Much Lower Launch Costs Make Resupply Cheaper Than Recycling for Space Life Support

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The development of commercial launch vehicles by SpaceX has greatly reduced the cost of launching mass to Low Earth Orbit (LEO). Reusable launch vehicles may further reduce the launch cost per kilogram. The new low launch cost makes open loop life support much cheaper than before. Open loop systems resupply water and oxygen in tanks for crew use and provide disposable lithium hydroxide (LiOH) in canisters to remove carbon dioxide. Short human space missions such as Apollo and shuttle have used open loop life support, but the long duration International Space Station (ISS) recycles water and oxygen and removes carbon dioxide with a regenerative molecular sieve. These ISS regenerative and recycling life support systems have significantly reduced the total launch mass needed for life support. But, since the development cost of recycling systems is much higher than the cost of tanks and canisters, the relative cost savings have been much less than the launch mass savings. The Life Cycle Cost (LCC) includes development, launch, and operations. If another space station was built in LEO, resupply life support would be much cheaper than the current recycling systems. The mission most favorable to recycling would be a long term lunar base, since the resupply mass would be large, the proximity to Earth would reduce the need for recycling reliability and spares, and the launch cost would be much higher than for LEO due to the need for lunar transit and descent propulsion systems. For a ten-year lunar base, the new low launch costs make resupply cheaper than recycling systems similar to ISS life support.

Nomenclature

AMCM	=	Advanced Missions Cost Model
BVAD	=	Baseline Values and Assumptions Document
CM	=	Crew member
COPV	=	Composite Overwrapped Pressure Vessel
d	=	days
DDT&E	=	Design, Development, Test, and Evaluation
ECLSS	=	Environmental Control and Life Support Systems
ESM	=	Equivalent System Mass
ISS	=	International Space Station
ILO	=	Initial Lunar Outpost
kg	=	kilograms
LCC	=	Life Cycle Cost
LEO	=	Low Earth Orbit
LiOH	=	Lithium hydroxide
MOCM	=	Mission Operations Cost Model

I. Introduction

THE justification for using recycling instead of direct resupply of water and oxygen is that it saves significant launch mass on longer missions. The ISS is a very long mission that uses recycling life support systems, but the much shorter shuttle and Apollo missions used resupply. Launch mass is usually measured by the Equivalent System Mass (ESM). In addition to the system's hardware mass, the ESM includes the launch mass required to provide the pressurized habitat volume needed to contain the system and the part of the power and cooling systems used to support

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the recycling system. Recycling systems also require spare parts or systems to repair failures and help ensure the availability of life support. Resupply would require a large mass of materials every day, and recycling saves most of that mass every day of the mission. The recycling mass breakeven date is reached when the total mass saved by recycling equals the total ESM used to provide the recycling system.

An ESM analysis comparing resupply and recycling will be conducted first and will be followed by an LCC analysis. ESM is useful to compare technologies in early system trade-offs, but the LCC is more important in final design. LCC includes the system development, launch, and operations costs. The development cost of recycling systems is much greater than that of resupply tanks, but the launch cost of recycling systems is much lower. Since the operations cost of a system usually increases with its development cost, it is expected to be much higher for recycling than for resupply. A cost-effective recycling system has lower LCC than resupply for the mission duration. The recycling cost breakeven date is reached when the LCC of resupply that is saved by recycling exactly equals the LCC of the recycling system. Commercial launch services have significantly reduced the launch cost to LEO. Lower launch cost appreciably delays the recycling cost breakeven date. With the new low launch costs, resupply will cost less than recycling similar to ISS for a ten-year or longer lunar surface base.

II. Recycling formerly saved cost, but now resupply is cheaper

A rough preliminary cost calculation shows that recycling has saved cost for ISS but would not have saved cost if the launch cost was as low as it is now. Table 1 shows the rough costs for ISS resupply and recycling.

Table 1. Costs for ISS recycling and resupply with shuttle and SpaceX launch costs.

Cost factor		Units	Explanation	References
Resupply mass	10	kg/CM-d	~ 4.99 water + 1.14 oxygen + 1.75 LiOH	In text
10 year resupply mass	36,500	kg/CM	365 days/year * 10 years	
Shuttle launch cost to LEO	75	$k/kg	$1,200 M/16,000 kg	(Pielke and Byerly, 2011)
Shuttle 10 year resupply launch cost	2.74	$B/CM	36,500 kg/CM * 75 $k/kg	
ISS recycling total system cost	0.50	$B/CM		(Jones, 2016-111
SpaceX launch cost to LEO	2.72	$k/kg	$62 M/22,800 kg	
SpaceX 10 year resupply launch cost	0.10	$B/CM	36,500 kg/CM * 2.72 $k/kg	(Spacex.com, 2017)

For resupply life support, each crewmember requires about 10 kg per crewmember per day (kg/CM-d) of water, oxygen, and LiOH. This mass includes the tanks and canisters. The crew water need is 4.16 kg/CM-d, and tanks add 0.83 kg/CM-d, for a total of 4.99 kg/CM-d. (Wieland, 1994, p. 6) (Carrasquillo, Reuter and Philistine, 1997) The crew required oxygen is 0.84 kg/CM-d in a tank mass of 0.30 kg/CM-d, for a total of 1.14 kg/CM-d. (BVAD, p. 31) (Orbital DS436, 2016) The mass of LiOH plus canister is 1.75 kg/CM-d. (Eckart, 1996. p. 192) The total of 7.88 kg/CM-d is rounded up to 10 to simplify the calculation. More explanation and references and a more exact calculation are provided later. The ten-year resupply mass is 36,500 kg/CM.

The shuttle launch cost was about 75 $k/kg. This corresponds to the actual cost of cost per launch of 1.2 billion dollars for 16,000 kg each to LEO. (Pielke and Byerly, 2011) The total ten-year launch cost for resupply would be 2.74 billion dollars per crewmember.

The total cost of the ISS life support system seems to be about 2 billion dollars, one billion for hardware development, and one billion for launch and operations. (Jones, 2016-111) The ISS recycling system is designed to support four crew members with some capacity margin, so the ISS recycling life support costs about one-half billion dollars per crewmember. Based only on the resupply launch cost, without the development and operations costs, resupply is more than five times as expensive as recycling.

This changes significantly if the new lower commercial launch cost is used. The SpaceX Falcon 9 launch cost is 2.72 $k/kg, since a Falcon 9 launch costs 62 million dollars and can place 22,800 kg in LEO. (Spacex.com, 2017)

The total ten-year launch cost for resupply using this new lower launch cost is 0.1 billion dollars per crewmember, only one-fifth of the cost of the recycling system. Decreasing the launch cost by a factor of about 25 changed the cost comparison from favoring recycling by 5 to 1 to favoring resupply by 5 to 1.

It seems that a future space station in LEO might use resupply instead of recycling, and that if lower cost commercial launch had been available when ISS was planned, the ISS might have used resupply instead of recycling. However, LEO is only the staging area for the moon and Mars and the launch costs to emplace mass on them are nearly an order of magnitude higher than for LEO. A long duration lunar base is the mission most favorable for recycling, since loss of life support is less critical than for Mars. The cost of recycling and resupply will be compared in detail for a ten-year lunar base.

It seems obvious that resupply would cost less than recycling when launch cost becomes low enough. The resupply materials, the water, oxygen, and LiOH, are not expensive, nor are their containers costly compared to recycling systems. With the previous high launch costs, the major resupply expense has been for launch. Recycling equipment has much less mass and much lower launch cost than resupply, but it has much higher development and operations costs. Since the new lower launch costs greatly reduce the cost of resupply, the cost - and the time, effort, and risk - of developing and operating more complex recycling systems does not seem justified.

III. Equivalent System Mass

The system mass is frequently used to compare space systems. In life support, mass has been expanded into ESM, which includes the mass of the hardware, its spare parts and operating materials, the mass of the power and cooling systems required to support the system, and the structural mass required to provided the enclosed pressurized volume to house the system. A life support system using resupply of oxygen and water will have its launch mass increase rapidly with longer mission duration. Conversely, a recycling system will have a large initial mass of hardware and supporting equipment but then the logistics mass will increase slowly due to spare parts and a small materials supply. After a certain time, at the ESM breakeven date, the rapidly increasing mass of a resupply system will exceed the ESM of a recycling system. The ESM of the ISS Environmental Control and Life Support System (ECLSS) will be compared to the mass used by resupply systems such as the space shuttle.

A. Definition of Equivalent System Mass

The ESM of a system is obtained by identifying its mass, volume, power, and cooling requirements and then computing its equivalent mass using the appropriate mass equivalents. The initial or fixed ESM is based on the system mass, **m**, volume, **v**, power, **p**, cooling, **c.** The volume, power, and cooling amounts are multiplied by their mass equivalents. (Levri et al., 2003)

$$\text{ESM}(\mathbf{m}, \mathbf{v}, \mathbf{p}, \mathbf{c}) = \mathbf{m} + \mathbf{v} * \text{me}(\mathbf{v}) + \mathbf{p} * \text{me}(\mathbf{p}) + \mathbf{c} * \text{me}(\mathbf{c})$$

The mass equivalent of volume is me(**v**), in kg/m^3, me(**p**) is the mass equivalent of power in kg/kW, and me(**c**) is the mass equivalent of cooling in kg/kW.

Usually a recycling system will require spare parts or periodic component replacement. It may also require a continual flow of input materials. If the logistics mass per year is **l**, and **t** is the elapsed time, the total ESM is increased by the **l** * **t** logistics mass.

$$\text{ESM}(\mathbf{m}, \mathbf{v}, \mathbf{p}, \mathbf{c}, \mathbf{l}, \mathbf{t}) = \mathbf{m} + \mathbf{v} * \text{me}(\mathbf{v}) + \mathbf{p} * \text{me}(\mathbf{p}) + \mathbf{c} * \text{me}(\mathbf{c}) + \mathbf{l} * \mathbf{t}$$

The ESM of a recycling system is largely an initial fixed mass, but the ESM of a resupply system is usually only an increasing variable mass. Oxygen, water, and the LiOH used to remove carbon dioxide require the additional mass of tanks or containers but they do not require power, cooling, or storage in a pressurized volume.

1. *The mass equivalents of volume, power, and cooling*

The mission is assumed to be to a long term lunar surface base, with a mission duration of at least 10 years and possibly longer. This is probably the most favorable mission for recycling as compared to resupply. The long mission duration allows the gradually increasing mass saved by recycling to pay back the mass initially launched to provide the recycling system.

The values of the mass equivalents depend on the mission location and the specific implementation of the habitat, power, and cooling systems. The mass equivalent of volume, me(**v**), on the lunar surface is 133.1 kg/m^3. The mass equivalent of power, me(**p**), is 749 kg/kW for solar power with fuel cell storage at the lunar equator. The mass equivalent of cooling, me(**c**), is 190 kg/kW using lightweight horizontal radiators at the lunar equator. (Baseline Values and Asumptions Document, BVAD, 2004)

2. The mass of spares

How many spare parts or full system back ups should a lunar surface base have? The recycling life support technology is assumed to be similar to ISS. The ISS has two or three onboard spares for each life support replaceable unit, but reliability is high enough that most spares will never be needed. The spares are provided to ensure that the probability of not having an immediate spare is very low. An analysis of a Mars transit system using technology similar to ISS assumed some double but mostly triple redundancy of full systems. (Connelly, 2000) Providing additional spares would be almost impossible during a Mars transit. A future lunar base will not need as many spares as Mars transit, and if launching spares on demand is easier, it will not need as many as ISS.

It is hoped that future research and development will produce recycling systems with higher reliability than current ISS systems and that improved rocket systems will allow the spares to be provided more quickly and easily. Therefore, it is assumed that a lunar surface base will need one operating version of each life support system and one off-line spare at the base.

3. Gear ratio or location factor to include propulsion mass

The recycling or resupply ESM is the mass of the materials and equipment that must be built on Earth, launched to LEO, then accelerated out to lunar orbit, and finally emplaced on the Moon's surface. A major mass cost is the mass to launch to LEO the rocket and fuel needed to move the life support system from LEO to the lunar surface. For each kilogram of material placed on the lunar surface, a 6.98 kg mass of the rocket and rocket fuel must also be placed in LEO. (BVAD, 2004)

Since all ESM is multiplied by this same 6.98 kg/kg gear ratio or location factor, the gear ratio does not affect the ESM comparison of resupply and recycling. The ESM breakeven date would be the same in LEO or on the lunar surface. However, the launch cost is a much larger component of LCC for resupply than it is for recycling, so the mission location and the gear ratio do affect LCC comparisons. The gear ratio will be applied to the system mass including its ESM and spares in the later computation of the LCC.

IV. Resupply launch mass

If the life support system does not use recycling, all the oxygen, water, and LiOH used to remove carbon dioxide must be resupplied. As these do not require hardware systems processors, the only component of ESM for resupply is the logistics mass.

On the ISS, a Sabatier processor is used to convert carbon dioxide to water and methane. Since the methane is vented, the hydrogen in the methane is lost and must be resupplied if the Sabatier is to recover all the oxygen in carbon dioxide. The hydrogen logistics mass is also computed.

A. Mass of the LiOH resupply used for carbon dioxide removal

LiOH is provided in multiple LiOH canisters. Each standard crewmember consumes 0.84 kg/crewmember-day of oxygen and produces 1.00 kg/crewmember-day of carbon dioxide. "These values are based on an average metabolic rate of 136.7 W/person (11,200 Btu/person/day) and a respiration quotient of 0.87." (Weiland, 1994, p.6) About 1 kg of LiOH is required to remove the 1 kg of carbon dioxide per crewmember per day. (Eckart, 1996. p. 192) The shuttle LiOH canister weighed 7 kg and was rated at 4 crewmember-days, so the required resupply mass of LiOH plus canister is 1.75 kg/crewmember-day.

B. Mass of the oxygen and possible hydrogen resupply

Oxygen and hydrogen are provided in multiple tanks. About 0.4 kg of tank mass is required per kg of oxygen (BVAD, p. 31) The best existing Orbital AKT Composite Overwrapped Pressure Vessel (COPV) weighs 36% of the mass of gas it can contain. The tank is constructed of a titanium center cylinder welded to two titanium end domes and overwrapped with carbon fiber. (Orbital DS436, 2016)

The required 0.84 kg/crewmember-day of oxygen is supplied in a tank mass of 0.84 * 0.36 = 0.30 kg/crewmember-day. The total of oxygen and tanks is 1.14 kg/crewmember-day.

The Sabatier converts carbon dioxide and hydrogen to water and methane. If the product water is converted to oxygen and hydrogen by electrolysis, half of the input hydrogen is recovered. If the methane is vented, the other half of the input hydrogen is lost, 0.18 kg/crewmember-day. The tankage for this hydrogen is 0.18 * 0.36 = 0.07 kg/crewmember-day. The total resupply mass of hydrogen and tanks is 0.25 kg/crewmember-day.

C. Mass of the water resupply

The minimum crew water requirements are: drinking and food preparation water, 2.37 kg/crewmember, urine flush water, 0.50 kg/crewmember, and wash water, 1.29 kg/crewmember, for a total of 4.16 kg/crewmember. The minimal water requirements are based on space station analysis, except that showers, dish washing, and most hygiene water have been eliminated. (Wieland, 1994, p. 6) (Reed and Coulter, 2000, pp. 122, 125) (Jones and Kliss, 2005-01-2810) (Jones and Kliss, 2010-6036)

A reasonable estimate is 0.2 kg of tank per kg of water. (ILO, 1991, p. 99) A shuttle water tank weighs 21.2 kg and holds 103 kg of water. (Carrasquillo, Reuter and Philistine, 1997) The required 4.16 kg/crewmember-day of water is supplied in a tanks massing 4.16 * 0.2 = 0.83 kg/crewmember-day. The total of water and tanks is 4.99 kg/crewmember-day.

Table 2 summarizes the resupply masses.

Table 2. Resupply masses of LiOH, oxygen, and water

Material	Material mass, kg/CM-d	Container, kg/CM-d	Totals, kg/CM-d
LiOH	1.00	0.75	1.75
Oxygen	0.84	0.30	1.14
Water	4.16	0.83	4.99
Totals	6.00	1.88	7.88

The total resupply mass will be compared to the recycling ESM.

V. Recycling systems Equivalent System Mass

This section computes the ESM of the ISS life support systems using the mass equivalents for a lunar surface base. The recycling ESM will be compared to the resupply ESM, which is equal to the launch mass.

The functions and parameters of the ISS life support system are listed in Table 3. The total mass, volume, power, cooling, and logistics are from (Carrasquillo, Reuter and Philistine, 1997) except that the Sabatier is from (Eckart, 1996, p. 197) and (ARC, 1990) and the carbon dioxide reduction logistics mass for hydrogen and tanks is from the above calculation.

Table 3. ISS life support system parameters and ESM.

Function	# crew-members	mass, kg	volume, m^3	power, kW	cooling, kW	ESM, kg/crew-member	logistics, kg/ crew-member-day
Carbon dioxide removal	4	201	0.39	0.86	0.86	315	0.00
Carbon dioxide reduction	4	18	0.05	0.05	0.27	33	0.25
Oxygen generation	7	113	0.14	1.47	1.47	232	0.01
Water filtration	10	476	2.25	0.30	0.30	153	0.13
Urine processing	8	128	0.37	0.09	0.09	49	0.06
Life support totals						782	0.45
Mass equivalents		2	133.15	749	190		
		kg/kg	kg/m^3	kg/kW	kg/kW		

The ESM of the ISS recycling systems is also shown in Table 3. The ESM is adjusted to the number of crewmembers that each system can support. It includes twice the system hardware mass to account for the mass of the off-line spare. The mass is doubled by using a mass equivalent of 2 kg/kg for the system mass. The mass equivalents are for an equatorial lunar surface base. Since the spare system is stored, it does not have additional ESM requirements for volume, power, cooling, or logistics.

VI. Equivalent System Mass of recycling compared to resupply

Recycling can replace resupply for carbon dioxide removal, for water supply, for oxygen supply, or for all of these combined. Charts show the time growth of ESM and the breakeven dates for these cases.

A. LiOH versus carbon dioxide removal

The ESM of LiOH versus carbon dioxide removal is shown in Figure 1.

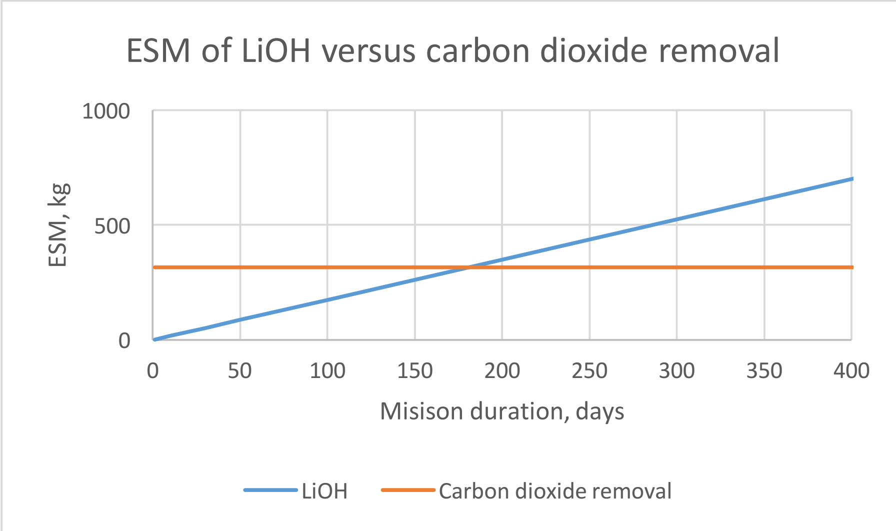

Figure 1. The ESM of LiOH versus carbon dioxide removal.

The carbon dioxide removal system does not have a logistics supply, so its ESM is constant over time. The breakeven date for carbon dioxide removal to replace LiOH canisters is 180 days. This is longer than for the other recycling systems below, due to its relatively high mass and power as shown in Table 3.

B. Water tanks versus water recycling

The ESM of water tanks versus water recycling is shown in Figure 2.

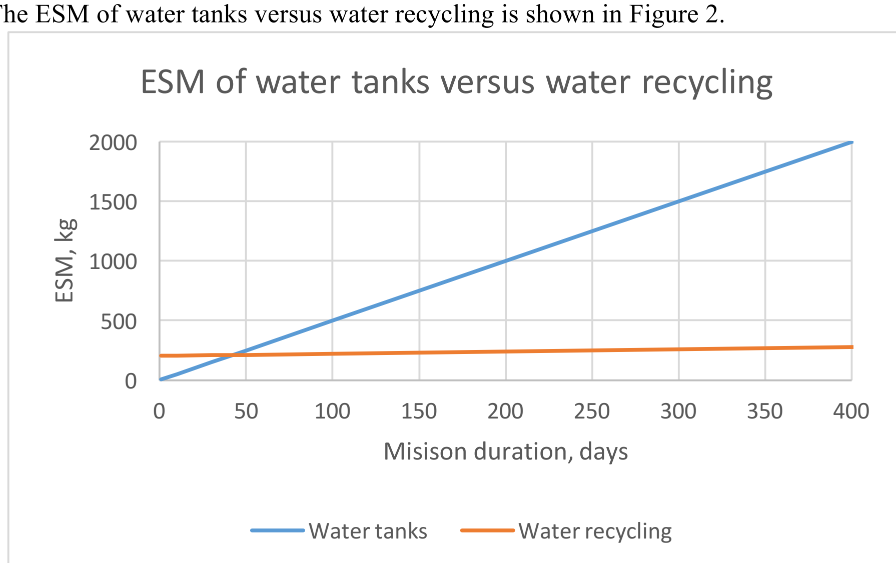

Figure 2. The ESM of water tanks versus water recycling.

The crew water is the largest component of resupply mass, about 50 percent. Water recycling has a shorter breakeven date than carbon dioxide removal or oxygen recycling, 42 days. Water recycling requires a small daily logistics mass.

Both water filtration and urine processing are included in water recycling. On ISS, the processed urine is passed through the water filtration system. Water filtration saves relatively more resupply mass than urine processing, since urine processing requires an added distillation process. Implementing water filtration alone would have the shortest breakeven date, but would require some additional water resupply.

C. Oxygen tanks versus oxygen recycling

The ESM of oxygen tanks versus oxygen recycling is shown in Figure 3.

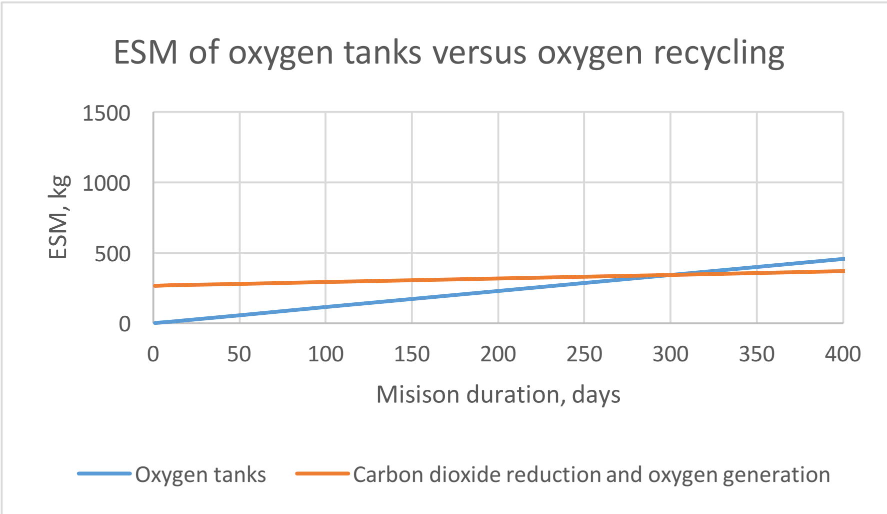

Figure 3. The ESM of oxygen tanks versus oxygen recycling.

On the ISS, oxygen is recycled from crew-produced carbon dioxide. This requires a Sabatier processor to convert the carbon dioxide to water and an electrolysis oxygen generator to produce oxygen from water. The ESM of carbon dioxide reduction and oxygen generation is compared to the mass of oxygen in tanks and the breakeven date is 301 days. Oxygen recycling depends on the existence of the other recycling systems, carbon dioxide removal and water recycling. The carbon dioxide removal system provides the carbon dioxide and the water system is needed to provide some additional water. Most of the oxygen breathed by the crew is converted to carbon dioxide, but a small portion becomes water. Some water from the water system must be added to the water from the Sabatier for the oxygen generator to provide the full crew oxygen requirement.

D. All resupply versus all recycling

The ESM of all resupply versus all recycling is shown in Figure 4.

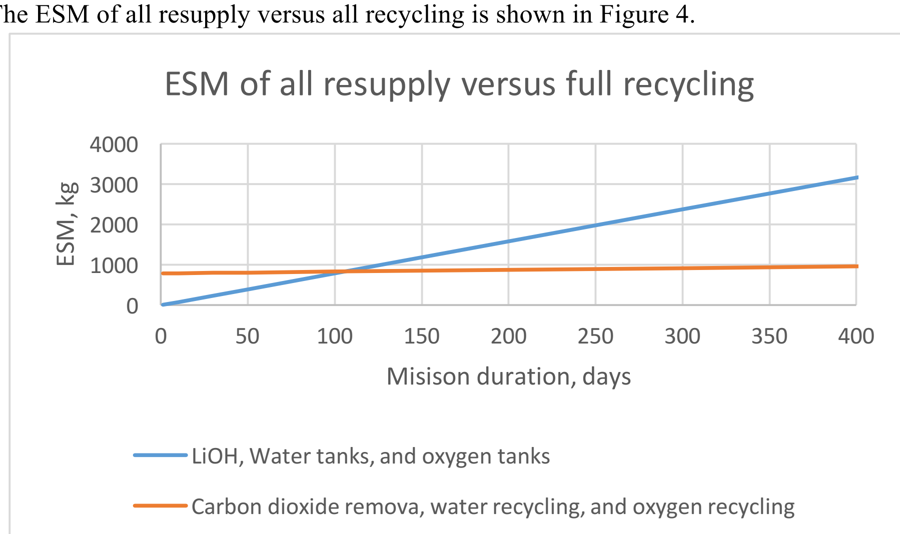

Figure 4. The ESM of all resupply versus all recycling.

The combined mass or ESM of all resupply, including LiOH, water and oxygen, is compared to the ESM of full recycling, including carbon dioxide, water, and oxygen. The full system breakeven date is 105 days.

If only partial recycling is implemented, perhaps for a shorter mission, water recycling would be implemented first. It saves the most launch mass and has the shortest breakeven date, 42 days. Carbon dioxide removal has a much longer breakeven date, 180 days, but it was implemented before water recycling on ISS. Considering the ESM payback, carbon dioxide removal should be implemented next after water recycling. Oxygen generation has longest breakeven date, 301 days, and it requires carbon dioxide removal and reduction, so it would be implemented last.

VII. System development cost

LCC includes all the costs incurred during the three phases of a space mission: development, launch and emplacement, and operations. 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). 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:

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

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). (Guerra and Shishko, 2000, pp. 946-7) (Jones 2013-3407) (Jones 2012-3618).

A. Resupply canister and tank development cost

Table 4 shows the AMCM cost estimation parameters and hardware development cost results for the LIOH resupply used for carbon dioxide removal, oxygen tanks, and water tanks on a ten-year lunar surface mission. The cost is in million dollars per crewmember, $M/CM.

Table 4. AMCM cost estimates for LiOH canisters, oxygen tanks, and water tanks.

AMCM parameter		LiOH canisters	Oxygen tanks	Water tanks
Q	Quantity	913	87	147
M	Mass, lb.	3.1	27.9	46.6
M	Mass, kg	1.4	12.7	21.2
S	Specification	2.39	2.39	2.39
IOC	Initial Operation Capability	2030	2030	2030
B	Block	7	20	2
D	Difficulty	-3	-3	-3
	Hardware development cost, $M/CM	122	88	385

The hardware development costs are produced directly by the AMCM. The total resupply development cost is 595 $M/CM. Mass, M, is given in lb. as in the AMCM formula but also in kg. The specification, S, initial operation capability date, IOC, and difficulty, D, are the same for the three types of resupply. The specification, S, is 2.39 for a moon base. The IOC date was set to 2030. The resupply storage systems are not at all difficult to develop. The resupply difficulty was set to -3, very extremely easy, for the future moon base. This is below the prescribed AMCM minimum of -2.5, but -3 seems more appropriate because of the very extremely easy technology of gas pressure tanks, water tanks, and material containers. If the difficulty was set to -2.5 extremely easy, the total resupply development cost would be 745 $M/CM, 25% higher.

The AMCM quantity, Q, mass, M, and block, B, differ for the three types of resupply. About 2 kg of LiOH is required to remove the 1 kg of carbon dioxide per crewmember per day. (Eckart, 1996, p. 192) The shuttle LiOH canister weighs 7 kg and is rated at 4 crewmember-days, which gives 1.75 kg per crewmember per day. The mass of the LiOH canister is estimated to be 20 percent of the total mass of the LiOH and container or 1.4 kg. One crewmember requires one 7 kg LiOH canister every four days, or quantity, Q, of 913 on a ten-year mission. LiOH has been primary on all human missions except Skylab and ISS, so counting Mercury, Gemini, Apollo transit and lander, shuttle, and spacelab, the block, B, is estimated at 7. (Wieland, 1994, p. 281)

The most mass-efficient existing Orbital AKT COPV weighs 36% of the mass of gas it can contain. The tank has 12.7 kg tank mass and contains 35.4 kg of oxygen. (Orbital, 2016) For the daily requirement of 0.84 kg of oxygen per crewmember per day, the tank supplies 42 crewmember days and quantity, Q, of 87 are needed on a ten-year mission.

The NASA space shuttle orbiter had twenty-four internal gas pressure vessels, many of different design, but the technology has been improved. The ISS has thirteen different types of on-board pressure vessels, some in multiple copies. Orbital ATK has produced 20 different pressure vessels for space use. (Jones, 2017-89) The oxygen tank block, B, is estimated at 20.

A reasonable estimate is 0.2 kg of tanks per kg of water. (ILO, 1991, p. 99) A shuttle water tank weighs 21.2 kg and holds 103 kg of water. (Carrasquillo, Reuter and Philistine, 1997) A crewmember requires about of 4.16 kg of water per day, so the shuttle water tank holds 24.8 day supply. The quantity, Q, of 147 is needed on a ten-year mission. Water tanks have been used on all human missions but designs have changed. The block, B, is estimated at 2, assuming a second generation design. (Wieland, 1994, p. 281) The hardware development costs include all the LiOH canisters and oxygen and water tanks for a ten-year mission.

B. Recycling hardware system development cost

Table 5 shows the AMCM cost estimation parameters and hardware development cost results for the recycling systems; carbon dioxide removal, carbon dioxide reduction, oxygen generation, water filtration, and urine processing for a ten-year lunar surface mission.

Table 5. AMCM hardware development cost estimates for carbon dioxide removal, carbon dioxide reduction, oxygen generation, water filtration, and urine processing.

AMCM parameter		Carbon dioxide removal	Carbon dioxide reduction	Oxygen generation	Water filtration	Urine processing
Q	Quantity	3	3	3	3	3
M	Mass, lb.	110.7	9.9	35.4	104.7	35.2
M	Mass, kg	50.3	4.5	16.1	47.6	16.0
S	Specification	2.39	2.39	2.39	2.39	2.39
IOC	Initial Operation Capability	2030	2030	2030	2030	2030
B	Block	2	2	2	2	2
D	Difficulty	1	1	1	1	1
	Hardware development cost, $M/CM	409	83	193	394	192

The hardware development costs are produced directly by the AMCM. The total recycling development cost is 1,271 $M/CM. Mass, M, is given in lb. for the AMCM formula and in kg. The specification, S, initial operation capability date, IOC, and difficulty, D, are the same for all the recycling systems. The specification, S, is 2.39 for a moon base. The IOC date was set to 2030. Recycling physical-chemical technology is not especially difficult. The recycling difficulty was set to 1, more than average, for a future moon base. A moon base will be risky even though emergency resupply or crew return are possible.

All the recycling systems have a quantity of three, corresponding to an operating system, an off-line spare on the moon, and a back-up on Earth. The recycling system hardware mass per crewmember is obtained from Table 1. The hardware block, B, was set to 2, second generation, for a future a moon base, assuming that the systems would be based on the ISS designs. If all block counts were set equal to 1, corresponding to a new non-ISS design, the total recycling development cost would be 1,625 $M/CM, a 29% increase.

VIII. Launch and emplacement cost

The launch cost in dollars per kilogram will be used in computing total cost. The effect of the new reduced launch costs is considered. The total launch cost includes the cost of launching the life support system and of launching the rocket and fuels needed to emplace the life support system on the moon's surface.

A. Launch cost

The space shuttle cost to launch to LEO was typically quoted as $25 k/kg. (Wertz and Larson, 1996, p. 125) The initially planned yearly space shuttle budget of 4 billion dollars for 10 launches of 16,000 kg each to LEO corresponds to this cost of $25 k/kg. Actual costs were higher due to a slower launch rate. The actual incremental cost per launch of 1.2 billion dollars corresponds to a three times higher cost of $75 k/kg. (Pielke and Byerly, 2011)

The SpaceX web page quotes costs for Falcon 9 and future Falcon Heavy launches. A Falcon 9 launch costs 62 million dollars and can place 22,800 kg in LEO, for a cost of 2.72 $k/kg. A Falcon Heavy launch is planned to cost 90 million dollars and would place 54,400 kg in LEO, for a cost of 1.65 $k/kg. These costs are for an expendable first stage. (Spacex.com, 2017)

A reusable first stage would have a payload 30% to 40% smaller because of the need to carry more fuel for reentry. SpaceX has suggested that the launch cost would also be reduced 30%, which would give the same launch cost per kilogram. (de Selding, 2016) However, the same SpaceX spokesperson earlier said that, "If we get this right, and we're trying very hard to get this right, we're looking at launches to be in the 5 to 7 million dollar range, which would really change things dramatically." (Messier, 2014)

If the cost of the Falcon 9 was reduced to $6 million and the payload was reduced by 35% to 14,820 kg, the launch cost per kilogram would be $405/kg. If the cost and payload for the Falcon Heavy were reduced similarly, the cost would be $9 million and the payload would be 35,360 kg, and the launch cost per kilogram would be $254/kg. These launch cost calculations are shown in Table 6.

Table 6. Launch costs for the shuttle and Falcon launch systems.

System	Shuttle actual	Shuttle planned	Falcon 9	Falcon Heavy	Reusable Falcon 9	Reusable Falcon Heavy
Cost per launch, $M	1,200	400	62	90	6	9
Payload in LEO, k kg	16	16	22.8	54.4	14.8	35.4
Launch cost to LEO, $k/kg	75	25	2.72	1.65	0.40	0.25
Lunar surface emplacement cost, $k/kg	524	175	19.0	11.5	2.83	1.78

The actual experienced launch costs range from $75 k/kg down to $2.72 k/kg, roughly a reduction by a factor of 28. Reusability of the first stage may provide another cost reduction by about 10, for a total launch cost reduction factor of 300 times compared to the space shuttle costs that were actually incurred to place the ISS life support system in LEO. A high launch cost in dollars per kilogram justifies developing recycling systems and may even justify spending more development cost to reduce the recycling system mass. However, the major mass saving is due to using recycling rather than resupply and reducing the mass of the recycling system seems less important than improving recycling system performance and reliability. The recent lower launch cost allows the use of resupply on missions 25 or 30 times longer than before.

B. Lunar surface emplacement cost and gear ratio

For a Moon surface mission, we must launch to LEO the payload and the propulsion system - including the vehicle and propellant – that are needed to get the payload to the lunar surface. For each kilogram of material placed on the lunar surface, a 6.98 kg total mass including the rocket and rocket fuel must be placed in LEO. (BVAD, 2004)

All mass launched, including the supporting ESM, is effectively multiplied by this 6.98 kg/kg gear ratio or location factor. That is, each kilogram of ESM on the moon requires 6.98 kg of ESM, rocket, and propulsion fuel. This will be accounted for by using the cost per kilogram for emplacement on the lunar surface, which is equal to the launch cost to LEO multiplied by 6.98. The lunar surface emplacement cost is shown in the last row of Table 5.

IX. Operations cost

The operations phase of most human space missions has been short, but ISS and possibly a future lunar surface base will operate for more than a decade. Future 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 = 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 = 10.4% of development cost per year, not including launch. (Guerra and Shishko, p. 938) The JSC Mission Operations Cost Model (MOCM) estimates the operations cost as a percentage of the total development and production cost of the spacecraft. For manned spacecraft, the estimated operations cost per year is 10.9% of the total development and production cost. (MOCM) It is apparent that if the mission is longer than ten years, the total operations cost will be larger than the system development cost.

Development cost and operations cost tend to be correlated because share the same cost drivers of system size, complexity, demanding requirements, technical difficulty, and strenuous operating conditions. Expensive systems tend to have have expensive parts and systems that are hard to design are often hard to trouble shoot. And it seems reasonable to invest in keeping an expensive system operating.

X. Resupply Life Cycle Cost

The LCC of LiOH, oxygen, and water resupply is shown in Table 7 for a ten-year lunar surface mission.

Table 7. Resupply Life Cycle Cost

	LiOH canisters	Oxygen tanks	Water tanks	Total
Fixed development cost, $M/CM	**122**	**88**	**385**	**595**
Fixed ESM, kg/CM	0	0	0	0
Variable ESM, kg/CM-day	1.75	1.14	4.99	7.88
Emplacement cost, $M/kg	0.02	0.02	0.02	
Fixed emplacement cost, $M/CM	**0**	**0**	**0**	**0**
Variable emplacement cost, $M/CM-day	0.035	0.023	0.100	0.158
10 year total variable emplacement cost, $M/CM	**128**	**83**	**364**	**575**
Variable operations cost, $M/CM-day	0.036	0.026	0.115	0.178
10 year total variable operations cost, $M/CM	**133**	**96**	**419**	**648**
Total fixed cost, $M/CM	122	88	385	595
Total variable cost, $M/CM-day	0.071	0.049	0.215	0.335
Total 10 year variable cost, $M/CM	261	180	784	1,224
Total 10 year cost, $M/CM	**382**	**268**	**1168**	**1,818**

The fixed hardware development cost for resupply is from Table 4. There is no initial fixed ESM for resupply, so the resupply ESM includes only the daily crew resupply launch mass. The emplacement cost is the cost to place one kilogram on the lunar surface, as shown in Table 6. 0.02 $M/kg, is used to approximately the current cost for a Falcon 9 launch to LEO and the LEO to lunar surface gear ratio, 19 $k/kg * 6.98= 19 $k/kg. As there is no fixed initial ESM, the fixed mass emplacement cost is zero. The daily and ten-year total emplacement costs are shown. The variable operations cost is 10.9 % of the fixed development cost per year, so the total ten year operations cost is 9% larger than the original development cost. The total fixed cost, the total variable cost per day, the total ten-year variable cost, and the total ten-year cost are computed. Interestingly, the fixed development cost, the ten-year emplacement cost, and the ten-year operations cost are all similar in size. The launch and emplacement cost is only about one-third or the total, so it does not dominate the cost of resupply.

XI. Recycling Life Cycle Cost

The LCC of recycling is shown in Table 8 for a ten-year lunar surface mission. The format of Table 8 for recycling is identical to that of Table 7 for resupply.

Table 8. Recycling Life Cycle Cost

	Carbon dioxide removal	Carbon dioxide reduction	Oxygen generation	Water filtration	Urine processing	Total
Fixed development cost, $M/CM	**409**	**83**	**193**	**394**	**192**	**1,271**
Fixed ESM, kg/CM	315	33	232	153	49	782
Variable ESM, kg/CM-day	0	0.25	0.01	0.13	0.06	0.45
Emplacement cost, $M/kg	0.02	0.02	0.02	0.02	0.02	
Fixed emplacement cost, $M/CM	**6.3**	**0.7**	**4.6**	**3.1**	**1.0**	**15.6**
Variable emplacement cost, $M/CM-day	0.000	0.005	0.000	0.003	0.001	0.009
10 year total variable emplacement cost, $M/CM	**0.00**	**18.25**	**0.73**	**9.49**	**4.38**	**32.9**
Variable operations cost, $M/CM-day	0.122	0.025	0.058	0.118	0.057	0.379
10 year total variable operations cost, $M/CM	**446**	**91**	**210**	**430**	**209**	**1,385**
Total fixed cost, $M/CM	415	84	197	397	193	1,286
Total variable cost, $M/CM-day	0.122	0.030	0.058	0.120	0.059	0.388
Total 10 year variable cost, $M/CM	446	109	211	439	214	863
Total 10 year cost, $M/CM	**861**	**192**	**408**	**836**	**406**	**2,704**

The fixed hardware development cost for recycling is from Table 5. The fixed and variable ESM, the fixed and variable emplacement cost, and the variable operations cost are computed as in Table 7 for resupply. The total fixed cost, the total variable cost per day, the ten-year total variable cost, and the total ten-year cost are also computed. The recycling LCC includes the logistics mass as Variable ESM and the mass of a spare system in the Fixed ESM. As for resupply, the total ten year operations cost is 9% larger than the original development cost. The total fixed plus ten-year variable launch and emplacement cost is much lower than for resupply, typically only a few percent of the total cost. Further reducing the hardware mass or the ESM of the recycling systems would save little cost.

XII. Comparing the Life Cycle Cost of recycling to resupply

As seen by comparing Tables 7 and 8 for a ten-year lunar surface mission, the cost of recycling at 2.7 $B is about 50% higher than resupply at 1.8 $B. The comparative costs of LiOH and carbon dioxide removal, water resupply tanks versus water recycling, and oxygen resupply tanks versus oxygen recycling are shown in Figure 5.

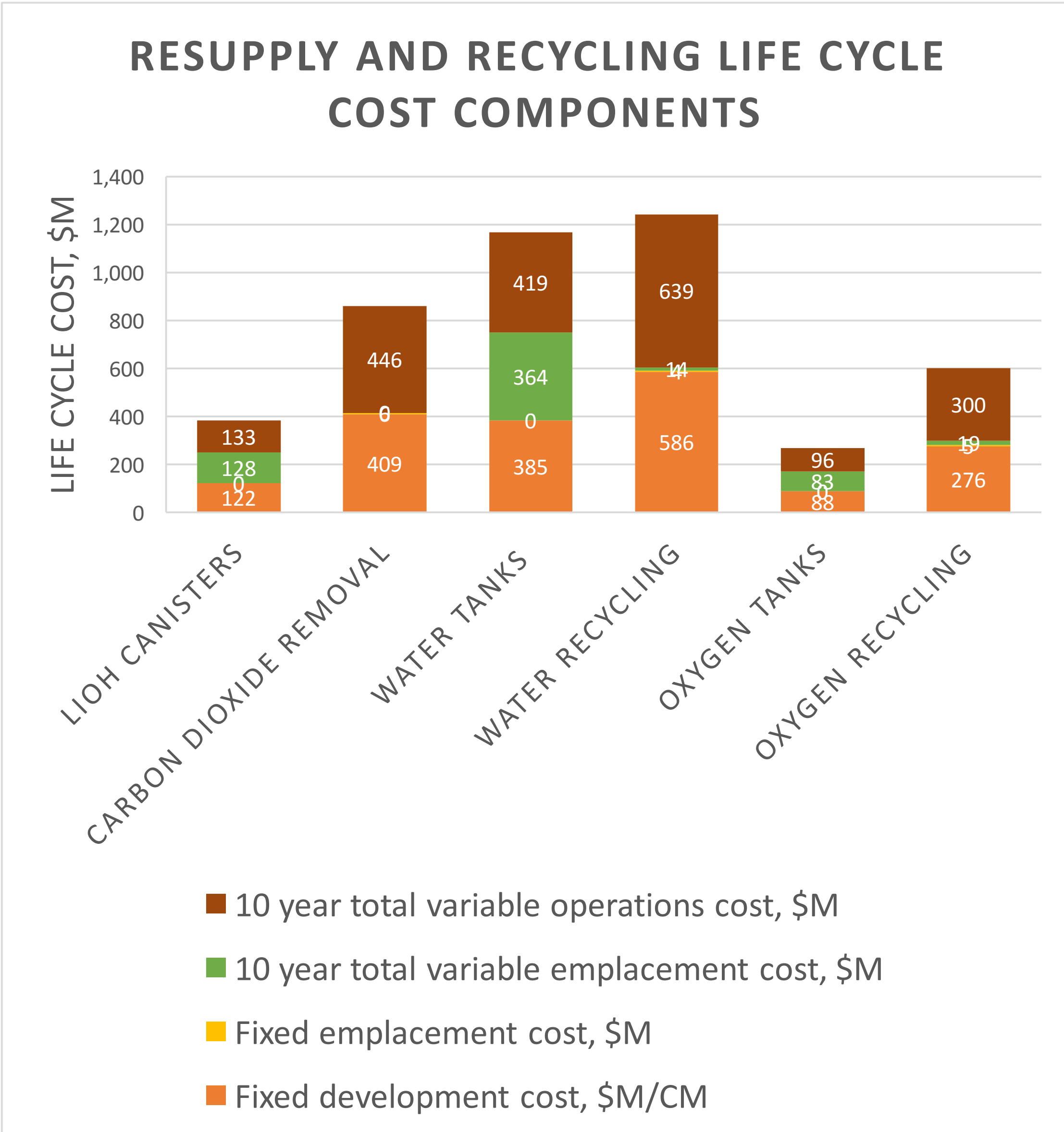

Figure 5. Resupply and recycling cost components for carbon dioxide, water and oxygen.

In Figure 5, water recycling includes both water filtration and urine processing and oxygen recycling includes both carbon dioxide reduction and oxygen generation. For all resupply and recycling systems on a ten-year lunar surface mission, the fixed development cost and the ten-year operations costs are roughly equal. For all systems, the fixed hardware emplacement cost is negligible. The variable emplacement cost is high for all resupply systems, LiOH, water tanks, and oxygen tanks, but is low for all recycling systems, carbon dioxide removal, water recycling, and oxygen recycling. In all three comparisons, carbon dioxide removal, water supply, and oxygen supply, the cost of recycling is greater than the cost of resupply. Water recycling is not much more expensive than water resupply, and a water filtration system without urine recovery would probably save cost over water tanks.

The LCC's of full resupply and full recycling systems for different mission durations are shown in Figure 6.

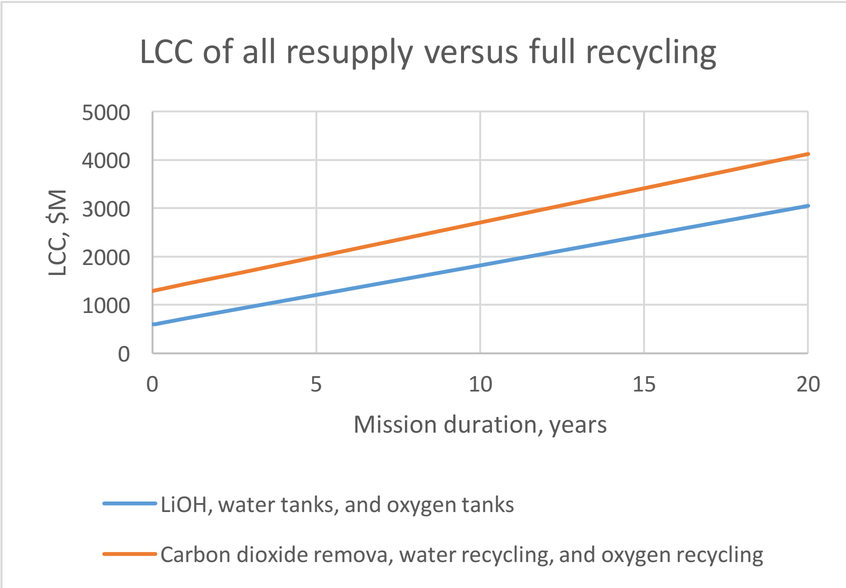

Figure 6. The LCC of LiOH, water tanks, and oxygen tanks versus the LCC of carbon dioxide removal, water recycling, and oxygen recycling versus mission duration.

As shown in the earlier Figure 4, full recycling does save ESM even for short missions. It would be expected that recycling would save LCC over a long enough mission. Surprisingly, recycling does not save LCC compared to resupply, even for an infinitely long mission. This is because the total daily cost of recycling, including operations and a little resupply, slightly exceeds the daily cost of resupply due to the launch and emplacement cost for resupply mass. The new much lower launch cost makes resupply life support cheaper than recycling for a lunar surface mission however long. Recycling never costs less than resupply.

XIII. The relative Life Cycle Cost of resupply and recycling depends on launch cost

Figure 7 shows how the LCC of resupply and recycling for a ten-year mission depends on the launch and emplacement cost. The range of launch costs includes the costs for launch to LEO only and the total launch and emplacement costs for the lunar surface, as shown in Table 6.

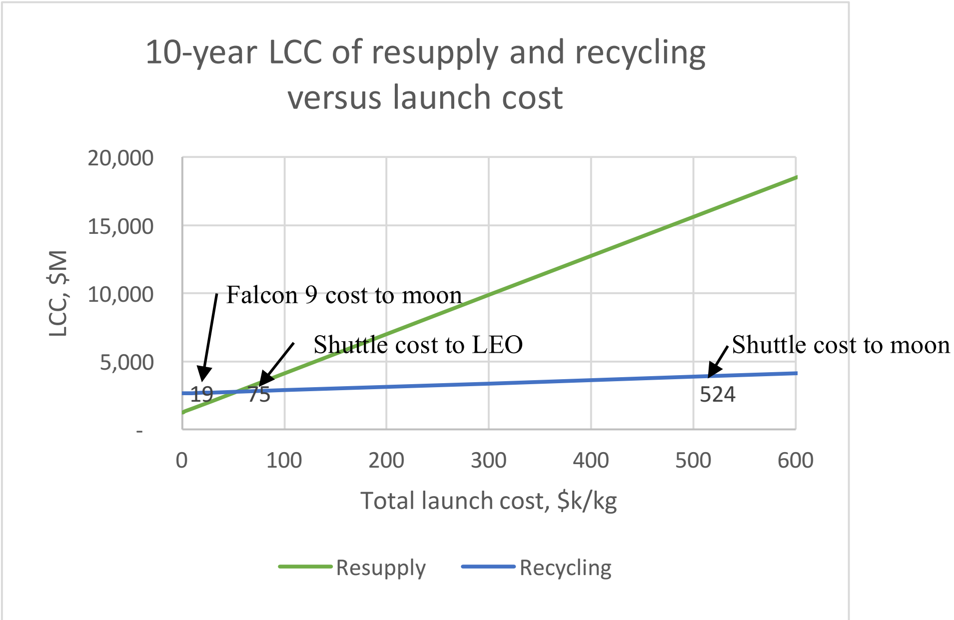

Figure 7. The 10-year LCC of resupply and recycling for a range of launch costs.

As expected, resupply has much higher cost than recycling for a ten-year mission when the launch cost is high. The LCC breakeven occurs at a total launch and emplacement cost of 54 $k/kg, whether the destination is LEO or the moon or beyond. Some launch costs from Table 6 are indicated in Figure 7. The shuttle cost of launch to LEO was 75 $k/kg and the shuttle cost for launch and emplacement on the moon would be 524 $k/kg. Using shuttle, recycling would be somewhat cheaper for LEO and much cheaper, 75% less, on the moon. The Falcon 9 cost for the moon would be 19 $k/kg, and for this low launch cost, recycling would cost 50% more than resupply. The Falcon 9 launch cost for LEO is only 2.72 $k/kg, and resupply costs only half as much as recycling.

XIV. Conclusion

When the ISS was being constructed, the cost of a space shuttle launch to LEO was about 1.2 billion dollars and the payload was 16,000 kg, so the launch cost was 75 thousand dollars per kg. Currently the Falcon 9 will launch 22,800 kg to LEO for 62 million dollars, a cost of 2.72 thousand dollars per kg. The launch cost to LEO has been cut by a factor of 28 times.

This very large reduction in launch costs has drastically changed the relative cost of resupply and recycling for space life support. Using the shuttle launch cost to LEO for ISS, the resupply launch cost is about five times the development and operations cost for recycling. Using the Falcon 9 launch cost to LEO, the resupply launch cost would be only one-fifth the development and operations cost for recycling. Considering the new lower launch costs to LEO, a new long duration space station in LEO would use resupply rather than recycling.

Because of the need for rockets and fuel to move systems from LEO to the lunar surface, the launch and emplacement cost is 6.98 times higher for a lunar base than for LEO. Recycling is more needed for a ten-year lunar base than for LEO, but even so, resupply is still about one-third cheaper than resupply. And because of the high operations cost of recycling, based on its high development cost, the actually daily cost of recycling is slightly larger than the daily cost of resupply. This means that resupply will be less expensive on a lunar base even for very much longer missions.

For decades, the high cost of space launch has been the major obstacle to the exploration of space. Now that launch costs have been greatly reduced, much more can be accomplished with the same budget. Direct resupply can provide water and oxygen much more cheaply, so the cost that could be saved by recycling is much less. The life support recycling systems that have been researched and developed since Apollo, and are being used on the ISS, may never be needed on a future space mission. The recent great reduction in launch cost has disrupted traditional life support recycling, but it has now made human space exploration more affordable.

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