Trash to Supply Gas: Optimizing Propellant Production

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Dana Lobmeyer
Amentum, Houston, TX
Thomas Chen & Michael Ewert
NASA, Houston, TX

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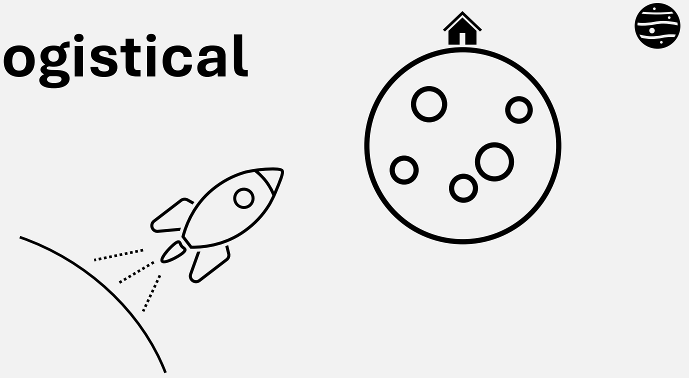
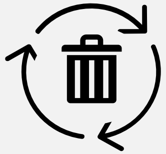
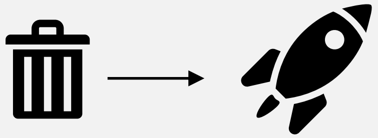
Resources and Waste Management



- **Extended manned missions on the Moon/Mars present logistical challenges to supply resources and remove waste**
  - Significant waste generation is anticipated
- **Waste management tactics**
  - Store waste on the surface
  - Process & remove waste - Trash to Gas (TtG)
    - Thermally process waste into ventable gases
    - Decrease volume of waste
  - Reuse/Repurpose waste – *Ideal*
    - Reduces resupply efforts
    - Sustainable

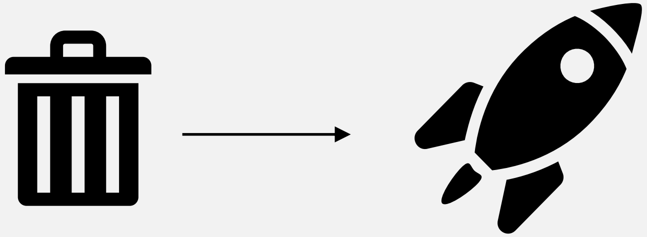


- **Trash to Supply Gas (TtSG) builds upon TtG processes to produce a gas that meets mission needs**
  - Optimize thermal processing of waste into a useful gas (i.e., supply gas)
  - Reuse primary elements in waste stream while reducing waste volume
    - *Fuels (CH_4, H_2, etc.)*, solid carbon, water, etc.



Hydrogen (H_2) Production using TtSG

- **The anticipated waste stream contains a surplus of hydrocarbons**
  - TtSG thermal processing schemes break this down primarily into small molecule gases (CO_2, O_2, H_2, CH_4, etc.)
- **H_2 is a primary fuel being considered, along with oxygen (O_2) and methane (CH_4)**
  - Propellant is a costly commodity: Fuel adds mass and mass requires more fuel
  - Current ISRU propellant production plans using electrolysis lead to hydrogen production as the limiting factor – i.e., TtSG of H_2 could supplement ISRU plants
- **Water and O_2 have various production routes from regolith and ice but fewer routes exist for H_2**
- **H_2 production is a large research area terrestrially for recycling waste**
  - TtSG for space applications can use this as a technical foundation



Mission Assumptions & Approach

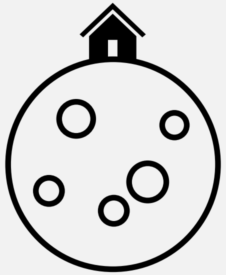
- **Compare the hydrogen production and effective equivalent system mass (ESM) of four TtSG technologies configured for waste management in space**

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

  - Waste generation rate sizes technology mass (M), power (P), and volume (V)
  - Benefits to hydrogen production (ESM_{H2}) and waste volume reduction (M_{MC}) are included
  - γ_{v} , γ_{p}, and γ_{c} correspond to habitat dependent factors that account for additional mass necessary to house, power, and cool the technology

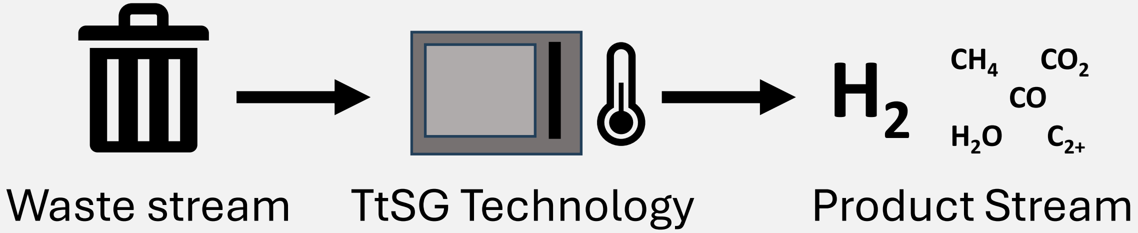
- **Conduct analysis over a consecutive 365-day lunar surface mission**

Habitat	# Crew	# EVAs/CM	Mission duration [days]	Resupply frequency
lunar surface habitat	4	3/week	365	Every 90 days



  - Resupply is provided in a mated carrier

- **General scheme:**



H_2

CH_4 CO_2 CO H_2O C_{2+}

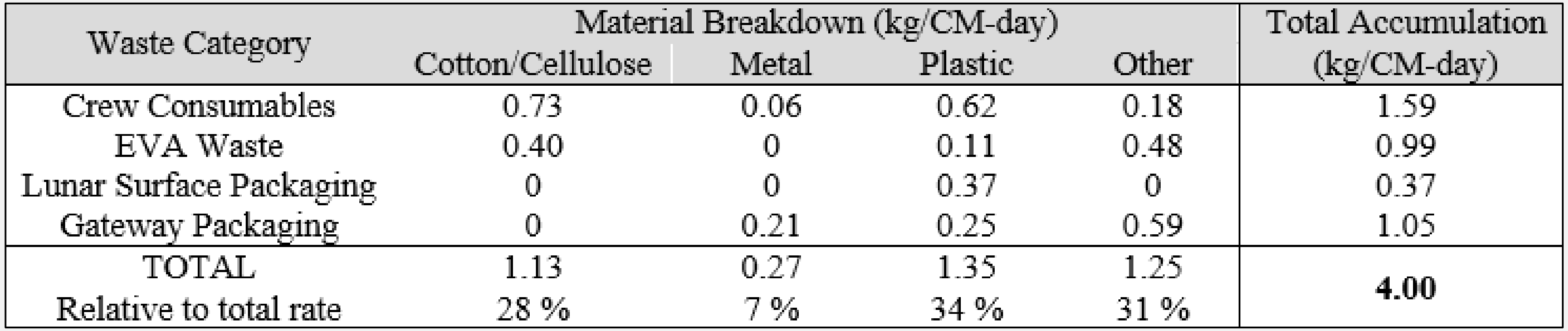
Waste stream

TtSG Technology

Product Stream

Waste Model

- **The waste model used is an estimate from the Strategy and Architecture Office (SAO) for Artemis missions – modified for maximum waste on the Moon**
  - Gateway packaging included to showcase “best case scenario” if this waste were brought down to the Moon for H_2 production

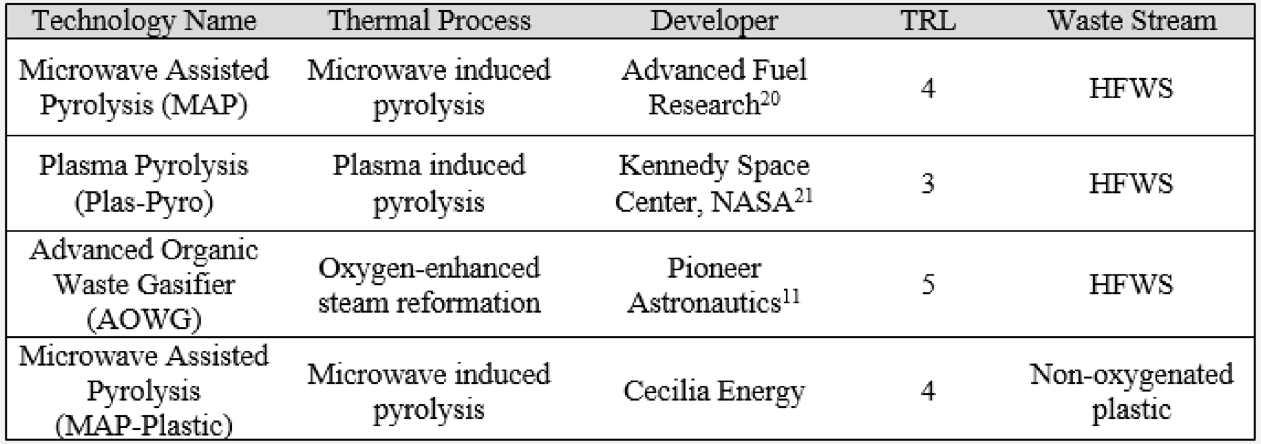


Waste Category	Material Breakdown (kg/CM-day)				Total Accumulation (kg/CM-day)
	Cotton/Cellulose	Metal	Plastic	Other	
Crew Consumables	0.73	0.06	0.62	0.18	1.59
EVA Waste	0.40	0	0.11	0.48	0.99
Lunar Surface Packaging	0	0	0.37	0	0.37
Gateway Packaging	0	0.21	0.25	0.59	1.05
TOTAL	1.13	0.27	1.35	1.25	**4.00**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

- **Material breakdowns are derived from current materials on the International Space Station**
- **Plastic was further categorized into separable plastics (assumed 100% plastic) that do not contain oxygen, and other plastics (composites/oxygenated)**
  - Some technologies selective for hydrogen have been optimized for a non-oxygenated plastic feed
  - Non-oxygenated, separable plastics account for 14% of the waste stream considered here

Waste Conversion Technologies

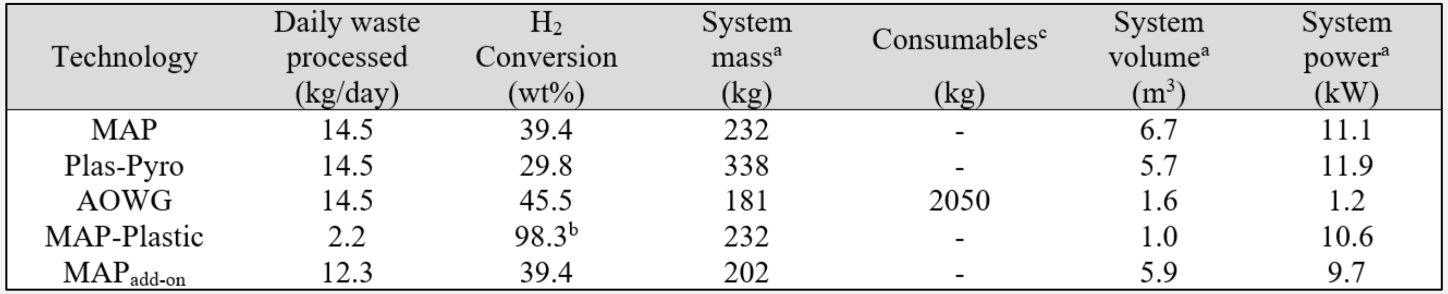
- **Three technologies accepting diverse waste streams are compared with one optimized for non-oxygenated plastic**
  - Based on an experimental reactor
  - HFWS = High fidelity waste simulant
    - Akin to the current waste model
  - Includes promising technologies from TtG that produce significant H_2
    - Pyrolysis & steam reformation



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

- **Mass, volume and power is scaled according to the waste processing rate using the 60/40 rule (60% scaled, 40% not) with the experimental reactor as the foundational values**
  - No post-processing components are considered
  - AOWG requires water to run, so mass of water is included in its ESM

- **H_2 production is based on experimental conversions**
  - MAP-Plastic reports H_2 recovery percentage



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
MAP$_{\text{add-on}}$	12.3	39.4	202	-	5.9	9.7

Benefits to ESM

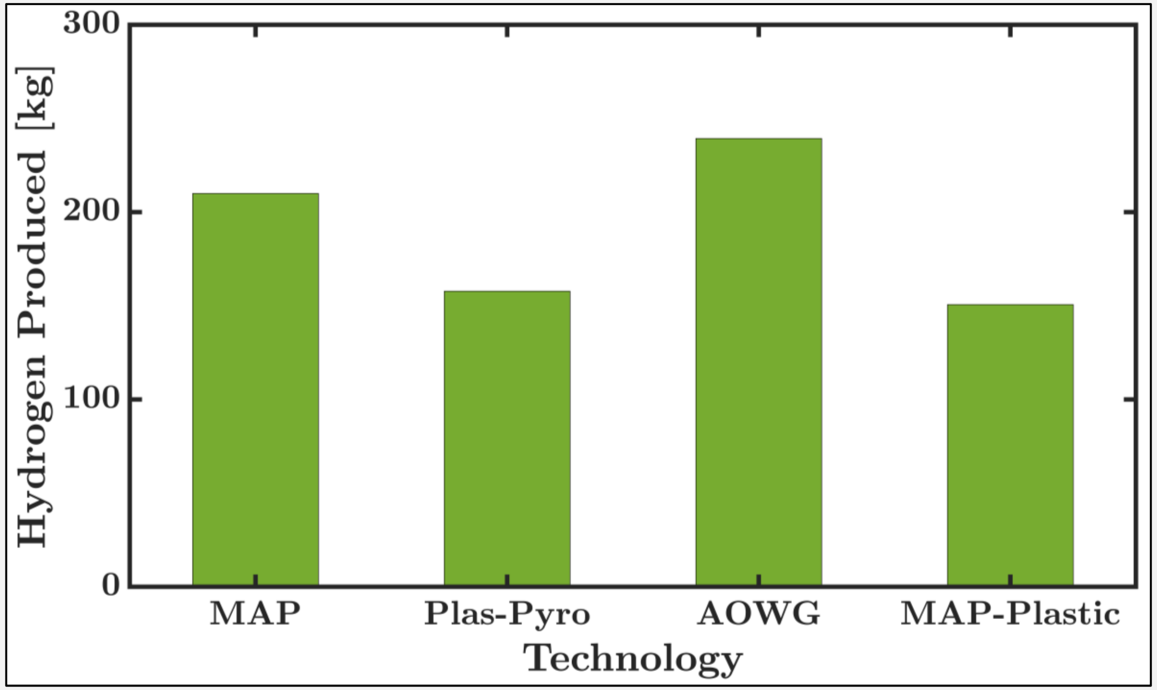
- **A technology's ESM is offset by the predicted mass benefits it will offer**
  - **H_2 production:** The mass savings of producing H_2 on the Moon = the equivalent mass of supplying the same amount of H_2 from Earth
    - Includes mass of H_2 produced (M_{H2}), mass of transport tank (M_{tank}), and equivalent mass required for the transit vehicle to support the volume of the tank ($V_{\mathrm{tank}} * \gamma_{\mathrm{v,transit}}$)

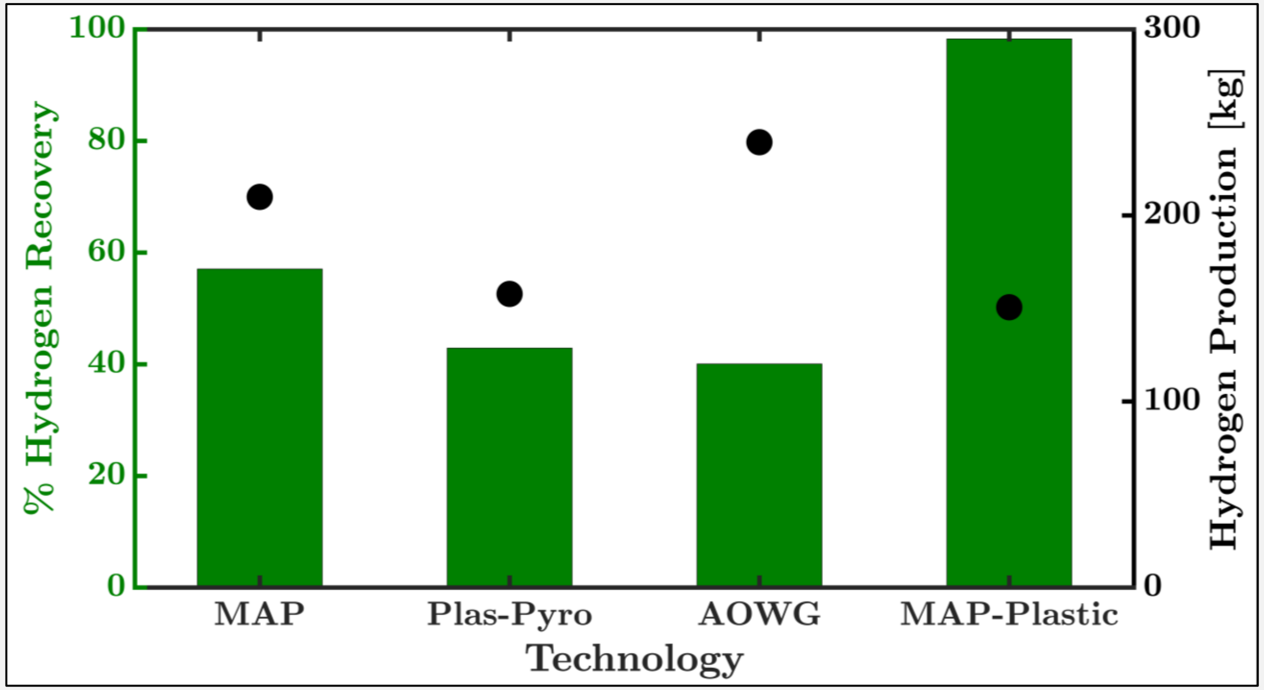
$$ESM_{\mathrm{H2}} = M_{\mathrm{H2}} + M_{\mathrm{tank}} + V_{\mathrm{tank}} * \gamma_{\mathrm{v,transit}}$$

  - **Volume reduction/Mated carrier (MC) benefit:** Mass of mated carriers above baseline that would be necessary to store the waste if it were not processed to a gas
    - Baseline: 3 mated carriers are assumed present from resupply efforts
    - Volume reduced (V_{reduced}) is the sum of the mass of waste converted to a gas and the mass remaining as liquid/solids, over their respective average density

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

Hydrogen Production

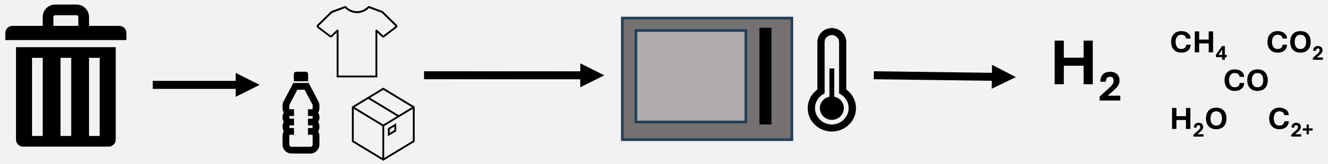




- **All technologies produce ~150-200 kg of H_2 despite not all processing the same amount of waste**
  - MAP, Plas-Pyro & AOWG process ~5,300 kg of waste, while MAP-Plastic processes ~800 kg (separable plastics only)
- **AOWG produces the most H_2 but has the lowest H_2 recovery**
  - Water is required for the reaction, so hydrogen is input – H_2 recovery from waste is low
- **MAP-Plastic has the highest H_2 recovery but has the lowest H_2 production**
  - Processes ~85% less waste than all other technologies
  - Highly selective for H_2 production

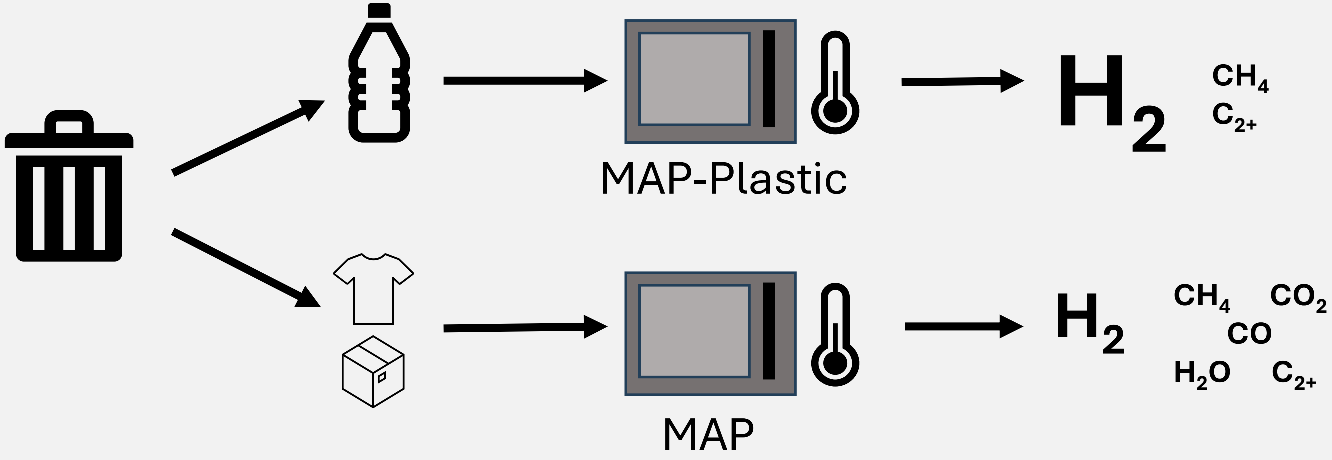
Optimizing Hydrogen Production

For technologies designed for a diverse waste stream → process all waste at once

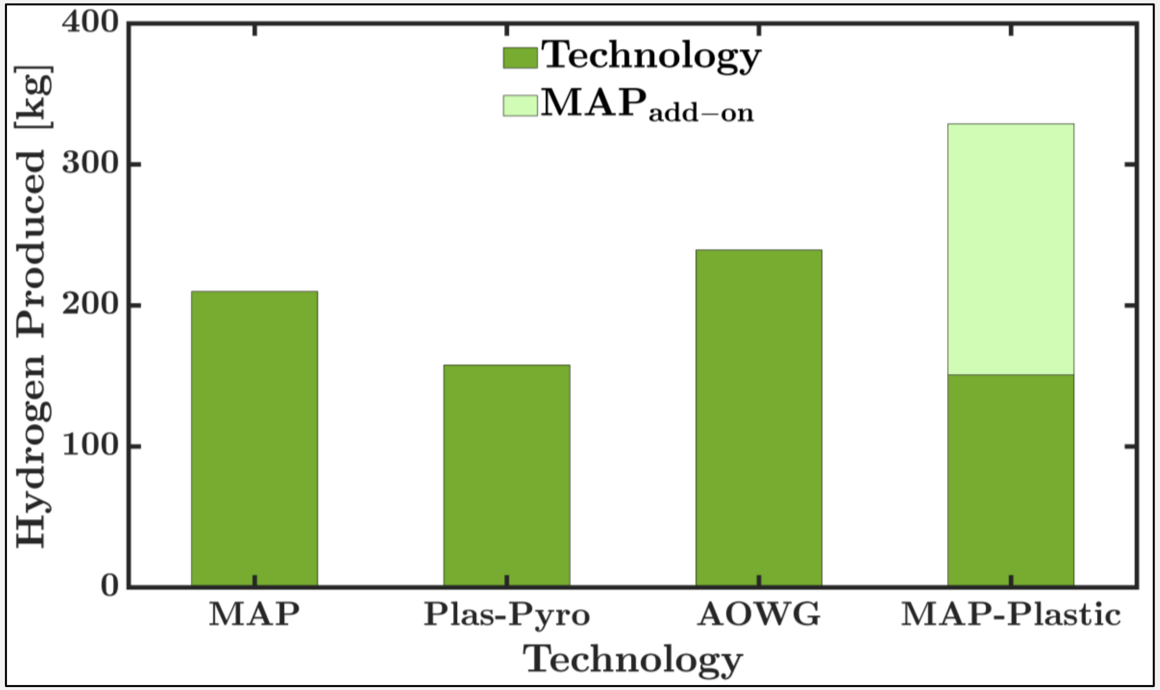


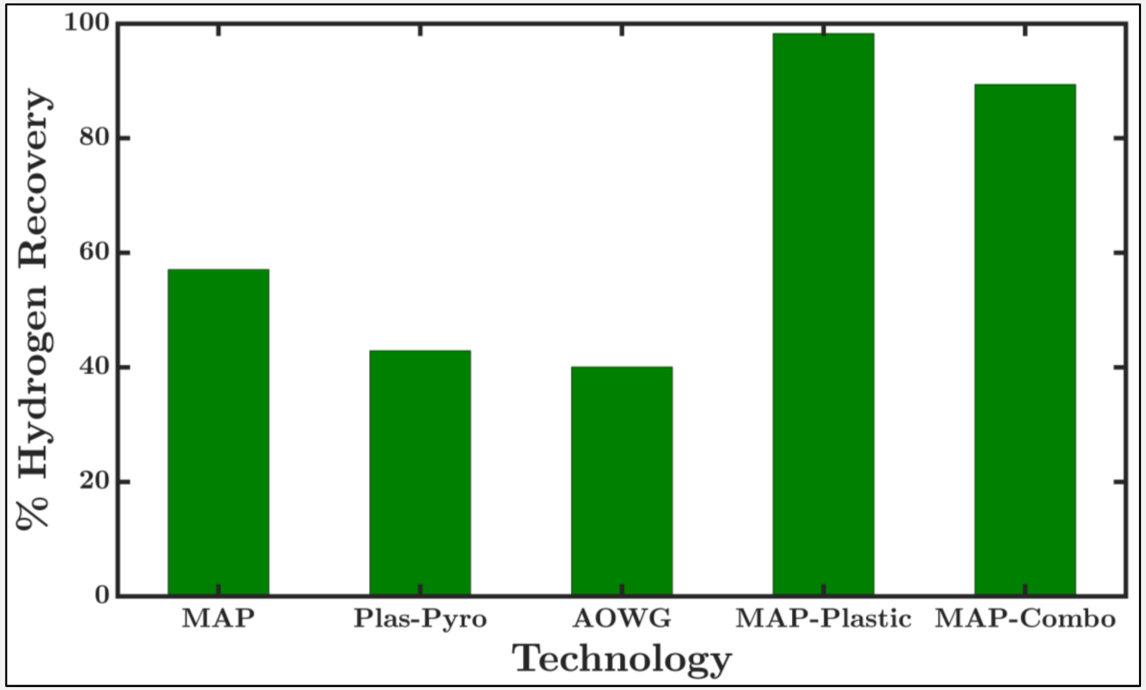
For technologies designed for a non-oxygenated plastics → process piece-wise

- Non-oxygenated plastics in hydrogen selection technology
- Remaining waste is processed in additional reactor designed for diverse waste
    - Consider MAP ($\text{MAP}_{\text{add on}}$)



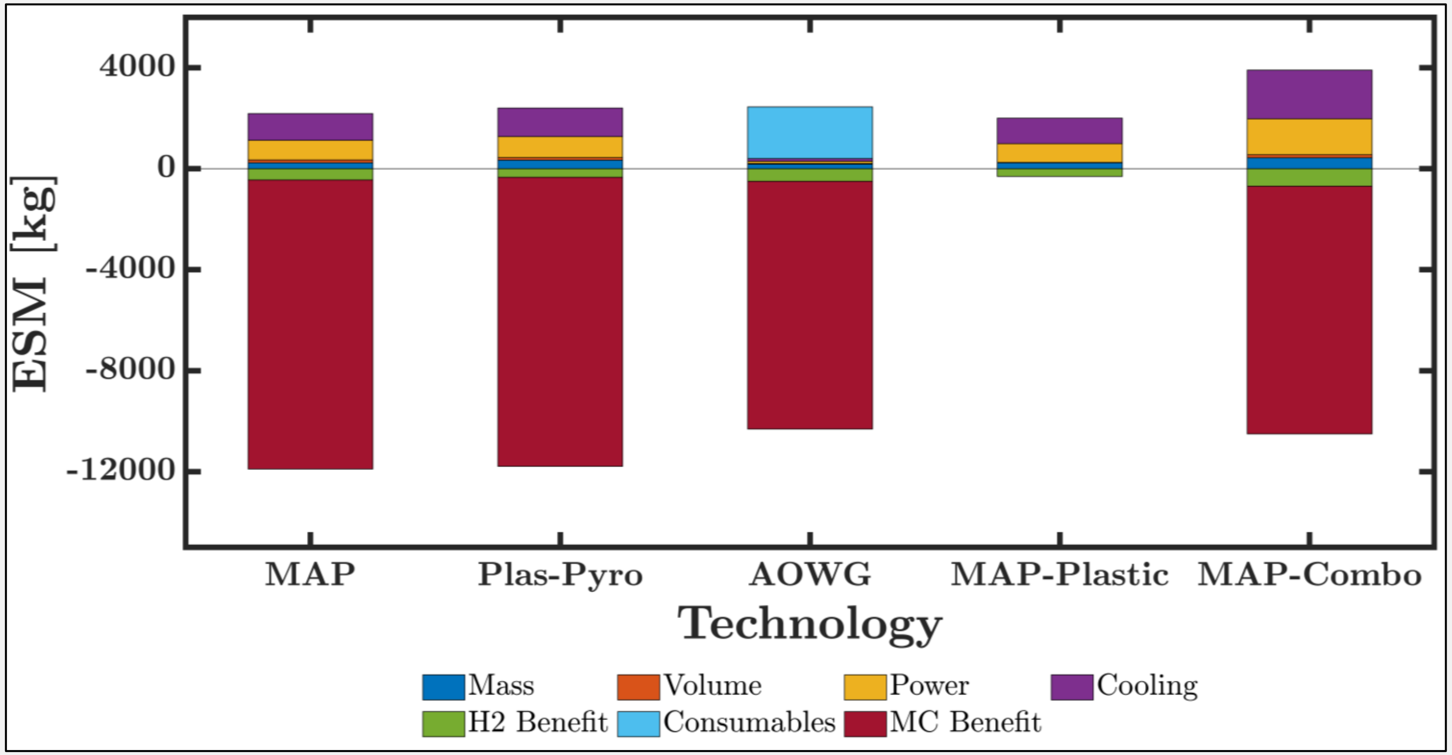
Optimized Hydrogen Production





- **H_2 production is optimized with two reactors and now exceeds the next highest single technology by almost 90 kgs**
- **Hydrogen recovery for the two reactors (MAP-Combo) remains above other technologies that process the same amount of waste**

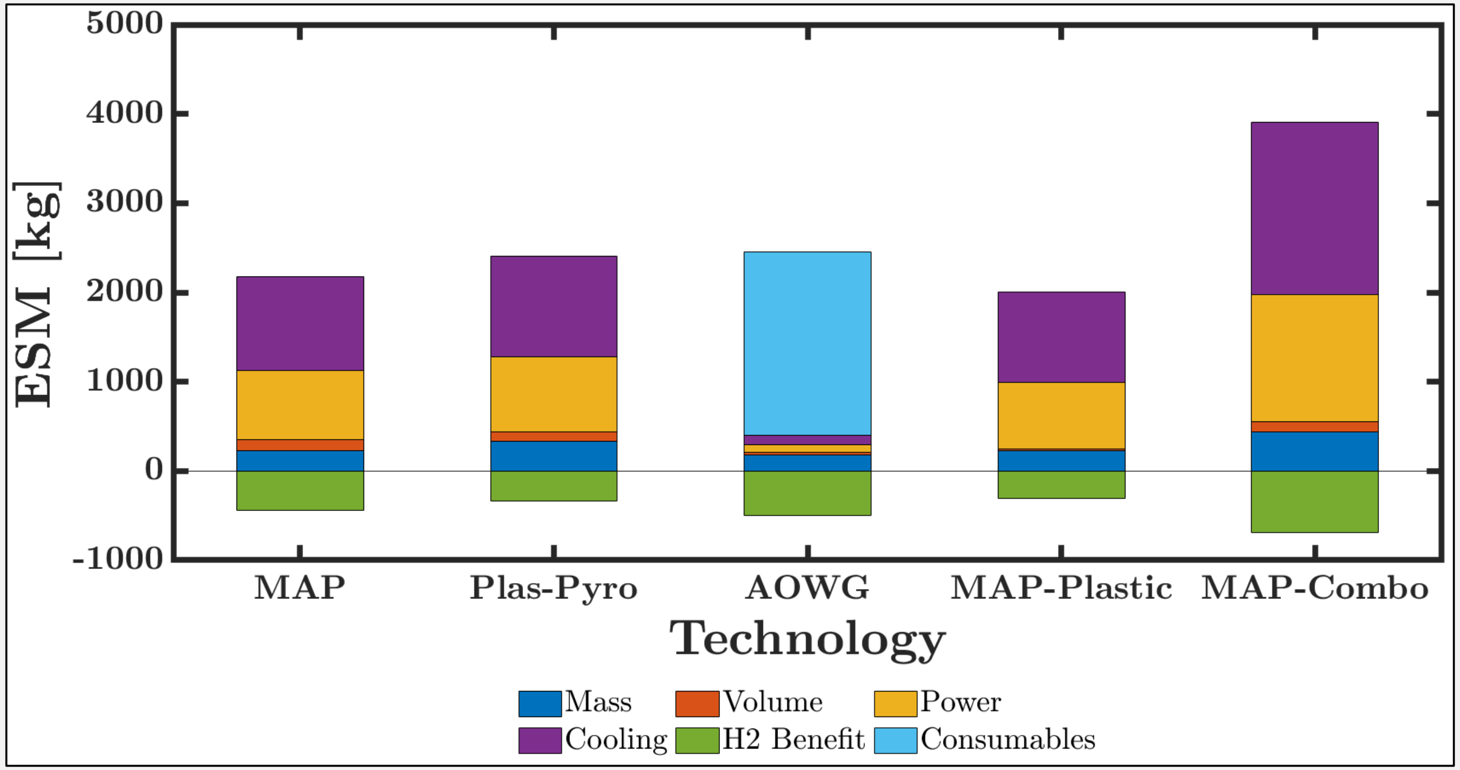
Equivalent System Mass



Technology	ESM_{eff} (kg) w/ MC benefit
MAP	-9,713
Plas-Pyro	-9,384
AOWG	-7,861
MAP-Plastic	1,698
MAP-Combo	-6,598

- **MAP and Plas-pyro have the greatest total benefit and therefore the smallest ESM_{eff}**
  - Greatest solid-to-gas conversion and processes the larger waste stream (saves an extra MC compared to AOWG & MAP-Combo)
  - MAP-Plastic does not process enough waste to warrant volume savings past baseline
- **The additional H_2 produced, and volume reduced does not off set the MPV of bringing two separate reactors (MAP-Combo)**
  - Volume reduction is the primary contributor to the ESM benefit

Equivalent System Mass – No volume reduction/MC benefit

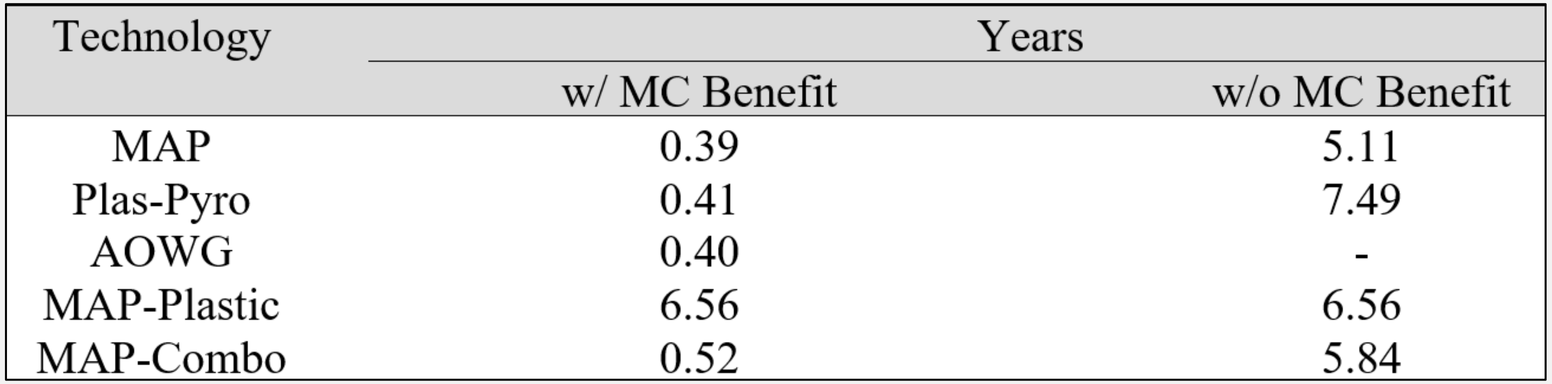


Technology	ESM_{eff} (kg) w/o MC benefit
MAP	1,738
Plas-Pyro	2,068
AOWG	1,955
MAP-Plastic	1,698
MAP-Combo	3,218

- **MAP-Plastic is sized for the least amount of waste and therefore has the lowest ESM_{eff} when only H_2 production is considered**
- **Production of H_2 must be balanced with MPV of respective processing scheme**
  - If H_2 production is simply a mass benefit, MAP-Combo is not a desirable option despite producing the most H_2

Technology Break-Even Point

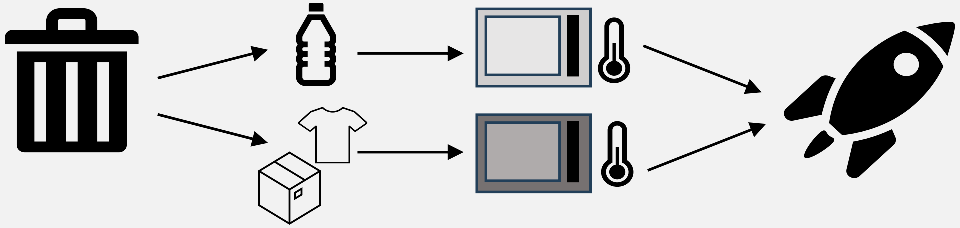
- **Break-even: when the benefits outweigh the baseline MPV of the technology**
  - Initial cost is baseline ESM without benefits
  - Each year the same amount of waste is processed – reducing waste volume and producing H_2
- **All but MAP-Plastic break-even within the first year when volume reduction (MC benefit) is considered**
  - Break even time is consistent with each technologies respective ESM_{eff}
- **Without the MC benefit, it takes a minimum of ~5 years for any technology to break even**
  - AOWG never breaks even because its H_2 produced never outweighs the water needed for the reaction
  - The remaining technologies break even according to their baseline MPV relative to their H_2 production



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

Conclusion

- **Processing the waste stream based on material composition may be advantageous to maximize H_2 formation but it comes at the cost of bringing two separate technologies**
  - Must balance selectivity of technology and mass/volume of waste processed
- **Optimizing H_2 production is most cost effective when volume savings results in a mass benefit (i.e., waste is not stored out in the open)**
  - If there is no volume savings, it would take years of constant lunar presence for all technologies considered to break-even



Looking forward:

- **Additional products could be created from the waste stream separate from or in conjunction with H_2, potentially adding to the benefit**
  - Reuse can also be accomplished through additive manufacturing
- **Considerations into post-processing and testing these technologies in microgravity are necessary to achieve the TtSG waste management strategy**

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Thank you!

Questions?