An Economic Comparison of Lunar Propellant Production Methods

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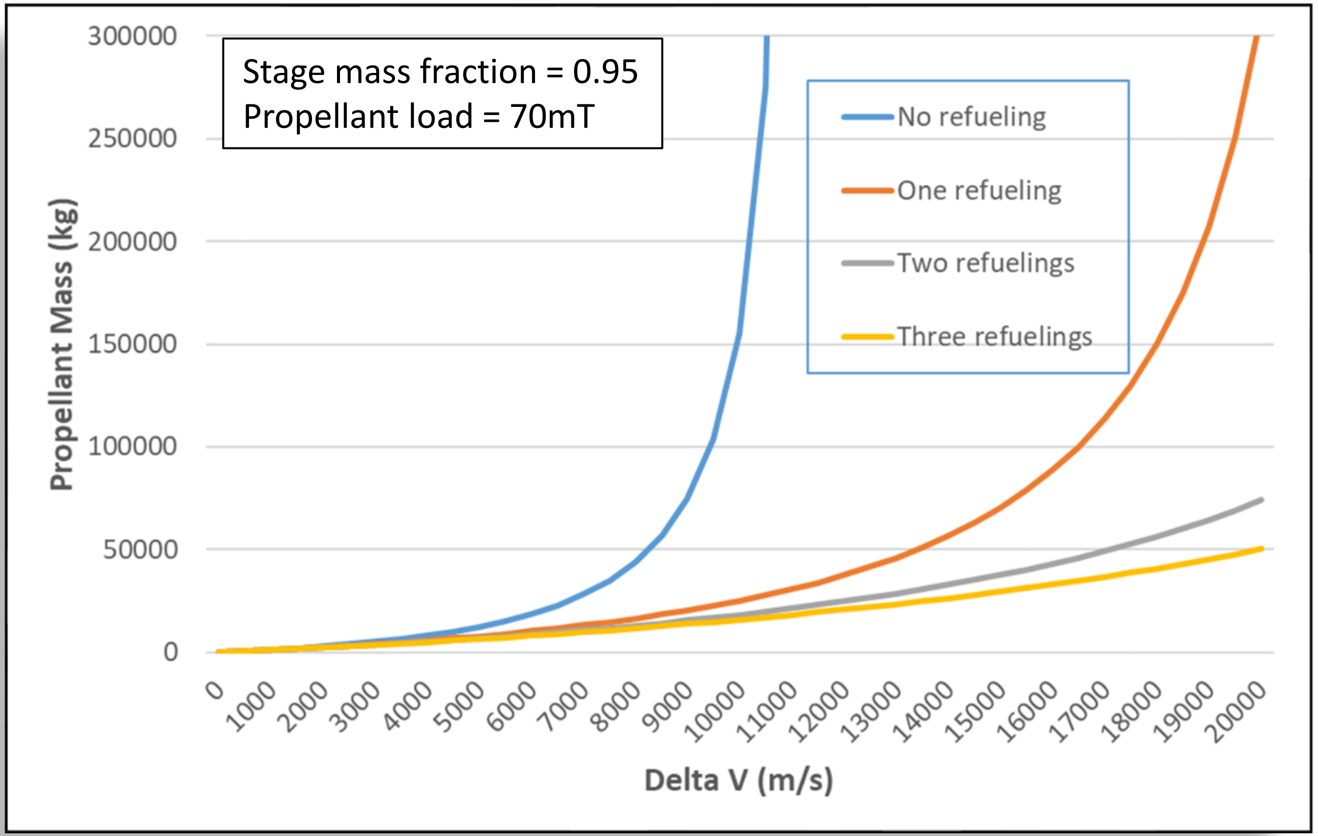
Refueling Economy in Cislunar Space

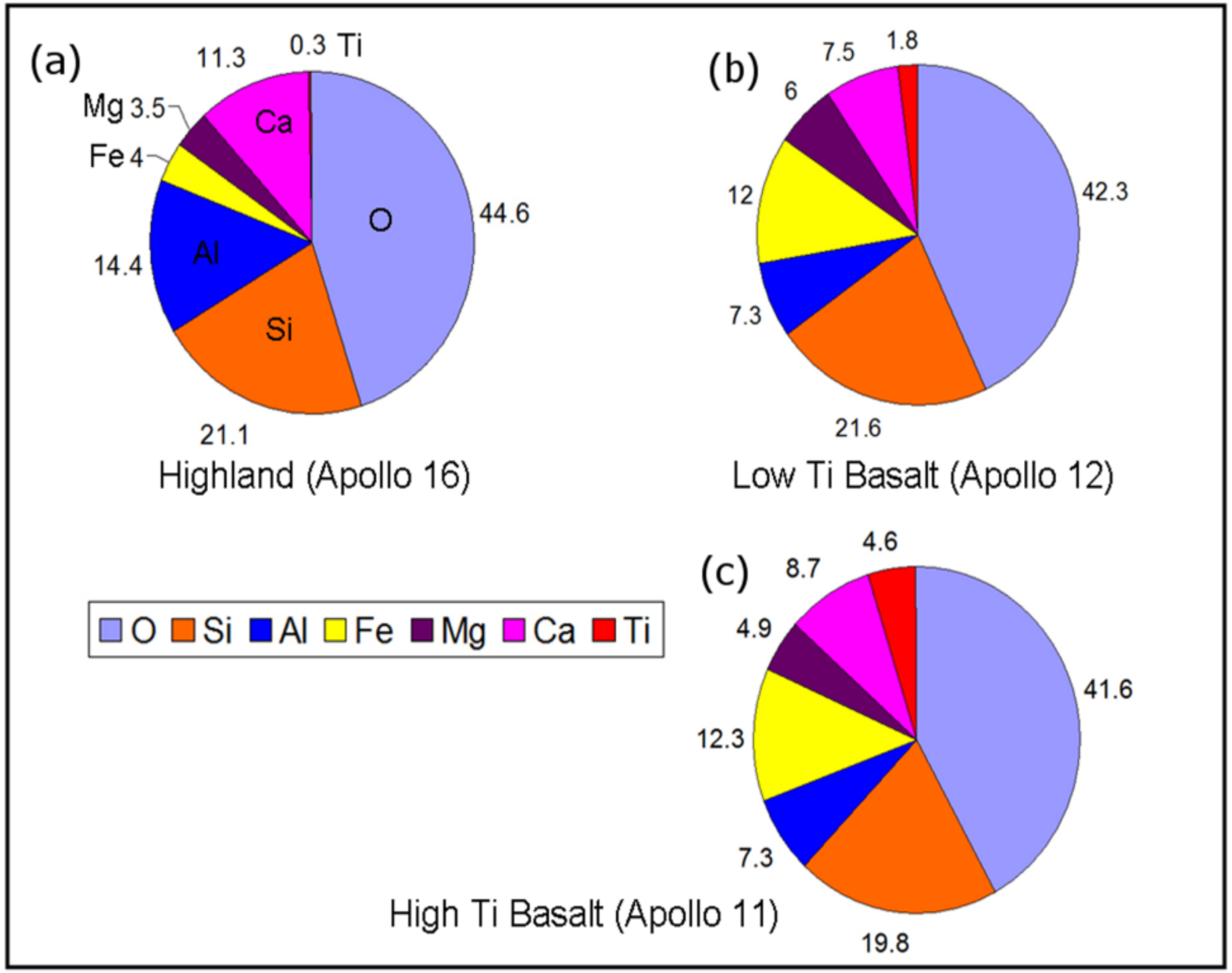
- Transportation underpins all economic activity in cislunar space and beyond
- Without refueling, all space activity is subject to the **tyranny of the rocket equation**
- Initially, propellant will come from Earth
- Eventually, propellant will be sourced in space: Moon, NEO's, Mars
  - Water, oxygen, methane
- Refueling is key to affordable and sustainable space development

Breaking the Tyranny of the Rocket Equation



Oxygen on the Moon

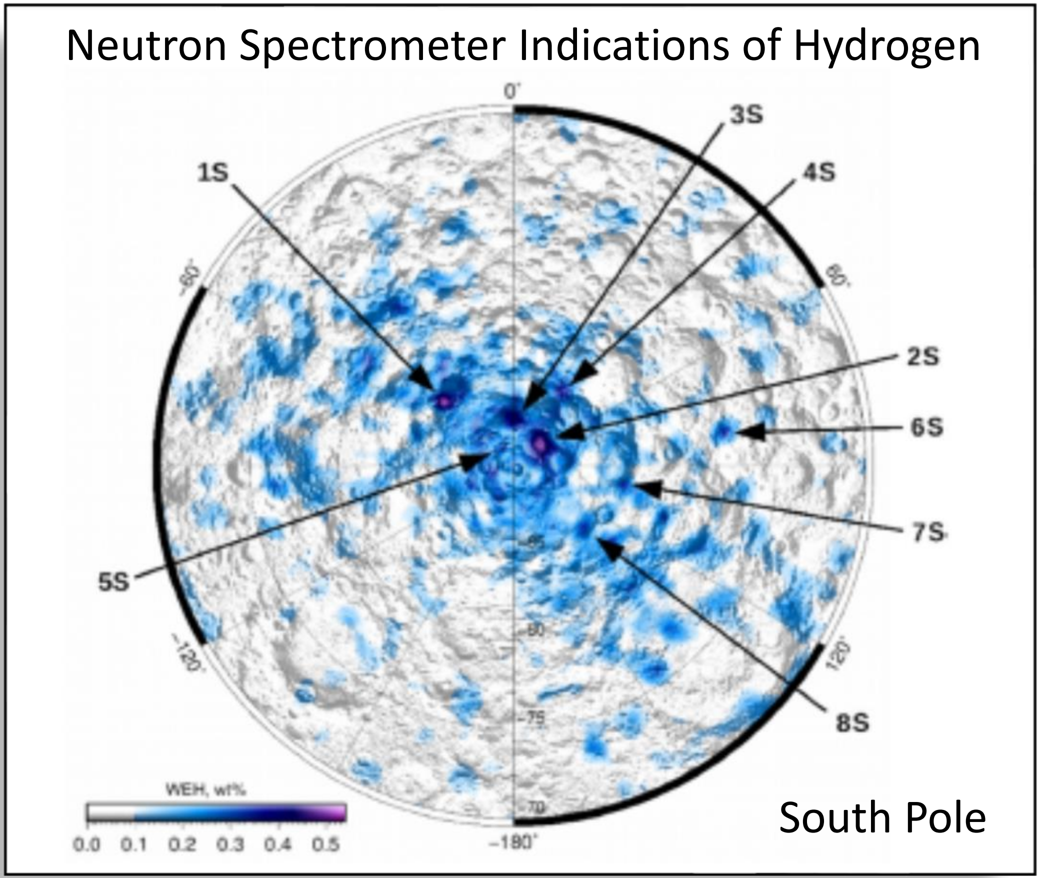
- Lunar regolith of all types is rich in oxygen
  - 41-45wt%
- Oxygen makes up a significant percentage of rocket propellant
  - 84% by mass for typical LO_2/LH_2 rocket engine
  - 78% by mass for a typical LO_2/methane engine



Planetary and Space Science, Vol. 74, Schwandt C, Hamilton JA, Fray DJ and Crawford IA, 'The production of oxygen and metal from lunar regolith' 49-56, (2012)

Water on the Moon

- Water exists in the Permanently Shadowed Regions (PSRs) near the Poles of the Moon
  - Low obliquity of the Moon results in constant grazing sunlight at the poles
  - Water vapor (& other volatiles) from comet and asteroid impacts becomes cold trapped in the PSRs
- Confirmed by many remote sensing data sets
- Directly confirmed by 2009 LCROSS mission
  - 5.6±1.9wt% ice in ejecta plume
- Water can be processed into LO_2/LH_2 propellants



Sanin AB, et al. (2017) Hydrogen distribution in the lunar polar regions. Icarus 283:20-30.

Water vs Oxygen

- Oxygen is abundant everywhere, but requires:
  - Very high temperatures to extract
  - Importing LH_2 or methane fuel to the Moon
- Water in the lunar PSRs can be a source of both LO_2 and LH_2, but requires:
  - A resource exploration campaign
  - Operating in a PSR
  - Transporting propellant out of the PSR
- Economic analysis can shed some light
  - What commodity prices can be supported for water derived LO_2/LH_2 and regolith derived LO_2?

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Cost Methodology Overview

- Mass based cost estimating approach
  - Standard across the aerospace industry
- Development cost and production cost
  - Mass based cost factor modified by a complexity factor
  - Values assume **commercial approach**
  - Development cost factor $50k/kg
  - Production cost factor $20k/kg
- Launch/landing cost
  - Launch and landing cost factor $35k/kg
- Reference: Sowers, G. (2021) The Business Case for Lunar Ice Mining," New Space 24 Feb 2021. https://doi.org/10.1089/space.2020.0045

Oxygen Method Cost Results

- Production rate = 10mT O_2 per year
- Operations & maintenance cost not included

Method	Molten Regolith Electrolysis	Carbothermal Reduction	Molten salt electrolysis (FFC)
Mass (kg)	974.0	675.0	3756.4
Power (kW)	65.4	55.8	21.7
Development & production cost ($k)	102,270.00	49,586.89	53,561.02
Launch/landing cost ($k)	22,277.50	23,625.00	131,474.00
Total cost ($k)	124,547.50	73,211.89	185,035.02

- Mass and power estimates from Fall 2021 CSM study (unpublished)
- Mass and power for regolith extraction and beneficiation NOT included
- Molten salt electrolysis mass includes 3010kg of salt
- MRE mass includes 338 kg of refractory mass included in dev & prod cost, but NOT included in launch mass

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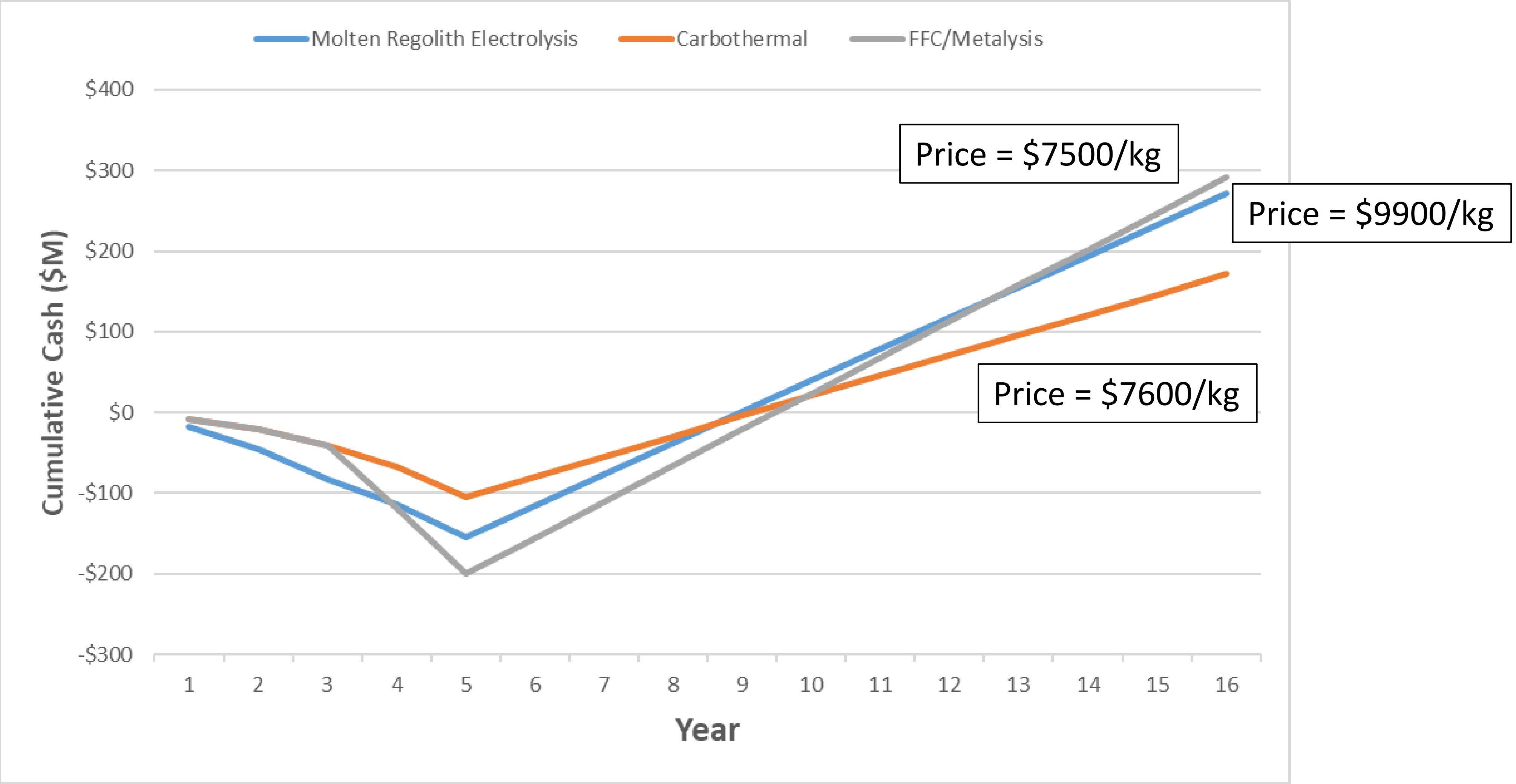
Cash Flow Analysis Methodology

- Price varied to obtain positive returns (> 15% IRR) for all three methods
- Development & Production cost spread over 4 years

Year	1	2	3	4
Dev cost	20%	35%	35%	10%
Prod cost	10%	10%	40%	40%

- Launch cost spread evenly over years 4 & 5
- Full operations begins in year 6
    - Ops & maintenance cost = $3k/kg
    - Power cost = $100/kWh (based on CSM grad student project (unpublished))
- Revenue stream begins in year 6

Oxygen Cash Flows (IRR = 15%)



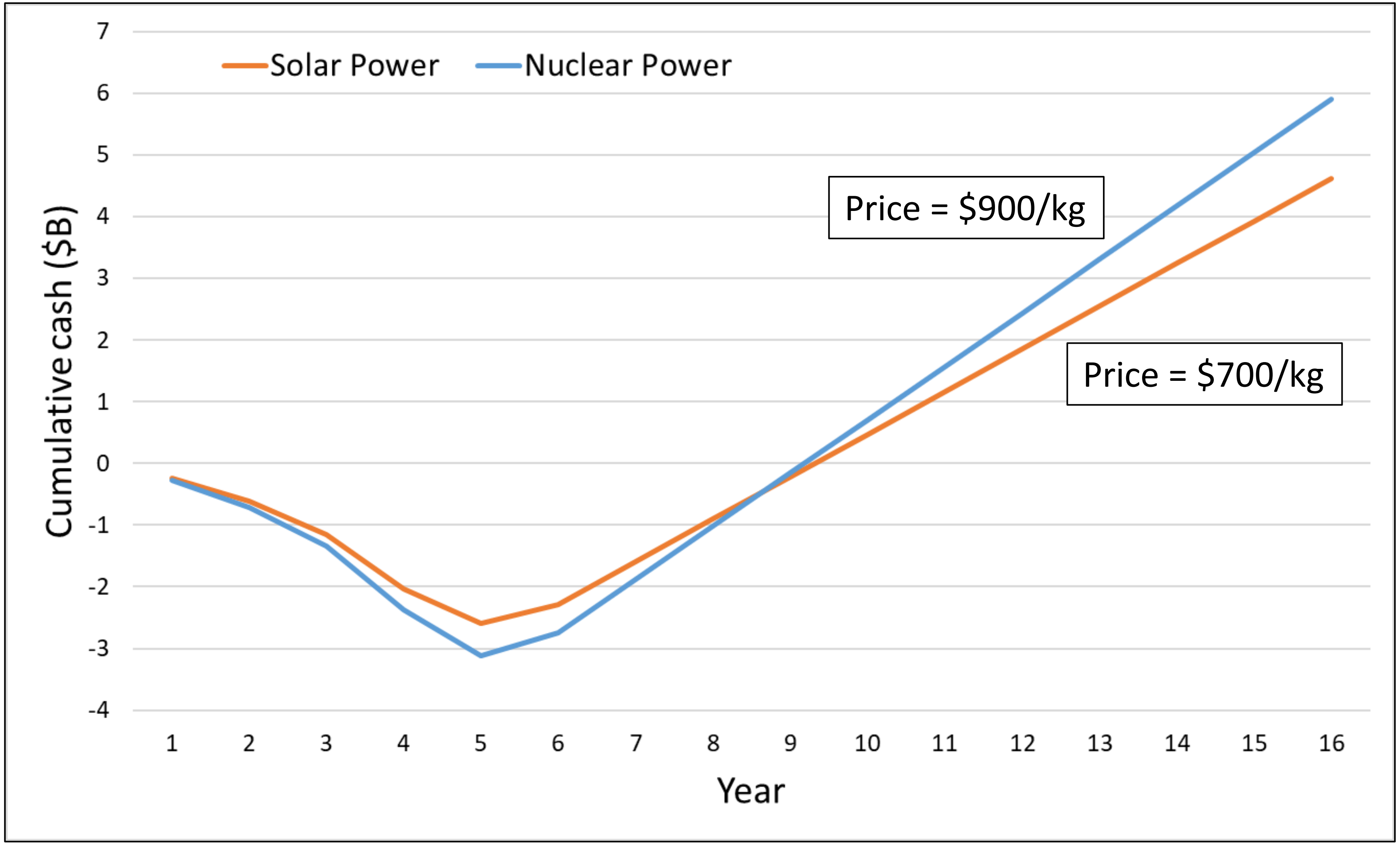
Water Cost Results

- Production rate = 1100mT LH_2/LO_2 per year
- Operations & maintenance cost not included

Method	Reflected Sunlight Architecture	Nuclear Architecture
Mass (kg)	26,200.0	41,700.0
Power (kW)	2000.0	1500.0
Development & production cost ($k)	1,497,000.0	1,686,000.0
Launch/landing cost ($k)	1,062,000.0	1,370,000.0
Total cost ($k)	2,559,000.0	3,056,000.0

- Reflected sunlight values from Sowers (2021)
- Nuclear values adapted from Sowers (2021)

Water Cash Flows (IRR = 15%)



Comparison

	Oxygen Methods			Water Methods	
Parameter	MRE	Carbothermal	FFC/Metalysis	Solar	Nuclear
Price ($/kg)	9,900	7,600	7,500	700	900
LO2/LH2 price ($/kg) on the lunar surface	13,800	11,800	11,700	700	900
Mass efficiency ((kg/yr)/kg)	10.3	14.8	2.7	42.0	26.4
Energy efficiency ((kg/yr)/kWh)	0.02	0.02	0.05	0.06	0.08
Specific cost, non-recurring ($/(kg/yr))	12,500	7,300	18,500	2,300	2,800
Specific cost, recurring (($/yr)/(kg/yr))	6,000	5,100	3,000	70	110

Limitations/Assumptions

Oxygen Methods	Effect on price
Missing mass and power for excavation and beneficiation	Increase (excavation and beneficiation are mass and power intensive operations)
Assumed production rate two orders of magnitude below that for water	Decrease (economies of scale)
Power purchased commercially versus dedicated infrastructure	Increase (non-recurring cost) Decrease (operating cost)
Metal byproducts not included	Decrease (provides additional revenue source)
Water Methods	
Resource exploration cost not included	Increase (but there are opportunities for government funding)
Cost to transport water/propellant out of PSR not included	Increase (depending on location of use)
Oxygen byproduct not included	Decrease (provides additional revenue source)

Conclusions

- Prices for both lunar derived oxygen and LO_2/LH_2 propellant from water are significantly below price to bring from Earth (~35,000/kg)
  - Public Private Partnership models can lower cost and risk
- Price of propellant from water is an order of magnitude less than oxygen
  - Even more if LH_2 from Earth is accounted for
- Oxygen is available everywhere while water is only in cold dark PSRs, requiring a resource exploration campaign
- **Development of oxygen methods should be pursued in parallel with conducting a water resource exploration (prospecting) campaign**


Questions?
95.1 ° W 53.3 ° S
100 km
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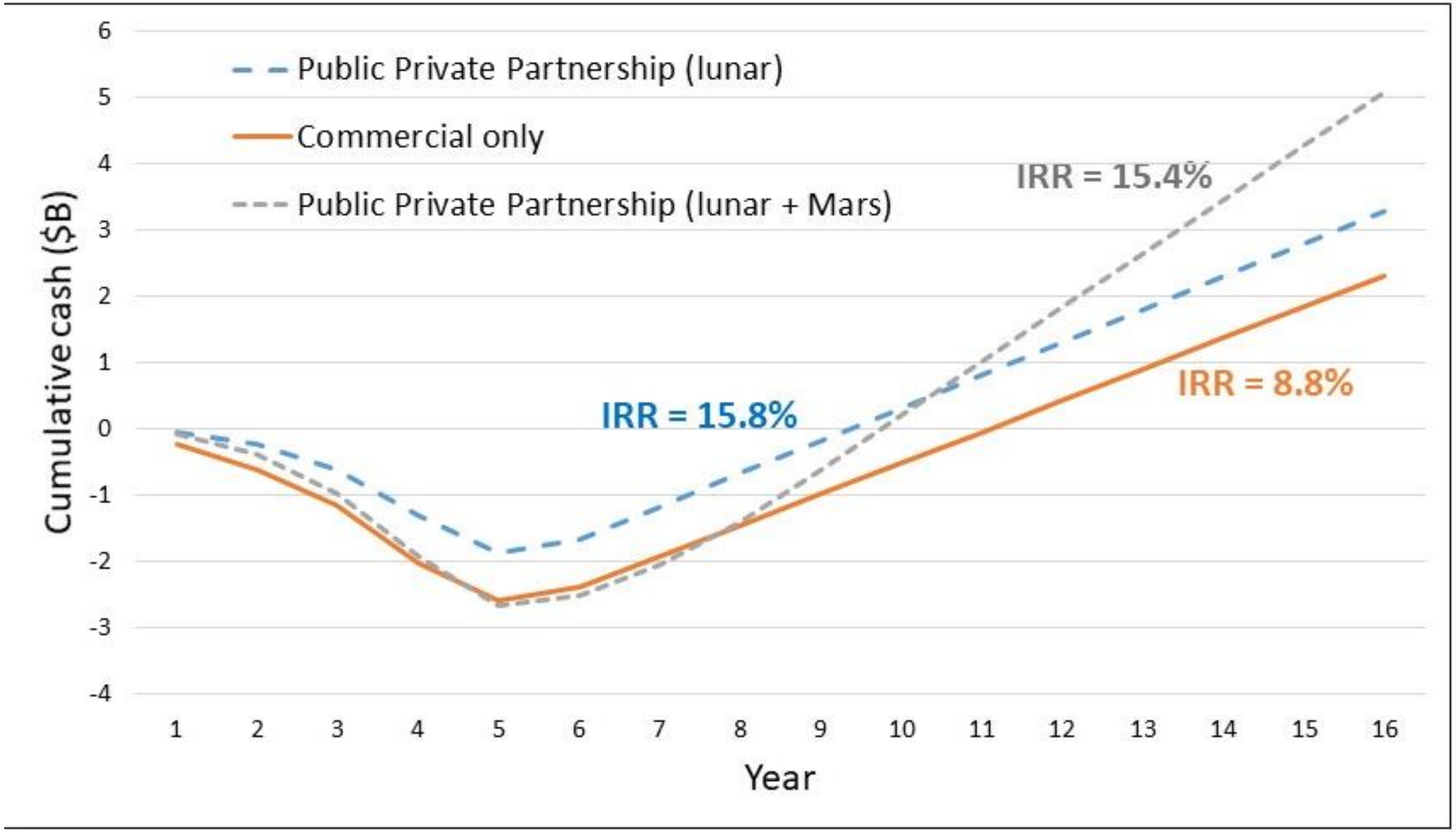
Water Cash Flows @ $500/kg



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Costs of Propellant in Cislunar Space