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Trash to Supply Gas: Optimizing Propellant Production

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Extended missions on the Moon and beyond are expected to generate a significant amount of waste that must be managed. While different storage and removal options are being considered, there has been a push to increase sustainability on long-term missions by reusing or repurposing resources. Converting waste into useful gases through trash-to-gas technologies is a promising method to reuse the elemental resources contained within the waste stream while simultaneously reducing volume. This paper looks at several promising trash to supply gas (TtSG) technologies and discusses ways the waste processing methods could be optimized for propellant production. The optimized methods are traded against one another based on an equivalent system mass (ESM) analysis that accounts for the reduction in waste volume and production of propellant over extended lunar surface missions. The results of this work inform waste management tactics and technological developments necessary for long-term sustainable space missions.

Acronyms and Nomenclature

AOWG = Advanced Organic Waste Gasifier
CH_4 = Methane
CM = Crew Member
CO = Carbon Monoxide
COPV = Composite Overwrap Pressure Vessel
CO_2 = Carbon Dioxide
CTBE = Cargo Transfer Bag Equivalent
ESM = Equivalent System Mass
EVA = Extravehicular Activity
HFWS = High Fidelity Waste Simulant
H_2 = Hydrogen
HLS = Human Landing System
H_2O = Water
ISRU = In- Situ Resource Utilization
ISS = International Space Station
MAP = Microwave Assisted Pyrolysis
MC = Mated Carrier
O_2 = Oxygen
Plas-Pyro = Plasma Pyrolysis
SAO = Strategy and Architecture Office
TRL = Technology Readiness Level
TtG = Trash to Gas
TtSG = Trash to Supply Gas

I. Introduction

WITH the Artemis campaign full swing ahead, human space exploration has its sights set for the surface of the Moon, Mars, and beyond.[1] Landing astronauts on the Moon is but only the beginning. Industry and international partners alike have been working alongside NASA to envision and make possible the dream of long-term lunar base camps, where human presence is commonplace and but a steppingstone to Mars and beyond.[2,3] To make this dream a reality, resources to maintain this presence must be resupplied and/or reused. Reusing/repurposing resources has become a major topic of discussion for such long-term missions far from Earth because of the cost benefit of reducing resupply efforts and the sustainability of reducing waste. Waste generation is expected to be significant for long duration missions.[4-6] Therefore, waste management strategies that reuse or recycle resources have an advantage over storing waste in carriers or on the surface.

Waste management strategies have historically focused on reducing waste mass and volume. Such strategies have included compaction and subsequent storage, jettison of the waste, and thermochemically processing the waste into

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vent-able gases, known as trash to gas (TtG).[7,8] However promising these methods are at the reduction of waste, these strategies, as they are, do not provide an option for reusing the resources held within the waste stream. There is the potential, however, for such methods to be a jumping off point for a strategy that does. Trash to supply gas (TtSG) is such a strategy that aims to convert waste into useful gases that can support the mission, e.g. fuels, life support consumables, etc. This can be accomplished through a number of technologies that thermally process the waste and break it down into small molecule gases (CO_2, O_2, H_2, CH_4, etc.), liquids (H_2O, tar, etc.), and solids (carbon, metals, etc.).[9,10] By optimizing process parameters, the product stream can be tailored to a desired gas, reducing the volume of waste while simultaneously repurposing it. This volume reduction alone can be a significant benefit. Previous trade studies that considered TtG waste management have shown a significant volume reduction of thermally processed waste.[11,12] While in these scenarios the produced gas is assumed to be unused and vented, the volume reduction benefit alone has led to TtG technologies trading well on long term missions, oftentimes on par or better than compaction and jettison strategies.[7,13,14] With this in mind, long-term missions could benefit from using optimized TtG technologies that not only reduce the volume of waste but repurpose it into a useful product, i.e. TtSG.[15]

The type of supply gas chosen and availability of reactants dictates the technologies and processing scheme that can be used. For example, while combustion requires O_2 and primarily produces carbon dioxide, pyrolysis and steam reformation technologies can be optimized to reduce or eliminate additional reactants and produce various fuels.[11] Turning waste into propellant through the optimization of hydrogen production is one promising scheme for TtSG. In particular, on the Lunar surface there are multiple methods of generating O_2 or H_2O from regolith processing or polar ice extraction, but there are fewer avenues to produce fuels like CH_4 and H_2. Therefore, the unique makeup of waste – containing a surplus of hydrocarbons – provides a potential avenue for fuel production. Propellant in general is a costly commodity that must be brought along, compounding upon itself as fuel adds mass and mass requires more fuel. Since hydrogen is one of the major fuels being considered for lunar mission vehicles and beyond, along with CH_4 and liquid oxygen, producing hydrogen from waste could have a distinct benefit. For the lunar surface, it's within the realm of possibility to imagine a fueling station on the way to Mars where fuel is produced primarily by means of ISRU or another large processing method and is supplemented by TtSG. Furthermore, hydrogen production is a large area of research terrestrially for recycling waste[16,17] and can be used as a technical foundation for space applications.

This work details a trade study on the hydrogen production of four TtSG technologies configured for waste management in space. To account for missions when waste generation is significant, a 365-day lunar surface mission of 4 crew members is considered. Production of hydrogen propellant is optimized by considering non-selective technologies that process a diverse waste stream and comparing them with a technology that is selective for hydrogen but processes only a portion of the waste stream. Since the primary objective of this work is to understand the feasibility of producing hydrogen from waste, an equivalent system mass (ESM) analysis is performed, and the potential benefits of hydrogen production and volume reduction are assessed. A break-even analysis is also conducted to determine when the hydrogen production benefit outweighs the cost of implementing each technology when a volume reduction benefit is accounted for and when it is not. The results of this study can be used to inform waste management tactics and determine technological developments that would be necessary for long-term sustainable space missions.

II. Methodology and Assumptions

The waste conversion technologies considered are compared to one another based on their effective equivalent system mass (ESM), shown in Eq. 1. An ESM analysis accounts for various physical representations of the system (mass, power, volume, etc.) and converts them into the single metric of mass, making for a simpler comparison. This conversion is accomplished by using equivalency factors. Equivalency factors are vehicle/habitat dependent and account for the additional mass necessary to say, house the technology's volume, for example.

$$ESM_{\mathrm{eff}} = M + V * \gamma_{\mathrm{v}} + P * \gamma_{\mathrm{p}} + P * \gamma_{\mathrm{c}} - ESM_{\mathrm{H2}} - M_{\mathrm{MC}} \quad (1)$$

Here M is the mass of the technology in kg, V is the volume of the technology in m^3, P is the power in kW necessary to run the technology, and $\gamma_{\mathrm{v}}/\gamma_{\mathrm{p}}/\gamma_{\mathrm{c}}$ are the equivalency factors for the lunar surface habitat, detailed in Table 1. The cooling required is assumed to be approximately equal to the power required for the technology. The effective ESM used in this study also includes the benefits of each technology, namely the benefit of producing hydrogen on the Moon (ESM_{H2}) and the benefit of reducing the amount of waste that must be stored (M_{MC}). A complete ESM with all benefits and an ESM with the hydrogen benefit only is used to assess the technologies. The latter would apply in a case where no additional containers are required to store unprocessed waste, as described in the next section.

Table 1. Lunar Surface Equivalency Factors.[18]

Parameter	Lunar Surface Habitat
Volume Equivalency (kg/m^3)	17.6
Power Equivalency (kg/kW)	70.3
Cooling Equivalency (kg/kW)	95.0

A. Mission Assumptions

This work considers a year-long lunar surface mission where a crew of four remains on the surface, operating out of the lunar surface habitat for a consecutive 365 days. Each crew member (CM) is assumed to conduct three 8-hour extravehicular activities (EVAs) per week and resupply missions occur every 90 days from the start of the mission.[4] The resupply arrives in a mated carrier with a cargo volume of 70 Cargo Transfer Bag Equivalents (CTBEs).[4] For this work, the carrier space is made available for waste storage after supplies are unloaded.

The waste conversion technologies are assumed to process waste daily as a single batch process per day. This mass processed per day is what sizes the respective technologies. The produced hydrogen is assumed to be stored in containers already supplied for In-situ Resource Utilization (ISRU) processes or immediately moved into propellant tanks. Therefore, no additional containment unit is accounted for. The amount of waste processed by each technology in a year is dependent on the type of waste each technology can process. For example, if the technology was developed to process a diverse waste stream, then the technology is assumed to process all of the waste – excluding metals since these remain after processing. Conversely, if the technology was developed to process plastic waste only, then the amount of waste processed is equivalent to how much plastic is in the waste stream.

B. Waste Model

The waste model used in this study is based on waste model estimates from the Strategy and Architecture Office (SAO) for Artemis missions, modified to predict the maximum waste that could be on the Moon.[4] The majority waste streams consist of the crew consumables, EVA waste, and packaging from logistics carriers for the lunar surface and nearby orbiting station, Gateway. Since propellant production is a main focus in this work, Gateway logistics carrier packaging is included to showcase a "best case scenario" for hydrogen production. Therefore, it is assumed that this additional waste is brought to the surface for processing via the human landing system (HLS). It should be noted that waste quantity estimates are still preliminary for both Gateway and the lunar surface.

Each waste category is broken down into individual items that were further broken down into their source materials. A material breakdown of the waste model provides the necessary fidelity to better predict product gas compositions and allow for optimization of the waste stream.[19] Material breakdowns are derived from the current materials used on the International Space Sation (ISS). Each major waste category is categorized into the percent it is cellulose/cotton, metals, plastics, and other when the material is unknown. Because some technologies are optimized with non-oxygen containing plastics, the plastic category was further split into oxygenated, non-separable non-oxygenated, and separable non-oxygenated. The separable naming scheme represents those items that were assumed to have a 100% plastic composition and therefore could more easily be separated from the waste stream than composite materials that include plastic. This non-oxygenated separable plastic waste stream accounts for 14% of the waste stream considered in this study.

The rate of waste production is determined primarily on a CM per day basis and converted to total waste accumulated for the mission profile. In situations where waste was assumed on a per-re-supply basis, e.g. packaging, the waste production was first converted to a per CM per day basis and then calculated for the mission profile. Three resupplies (~ every 90 days) were assumed for this waste model. A breakdown of waste accumulation per major waste category is found in Table 2.

Table 2. Waste Model.

Waste Category	Material Breakdown (kg/CM-day)				Total Accumulation (kg/CM-day)
	Cotton/Cellulose	Metal	Plastic	Other	
Crew Consumables	0.73	0.06	0.62	0.18	1.59
EVA Waste	0.40	0	0.11	0.48	0.99
Lunar Surface Packaging	0	0	0.37	0	0.37
Gateway Packaging	0	0.21	0.25	0.59	1.05
TOTAL	1.13	0.27	1.35	1.25	**4.00**
Relative to total rate	28 %	7 %	34 %	31 %	

C. Waste Conversion Technologies

Four waste processing technologies investigated for space TtG applications are evaluated in this study. Because several technologies have traded well in past TtG studies due to low mass and volume,[11,12] those capable of also producing hydrogen are evaluated in this work. They consist of microwave assisted pyrolysis (MAP), plasma pyrolysis (Plas-Pyro), and an advanced organic waste gasifier (AOWG), each of which are capable of processing a diverse waste stream and producing hydrogen in large quantities. However, these technologies are not selective to hydrogen production and produce other gases such as CO and CO_2 in larger quantities. Therefore, they are compared against a microwave assisted pyrolysis technology that has been optimized for hydrogen production but only processes a portion of the waste stream (MAP-Plastic).

Each of the TtSG systems evaluated are based on an experimental reactor that has been scaled up to accommodate the increased processing rate for the mission profile. The experimental reactors range in technology readiness level (TRL). The TtSG systems are detailed in Table 3. Since not all systems were designed with the same waste stream, only equivalent waste streams are considered processed by that technology. For example, the first three technologies were designed with high fidelity waste simulant (HFWS) which is akin to the current waste model sans metals. Therefore, everything except metals is processed in those technologies. Conversely, MAP-Plastic was designed to process non-oxygenated plastic in order to optimize hydrogen production. Therefore, only the portion of the current waste model corresponding to non-oxygenated plastics that can be separated from the rest of the waste stream (separable non-oxygenated plastic) are considered processed in MAP-Plastic.

Table 3. Evaluated Trash to Supply Gas Systems

Technology Name	Thermal Process	Developer	TRL	Waste Stream
Microwave Assisted Pyrolysis (MAP)	Microwave induced pyrolysis	Advanced Fuel Research[20]	4	HFWS
Plasma Pyrolysis (Plas-Pyro)	Plasma induced pyrolysis	Kennedy Space Center, NASA[21]	3	HFWS
Advanced Organic Waste Gasifier (AOWG)	Oxygen-enhanced steam reformation	Pioneer Astronautics[11]	5	HFWS
Microwave Assisted Pyrolysis (MAP-Plastic)	Microwave induced pyrolysis	Cecilia Energy	4	Non-oxygenated plastic

The mass, volume and power of each technology is determined using the corresponding apparatus' values and scaling them up according to the daily required processing rate. Scale up was accomplished through the six tenths rule of thumb, where 60% of the system is scaled linearly with the processing rate and 40% remains unchanged.[22] To maintain consistency across technologies, only the components and corresponding power necessary to run the waste processing reaction and produce a product stream were included in the mass, power and volume values. No additional post processing components were considered. These included chillers, condensers, filters, pre-processing grinders or shredders, centrifuges, etc. The only additional mass contribution was the water necessary to run the AOWG system and is categorized as a consumable. To calculate this consumable, it was assumed that gasification of the waste is accomplished via a 43% water content in the waste stream. For MAP-Plastic, both a batch reactor and continuous reactor are in development. However, only the batch reactor was chosen for this study because it is more applicable for space applications due to its size and is most similar in processing scheme to the non-selective alternative, MAP. For Plas-Pyro, it is likely this reactor would operate with a pulsed current to optimize energy usage, so a 50% duty cycle was assumed.

Hydrogen production of each technology was determined from experimental data and depends on the percentage of solid that the technology converts to hydrogen gas, denoted as mass conversion. Therefore, it is assumed the conversions of the experimental reactors can be applied to the scaled reactors used in this analysis. In some cases, this information was readily available, while in other cases it was estimated from experimental product stream data or an equivalent parameter was used, e.g. MAP-Plastic reports the hydrogen recovered rather than mass converted. Since MAP-Plastic only processes a portion of the waste, an additional "add-on" technology was considered to supplement MAP-Plastic and optimize hydrogen recovery. This $\mathrm{MAP}_{\text{add-on}}$ is the same technology as MAP but has been sized according to the waste that remains post processing with MAP-Plastic. This processing scheme considers the scenario where both reactors are available for waste processing such that the hydrogen recovery is maximized. The processing parameters and sizing used for the $\mathrm{MAP}_{\text{add-on}}$, as well as the remaining technologies, can be found in Table 4.

Table 4. Waste Processing Parameters

Technology	Daily waste processed (kg/day)	H_2 Conversion (wt%)	System mass[a] (kg)	Consumables[c] (kg)	System volume[a] (m^3)	System power[a] (kW)
MAP	14.5	39.4	232	-	6.7	11.1
Plas-Pyro	14.5	29.8	338	-	5.7	11.9
AOWG	14.5	45.5	181	2050	1.6	1.2
MAP-Plastic	2.2	98.3[b]	232	-	1.0	10.6
$\mathrm{MAP}_{\text{add-on}}$	12.3	39.4	202	-	5.9	9.7

[a] These are scaled values according to processing rate.

[b] MAP-Plastic reports a hydrogen recovery percentage rather than a mass conversion.

[c] Only AOWG requires a consumable. This consumable is water.

D. Benefits to ESM

In addition to mass, volume, cooling, and power "costs", two benefits to the ESM analysis are investigated: a hydrogen production benefit, estimating the benefit of producing hydrogen on the surface of the Moon, and a volume reduction benefit, estimating the waste container mass due to volume savings by processing the waste. Each benefit is subtracted from the overall ESM to obtain an effective ESM. By reducing the effective ESM of each technology according to how much hydrogen it produces and how much waste it can process over the course of the mission, the expected advantage of using each TtSG technology for waste management is quantified.

1. *Hydrogen Production*

The hydrogen production benefit encompasses the mass savings of producing hydrogen on the surface of the Moon with resources that have already been accounted for. For this mission, it is assumed that hydrogen can be stored as a compressed gas or liquid within a container already present on the Moon from ISRU activities or can be processed directly into the necessary fuel tanks. If the H2 must be stored for long periods of time, it is also assumed that there are no H_2 losses due to storage. Since this scenario requires no additional containment unit, the mass savings of producing hydrogen on the Moon are equivalent to the ESM of bringing that same amount of hydrogen from Earth, shown in Eq. 2.

$$ESM_{\mathrm{H2}} = M_{\mathrm{H2}} + M_{\mathrm{tank}} + V_{\mathrm{tank}} * \gamma_{\mathrm{v,transit}} \tag{2}$$

Here, M_{H2} is the mass of hydrogen produced, M_{tank} is the mass of the storage tanks that would have been necessary to hold that hydrogen coming from Earth, V_{tank} is the volume of the storage tanks, and $\gamma_{\mathrm{v,transit}}$ is the volume equivalency factor for transit to the lunar surface.[23] The mass of hydrogen produced by each technology is dependent on the processed mass of trash and how much of the solid mass is converted to hydrogen gas by the technology. In all cases, experimental data using a similar waste stream was used to estimate the solid to hydrogen gas conversion. This was either acquired from previous trade studies on the same technologies[12] or calculated specifically for this work. The tank mass and volume are estimated from composite overwrap pressure vessels (COPVs) that are designed for N_2 gas storage and are being planned for Artemis missions. This method accomplishes a first pass estimate since information is not yet available to estimate tank deltas for a H_2 system.

2. *Volume Reduction*

The volume reduction benefit accounts for the volume storage savings that each technology provides by converting the waste primarily into gaseous products that can be used (hydrogen) or vented (other product gases). Because waste will likely be stored inside a module on the lunar surface, it is assumed the mated carriers that provide resupply resources can be emptied and used for waste storage. In the event of no waste processing, this would keep waste away from the main habitat where the crew resides. However, the ratio of resupply logistics volume to final waste volume is a current knowledge gap and should be considered in future studies. Resources that initially arrive with the crew are assumed to be stored temporarily inside the habitat until the first resupply.

Over the course of a year, 3 mated carriers are assumed as a baseline for storage capacity. These represent the 3 resupply carriers that provide logistics for the year-long mission every 90 days. The volume savings are therefore represented by the mass of any additional mated carriers (MC) above baseline that would be necessary to store the waste if it were not processed (Eq. 3).

$$M_{\text{MC}} = M_{\text{MC,single}} * \left[\left(\frac{V_{\text{reduced}}}{V_{\text{MC,single}}}\right) - 3\right] \tag{3}$$

Here, $M_{\text{MC,single}}$ and $V_{\text{MC,single}}$ are the mass and volume of a single mated carrier, respectively. V_{reduced} is the volume of waste that was reduced via thermal processing and is calculated from Eq. 4.

$$V_{\text{reduced}} = \frac{M_{\text{gas}}}{\rho_{\text{avg}}} + \frac{M_{\text{remain}}}{\rho_{\text{H2O}}} \tag{4}$$

Here, M_{gas} is the mass of waste that was converted into a gas, M_{remain} is the mass of liquid and solid waste that remains after processing, ρ_{avg} is the average density of the waste prior to processing, and ρ_{H2O} is the density of water. ρ_{avg} accounts for the increase in volume that occurs when logistics items and packaging become waste and is equal to 150 kg/m^3.[24] Eq. 4 also assumes the density of the liquid and solid waste post processing can be estimated as the density of water. Since thermochemical liquid and solid products can range in density and differ across technologies, water is used as a middle ground between lighter products like ash and denser products like biochar or carbon black.

III. Results and Discussion

The following sections present the results and discussion of the above-mentioned waste processing technologies in regard to their hydrogen production and ESM for a 365-day lunar mission. The first section presents the hydrogen gas produced by each technology and discusses how splitting the waste stream can optimize hydrogen production. The equivalent system mass of each technology is then compared, including the feasibility of having two technologies for a split waste stream. This second section also looks at the impact of the hydrogen benefit on the ESM separately from the volume reduction benefit. Finally, a break-even analysis for the ESM with the hydrogen benefit only is presented to showcase when the technologies will break even if volume reduction is not a benefit, i.e. a case where waste is stored outside in a manner akin to the landfills on Earth.

A. Hydrogen Production

The total mass of hydrogen produced by each technology over the course of the year-long mission is presented in Figure 1. All technologies produce over 100 kg of hydrogen and in two cases (MAP and AOWG), over 200 kg. While this amount will not fuel a vehicle to Mars, or even back to Earth, it could supplement a larger propellant production

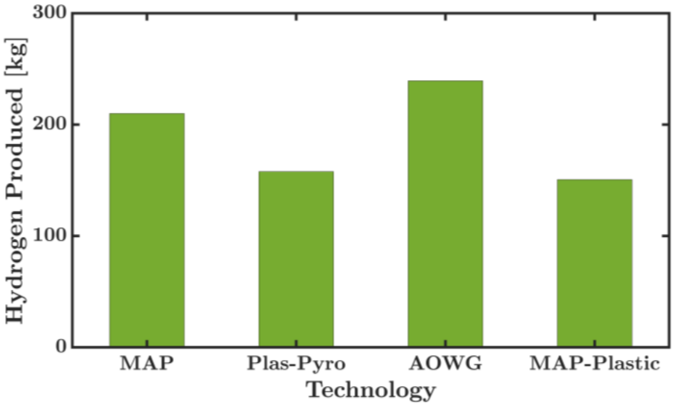

Figure 1. Total hydrogen production over the course of a one-year mission for each evaluated technology.

outfit on the surface while simultaneously removing waste. This is especially true considering that for every 10mT of O_2 required to fuel a vehicle, ~1.7mT of hydrogen is required. Current ISRU propellant production plans of using water electrolysis lead to hydrogen production as the limiting factor.[25] Therefore, 200 kgs (0.2mT) of hydrogen pulled from the waste would be a significant contribution and showcases the potential promise of repurposing trash into propellant.

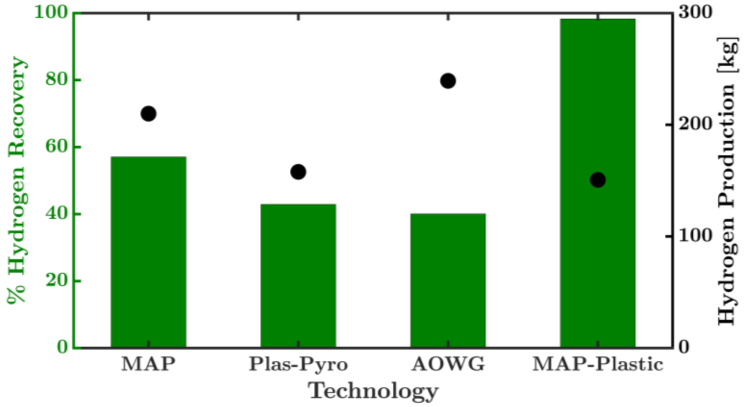

Figure 2. Percent hydrogen recovered from processed waste by each technology over the course of a year-long mission.

In comparing the technologies, AOWG produces the most hydrogen at 239 kg, followed by MAP, Plas-Pyro, and finally, MAP-Plastic. Despite producing the most hydrogen, however, AOWG requires a significant amount of water in the waste stream to carry out the steam reformation. This means that hydrogen in the form of water must be input into the reaction to achieve this final production value (see consumables in Table 4). While AOWG is still net positive in hydrogen production (~10 kg), this water requirement makes it less favorable over MAP, Plas-Pyro, or MAP-Plastic, which require no form of hydrogen input. This is highlighted by looking at the percentage of hydrogen recovered by each technology and comparing it with its hydrogen production (Figure 2). At 40% recovery, AOWG sits at the bottom of the four technologies for hydrogen recovery despite having the greatest hydrogen production.

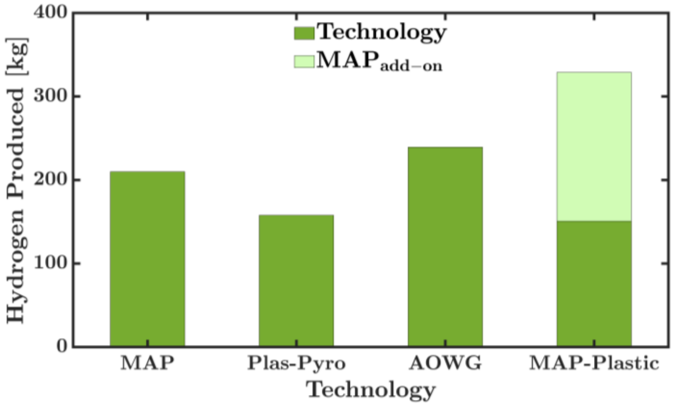

Figure 3. Optimized hydrogen production when additional technology is added to assist MAP-Plastic waste processing.

In contrast to AOWG, MAP-Plastic technology produces the least amount of hydrogen out of the four technologies but has the greatest hydrogen recovery. The reason MAP-Plastic has the lowest hydrogen production is because it processes the least amount of waste, processing ~85% less waste than AOWG, MAP, and Plas-Pyro. However, this technology's high selectivity for hydrogen, showcased by its percentage recovered, keeps it within only a few kg of the Plas-Pyro technology that processes all of the waste. With this in mind, the MAP-Plastic technology could be used to optimize propellant production if combined with another technology that could process the remaining waste.

To test this situation, a mission scenario was considered where the MAP-Plastic technology was used to process the non-oxygenated plastic waste as usual and the MAP technology was used to process the remaining waste. Since MAP has the next best combined hydrogen production and recovery, it is the best suited of the three non-

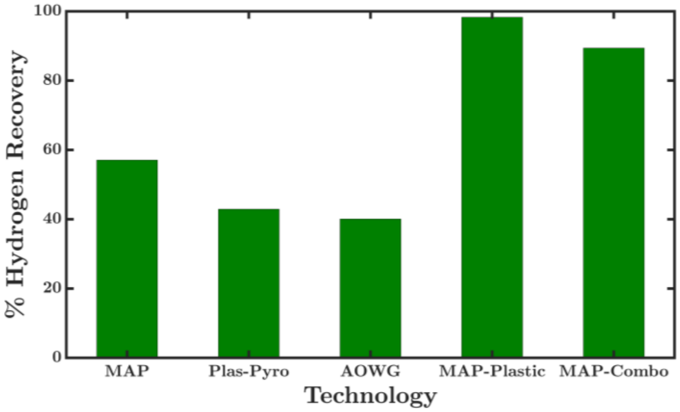

Figure 4. Optimized percent hydrogen recovered from waste when additional technology is added. MAP-combo refers to a combined effort of MAP-Plastic and MAP_{add-on} being used to process the waste for hydrogen recovery.

selective technologies to optimize hydrogen recovery. Figure 3 presents the hydrogen production of each individual technology compared to the combined MAP-Plastic and MAP_{add-on} scenario (MAP-Combo). As can be seen, the hydrogen production of the two technologies combined now exceeds the next highest production of a single technology by almost 90 kg. This is further reflected in Figure 4, where the combined hydrogen recovery of 89% remains well above the technologies that process the same quantity of waste. Since the two technologies combined now process almost the entire waste stream (~90%), an 89% hydrogen recovery means that ~80% of the hydrogen in the entire waste stream would be repurposed for propellant. In contrast, since MAP-Plastic only processes ~14% of the entire waste stream on its own, its higher relative recovery percentage of 98% only leads to a total hydrogen recovery of ~13.7 %.

B. Effective ESM

To estimate the “cost” of having a TtSG technology that converts the waste into hydrogen, an equivalent system mass analysis was conducted. Figure 5 depicts the ESM breakdown of each technology, showing the contributions of each system’s respective mass, volume, power, cooling, and consumables, as well as their associated hydrogen and volume reduction benefit for the year-long mission. The volume reduction benefit is noted as “MC benefit” to indicate the mass in mated carriers that would be saved by processing the waste.

As can be seen, the MAP and Plas-Pyro technologies have the greatest mass benefits and therefore have the lowest effective ESMs when the MC benefit is considered (column two of Table 5). They are followed closest by AOWG and MAP-Combo. Since these four technologies process the most waste, it stands to reason that they would have the greatest volume reduction benefit and subsequent effective ESM. However, despite processing the same amount of waste, their MC benefits are not the same. This is because the MC benefit considers the amount of waste that is converted to a gas by each technology. Since MAP and Plas-Pyro have the greatest solid-to-gas conversions of the four technologies, these two technologies reduce the waste volume the most and therefore have the greatest volume savings. Furthermore, since the benefit is accounted for in mass of mated carriers, the additional volume saved by MAP and Plas-Pyro results in an entire additional mated carrier compared to AOWG and MAP-Combo. This results in a significant difference in benefit and overall ESM (Table 5).

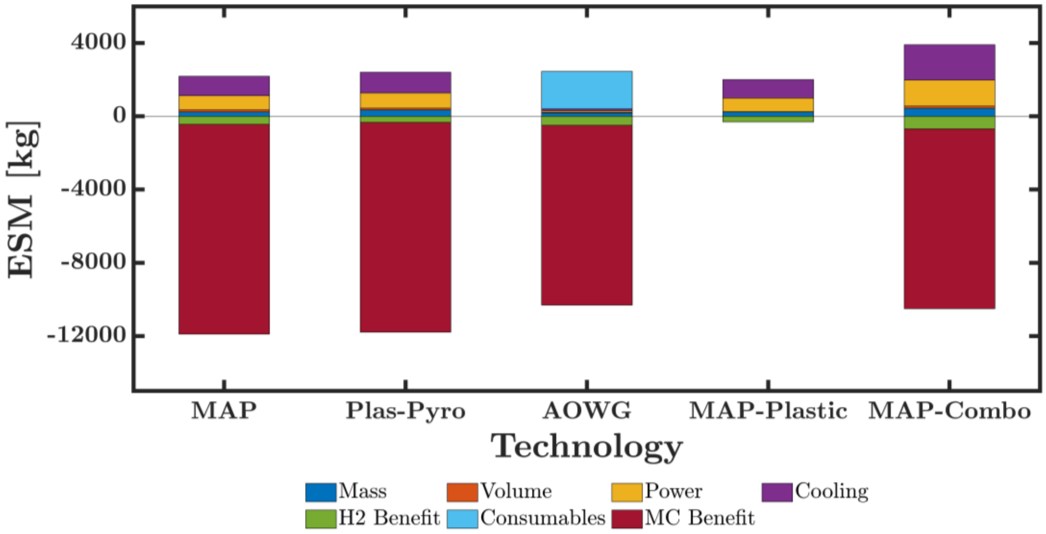

Figure 5. ESM with hydrogen and volume reduction benefit for one year.

MAP-Plastic on the other hand processes significantly less waste than the previous three technologies. Since this technology only processes plastic waste, the volume savings isn’t enough to negate additional mated carries than the ones that will resupply resources. For this reason, MAP-Plastic has the highest effective ESM when the MC benefit is considered. The combination technology MAP-Combo provides a middle ground to optimize hydrogen production while reducing volume. However, despite being able to recover most of the waste H_2 and significantly reduce waste volume, the total effective ESM of MAP-Combo (Table 5) is higher than MAP, Plas-Pyro, and AOWG technologies due to the increased mass, power, and volume of the combined MAP-Plastic and MAP_{add-on} technologies. This highlights volume reduction as the primary contributor to the ESM benefit and H_2 production seemingly secondary.

Therefore, low mass, power, and volume technologies that can provide significant volume reduction are likely to be the most advantageous, regardless of H_2 production. However, if H_2 recovery is desired for reasons not captured by this ESM, then utilizing two technologies to optimize H_2 production has a greater advantage than a single selective technology, simply because the combination reduces waste volume significantly more than the single selective technology.

Table 5. TtSG technology ESM comparison with and without volume reduction benefit for a 1-year mission

Technology	Effective ESM (w/ MC Benefit)	Effective ESM (no MC Benefit)
MAP	-9713	1738
Plas-Pyro	-9384	2068
AOWG	-7861	1955
MAP-Plastic	1698	1698
MAP-Combo	-6598	3218

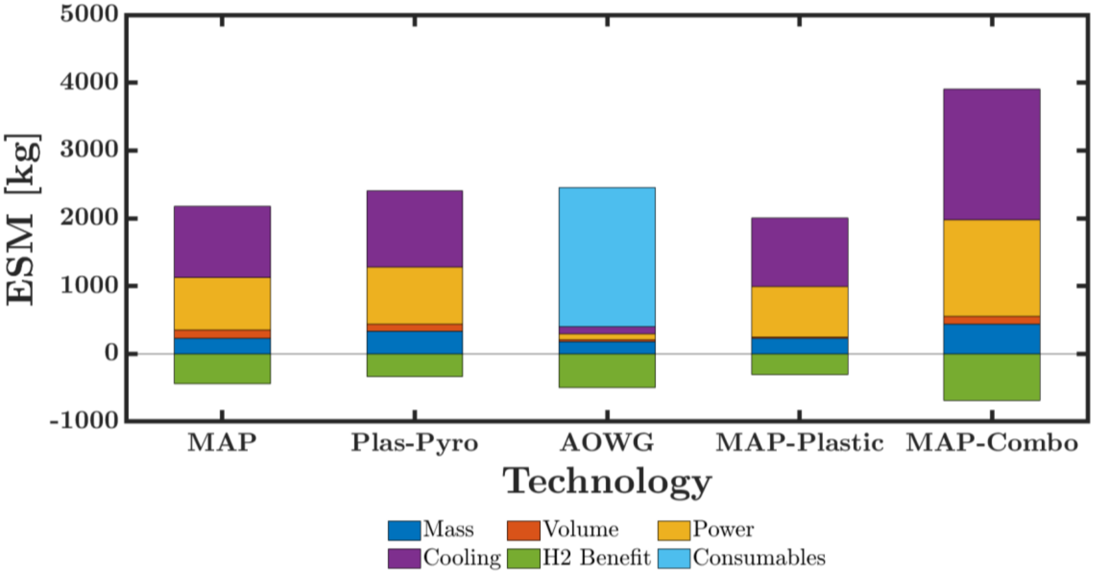

Figure 6. ESM of each technology with the hydrogen benefit only for a year-long mission.

The analysis thus far has assumed the waste will be stored inside carriers, leading to ESMs that are significantly reduced by the MC benefit. However, if the waste were stored directly on the surface of the Moon there would be no volume savings. While not ideal, this is not entirely out of the question considering the cost of bringing storage containers for the waste. Therefore, an additional analysis is conducted to consider this scenario where the only benefit to the ESM is the produced hydrogen. Figure 6 and column three of Table 5 show the effective ESM of each technology when the MC benefit is no longer included. Without a volume reduction benefit, MAP-Plastic now has the most favorable ESM. Because MAP-Plastic is sized for the least amount of waste, it follows that it would have a relatively small ESM compared to those that are sized for over six times the waste. This expectation is true when the equivalent volume is compared across technologies, but the mass, power, and cooling of MAP-Plastic are comparable to other technologies that process more waste. For example, MAP-Plastic and MAP have almost identical mass contributions and do not differ by more than a 100 kg in other “cost” categories. Therefore, while MAP-Plastic has the lowest ESM in this scenario, other technologies are close behind.

Closely following MAP-Plastic is MAP, followed by AOWG, Plas-Pyro, and finally, MAP-combo. With the MC benefit no longer considered, the combination technology option no longer closely follows MAP-Plastic but now has the highest ESM of all options. This is because the hydrogen produced by the combination technology is not enough to offset the “cost” of bringing two different reactors and having to supply their respective cooling and power. Therefore, when looking at a single year-long mission, this combination of technologies for hydrogen production is likely not desirable if processing waste has no volume reduction benefit.

C. Break-Even Point

For each technology or technology option, the point in time at which the benefits outweigh the cost of the technology was determined, otherwise known as the break-even point. This analysis was done under the assumption that the technology would have an initial cost (the base ESM without benefits) and each subsequent year it would continue to process the same amount of waste per year, reducing waste volume and producing hydrogen. This assumes a constant human presence on the Moon. The point at which the combined benefits equaled the base ESM is the break-even point, denoted in years. AOWG is the only exception as this technology additionally requires consumable water that must also be brought in subsequent years. This analysis was conducted for both the scenario where an MC benefit is included and the scenario where waste is stored on the surface and only a hydrogen benefit can be accounted for.

Table 6 displays the break-even point for each technology option when a MC benefit is included and when it is not. When the MC benefit is included, MAP, Plas-Pyro, AOWG, and MAP-Combo break even within a year, while MAP-Plastic takes just over 6.5 years to break even. This is consistent with their respective effective ESMs for the original year-long mission (Table 5). The technologies that break even before the year is up have negative effective ESMs, while the technology that breaks even after a year has a positive effective ESM. MAP-Plastic takes the longest to break even because it is the only technology without a MC benefit. This is further noted by looking at the no MC benefit column (Table 6) and seeing the break-even point for MAP-Plastic remains the same. In other words, the waste processed by MAP-Plastic does not provide enough volume savings to negate additional mated carriers, regardless of years in operation.

Table 6. Technology Break-Even Point

Technology	Years	
	w/ MC Benefit	w/o MC Benefit
MAP	0.39	5.11
Plas-Pyro	0.41	7.49
AOWG	0.40	-
MAP-Plastic	6.56	6.56
MAP-Combo	0.52	5.84

When the MC benefit is no longer considered, the break-even point for the remaining technologies increases significantly. MAP now requires just over 5 years to break even, MAP-combo requires just under 6 years, Plas-pyro requires almost 7.5 years, and AOWG does not break even because the cost of bringing water every year is higher than its hydrogen benefit alone. For the technologies that do break even, the time to break-even can be explained by how much waste each technology processes (for sizing considerations) relative to how much hydrogen it produces. Since Plas-Pyro is sized to process almost all the waste but produces the second lowest hydrogen amount, it takes the longest to break even. MAP and Map-Combo are also sized to process almost all the waste, but they produce significantly more hydrogen than Plas-Pyro, causing them to breakeven 2-2.5 years earlier. While MAP-combo is sized to process almost all of the waste, just as the previous technologies, two separate systems are being sized and so despite its large hydrogen production, it still breaks even after MAP. However, the high hydrogen production of MAP-Combo does allow it to break even before MAP-Plastic, despite MAP-Plastic being sized for less waste.

IV. Conclusion

This work presents a TtSG trade study that compares four propellant producing technologies using an ESM analysis that considers a year long lunar surface mission. Each technology was evaluated on the quantity of hydrogen it could produce and the amount of waste volume it reduced by processing the waste. These benefits were then weighed against the technologies' equivalent mass, power, volume and cooling. To compare the benefits and drawbacks of hydrogen selectivity, three technologies that are non-selective but can process diverse waste streams were compared to one technology that is selective but processes a much-reduced waste stream. Furthermore, an additional option that combined the best of both technology categories was considered to determine the feasibility of bringing two technologies to optimize hydrogen production. Two separate ESM and break-even analyses were conducted for all technology options, considering the case when reducing the volume of waste is a direct benefit (stored inside mated carriers) and when it is neutral (stored on the surface). From this analysis, it is evident that optimizing hydrogen production is the most cost effective when there is a volume savings associated with processing the waste. If there are no volume savings (i.e. waste is stored on the surface or not enough waste is processed), the cost is significantly higher in a single year and would take years of constant lunar presence for most of the considered technologies to break even.

The recovery of propellant from waste using a thermochemical system must consider the balance between selectivity and mass of waste processed. Hydrogen production is optimized when the waste stream is primarily composed of hydrogen and carbon. However, much of the waste stream contains other chemical components that will shift the thermodynamic equilibrium towards water or other gases. From this analysis, it is clear that combining a selective technology with a non-selective technology optimizes hydrogen recovery, but it comes at the cost of a significantly higher ESM than any one non-selective technology alone. If hydrogen is but an added benefit while volume reduction is of primary concern, then a non-selective technology like MAP or AWOG appear to “cost” less since they still produce hydrogen while significantly reducing the volume of waste. However, there are additional aspects to consider when using TtSG as a waste processing scheme. There are other products from the technologies that could be obtained separate from hydrogen or in conjunction with hydrogen, such as methane, high value carbon, or even water. These products could provide further benefit but the post processing to separate out many products would likely add an additional cost. Furthermore, the TtSG systems themselves would benefit from additional research, including optimization and testing in space environments. It is recommended that these considerations be included in future studies.

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