On the applicability of nuclear fusion for the sustenance of lunar civilization

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Abstract

In recent decades, our terrestrial civilization has become increasingly dependent on energy producing infrastructure. Accordingly, a great deal of thought and discourse has been devoted to the question of with what energy sources to feed Earth's ever growing demand. Despite this, a distressingly small amount of consideration has been given to the equivalent dilemma on the Moon. With a permanent moonbase largely considered a critical first step in the formation of an interplanetary civilization, the issue of powering such a base is naturally likewise important. The nature and location of the lunar ecosystem give rise to several unique issues, as well as some opportunities. In this study, the merits and weaknesses of several energy sources are considered alongside their applicability in a lunar context, and in particular compared to the nuclear fusion of deuterium and helium-3. It is determined that deuterium-helium-3 fusion is the most economically feasible technology for powering a moonbase and would therefore likely generate the majority of the power used by such a project.

1 Introduction

Energy is a critical element of any form of civilization. A steady power supply, be it biomass, livestock, coal, or nuclear reactions, is needed to cook food, warm homes, and produce and transport goods. Access to electricity, in particular, is strongly correlated with the human development index.[11] Earth alone consumed an average of 12 TW of power throughout 2015, a demand that only increases as time passes.[1] However, all known power sources have limitations and drawbacks, be it the scarcity of fuel, the repercussions of byproducts, or the cost of construction and maintenance.

The challenges of energy production will only become more acute when humanity inevitably expands its reach from Earth to the Moon and Mars. The Moon in particular is by far the nearest astronomical body, and therefore any interplanetary human civilization would almost certainly be preceded by at least one long-term self-sufficient moonbase. This base would face many novel challenges including intense solar radiation, fifteen-day nights, the need to recycle air and water, the need to grow food indoors, and the high cost of importation. In particular, these unique challenges will make the power requirements of such a settlement much higher than that of equivalently populated ones on Earth, as well as making some power sources far less feasible than they are on Earth.

A moonbase would have some unique assets, though. Lunar regolith is relatively abundant in helium-3, which is extremely rare on Earth. Furthermore, since any functional moonbase would be in the future, its denizens would likely have access to advanced technologies to which we currently do not, such as the advanced fusion reactors needed to burn helium-3 with deuterium. This makes deuterium-helium-3 fusion a potentially viable power source on the Moon where it is currently infeasible on Earth.

In this study, it is assumed that a moon base exists and has the technology to build igniting D^3He reactors, and the economic feasibility of D^3He fusion is then compared to that of other potential lunar power sources to meet that base's demand. Power sources are judged by their associated costs, as well as other features that impact their ability to be implemented and sustained.

2 Energy consumption

The first step in assessing the feasibility of any energy supply is to determine the corresponding demand. A moonbase will likely consume much more power per capita than a similarly-sized settlement on Earth, as unlike Earthlings, Lunarians must use electricity to grow plants, recycle their water, and pressurize their air. It is difficult to say how much energy all of this will require, but the closest existing analog is the International Space Station (ISS), which imports its food and much of its water from Earth, but does pay some air and water conservation related energy expenditures.

The ISS generates about 80 kW of electricity with its array of solar panels and sustains a crew of about six. As a conservative estimate, we can posit that a sustainable moonbase of 200 inhabitants would use the same amount of energy per capita, times two to account for the local agriculture and increased amenities a larger and more permanent population would likely demand. This would place our hypothetical base's energy consumption at about 6 MW total. This would be trivial to generate with existing technologies on Earth. However, on the Moon, various factors would increase costs—particularly of fuel—depending on the type of power generation.

3 Candidates

In this study, the primary means of energy production on Earth, as well as several proposed energy production technologies for the near future, will be considered. Those that depend on the direct harvesting of terrestrial resources, such as hydroelectric and wind, may be immediately discarded. That leaves solar, coal, natural gas, petroleum, uranium fission, deuterium-tritium (DT) fusion, and deuterium-helium-3 (D^3He) fusion. Of these, only solar power can definitely be utilized using only materials obtainable on the Moon. D^3He fusion depends on helium-3, which is obtainable on the moon, and deuterium, which might be obtainable on the moon. For the purposes of this study, it will be assumed that it is not. The rest would certainly require a constant supply of fuel imported from Earth. Imported fuels carry several significant drawbacks beyond the inherent fragility of a lunar civilization that depends on interplanetary trade for its survival. For instance, depending on the mass of fuel required to produce one unit of energy, transporting it from Earth to the Moon may be far more expensive than extracting or using it. For this reason, NASA primarily uses uranium to power spacecraft when solar panels are insufficient, as it has a much higher specific energy than other proven fuels. However, uranium is radioactive, which makes it ecologically dangerous and politically difficult to send large amounts of it into space.

All of these qualitative benefits and drawbacks are summarized in table 1. Each point will be expanded and quantitatively assessed in the following sections.

Source	Pros	Cons
Solar	Capital cost, independence	Durability, scalability
Coal		Import cost
Natural gas		Import cost
Petroleum		Import cost
Uranium fission	Independence	Capital cost, radioactivity
DT fusion		Capital cost, radioactivity
D^3He fusion	Independence, size	Capital cost

Table 1: A qualitative overview of potential energy sources for lunar civilization.

4 Abundance

The most commonly used energy sources on Earth are fossil fuels: coal, oil, and natural gas. Less often used but conceptually similar is enriched uranium.[1] Unfortunately, none of these resources have proven deposits on the Moon. Therefore, it is advantageous to look for alternative energy sources that can be harvested on site.

Solar energy is not only obtainable from the Moon's surface, but slightly more obtainable than on Earth in some respects due to the absence of a lunar atmosphere. The abundance of this energy can expressed by the solar constant $1.361\,\frac{\mathrm{kW}}{\mathrm{m}^2}$, which implies $4000\,\mathrm{m}^2$ of paneling to power the base.[5] This figure is misleading, however, as it fails to account for the 29.5 d lunar day cycle. In order to power a colony alone rather than simply supplementing a nonrenewable energy source during the day, equatorial solar farms would need to be have more like $12\,000\,\mathrm{m}^2$, and to either be broken up at several equally spaced longitudes or store surplus energy during the day and tap into that reserve at night. The former would require thousands of kilometers of cabling,[13] and the latter would require batteries capable of storing large amounts of energy for weeks at a time, but both would likely be achievable with future technology.

The assumption of an equatorial moonbase in the first place may be ill-founded, though. Measurements indicate that the Moon's water deposits are concentrated near the poles,[7] and recent estimates suggest that its largest helium-3 deposits may be concentrated there as well.[3] This suggests that the most advantageous location for a moonbase would be polar, not tropical. This would allow for solar farms to remain near their consumers while also receiving sunlight almost year-round by either comprising multiple outward-facing panels in a circle, or by constantly rotating. In either case they would need to be built vertically rather than horizontally. A rotating panel three stories high and four city blocks across would prove a technological challenge, but could be feasible given the combination of the Moon's weaker gravity and advanced technology. Nevertheless, multiple circumferential would be preferable for their improved scalability and durability, as discussed in section 7.

One resource that the Moon possesses in larger quantities than does Earth is helium-3, a fusable isotope of helium.[6] It occurs naturally in the top 2 m of lunar regolith, and can be extracted efficiently by heating that regolith up to 800 °C.[6] Helium-3 is not currently used as fuel on Earth because it is very rare (Earth's magnetic field diverts the solar wind that deposits it on the Moon), and the highly advanced reactor technology needed to conduct D^3He fusion is not currently available. Given a lunar colony with the advanced technology needed to establish such a base in the first place, though, D^3He fusion is perfectly feasible.

One helium-3 atom has a mass of 3.016 Da and can fuel one fusion event that releases 18.3 MeV of energy. This means that one kilogram of helium-3 can produce 163 GWh in a D^3He reactor. Low estimates place the total mass of helium-3 deposited in lunar regolith at 2 469 158 Mg,[9] distributed across the Moon's surface. This corresponds to a total energy of 4.02×10^{20} Wh, enough to power our fledgling lunar city for over seven billion years.

Of course, helium-3 is useless without its reagent counterpart, deuterium. Measurement of the Moon's polar ice deposits are far rougher than those of the Moon's helium-3 deposits, but recent estimates place the total mass of lunar ice deposits at up to 100 000 000 000 Mg[8] which, assuming a similar concentration of deuterium in lunar hydrogen as in terrestrial hydrogen, is equivalent to about 2 000 000 Mg of deuterium. If this number is accurate, there is more deuterium on the Moon than there is helium-3. However, this assumption is only safe if lunar water comes from the same meteorites that provided Earth's. The source of the Moon's water is not currently clear, so it is also not clear that the deuterium for a D^3He reactor could be harvested locally. The potential need to import deuterium from Earth is considered in section 5.

5 Importation

Given the proven effectiveness of more conventional fuels on Earth, the possibility of importing combustible, fissile, or fusable material to power a moonbase must also be considered. Byproduct disposal, the most controversial aspect of these fuels on Earth, is largely irrelevant, as any reaction byproduct can be harmlessly pumped into the circumlunar quasivacuum just as easily.

The lack of an atmosphere poses a challenge, as well. Most fuels rely on heat engines to extract their energy, which must expel heat to generate electricity. A plant that operates on a 0 °C–1000 °C temperature differential can be no more than 79% efficient; it must expel at least 273 kW of heat into the environment for every 1 MW of usable electricity it produces. Modern power plants depend on convection into environmental air or water to do this. On the Moon, the absence of any substantial atmosphere or ocean makes this impossible, leaving radiative heat transfer as the only alternative. Because radiative heat transfer is so much slower than convective heat transfer, engines that rely on it are limited to lower efficiencies. For example, Kilopower Reactors, which use Stirling converters powered by uranium fission and are designed to operate in space, have been shown to achieve efficiencies of only 23%.[4] This limitation increases the required amount of fuel from its nominal value by a factor of four.

Combustion in particular also faces additional challenges. Where on Earth oxygen is largely considered an unlimited resource, on the Moon it is just a scarce as the combustible fuel itself. The reaction would need to take place in a pressurized system where oxygen is pumped in. The oxygen often cannot be separated from the resulting carbon dioxide and water without expending as much or more energy than was released by the fuel. Thus, the total fuel mass to be imported must include the oxygen along with the combustible material itself.

The most expensive step in this process will most likely be the transportation of these fuels into space. While it varies based on the quantity of payload and is currently rapidly declining due to advancing technology, the cost of launching material into high Earth orbit is currently on the order of $1000 per kilogram of payload.[10] For comparison, extracting and refining a kilogram of oil on Earth only costs $0.66, and has been known to cost as low as -$0.32.[1] Therefore, the economic cost of using any of these fuels to power a moonbase can be determined from their specific energy, or the annual mass of fuel that would need to be imported.

The specific energies of common fuels are well documented, and those of fusion fuels can be easily computed. All are given in table 2. The mass of oxygen is included in the cost calculations for combustion fuels in stoichiometric proportion: two oxygen atoms for every carbon atom and one oxygen atom for every two hydrogen atoms. In addition, the total cost of importing fuel for a 6 MW plant is computed, assuming a rate of 1000 $\frac{\$}{\text{kg}}$, as well as an efficiency of 23% for thermal reactions.

Substance	Reaction	Spec. energy ($\frac{\text{MWh}}{\text{kg}}$)[2]	Spec. energy + O_2 ($\frac{\text{MWh}}{\text{kg}}$)	Orbit cost ($\frac{\$}{\text{MWh}}$)	Total cost ($\frac{\text{k\$}}{\text{y}}$)
Coal	Combustion	0.0067	0.0018	560 000	160 000 000
Natural gas	Combustion	0.013	0.0026	380 000	110 000 000
Petrol	Combustion	0.012	0.027	370 000	100 000 000
Enriched UO_2	Fission	970	970	1.0	290
DT	DT fusion	76 000	76 000	0.013	3.7
DTO	DT fusion	18 000	18 000	0.056	16
D_2	D^3He fusion	250 000	250 000	0.004	1.1
D_2O	D^3He fusion	25 000	25 000	0.04	11

Table 2: Several common fuels with their specific energies, and the specific cost of propelling them into high Earth orbit.

It can be seen that nuclear fuel sources bear a considerable advantage over combustible ones. Using this metric alone, in the absence of any power supplies on the Moon, pure deuterium and tritium for use in a fusion reactor would be the best fuel to import, as it would cost only $3700 per year in transportation costs to supply the Moon with power this way. If helium-3 is harvested on the moon and deuterium is imported alone, that cost drops to $1100 per year. Considering other limitations, this may not actually be optimal. The low freezing point of hydrogen means that fusion fuel would likely need to be transported into space as a cryogenic liquid or a gas, which presents technical challenges to containment. Binding it to oxygen allows it to freeze at relatively mild temperatures with about a factor of ten in cost increase. The energy required to divorce fusion reagents from oxygen is negligible compared to the energy each reaction releases.

More importantly, however, tritium as well as uranium is radioactive. Prospective shipping companies would therefore face substantial regulatory burdens associated with launching several hundred kilograms of either into orbit annually. If indeed only radiopassive materials may be launched into space, then the best alternative to solar and D^3He becomes natural gas. Natural gas requires much more mass to store the same amount of energy as nuclear fuels, and it would cost hundreds of billions of dollars annually to ship enough gas to the Moon to power one base.

6 Capital costs

Just because a resource is available locally doesn't mean it will be cheap to use it. Furthermore, the cost of transporting fuel is not the only cost that must be taken into account. All forms of power generation have physical infrastructure that must be built on the Moon. This infrastructure will likely be much more difficult to build on the Moon than on Earth; the 6×reduction in gravity will relax structural requirements, but all tools and materials (and most likely some assembled components) will need to be flown in from Earth, and all personnel will need to wear space suits while performing work on site. Furthermore, construction personnel will initially need to live in temporary housing, potentially in low Moon orbit, as the moonbase will not be habitable until it has some power generation capacity. These difficulties highlight the magnified importance of capital costs of power generation infrastructure on the Moon.

While the exact values of these costs are difficult to estimate, relative costs of different types of power plants can be compared using the most relevant statistics on Earth. Typically, power plant capital costs on Earth scale linearly with the number of required plants, which scales with power capacity. However, with the exception of solar farms, most power plants on Earth generate much more than the 6 MW our colony initially needs. Smaller plants could be designed to meet the moonbase's needs, but many of the components would not scale down linearly. Thus, best estimate for the capital cost of a power plant for a moonbase is the construction cost of a single plant on Earth. Typical and predicted values for existing power plants are documented by Tidball et al., and assembled in table 3. Notably absent are oil-fired plants and fusion-powered tokamaks, which were not included in Tidball et al.'s data sets. Oil plants are similar in size and complexity to coal and gas plants, and may be assumed to have similar capital costs. The overnight capital cost of a tokamak-based power plant is difficult to predict, since no tokamaks built to date have been designed to convert power into electricity. It would likely be somewhat higher than that of a fission reactor.

Plant type	Plant size (MW)[12]	Overnight capital cost ($\frac{\$}{\text{kW}}$)[12]	Total plant cost (M$)
Photovoltaic (solar)	5	5100	26
Coal	600	2200	1300
Combustion turbine (natural gas)	230	700	160
Nuclear (uranium)	1350	3400	4600

Table 3: Overnight capital costs of different types of power plants in 2007.

It can be seen that nuclear power bears a distinct disadvantage in this regard, as the technology to construct nuclear reactors on smaller, more affordable scales is not widely available. Solar panels, on the other hand, bear a considerable cost advantage, even accounting for the fact that multiple solar plants would need to be built. Fossil fuels have single plant costs that look quite reasonable, though they are dwarfed by the ongoing cost of importing their fuel (see section 5). Several factors will change these values relative to each other in a lunar context. First and foremost is the rapidly declining cost of newer technologies. Solar panels, in particular, are expected to continue to become more affordable in the future,[12] and smaller nuclear reactors that are be better suited to space applications are in development.[4]

Perhaps more pressing would be the heatsinks required for thermal power plants. Since radiative heat transfer is more limited by surface area than convection, heat engines on the Moon would need much more space dedicated to heatsinks than their counterparts on Earth. Assuming a maximally emmissive skyward-facing blackbody heatsink at 500 °C, a 6 MW plant with 79% efficiency would still require 64 m^2. That number is proportional to the plant size, and rises dramatically as the thermodynamic efficiency and heatsink temperature decrease; more conservative estimates of 23%, and 0 °C demand 64 000 km^2 of heatsink.

D^{3}He fusion circumvents this requirement where uranium fission and DT fusion do not, because its byproducts (protons and alpha particles) are electrically charged when created. This means that their kinetic energies can be extracted directly rather than thermally, bypassing the need for thermodynamic cycles and square-kilometer heatsinks while also reducing the amount of fuel required.[6]

D^{3}He fusion does have other expenses that thermal fuel cycles do not, however. In particular, harvesting fuel locally requires machinery to harvest and transport the helium-3 from the lunar regolith. Because of the simplicity of the technology required for this, it will most likely be negligible compared to the cost of the reactor itself. All that is required is devices capable of lifting lunar soil, heating it to 800 °C, chemically extracting the helium from the resulting gaseous mixture, centrifugally extracting the helium-3 from that, and transporting that to the reactor. Low estimates place the concentration of helium-3 in soil at 10 ppm by weight,[6] so only 0.32 mg of helium-3 and 32 g of soil annually will need to be processed this way. This would be easily accomplishable by a small mobile facility.

7 Adaptability

While it has been shown that several potential power sources could meet a small moonbase's energy needs initially, one must also consider the ability of such infrastructure to adapt to unforeseen changes. Any number of unexpected events could damage or hinder the Moon's power generation infrastructure.

The most obvious such event is the moonbase's growth over time. Ideally, an initial settlement of 200 or so volunteers would become economically self-sufficient, then expand into a proper colony and facilitate the creation of further cities on the Moon and other planets. Such growth could be made prohibitively expensive or impossible if the original base's infrastructure is not scalable. Specifically, solar farms and thermal power plants take up large amounts of space, which could make it difficult to build more after the moonbase is laid out. This is not necessarily prohibitive, since the moon currently bears about 40 000 000 km^2 of undeveloped land, which should offer plenty of potential building sites. However, solar panels must be spaced carefully so as not to cast shadows on each other, reducing the number of viable sites considerably. If they are constructed vertically in the vicinity of a polar moonbase, then new panels will need to be added on top of existing ones, or else sufficiently far away that they do not luminally interfere with each other. Either way, any supplemental panels will be much more costly to build than the original farm.

Less likely but perhaps more important is the interruption of trade with Earth, possibly due to terrestrial resource depletion, polticial conflict, or Kessler Syndrome. In this respect, energy that can be obtained on the Moon is inherently more secure than energy that relies of terrestrial agents for a constant supply, as it would allow lunar denizens to continue to eat and breathe in the absence of support from Earth. The only power source that could truly guarantee security from such an eventuality is solar power. However, imported fuels could be stockpiled, giving lunarians time to work out a solution if a problem were to arise. This is most viable for uranium and deuterium, since they are both cheap to transport and abundant on Earth.

Since power generation is so critical for life on the Moon, these systems should also be resilient against more general faults, such as accidents and lunar terrorism. A single power plant disaster should not seal the fates of all who live on the Moon. This primarily means that the colony should have multiple facilities, each of which can provide enough power for basic life support until the other can be repaired. Most forms of power could be split up among several plants with relative ease, though this constraint casts further doubt on the long-term viability of a single rotating solar panel. This would also discourage energy infrastructure that involves large and vulnerable components, such as the long cables that would be required to bring energy from remote solar panels. Even if redundant cables are installed, a series of disasters impacting large regions far from the moonbase could still leave it without power for certain weeks of the month. This leaves large monodirectional solar panels with advanced batteries to go with them as the only form of lunar solar power that is truly future-proof.

8 Conclusion

Several common terrestrial power generation technologies, as well as some currently developing ones, have been considered for use in a lunar context. While many of them are certainly feasible, all have significant associated challenges. Solar energy would require large vertically-mounted panels that could not be easily expanded, or kilometers of cabling that would be susceptible to severance. Importing conventional fuels would cost the lunar colony billions of dollars every year and require large heatsinks. Other nuclear materials could conceivably carry enough energy to sustain a moonbase for much less, but the radioactivity of tritium and uranium are notable drawbacks, as are the large and expensive facilities they would need. A D^3He fusion reactor would likely be the most expensive type of reactor that could be built. However, this would be outweighed by its relatively small size, due to the lack of thermodynamic heatsinks, and by the low cost of importing deuterium alone. The technology required to build such a reactor does not currently exist, but given the knowledge and means of lunar society, this would most likely be doable. For these reasons, it is clear that D^3He fusion will be the ideal means by which to power a moonbase.

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