Should Oxygen, Hydrogen, and Water on the Moon Be Provided by Earth Supply, Life Support Recycling, or Regolith Mining?

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The water needed for space life support has so far been provided by either direct supply from Earth on most missions or by life support wastewater recycling on the International Space Station (ISS). With the recent large reduction in launch cost, Earth resupply has become more attractive, but recycling always costs less than resupply for a large enough crew on a long enough mission. Water is also needed to make up recycling losses and oxygen and hydrogen are needed for propulsion fuel. This paper compares the costs of oxygen, hydrogen, and water on the moon for Earth supply, lunar recycling, and lunar mining. While Earth supply is the most expensive by far, lunar recycling and mining costs are not much different. Life support wastewater provides a large but limited supply, so lunar mining will always be needed. Minor cost reductions may make mining less expensive than recycling.

Nomenclature

AMCM	=	Advanced Missions Cost Model
BVAD	=	Baseline Values and Assumptions Document
CRS	=	Carbothermal Reduction of Silicates
DDT&E	=	Design, Development, Test, and Engineering
ESM	=	Equivalent System Mass
HRI	=	Hydrogen Reduction of Ilmenite
ISRU	=	In-Situ Resource Utilization
ISS	=	International Space Station
LCC	=	Life Cycle Cost
LEO	=	Low Earth Orbit
LH	=	Liquid Hydrogen
LOX	=	Liquid Oxygen
MOCM	=	Mission Operations Cost Model
MRE	=	Molten Regolith Electrolysis

I. Introduction

IN the future permanent human bases will be established on the moon. Supporting the lunar inhabitants will require water and oxygen and fueling their Earth return rockets will require oxygen and hydrogen. The possible sources of water, oxygen, and hydrogen are supply from Earth, mining on the moon, and wastewater recycling on the moon.

It is anticipated that the initial missions to the moon will use material supplied from Earth but that larger long duration bases will recycle material used by the crew. However, the recycling losses and the material used in propulsion must be made up either by Earth supply or lunar mining. Providing water, oxygen, and hydrogen by lunar mining or recycling requires equipment built on Earth and transported to the moon. Earth equipment has a high initial cost for development and launch, while Earth supply has a low initial cost but a large continuing development and launch cost. This means that as the total usage of water or oxygen and hydrogen grows, the increasing cost of Earth supply becomes greater than the cost of mining or recycling. For large requirements, Earth supply will be most

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expensive, but it is not clear if lunar mining or recycling is the better choice. Even if recycling is most cost-effective, lunar mining will still be needed to supply recycling losses and propulsion fuel.

Lunar mining was explained in detail in 1963 by Carr in, "Recovery of Water or Oxygen by Reduction of Lunar Rock."[1] A recent review cited more than 100 references on lunar mining.[2] Most work has been paper studies and bench experiments.[3] Many studies have found that lunar mining saves propulsion cost compared to Earth supply.[4]

A key reference is the 1988 Eagle Engineering report, "Conceptual Design of a Lunar Oxygen Pilot Plant: Lunar Base Systems Study."[5] It is comprehensive and detailed and has been used to support further work,[3,4] including this paper. The author and others have relied on the Eagle report because it is the only reference of this type. Schreiner examines it extensively.[4] Eagle reviewed thirteen different chemical processes. They developed a detailed approach for hydrogen reduction of ilmenite ore to produce oxygen. They considered very high oxygen production rates of 100 to 1,000 mt/year to provide propellant. They also investigated extraction of hydrogen from the regolith for propellant.

Many papers investigating In-Situ Resource Utilization (ISRU) mention both the propulsion and life support demand for oxygen, hydrogen, and/or water, but it does not seem that the combined demands have been considered in comparing the cost of Earth supply, lunar recycling, and lunar mining.

This paper will explain the processes for mining oxygen and hydrogen from lunar regolith, for supplying oxygen, hydrogen, and water from Earth, and for recycling crew wastewater on the moon. It will describe computing the factors of Life Cycle Cost (LCC), system development, power supply, launch, and operations. Then the costs for oxygen, hydrogen, and water will be computed for regolith mining, Earth supply, and lunar recycling. The costs will be compared for a variable required production rate in metric tons per year. The minimum cost is computed to meet the requirements of 100 crew over ten years of lunar base operation.

II. Assumptions

This paper is an economic analysis of the cost to provide water for a large future base on the moon, so the key assumptions involve water supply and demand. While many fundamental facts are known, much of the analysis is based on assumptions that should be considered.

The different water supply chains require resources, production, and transportation. The most crucial resources, the oxygen, hydrogen, and water in regolith on the moon, have been well quantified by Apollo sample analysis and remote observation. These same resources are freely available on Earth or can be recovered from crew wastewater on the moon.

The chemical reactions that can produce oxygen and hydrogen from lunar ore are well known and the mining, refining, and extraction process have been carefully studied. The construction, size, and operation of the equipment is likely to be similar to that expected by Eagle Engineering, which included near autonomous operation with remote control from a nearby lunar location. The use of artificial intelligence instead of human control would not reduce operations cost by much, since operations cost is typically only ten or twenty percent of total cost and includes much more than manpower. Recycling crew wastewater has been studied since the Apollo era and is well understood. Nuclear power was assumed because analysis shows that it requires much less mass than solar power. Since the nuclear reactor uses about forty percent of the mass required for oxygen mining, a lower mass nuclear power design would make lunar oxygen mining more attractive.

The water resources and production methods are well understood, but space transportation costs have changed and may change further. The space shuttle launch cost was very high and the SpaceX Falcon 9 reduced launch cost by a factor of twenty. Chinese developments could produce a similar further cost reduction. Nuclear may replace chemical rockets.

A much lower cost to launch from Earth to LEO would make Earth resupply competitive with lunar mining and recycling. One suggestion, originally made for a proposed Mars direct mission, would be to obtain oxygen from local resources and supply hydrogen from Earth. This option is not competitive for current launch costs, but lunar mined oxygen with Earth supplied hydrogen would be competitive if the current launch cost fell by a factor of ten.

The supply side assumptions seem reasonable and the effect of changing them is predictable, but the demand side is more arbitrary. The paper assumes that there will be a lunar base with 100 crew and that each crewmember will stay only six months, requiring two flights to Earth per crewmember per year. If permanent lunar habitation is possible, removing the return flight requirement would reduce total cost by twenty-five percent. The cost estimates apply to a large demand for water, but the costs scale with the total water demand.

The cost is most sensitive to lunar reactor mass and Earth to LEO launch costs.

A lower lunar reactor mass would make lunar oxygen mining more attractive and a much lower Earth to LEO launch cost could make resupply from Earth competitive.

III. Oxygen from Lunar Regolith

The lunar regolith contains about 42% oxygen by mass. Most of this is in the form of glasses such as SiO and metal oxides, especially iron oxide, FeO.[3] More than twenty different techniques to produce oxygen from lunar soil have been proposed, but the most studied and advanced are Hydrogen Reduction of Ilmenite (HRI), Carbothermal Reduction of Silicates (CRS), and Molten Regolith Electrolysis (MRE).[3,4]

In general, hydrogen reduction processes remove oxygen from the iron oxide, FeO, in the glasses and metal oxides. They are capable of extracting oxygen having a few percent of the mass of the regolith. The regolith is heated to 700 to 1000°C and exposed to hydrogen that reacts with weakly bound oxygen to form water. The water vapor is electrolyzed to produce oxygen and hydrogen that is recycled to continue the process.[3] The 1988 Eagle Engineering report included a thorough analysis of the Hydrogen Reduction of Ilmenite (HRI), including its mass and power requirements.[5] The Eagle analysis of HRI is used as the basis of cost estimates for obtaining oxygen from lunar regolith.

A. Hydrogen Reduction of Ilmenite (HRI)

In the HRI process, enriched ilmenite feedstock is heated to 900 to 1000°C in the presence of hydrogen gas. The hydrogen reacts with the iron oxides in ilmenite to form water.[3,4,5]

$$FeOTiO_2 + H_2 \rightarrow Fe + TiO_2 + H_2O \tag{1}$$

HRI can probably extract around 10% of the oxygen in lunar regolith in the equatorial mare regions (4 kg of oxygen per 100 kg regolith) and 3% of the oxygen from the much less abundant ilmenite in lunar regolith in the highland regions (1.3 kg of oxygen per 100 kg regolith).[4]

B. Ilmenite Mining and the Hydrogen Reduction Process

The Eagle Engineering report created detailed hardware designs for Lunar regolith mining and oxygen generation by the HRI process. Their design included an excavator, hauler, magnetic feedstock beneficiation to concentrate ilmenite, low-pressure and high-pressure hoppers, a fluidized bed reactor, a hydrogen recycling system, water electrolysis to produce oxygen and hydrogen, hydrogen recycling, oxygen cryogenic storage, a thermal control system, and many other subsystems. Parametric models were used to predict the mass and power of the lunar HRI process.[4,5]

C. Mining Mass and Power Requirements

Eagle produced a detailed conceptual design of a 2 mt/month lunar liquid oxygen (LOX) production plant. It used HRI, solar power arrays and regenerative fuel cells, and operated at a 45% duty cycle during lunar sunlight. If ilmenite rich mare basalt rock was used as feedstock, the mass of the plant plus a 146 kW solar power system power was estimated as 24.7 mt. Using more abundant mare soil did not increase the mass of the plant but more power was required to heat a greater less concentrated mass. Using mare basalt would save 15% of the mass, but the mass requirements for soil fed plants will be used here.

For a soil-fed pilot plant (1-5 mt LOX/month), solar power, 45% duty cycle:

$$\text{Oxygen plant mass (mt)} = 4.05 * \text{LOX (mt/month)} + 6.6 \tag{2}$$

$$\text{Total plant and power system mass (mt)} = 7.21 * \text{LOX (mt/month)} + 10.0 \tag{3}$$

$$\text{Power (kw)} = 71.1 * \text{LOX (mt/month)} + 22.8 \tag{4}$$

These equations for mass and power are based on the parametric sizing models developed by Eagle based on their detailed hardware designs.[4] A 30% margin is included. The solar power system requires nearly one-half the total pilot plant and power mass. Nuclear power offers the greatest potential for significant plant mass reductions. Total mass reductions of 45-50 percent are possible using nuclear power at a 90% plant duty cycle instead of a solar system at 45% duty cycle. Nuclear power is assumed for a production plant two orders of magnitude higher in capacity.

For a soil-fed production plant (144-1,500 mt/yr), nuclear power, 90% duty cycle:

$$\text{Oxygen plant mass (mt)} = 0.217 * \text{LOX (mt/yr)} + 8.73 \tag{5}$$

$$\text{Total plant and power system mass (mt)} = 0.231 * \text{LOX (mt/yr)} + 13.6 \tag{6}$$

$$\text{Power (kw)} = 2.95 * \text{LOX (mt/yr)} + 27.7 \quad (7)$$

The equations are from Eagle, pp. 100-101. P. 155 differs slightly.[5] The production plant has much higher production per unit of plant mass than the pilot plant, reflecting a significantly different design approach. LOX units in equations 2, 3, and 4 are mt/month while the LOX units in equations 5, 6, and 7 are mt/year. There is a very large decrease in the required plant mass per mt of LOX going from a pilot plant producing 1-5 mt LOX/month to a production plant producing 144-1,500 mt/yr, or 12-125 mt/month. The average production increases from about 3 to about 60 mt/month, a production increase by about a factor of 20, while the required plant mass decreases from mt = 4.05 * LOX (mt/month) to mt = 0.0180 LOX (mt/month), a reduction by a factor of 225.

The nuclear power plant mass is negligible, 7% of the total. The plant mass and power requirement will be used in estimating lunar oxygen production cost, but not the total plant and power mass since a new estimate of the mass of a nuclear power plant mass is used.

IV. Hydrogen from Lunar Regolith

Hydrogen is deposited by the solar wind in the lunar surface regolith and almost all of it can be extracted by heating to 900°C. Some of this hydrogen will react with the ferrous oxide in ilmenite to produce water, which can be used to produce oxygen and hydrogen.[5]

A. Hydrogen Content of Regolith

The solar wind flow at the moon's surface is about 1 gram of hydrogen per square meter in 63 million years. Solar wind hydrogen usually penetrates less than 200 angstroms into lunar regolith materials and small particles have a higher concentration of hydrogen than larger ones. The typical abundance of hydrogen in lunar soils is 40-50 ppm. Over 80 percent of the hydrogen is found in the sub 45 micron particles and separating the smaller material reduces the energy required to heat the soil. [5]

B. Hydrogen Production Process

The lunar regolith is gathered, transported, and loaded into a reactor after large (>1 cm) particles are removed. The regolith is heated in a reactor to 900°C to release hydrogen and produce water by reaction with ilmenite. Since the hydrogen content in regolith is roughly 50 ppm, about 20,000 kg must be heated to produce 1 kg of hydrogen. Thermal energy requirements are large and heat is recovered by preheating. Mining occurs during lunar daylight, 35% of the time, while processing occurs 90% of the time. Much of the thermal heat required is supplied by recovered reactor heat or nuclear power waste heat.[5]

C. Mining Mass and Power Requirements

The hydrogen plant mass includes mining and process areas and 30% margin,

$$\text{Hydrogen system mass (mt)} = 2.64 * \text{LH (mt/yr)} + 10.8 \quad (8)$$

$$\text{Electric power (MW)} = 0.122 * \text{LH (mt/yr)} + 0.021 \quad (9)$$

A 30% margin is included. The equations are from Eagle, p. 151. P. 155 differs slightly.[5]

V. Oxygen, Hydrogen, and Water Resupply from Earth

The provision of water and oxygen from Earth for lunar life support has been investigated.[6] A space qualified oxygen tank weighs 12.7 kg and contains 35.4 kg of oxygen, 0.36 kg tank mass per kg of oxygen. A space station water tank weighs 21.2 kg and holds 103 kg of water, 0.21 tank mass per kg of water. These current tanks are much too small for future lunar base supply. As a first approximation, changing the container capacity does not change the ratio of container to content mass, but would probably require new design and manufacturing approaches. It is assumed that the oxygen, hydrogen, and water containers will each hold 1,000 kg of material and mass 300 kg.

$$\text{Resupply mass (mt)} = 1.3 * \text{material (mt)} \quad (10)$$

VI. Water and Oxygen Supply by Recycling

A crewmembers oxygen need is only 0.84 kg/day, while their minimized water requirement is about 5 kg/day but it can be 10 or even 28 kg/day, if clothes washing, dish washing, and showers are provided[7,8] On the International Space Station (ISS), wastewater, urine, and carbon dioxide are recycled to produce water, some of which is used to produce oxygen. The oxygen generation system used on the ISS would not save mass or cost and oxygen recycling is much less cost-effective than water recycling.[9]

Since oxygen recycling is less efficient, we consider water recycling only. The water recycling system includes water filtration and urine processing systems. Their total mass is 604 kg, power is 0.39 kW, and logistics 0.19 kg per crewmember day. The total mass, volume, power, cooling, and logistics are from Carrasquillo, Reuter and Philistine.[10] The system can support 8-10 crewmembers, using roughly 40-50 kg/day of water total, or 14,600 -18,250 kg/year. The crew typically numbers six and the water recycling system does not run full time. The reported amount of water recycling is 6,000 kg/year. We will estimate the water recycling product as 10 mt/yr. The initial mass cost is 0.604 mt for 10 mt/yr production, 0.0604 mt/(mt/yr). The logistics cost is 0.19 kg per crewmember day, roughly 0.19 kg per day logistics for 5 kg per day production. This is 0.038 kg of logistics for each kg of water, or 0.038 mt/mt. The electric power is 0.39 kW for 10 mt/yr water recycling, 0.039 kW/mt/yr.

The recycling system masses and power are:

$$\text{Recycling system mass (mt)} = 0.0604 * \text{H2O (mt/yr)} \tag{11}$$

$$\text{Recycling logistics mass (mt)} = 0.038 \text{ H2O (mt)} \tag{12}$$

$$\text{Electric power (kW)} = 0.039 * \text{H2O (mt/yr)} \tag{13}$$

An investigation of water recycling for partial gravity moon or Mars missions considered alternate technologies with separated waste streams and a variable rate of recovery.[11] The smallest plant mass of about 1 mt was achieved at about 90% recovery. The flow rate for 4 crew each using 14.44 kg of water per day was 21 mt/year, so the plant mass requirement per unit flow was about 0.0474 mt for each mt/year of flow. This is similar to but about 20% less than the value of 0.0604 in equation 11, which will be used.

An investigation of water recovery for long duration missions found a plant mass requirement per unit flow that was more than 50 times higher.[12] Space station technology was used and the mass requirement was for Equivalent System Mass (ESM), which includes power system mass and other mass in addition to hardware mass. The assumed individual crew water requirement was only 5.05 kg per day, about one third that in the partial gravity study. Spares were included because of the impossibility of resupply or return on a deep space mission.

VII. Life Cycle Cost (LCC) Factors

To compare the costs of lunar mining, Earth supply, and lunar recycling we must consider the full Life Cycle Cost (LCC). LCC includes all the costs incurred during the three phases of a space mission: development, launch and emplacement, and operations.

A. System Development Cost

Development cost includes DDT&E (Design, Development, Test, and Engineering) and hardware production. Development cost can be estimated using the Advanced Missions Cost Model (AMCM).[13] The model is a single equation using mass, quantity, mission type, number of design generations, and technical difficulty to estimate the total cost for DDT&E and production.

The AMCM formula for the cost of DDT&E and production in millions of 1999 dollars is:

$$\text{Cost} = 5.65 * 10^{-4}\, Q^{0.59}\, M^{0.66}\, 80.6^{S}\, (3.81 * 10^{-55})^{(1/(IOC-1900))}\, B^{-0.36}\, 1.57^{D} \tag{14}$$

Q is the total quantity of development and production units, M is the system dry mass in pounds, S is the specification according to the type of mission (2.13 for human habitat, 2.39 for planetary base, 2.46 for crewed planetary lander), IOC is the year of initial operation capability, B is the block or hardware design generation (1 for new design, 2 for second generation), and D is the estimated difficulty (0 for average, 2.5 for extremely difficult, and -2.5 for extremely easy).[13] The difficulty, D, is determined by engineering judgment and is the only subjective element in the AMCM. For lunar mining and recycling, S = 2.39, IOC = 2040, B = 1, and D = 0. For large resupply containers, D = -1.5.[6] The AMCM equation is used to compute the cost of the mining plants, power plants, and containers used.

B. Power Cost

Nuclear power on the moon was assumed because it is much less expensive than solar power. Even the smallest nuclear power systems have a high mass, especially for shielding. Increasing the generating capacity only gradually increases the total system mass. For example, a 25 kW nuclear plant would typically have a mass of 5,000 kg, doubling the power output to 50 kW would increases the mass to approximately 7,000 kg, and doubling the power output again to 100 kW would increases the mass to around 10,000 kg. The Life Support Baseline Values and Assumptions Document (BVAD) gives the masses of ten nuclear reactors suitable for the moon with power from 16 to 100 kW and another with 550kW power.[14] The data is somewhat scattered but a reasonable data fit can be computed. (Mass (kg/kW) = 985 * Power (kW) $^{-0.54}$, $R^2 = 0.63$.)

The mass of a nuclear electric power plant for a given kilowatt capacity is:

$$\text{Mass of nuclear power plant (kg)} = 1{,}000^{*}\ \text{Power capacity (kw)}^{1/2} \tag{15}$$

The mass of a nuclear electric power plant per kilowatt capacity is:

$$\text{Mass per kW of nuclear power (kg/kW)} = 1{,}000^{*}\ \text{Power capacity (kW)}^{-1/2} \tag{16}$$

C. Launch Cost

Commercial rockets have greatly reduced the cost to launch to Low Earth Orbit (LEO). Launch to LEO is a small part of the total cost to emplace mass on the Moon. The Falcon 9 launches 22,800 kg to LEO at a cost of 62 million dollars, so the launch cost is $2.7 k/kg. The Falcon Heavy launches 63,800 kg to LEO at a cost of 90 million dollars, for a launch cost is $1.4 k/kg. The space shuttle cost was twenty to fifty times higher. The new low launch cost makes Earth supply more attractive.

The moon base cost per kg of payload is much higher than for LEO. The mass that must be placed in LEO includes the rockets and propulsion mass needed to take a surface payload to the Moon. A rocket's stack-to-payload mass ratio or gear ratio is the total mass needed in LEO (payload mass plus rocket mass plus propulsion mass) divided by the payload mass. To send hardware from LEO to lunar orbit and then land it on the surface has a gear ratio of 6.6. A reasonable launch cost for a Moon base would be about 10,000 $/kg, based on the Falcon Heavy cost of 1,400 $/kg and a Moon base gear ratio of 6.6. [6] An assumed launch cost of $10 M/mt will be used.

D. Operations Cost

Operations costs are usually estimated as a percentage of the development cost per year. For the shuttle, the ten year operations costs were 58% of the total cost, so that the yearly operations cost was 0.58/(0.42*10) or 13.8% of development cost per year. In an estimate for ISS, the ten year operations costs were 51% of the total cost, so that the yearly operations cost was 0.51/(0.49*10) or 10.4% of development cost per year, not including launch.[13] The JSC Mission Operations Cost Model (MOCM) estimates the operations cost per year as 10.9% of the total development and production cost.[15] The operations cost is estimated at 10% of the development cost per year.

VIII. Costs of Oxygen, Hydrogen, and Water

In this section we will consider the life cycle cost of oxygen from lunar regolith, of hydrogen from lunar regolith, of oxygen, hydrogen, and water supplied from Earth, and of water and oxygen from life support waste recycling.

A. Cost of Oxygen from Lunar Regolith

The AMCM formula for the cost of system development is given in equation 14. Setting the parameters for lunar mining (and recycling), S = 2.39, IOC = 2040, B = 1, and D = 0. There will be only one large plant, Q = 1. The formula was revised for mass in kg and 2021 dollars. $1 in 1999 had the same buying power as $1.601 in 2021.[16] The resulting formula is:

$$\text{Cost of oxygen (2021 \$M)} = 34\ (\text{Mass(kg)}^{*}2.2)^{0.66} \tag{17}$$

Equations 2 and 5 give the oxygen plant mass for a plant of a specific production rate in mt/month or year, so the development cost of the plant can be computed.

The power requirements for the oxygen plant are given in equations 4 and 7, and the mass of a nuclear power plant for a given power output is given in equation 15. The launch cost per kilogram will determine launch cost. The operations cost is estimated at 10% of the development cost per year. Assuming a ten-year operational life of the oxygen plant and nuclear reactor, their operations cost equals their development cost.

B. Cost of Hydrogen from Lunar Regolith

The computation of the cost of hydrogen production is similar to that for oxygen production. The mass and power requirements for a hydrogen plant are given in equations 8 and 9.

C. Cost of Oxygen, Hydrogen, and Water Resupply from Earth

All the tanks include 1,000 kg of material and have a mass of 300 kg. The AMCM the parameters for container supply are M = 300 kg, S = 2.39, IOC = 2040, B = 1, and D = -1.5. There will a large quantity of tanks, Q. The formula in 2021 dollars is:

$$\text{Earth supply cost (2021 \$M)} = 492\ Q^{0.59} \tag{18}$$

Since each tank holds 1,000 kg, the quantity Q of tanks is equal to the mass of the supplied material in metric tons. The containers have no power cost but the launch cost can be significant. Since they are emptied and discarded, few tanks are in concurrent use, so their operations cost is set to zero.

The development cost of tanks depends on the amount of material supplied. The cost of mining plants depends on their production rate, so the costs of mining and supply will be compared for a ten-year period, corresponding to the assumed operational life of the mining plants and reactors.

D. Cost of Water and Oxygen Supply from Recycling

There is an interesting issue in the design of water recycling for the moon. Should there be one large recycling plant, many small ones, of several for redundancy? Even though there is an economy of scale with an increasing number of systems there is also an economy of scale with an increasing mass of each system. The total mass of the system is equal to the quantity of units, Q, times the mass of one unit, so total mass is Q M. The cost of units in equation 14 is $Q^{0.59}\ M^{0.66}$, so a similar economy of scale is obtained no matter how the total recycling system mass is divided into units.

The recycling mass, logistics, and power requirements are given in equations 11, 12, and 13. The calculation of the cost of system mass and power is similar to that for oxygen and hydrogen mining. The logistics cost is treated similarly to the cost of Earth resupply. The recycling logistics cost depends on the amount of production, not the rate of production. The cost of recycling logistics will be the cost for 10 years at the specified production rate.

The option of using recycled water to produce hydrogen and oxygen was not included. The cost results in the next section show that water recycling is the least expensive option, which suggests that producing hydrogen and oxygen from water could be cost effective. Because human metabolism produces water from food and oxygen, the amount of wastewater exceeds the total input water, and the ISS electrolyzes some water to produce crew oxygen. However, since water recycling is not 100 percent efficient, all of the recycled water and more is needed by the crew. Oxygen and hydrogen from recycled crew wastewater are comparatively small resources. Also, the cost of producing oxygen and hydrogen from water is relatively high, due to difficult pressure safety and high power requirements. The mass of the ISS water recycling system that is used in the AMCM to compute plant cost is 604 kg and using the ISS oxygen generator would add another 113 kg.[6] The total mass would increase 19% and the cost would increase 12%, since cost increases as the two-thirds power of mass. Including unnecessary and difficult oxygen recycling with water recycling would make recycling cost similar to that of oxygen mining.

IX. Comparative Costs of Regolith Mining, Earth Resupply, and Lunar Recycling

The costs were computed for oxygen mining, hydrogen mining, Earth supply, and recycling for supply rates from 10 to 300 mt/year. The costs of plant, launch, and operations were computed and added to give the total Life Cycle Cost (LCC). The results are shown in Table 1, for the cases where the launch cost is 10 $M/mt and the mission duration is 10 years.

Table 1. LCC, $M, for oxygen, hydrogen, and water supply on the moon.

Process	Cost Category	Production capacity, mt/year			
		10	30	100	300
O2 Mining	Plant	93	185	261	433
	Launch	101	287	484	1,040
	Operations	93	185	261	433
	Total LCC	**287**	**658**	**1,007**	**1,907**
H2 Mining	Plant	223	399	830	1,678
	Launch	381	919	2,783	8,089
	Operations	223	399	830	1,678
	Total LCC	**828**	**1,718**	**4,442**	**11,444**
Earth Supply	Containers	7,447	14,239	28,971	55,394
	Launch	1,300	3,900	13,000	39,000
	Total LCC	**8,747**	**18,139**	**41,971**	**94,394**
Recycling	Plant	34	41	80	153
	Launch	60	143	460	1,355
	Operations	34	41	80	153
	Total LCC	**128**	**224**	**620**	**1,662**

Over the full range of process capacity, 10 to 300 mt/year, the four different processes have the same relative cost ranking. Recycling is least expensive, oxygen mining has similar but slightly higher cost, hydrogen mining is roughly 7 times as expensive as recycling, and Earth supply is roughly 50 times as expensive as recycling. Earth supply has a significantly higher cost than the other alternates. Even when the launch cost is reduced to 1 $M/mt and the mission duration is reduced to 1 year, which is more favorable for Earth resupply, the relative costs remain unchanged.

Although the launch cost is highest for Earth supply, its major cost is for manufacturing the containers, which are sent to the moon once and then disposed of. In contrast, the mining and recycling approaches build and launch a single set of equipment that is used for a mission duration of 10 years. The mining and recycling approaches also use regolith or wastewater that is already on the moon. Figure 1 gives the ten year costs for oxygen mining, hydrogen mining, Earth supply, and recycling for supply rates from 10 to 300 mt/year, using data from Table 1.

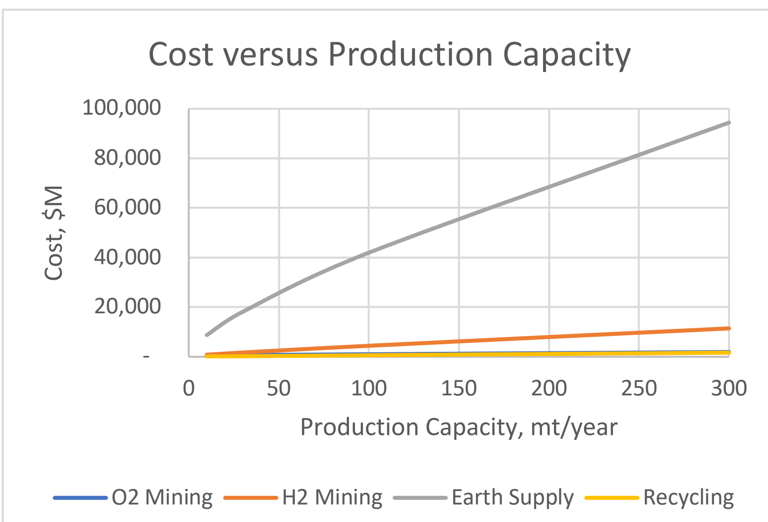

Figure 1. Total costs for mining, resupply, and recycling for supply rates from 10 to 300 mt/year.

Figure 1 shows the much higher cost of Earth supply and that oxygen mining and water recycling are very similar in cost. Figure 2 eliminates resupply to show the similar costs of oxygen mining and crew water recycling.

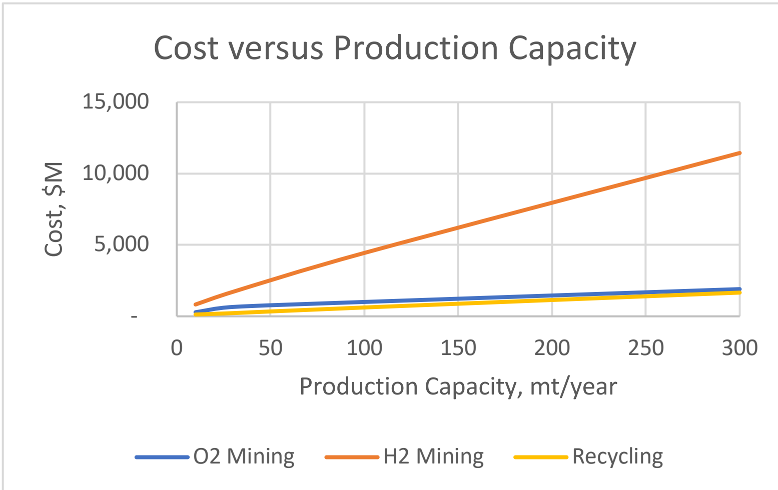

Figure 2. Total costs for mining and recycling for supply rates from 10 to 300 mt/year without resupply.

Oxygen mining is twice as expensive as recycling at low capacity but similar in cost at high capacity.

X. 10 Year Costs for Oxygen, Hydrogen, and Water for a Moon Base

As before, we compute LCC for an assumed launch cost of $10M/mt and a lunar mission duration of 10 years. We also assume that the moon base has 100 personnel so that the requirement for production of oxygen and hydrogen by regolith mining is in the investigated range of 10's to 100's of mt/year. We further assume that the total water usage is 50 kg/crewmember-day, 25 kg for personal use and 25 kg to support the habitat. The least expensive water source is recycling which we assume is 90% efficient. The lost 10% is produced from mined oxygen and hydrogen. The quantities and costs are shown in Table 2.

Table 2. Quantities and costs of crew and habitat water.

Supply	100 crew mt/y	Cost, $M
50 kg/crew-day	1,825	
90% recycling water	1,643	8,200
10% mining	183	
8/9 oxygen	162	1,308
1/9 hydrogen	20	1,288
	Total cost	**10,796**

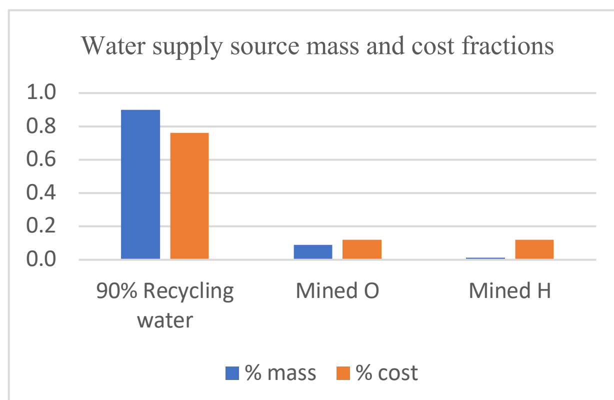

Figure 3. Water supply sources and costs.

The recycling and mining plant costs were computed as described above and used to prepare Table 2. The masses and costs of the water supply sources are shown in Figure 3. The bulk of the cost is for a very large water recycling plant. Although recycling is the current lowest cost water option, improving its cost and efficiency would have a strong effect on total cost. The 10 percent of water obtained by mining oxygen and hydrogen accounts for 24 percent of the total cost, so cutting mining cost would have less effect on total cost. The costs of the production capacity in Table 1 are 4.99 $M/(mt/y) for recycled water, 8.06 $M/(mt/y) for mined oxygen, 63.53 $M/(mt/y) for mined hydrogen and 14.22 $M/(mt/y) for water from mined oxygen and hydrogen.

The recent confirmation and more precise measurement of molecular water in shaded polar regions on the moon does not significantly change the cost of mining water. SOFIA found water in concentrations of 100 to 400 ppm.[17] Hydrogen is present in concentrations of 40 to 50 ppm. Water is 2 to 10 times as abundant as hydrogen, so the regolith collection costs would be reduced by a factor of 2 to 10. The regolith would be heated to a few 100°C rather than

900°C, but the power cost for hydrogen mining is only 1 or 2 percent of the total. The cost of mining molecular water could be the cost of mining hydrogen, 63.53 $M/(mt/y), divided by 2, 5, or 10, giving costs of 31.76, 12.71, and 6.35 $M/(mt/y). These costs are roughly twice, similar to, and half of 14.22 $M/(mt/y), the cost of producing water from mined oxygen and hydrogen.

Although life support requirements are most significant, the major reason for mining oxygen and hydrogen on the moon is to provide rocket propulsion fuel. The Eagle study considered providing fuel to lunar orbit and even to LEO but found it impractical.[5] Providing oxygen and hydrogen by lunar mining is clearly much more cost effective than supplying it from Earth. Suppose that the moon, with its 1/6 gravity and high radiation is nearly as inhospitable as deep space with microgravity and no lunar radiation shielding. The crew might be limited to six month stays. We assume that there will be two ascents to lunar orbit per crewmember per year.

The Apollo lunar ascent vehicle had 2,353 kg of hypergolic fuel to launch two astronauts to lunar orbit.[18] As oxygen and hydrogen are more effective propellants, we assume 2,353 kg of fuel will suffice, 1,177 kg per crewmember launch. Oxygen-hydrogen rockets are not run at the H2O stoichiometric mass ratio of 1 hydrogen to 8 oxygen, but with a hydrogen rich mixture of 1 hydrogen to 4 oxygen.[19] The quantities and costs of lunar rocket propellant for 100 crew making two ascents per year are shown in Table 3.

Table 3. Quantities and costs of oxygen and hydrogen propellant.

Supply	100 crew mt/y	Cost, $M
Fuel	235	
80% oxygen	188	1,431
20% hydrogen	47	2,413
	Total cost	**3,845**

Even at the high assumed number of two flights per crewmember per year, the cost of propulsion is much less than the cost of crew and habitat water. Adding the costs of habitat and propulsion material in Tables 2 and 3 gives a total cost of 14,641 $M, but combining the hydrogen and oxygen demands has some economy of scale with a reduced total cost of 13,512 $M.

XI. Comparison with Past Results

The prospect of mining for oxygen and water on the moon has frequently been considered. Some past work is listed in Table 4.

Table 4. Past work on lunar oxygen and water mining.

Publication	Date	Product	Rate, mt/y	Publication plant mass, mt	This paper plant mass, mt
Carr, B. B.	1963	Oxygen	20	5	25
Chepko, A. B., de Weck, O., Linne, D., Santiago-Maldonado, E., and Crossley, W. A.	2008	Oxygen	6	0.7	8.8
Schreiner, S. S.	2015	Oxygen	10	1.59	10.1

Carr found the total mass of an oxygen mining plant producing 20 mt/y to be about 5 mt, much less than the current paper's estimate of 25 mt.[1] Another study by Chepko et al.[20] found that production of 6 mt/y of oxygen required a plant of only 0.7 mt, much less than the current paper's estimate of 8.76 mt. A third study by Schreiner found that production of 10 mt/y required a plant of only 1.59 mt, much less than the current paper's estimate of 10.1.[4] Both Chepko et al. and Schreiner used the Eagle Engineering report and Schreiner followed it closely. Since the mass estimating functions used in Schreiner and this paper were derived from the Eagle report[5], the oxygen plant mass estimates are similar. However, the nuclear power masses in this paper are significantly larger, which increases the total plant mass in this paper. Furthermore, a recent paper finds that the required regolith mining rate and plant size, "is at least five times higher than previous estimates."[21] If the oxygen plant mass was much lower than in this paper, lunar mining could be much less expensive than recycling.

As previously noted, the French and Lange investigation of water recycling for long duration deep space missions found the ESM was about 20 mt for a recycling system that supplied 7.4 mt/year.[12] This paper estimates a recycling plant mass of only 0.45 mt, a few percent of their recycling mass estimate. The results are not comparable and several factors contribute to the difference. The system mass estimate is for Equivalent System Mass (ESM), which includes volume, power, and cooling mass in addition to hardware mass. They included spare systems because of the need for high reliability on a deep space mission but they are not included in this paper. Their water recycling system includes the ISS water filtration and urine processing as in this paper, but the individual crew water requirement was only 5.05 kg per day, about one third of that in this paper.

As previously noted, the work by Baryakova and Lange[11] on water recycling for moon or Mars missions considered alternate technologies with separated waste streams. The smallest plant mass to produce the required product was about 1 mt. The flow rate for 4 crew each using 14.44 kg of water per day was 21 mt/year, so the plant mass requirement per unit flow was about 0.0474 mt for each mt/year of flow. The current work uses a similar 0.0604 mt plant mass for each mt/year of flow, as initially assumed in equation 11 of this paper.

An earlier paper compared resupply and recycling for a moon base using cost estimating methods similar to those in this paper.[6] The costs for resupply are similar, but the previous recycling costs were much higher. As the quantity of supply increases, lunar recycling always becomes cheaper than Earth supply. In the previous paper, the breakeven between recycling and resupply, for a launch cost of 10 $M/mt also used here, does not occur until the total water production reaches about 100 mt. In the current paper, lunar recycling is always very much cheaper than Earth resupply. The previous paper used a full ISS life support system, including carbon dioxide removal and oxygen generation, not just the water system used here, which increases the recycling system mass by 55%. It has been past practice to compare complete high closure recycling systems to full resupply, but recycling water has higher efficiency than recycling oxygen. The previous paper also used 3 or 4 spares of each system for high reliability, while no spares are used in this paper.

XII. Conclusion

Recycling life support is obviously cheaper than Earth resupply for larger crews on longer missions, but limiting recycling to water only, not providing spares, and considering very large production quantities greatly increases the advantage of recycling. A large recycling capacity provided by many operating units requires many fewer spares for reliability. Although recycling is least expensive, oxygen mining has a similar but slightly higher cost, and hydrogen mining is only about seven times as expensive as recycling. Water from oxygen and hydrogen mining is about three times as expensive as life support recycling water. Water directly mined in polar regions has cost similar to water from oxygen and hydrogen mining. Life support water recycling must be supplemented by mined oxygen and hydrogen or water to make up lost recycling water and to provide propulsion fuel. Some investigators have found a much lower cost for oxygen mining, and a factor of ten reduction in this paper's mining costs would make mining cheaper than recycling.

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