleton Crater to achieve 99% annual sunlight availability [15]

If the setup was built on Earth, the tower and mirror construction mass is calculated as follows. Without any tower, the total mass is simply the original mirror mass, as calculated in the next section 4.1.3:

$$M_{tot}(0) = M_{mirror}$$

The first tower segment is added to the bottom of the adjustable mirror, and has the same mass as the mirror.

$$M_{tot}(1) = M_{mirror} * 2$$

The mass of this construction is twice the mass of the original mirror, and can be thought of as the top load of the second tower segment. Since the load is twice as large, the second tower segment will have approximately twice as much mass as the first, so

$$M_{tot}(2) = (M_{mirror} * 2) * 2$$

Continuing this trend, the total mass can be modeled as an exponential function as follows:

$$M_{tot}(n) = M_{mirror} * 2^{n}$$

Since each increase of n by 1 corresponds with a increase in tower height of h_{seg}, $n = \frac{h}{h_{seg}}$ for some final tower height h, so

$$M_{tot}(h) = M_{mirror} * 2^{h/h_{seg}}$$

for some final tower height h.

Since the Moon's gravity is 6 times less than Earth's, h_{seg} should be increased by of g/g_{moon}; since the load at the top is lowered by a factor of g/g_{moon}, tower material can be spread g/g_{moon} times thinner vertically. Plugging in $h = h_{tower}$,

$$M_{tower+mirr} = M_{mirror} * 2^{h_{tower}/(g/g_{moon} * h_{seg})} = 3,187.45\ kg$$

Therefore, since the 3 tower configuration was chosen, and a collector is required at the bottom,

$$C_{soltow} = (3 * M_{tower+mirr} + M_{collector}) * \delta = \$970,649,887$$

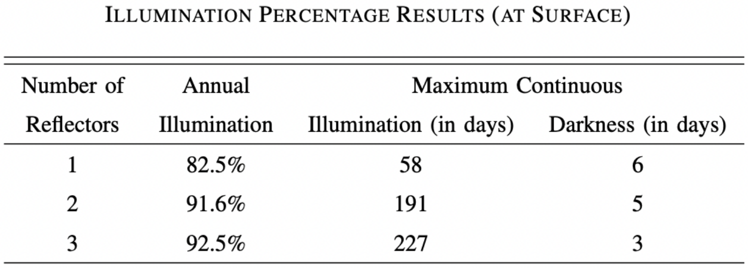
This is a high but still somewhat reasonable cost.

4.1.3 Solar Panel Batteries

Additional symbols are used for the following cost calculations:

Symbol	Value	Description	Source
α_{li-ion}	180 Wh/kg	The energy density of the cobalt lithium-ion batteries used as energy storage.	[6]
$t_{darkness}$	3 days = 72 hrs	The maximum continuous time in darkness, without solar panel power production.	Table 7.
μ_{panels}	360 W/kg	The power density of solar panels.	Table 8.
α_{cont}	1.4	A contingency factor for the possibility of solar proton events, as well as background radiation, damaging the solar cells. Value approximated assuming 2 solar proton events and background radiation.	[2]

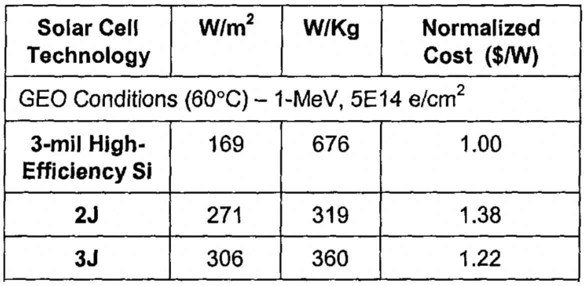
Table 6: List of Solar Panels with Batteries Symbols



ILLUMINATION PERCENTAGE RESULTS (AT SURFACE)

Number of Reflectors	Annual Illumination	Maximum Continuous Illumination (in days)	Maximum Continuous Darkness (in days)
1	82.5%	58	6
2	91.6%	191	5
3	92.5%	227	3

Table 7. Information about reflector configurations at the lunar surface at Shackleton Crater Rim. [16]



Solar Cell Technology	W/m^2	W/Kg	Normalized Cost ($/W)
GEO Conditions (60°C) – 1-MeV, 5E14 e/cm^2			
3-mil High-Efficiency Si	169	676	1.00
2J	271	319	1.38
3J	306	360	1.22

Table 8. Solar Panel Information.[1] [17]

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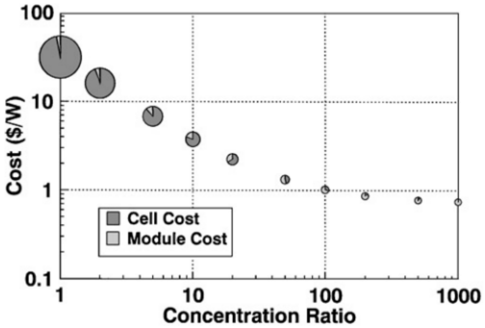
[1] *It is assumed this refers to a concentrated PV system, where mirrors reflect light onto a collector system. Multijunction PV cells can only realize the described cost if this is so and the concentration ratio is about 50, as shown by Fig 1. Also, only the GEO part of the Table 8 is shown, because it's conditions are more similar to the lunar surface[https://elib.dlr.de/84844/1/IAC_GHM_final_v1.xpdf].*

M. Yamaguchi / Solar Energy Materials & Solar Cells 75 (2003) 261–269



Summary of estimated cost for the concentrator PV systems vs. concentration ratio.

Figure 1. Cost of multi-junction concentrator solar panel systems as a function of concentration ratio. [12]

The efficiency of regenerative fuel cells is quite low at 44% [Figure 4], so over half of the energy is lost as they charge and discharge. Therefore, lithium-ion batteries seem to be the best option. Due to the weight being predominantly batteries, it is beneficial to optimize lowering the maximum continuous time in darkness, so the 3-reflector solution is the best.

The manufacturing costs of lithium-ion batteries [19] and solar panels [Figure 1] are low, so they are neglected to simplify the calculation.

The total mass of the batteries is what is required to power the base for the maximum darkness period, multiplied by a safety factor of 1.5 in case more darkness follows too soon for them to recharge.

$$M_{batteries} = 1.5 * \alpha_{cont} \frac{P_{tot} * t_{darkness}}{\alpha_{li-ion}} = 86,520\ kg$$

The total mass of the solar panels and mirrors is what is required to power P_{tot}, accounting for the annual illumination percentage of 92.5%, as well as a safety factor of 1.5 to quickly recharge the batteries after a dark period.

$$M_{collector} + M_{mirror} = \frac{1.5}{0.925} * \alpha_{cont} * \frac{P_{tot}}{\mu_{panels}} = 649.54\ kg$$

According to Figure 1, at a concentration ratio of about 50, the mirror cost is slightly over half of the total cost. Since mirrors likely have a lower cost-to-mass ratio, the mirrors likely take an even larger proportion of the mass, assumed to be 75%. Thus,

$$M_{mirror} \cong 0.75 * (M_{collector} + M_{mirror}) = 487.16\ kg$$

and

$$M_{collector} \cong 0.25 * (M_{collector} + M_{mirror}) = 162.39\ kg$$

Therefore, since the system needs 3 mirrors and 1 collector,

$$C_{solbatt} \cong (M_{batteries} + 3 * M_{mirror} + M_{collector}) * \delta = \$8,814,388,000$$

a surprisingly high cost.

4.1.4 Nuclear Fission

Additional symbols are used for the following cost calculations:

Symbol	Value	Description	Source
M_{fsps}	7777 kg	Mass of one FSPS surface plant, with 20% contingency	[4]
P_{fsps}	50 kW	Power of one FSPS surface plant, with 20% contingency	[4]

Table 9: List of Nuclear Fission Symbols

Due to the nature of the power production method, the cost can of the nuclear power plant itself can be ignored since it will likely be much less than the transport cost. Therefore,

$$C_{nucfis} \cong C_{initial,nucfis} = M_{nucfis} * \delta$$

Assuming the power plant can be scaled up according to $\frac{P_{tot}}{P_{fsps}}$,

$$C_{nucfis} \cong M_{nucfis} * \delta = \frac{P_{tot}}{P_{fsps}} * M_{fsps} * \delta = \$1,602,062,000$$

quite a high cost compared to other options.

4.1.5 Nuclear Fusion

An additional symbol is used for the following cost calculations:

Symbol	Value	Description
M_{nucfus}	TBC	Minimum mass of a nuclear fusion plant

Table 10: List of Nuclear Fusion Symbols

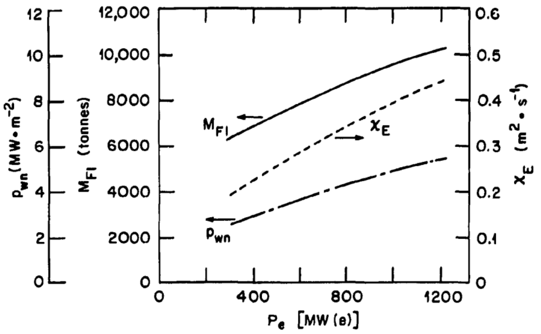


Fig. 4.17. Dependence on the net electric power P_e of (a) COE and (b) M_{FI}, p_{wn}, and χ_E.

Figure 2: Scaling of a nuclear fusion reactor [20]

Nuclear fusion reactors cannot be scaled down beyond a certain point. According to Figure 2, such fusion reactors cannot go below about 6000 tons. Therefore, $M_{nucfus} = 6 * 10^6\, kg$.

$$C_{nucfus} \cong C_{initial,\, nucfus} = M_{nucfus} * \delta = \$600,000,000,000$$

This reactor, of course, will provide thousands of times more power than what is needed for the lunar base[Figure 2]. The current size limitations, however, clearly make this concept unfeasible in the near future.

4.1.6 Beaming

Additional symbols are used for the following cost calculations:

Symbol	Value	Description	Source
θ	$0 < \theta <$	The zenith angle from an Earth power station to the lunar power collection system	N/A
λ	870 nm	The wavelength of the laser. Note: value obtained from source claim of 800-940 nm for a typical high power diode laser.	[21]
$\beta_{manufac, earth}$	\$4/W		[21]
$\beta_{manufac, laser}$	\$64/W	Earth based laser manufacturing costs. Note: value obtained from source claim of €155,000–200,000 for a 3 kW diode laser.	[22]
η_{laser}	10%	Laser efficiency. Note: value obtained from source claim of 400W laser power and 40 W input power using a diode laser.	[23]
$\eta_{transmit}(\theta, \lambda)$	N/A	Transmittance of the atmosphere based on a specific angle θ and wavelength λ.	N/A
$M_{collector}$	162.39 kg	The mass of one of the collectors, accounting for α_{cont}. This assumes it has a similar mass to in solar concentrator designs.	See Section 4.1.3 of this paper

Table 11: List of Beaming Power Symbols

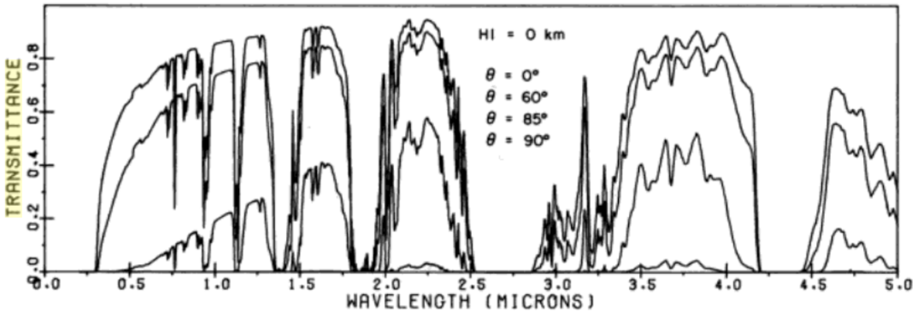


Figure 3. Atmospheric Transmittance with the 1962 US standard atmosphere.[24]

A power plant base on the Earth's South Pole, despite being able to always supply the lunar base with electricity, is simply unviable due to the astronomically low efficiency of $\theta = 90^\circ$ approaches. Instead, this paper proposes having three power bases, each 120 degrees apart on the Earth's equator, similar to NASA's Deep Space Network. This approach has more redundancy, as one failing does not mean a complete power loss for the lunar base. It also circumvents the low efficiency of high-θ approaches, as the maximum azimuth angle a powerplant would have with the line of sight to the moon, while supplying sole power, would be $\theta = 30^\circ$. In Figure 3, see that

$$\eta_{transmit}(60^\circ, \lambda_{laser}) \cong (\eta_{transmit}(0, \lambda_{laser})) * \cos(60^\circ)$$

and

$$\eta_{transmit}(90^{\circ}, \lambda_{laser}) \cong (\eta_{transmit}(0, \lambda_{laser})) * \cos(90^{\circ})$$

It may also be approximated,

$$\eta_{transmit}(85^{\circ}, \lambda_{laser}) \cong (\eta_{transmit}(0, \lambda_{laser})) * \cos(85^{\circ})$$

Extrapolating this trend for low values of θ,

$$\eta_{transmit}(\theta, \lambda_{laser}) \cong (\eta_{transmit}(0, \lambda_{laser})) * \cos(\theta)$$

for $0 < \theta < 60^{\circ}$. Therefore,

$$\eta_{transmit}(30^{\circ}, \lambda_{laser}) \cong (\eta_{transmit}(0, \lambda_{laser})) * \cos(30^{\circ}) = 0.82 * \cos(30^{\circ}) = 0.71$$

as the minimum transmittance value.

The power requirement for each of the 3 Earth ground lasers, accounting for inefficiencies relating to transmittance, is then

$$P_{laser} = \frac{P_{tot}}{\eta_{laser} * \eta_{transmit}(30^{\circ}, \lambda_{laser})} \cong 1,450.707\ kW$$

The cost of each laser is therefore

$$C_{laser} \cong C_{manufac,\, laser} = P_{laser} * \beta_{manufac,\, laser} \cong \$92,845,277$$

The power for these lasers comes from off-grid nuclear power plants stationed close to the lasers for maximum reliability. The manufacturing cost for each plant is

$$C_{earthfis} \cong P_{laser} * \beta_{earthfis} \cong \$7,323,960$$

The cost of the collector is

$$C_{collector} \cong M_{collector} * \delta = \$16,239,138$$

The total cost is

$$C_{beam} \cong 3 * (C_{laser} + C_{earthfis}) + C_{collector} \cong \$302,098,929$$

4.1.7 Space Mirrors

Additional symbols are used for the following cost calculations:

Symbol	Value	Description	Source
M_{mirror}	487.16 kg	The mass of one of the mirrors, accounting for α_{cont}.	See Section 4.1.3 of this paper
$M_{collector}$	162.39 kg	The mass of one of the collectors, accounting for α_{cont}.	See Section 4.1.3 of this paper
I_{sp}	228 seconds	The specific impulse of a hydrazine monopropellant thruster.	[25]
ϵ	TBC	The mass ratio of total mass to dry mass.	N/A
Δv	1.2 km/s	The delta-v saved from going into high lunar orbit instead of landing on the Moon.	N/A
α_{cont}	1.4	A contingency factor for the possibility of solar proton events, as well as background radiation, damaging the solar cells. Value approximated assuming 2 solar proton events and background radiation.	[2]

Table 12: List of Symbols for Space Mirrors

Since space mirrors stay in high lunar orbit, they do not have to spend fuel landing, so their transport cost decreases. To find how much, the rocket equation is used to find the mass ratio ϵ.

$$\Delta v = I_{sp} * g * ln(\epsilon)$$

Rearranging,

$$\epsilon = e^{\frac{\Delta v}{I_{sp} * g}} = 1.71$$

The transport cost is ϵ times less because ϵ times less mass will need to be transported due to the lowered fuel requirements. Approximately 12 mirrors are needed in high lunar orbit to provide enough power.

Therefore, the total cost is:

$$C_{spacemirr} \cong \frac{(12 * M_{mirror} + M_{collector}) * \delta}{\epsilon} = \$351,365,300$$

This is quite cheap relative to other options.

4.1.8 Primary Fuel Cells

Additional symbols are used for the following cost calculations:

Symbol	Value	Description	Source
$\gamma(t)$	N/A	The power density of a fuel cell with discharge time t, with t measured in hours.	Figure 4
$E_{hydrolox}$	$\frac{3.0*10^{-22}\ kJ}{reaction}$	The enthalpy of the $H_2 + ½O_2 \rightarrow H_2O$ reaction. Note: value obtained from source claim of 2.0 eV per reaction.	[26]
$\mu_{hydrolox}$	$\frac{3.0*10^{-26}\ kg}{reaction}$	The mass of hydrolox needed for one reaction, calculated using the molar mass $\frac{18g}{mol(H_2 + ½\,O_2)}$	N/A
η_e	50%	The efficiency of the chosen primary fuel cell.	Fig 4
t_{refill}	6 months = 4383 hours	The time between refills of the fuel cell system, assumed to be 6 months, with transport being along with crew rotation and supply refills.	N/A
$M_{pfuelcell,\,dry}$	TBC	The total mass of the initial fuel cell system, consisting of the fuel cell and tanks, without any hydrolox fuel.	N/A

Table 13: Symbols for Cost Calculations

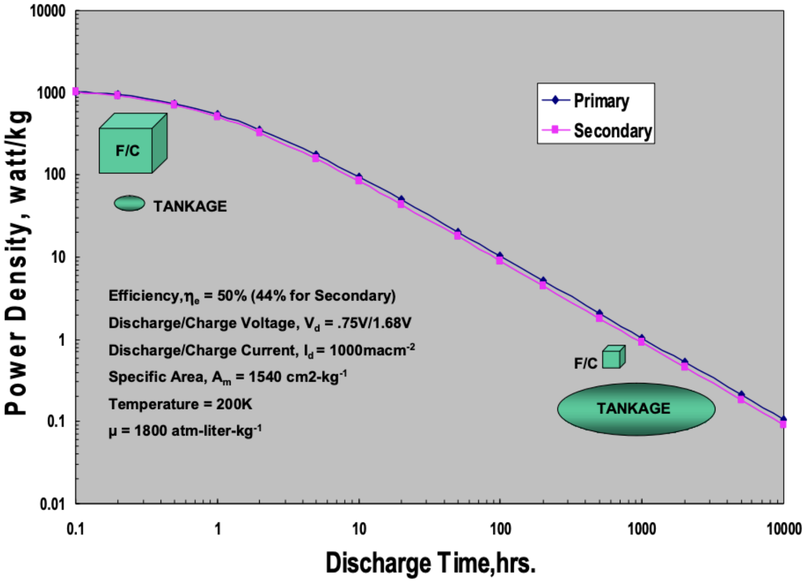


Figure 4 [27]

The initial cost $C_{intial,\,pfuelcell}$ consists of the fuel cell itself, the necessary lunar tankage, and initial fuel weight. The weight of the initial system is therefore:

$$M_{pfuelcell} = M_{pfuelcell,dry} + M_{hydrolox} = \frac{P_{tot}}{\gamma(4383)} + M_{hydrolox}$$

with $\gamma(4383) = 0.27\,W/kg$. By the conservation of energy, with $\frac{E_{hydrolox}}{\mu_{hydrolox}}$ giving the energy density of hydrolox in kJ/kg,

$$P_{tot} * t_{refill} = \eta_e * M_{hydrolox} * \frac{E_{hydrolox}}{\mu_{hydrolox}}$$

Rearranging,

$$M_{hydrolox} = \frac{P_{tot} * t_{refill} * \mu_{hydrolox}}{\eta_e * E_{hydrolox}}$$

Therefore,

$$C_{intial,\,pfuelcell} = M_{pfuelcell} * \delta = (M_{pfuelcell,\,dry} + M_{hydrolox}) * \delta = (\frac{P_{tot}}{\gamma(4383)} + \frac{P_{tot} * t_{refill} * \mu_{hydrolox}}{\eta_e * E_{hydrolox}}) * \delta$$

with $\gamma(4383) = 0.27\,W/kg$.

The resupply vehicle also needs to carry the tanks necessary for this hydrolox transport. As Fig 4 indicates, the mass of the tankage dominates as the discharge time increases, so since t_{refill} is high, the weight of the fuel cell itself can be ignored and $M_{pfuelcell,\,dry}$ is assumed to be mostly tankage weight. Therefore, the total transport weight for a refill is $M_{pfuelcell,\,dry} + M_{hydrolox}$. This needs to be transported twice a year, so

$$C_{annual,\,pfuelcell} = 2 * (M_{pfuelcell,\,dry} + M_{hydrolox}) * \delta$$

Thus, the total cost is

$$C_{pfuelcell} = 10 * C_{annual,\,pfuelcell} + C_{initial,\,pfuelcell} = 21 * (M_{pfuelcell,\,dry} + M_{hydrolox}) * \delta = 21 * (\frac{P_{tot}}{\gamma(4383)} + \frac{P_{tot} * t_{refill} * \mu_{hydrolox}}{\eta_e * E_{hydrolox}}) * \delta$$
$$= \$1,483,702,000,000$$

This is the highest cost of any option of the 7, surpassing even nuclear fusion.

4.2 Safety Estimates

Safety is considered to be the risk of injury to base inhabitants or of damage to critical infrastructure. The following table gives safety estimates and rationale for each system.

System	Rating	Reasoning
Solar Panel Tower	8	Risk of towers falling on base due to improper anchorage to the lunar surface
Solar Panel Batteries	9	It is assumed batteries cannot catch fire without oxygen.
Nuclear Fission	7	Risk of meltdown in the lunar environment. Can be made with low risk options
Nuclear Fusion	8	Construction unsafe, but low risk of explosion due to the low amount of fuel in the reactor at any given time [6].
Beaming	6	High radiant heat, beam may become misaligned and hit the settlement, many terrestrial nuclear operations/transport
Space Mirrors	7	Beam may become misaligned and hit the settlement
Primary Fuel Cells	7	Established technology, but accidents similar to Apollo 13 may occur, and the high tankage volume may result in such accidents being catastrophic.

Table 14: List of Safety Estimates.

4.3 Reliability Estimates

Reliability is considered to be the consistency with which power is provided and the risk of outage. Technological readiness plays a major role in determining reliability. The following table gives reliability estimates for each system.

System	Rating	Reasoning
Solar Panel Tower	7	Somewhat complex, issues may occur in construction, and low levels of lunar dust may block the panels
Solar Panel Batteries	8	Established battery technology, but heat management in batteries may be a challenge, and moderate levels of lunar dust may block the panels
Nuclear Fission	8	Established nuclear technology, but issues may arise with the low-gravity environment and waste heat management
Nuclear Fusion	6	Unestablished fusion technology, needs constant He3, high plasma temperature, issues may occur in construction

Beaming	5	Beam may become occluded by weather or get misaligned, moderate levels of lunar dust may block the collector, nuclear power plants may need maintenance
Space Mirrors	8	Beam may get misaligned, moderate levels of lunar dust may block the collector
Primary Fuel Cells	9	Established fuel cell technology

Table 15: List of Reliability Estimates.

4.4 Technological Readiness Estimates

Technological Readiness is considered to be how far the power system has technologically advanced so far. It is evaluated by the success of the power source on Earth and in space. The following table gives technological estimates for each system.

System	Rating	Reasoning
Solar Panel Tower	8	It is unknown how to anchor such a tall and heavy tower to lunar regolith.
Solar Panel Batteries	9	Solar panels and batteries have been widely used on most satellites. Thermal regulation of batteries on the Moon's surface, however, may be challenging.
Nuclear Fission	7	It is unknown how large-scale nuclear reactors may work in a low-gravity environment.
Nuclear Fusion	2	No successful system has been built on Earth.
Beaming	8	Optics for the lasers may be challenging due to the high distance requirements, requirement to hit a very specific spot, and the changing angle, but many missions, such as NASA's Dart mission, have used lasers to communicate.
Space Mirrors	8	The mirrors need adjustable focal lengths and need to hit a very specific spot.
Primary Fuel Cells	9	Have widely been used on submarines in extreme environments on Earth [28] , and have been used in space on the Apollo missions [27].

Table 16: List of Technological Readiness Estimates.

4.5 Miscellaneous Estimates

Miscellaneous factors include future scalability and sustainability, risk posed to ground personnel or launch site, possible delays, compactness, environmental impact, and political risk.

System	Rating	Reasoning
Solar Panel Tower	7	Linear scalability
Solar Panel Batteries	6	Linear scalability and not compact
Nuclear Fission	7	Radioactive material needs to be launched, which is risky, but is compact, has nonlinear scalability, and more flexibility for settlement location.
Nuclear Fusion	8	Good sustainability and scalability, but not compact. Abundant Helium–3 on the lunar surface [29].
Beaming	8	Doesn't heat up earth [30] and beam can be redirected easily, but satellites and planes need to avoid the beam, and has a high political risk since it can be used to shoot down satellites and requires three different global locations
Space Mirrors	9	Can be redirected and easily scaled with a lunar railgun
Primary Fuel Cells	8	Generates water

Table 17: List of Miscellaneous Estimates.

This section gives estimates for all 5 factors of the design matrix.

4.6 Overall Estimates

Estimates from all 5 factors are presented in Table 18.

	Cost	Safety	Reliability	Technological Readiness	Misc.	Total
Solar Panel Ship(Tower)	7	8	7	8	7	37/50
Solar Panel Ship(Surface with Batteries)	5	9	8	9	6	37/50
Nuclear Fission	6	7	8	7	7	35/50

Nuclear Fusion	1	8	6	2	8	25/50
Beaming	8	6	5	8	8	35/50
Space Mirrors	8	7	8	8	9	40/50
Primary Fuel Cells	0	7	9	9	8	33/50

Table 18. Design matrix.

5 Proposed Design

The best option seems to be the solar-concentrator-based design, which is not unexpected due to its lightweight and ease of setup compared to other options such as nuclear. While the concept of space mirrors may be complex, it was still deemed to be the best solution due to its low cost and maintenance.

For this concept, twelve mirrors will be placed in a high, polar lunar orbit, together providing constant power to the collector at the lunar base. The mirrors will have gyroscopes to adjust their angle, as well as solar panels of their own. They may also need to carry a small amount of propellant, as the mirror acts somewhat like a solar sail that might change the orbit slightly (although this may be compensated for by controlling the angle of the mirror when the mirror is not providing power to the base). Lastly, each needs an adjustable focal length to compensate for the changing distance of the mirror to the collector. Large batteries need not be included in the mirrors, as the solar panels provide power when there is sunlight, and the satellite need not be active when it is in darkness. A satellite will rarely pass on the other side of the Moon from Earth, but it can still communicate with Earth via the other satellites when it does.

The total weight of the system is $M_{collector} + 12 * M_{mirror} = 6008\, kg$, light enough to be carried in any cargo variant of the SLS rocket [31]. Since energy will likely be useful in the setup of the lunar base, this power system needs to be established as soon as possible, especially since the satellites may need time to adjust into their required orbits.

6 Maintenance

Since lunar dust does not extend up to the height of the mirrors, little maintenance of satellites is required. Satellites may run out of propellant and need to be refilled to maintain their orbit, but this likely only occurs well after the 10 year period due to the low delta-v necessary for high lunar orbit adjustments. The orbit may also be optimized for low orbital maintenance.

7 Conclusions

This paper presented current-day estimates for the required power to maintain an eight-person capacity lunar base on the rim of Shackelton crater for 10 years. Estimates for the amount of power required, methods of satisfying those constraints, and an analysis into seven different power sources was conducted. The authors weighed power production methods and concluded that the power source of orbital solar mirrors would be the best current option for powering a lunar base according to a design matrix of total cost, reliability, technological readiness, and safety. With estimated costs of $316 million, 12 solar mirrors could be deployed in high polar lunar orbit, supplying 130 kW to power an 8-person lunar base at Shackleton Crater.

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