The Business Case for Lunar Ice Mining

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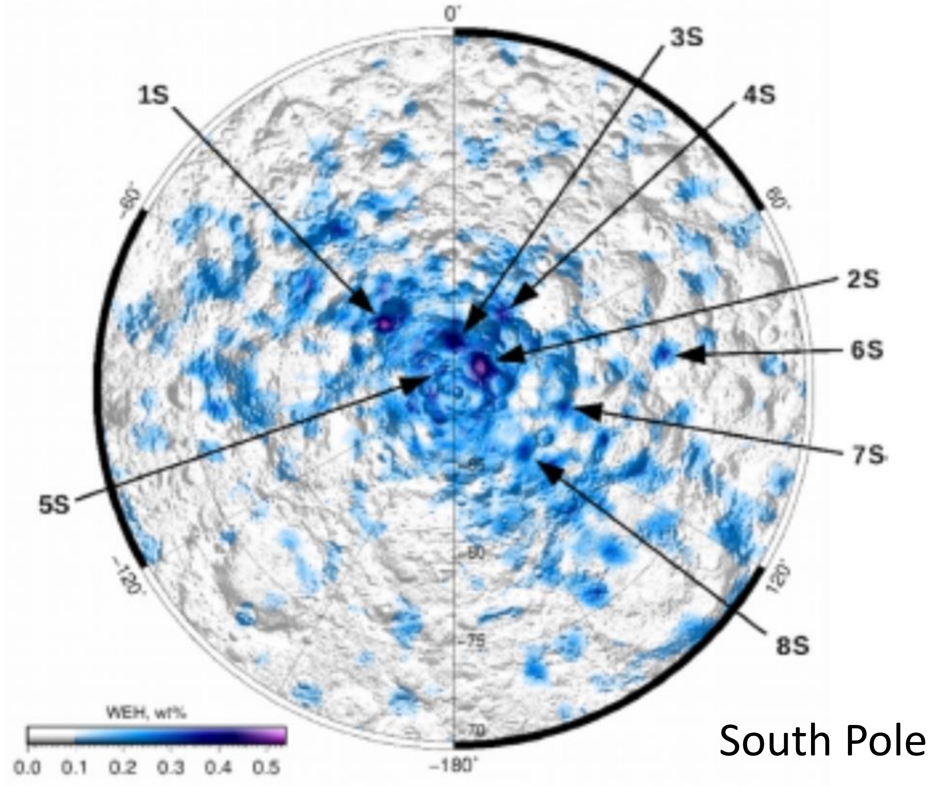
Background

- Water exists in the Permanently Shadowed Regions (PSRs) near the Poles of the Moon
  - Confirmed by many remote sensing data sets
  - Directly confirmed by 2009 LCROSS mission
    - 5.6±1.9wt% ice in ejecta plume
- Water can be split and liquified into LO_2/LH_2 propellants

Water is the Oil of Space

Neutron Spectrometer Indications of Hydrogen

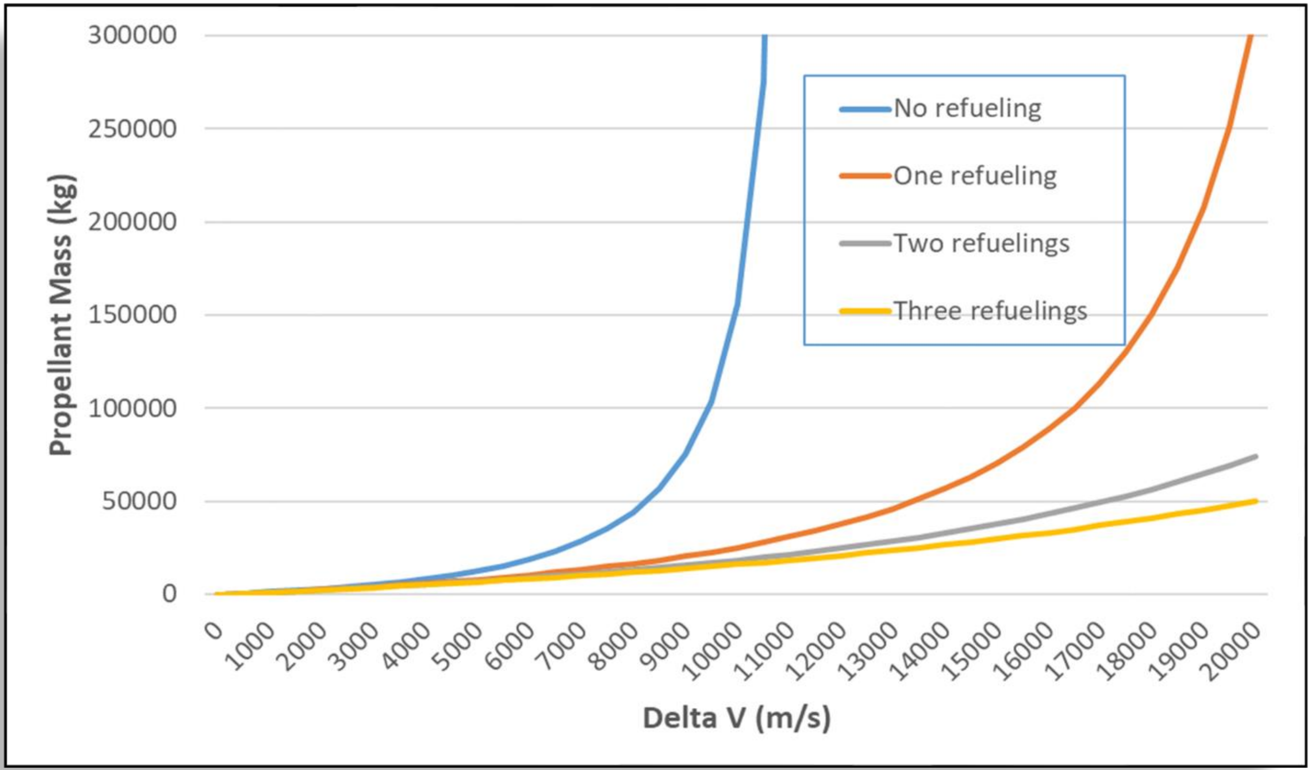


Sanin AB, et al. (2017) Hydrogen distribution in the lunar polar regions. Icarus 283:20-30.

Propellant Markets

- **All** beyond LEO missions and space activities benefit from lunar propellant (via refueling)
  - NASA
  - Military
  - Commercial
  - International
- Eventual transition to refuellable water based propulsion (steam, plasma, LO_2/LH_2)
  - Satellites
  - In-space stages
  - Upper stages

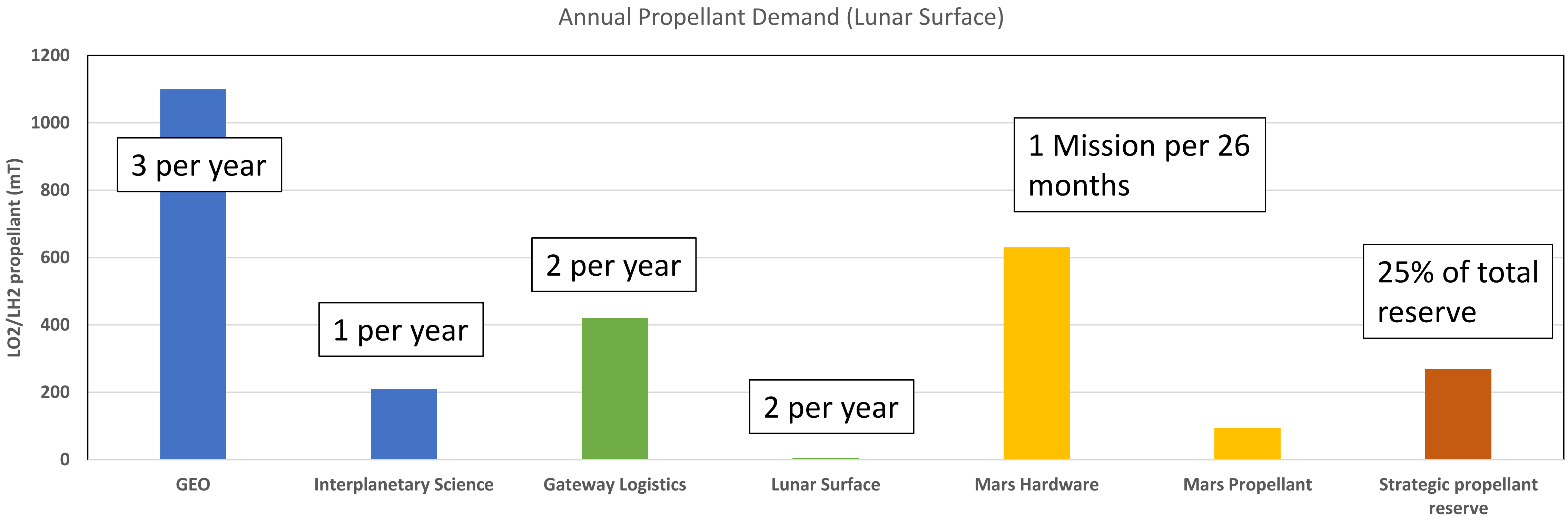
Breaking the Tyranny of the Rocket Equation



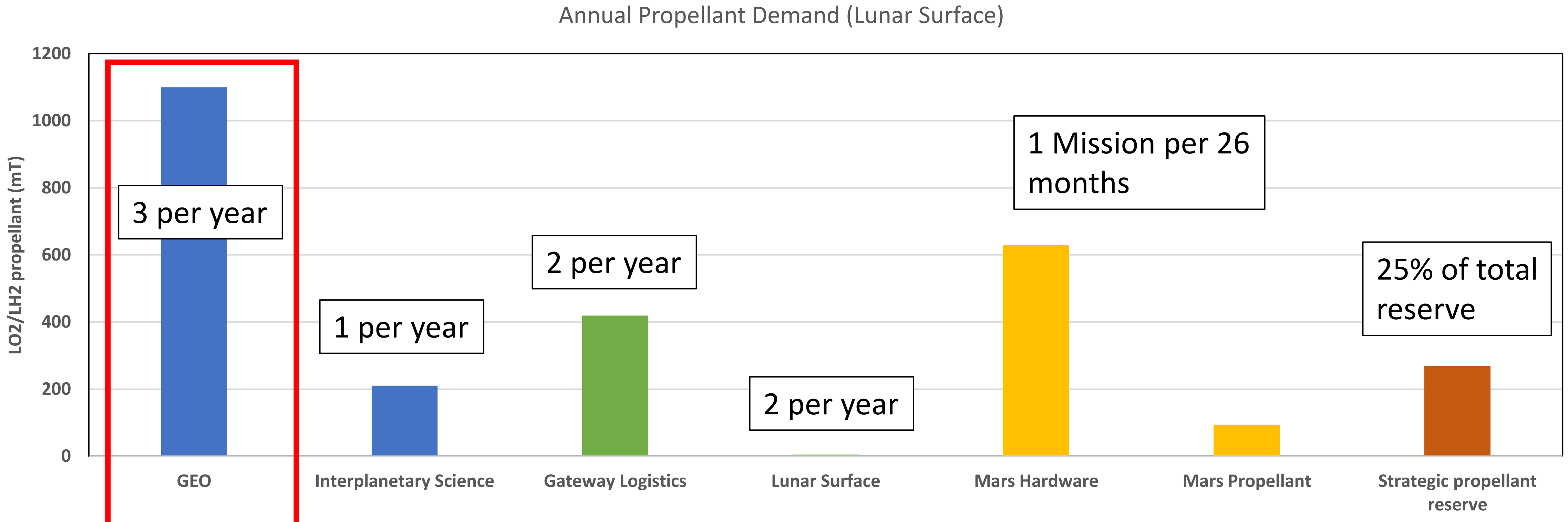
A necessary prerequisite for propellant markets is a refuellable transportation architecture

LO_2/LH_2 Propellant Demand Estimate

- 2730 mT/year
  - Normalized to lunar surface production in metric tons
  - Includes propellant expended to move the commodity to the point of refueling

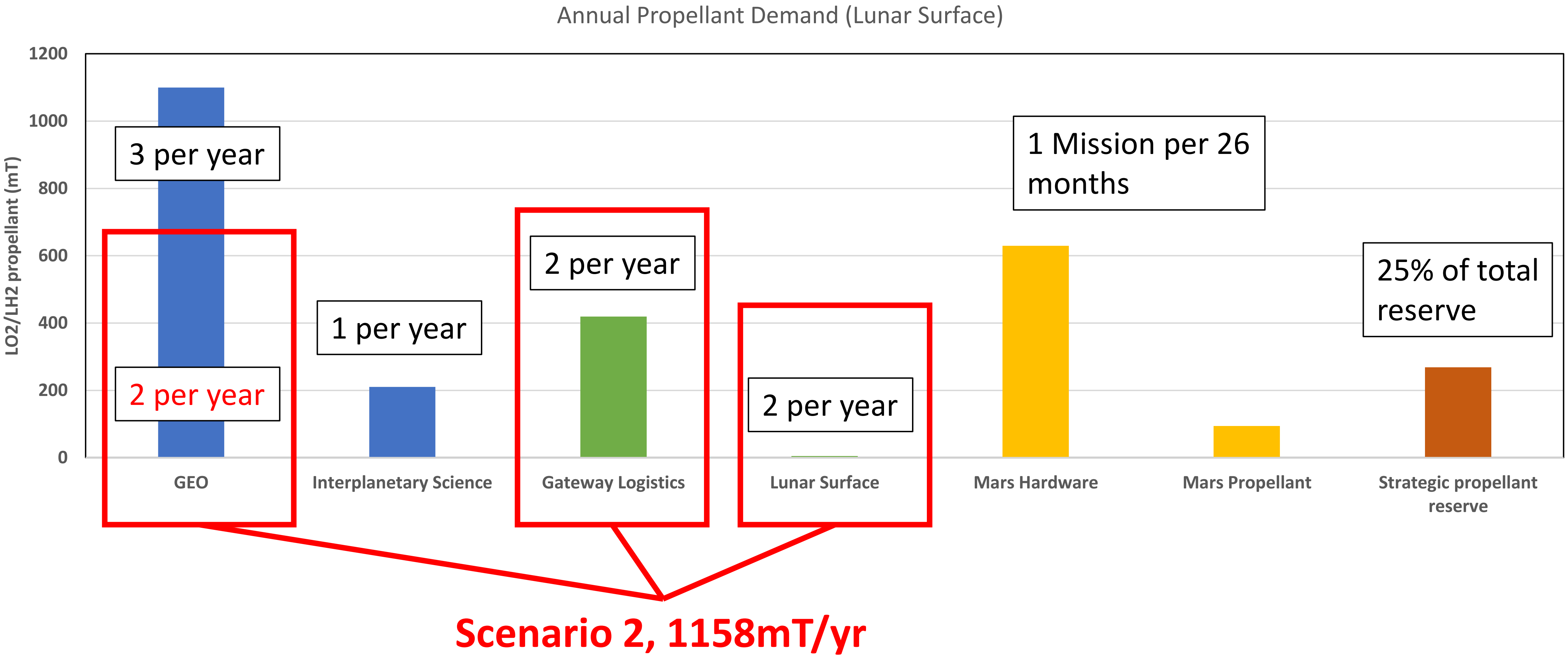


Demand Scenarios

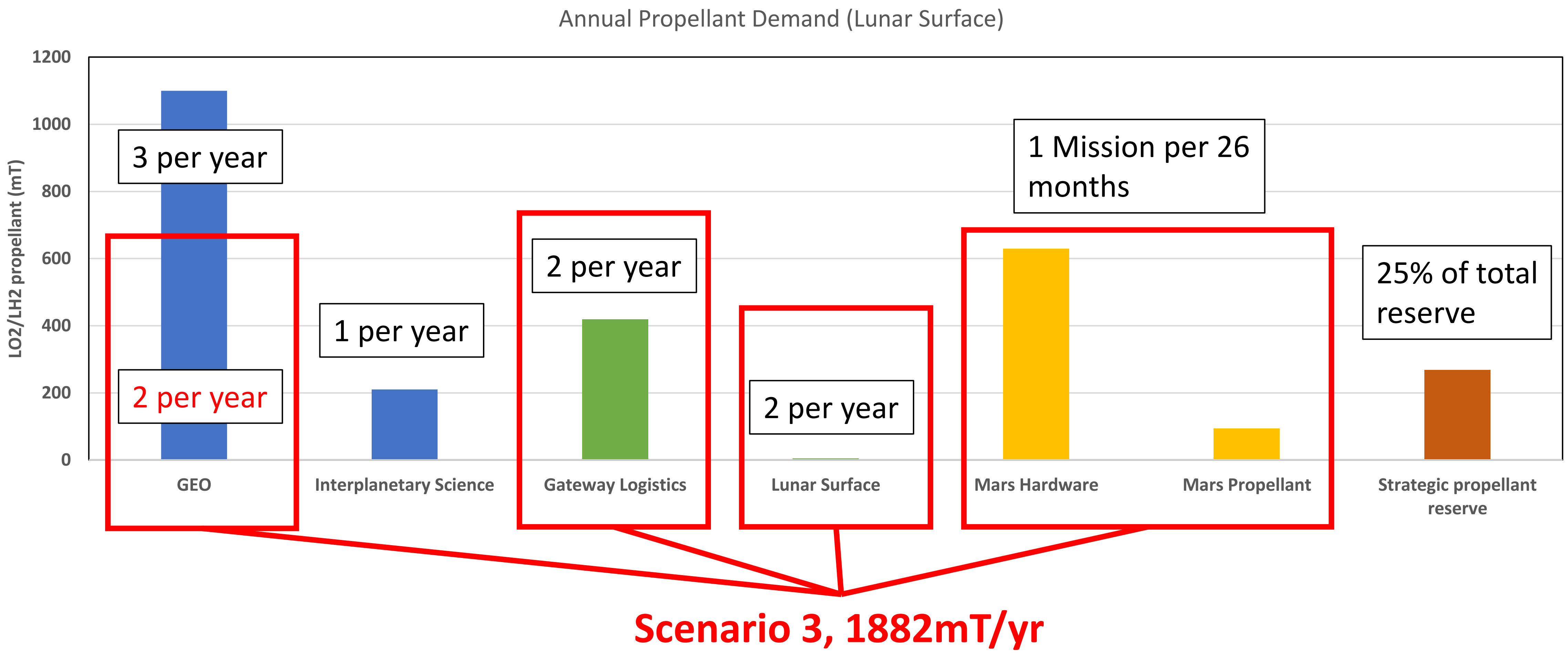


Scenario 1, 1100mT/yr

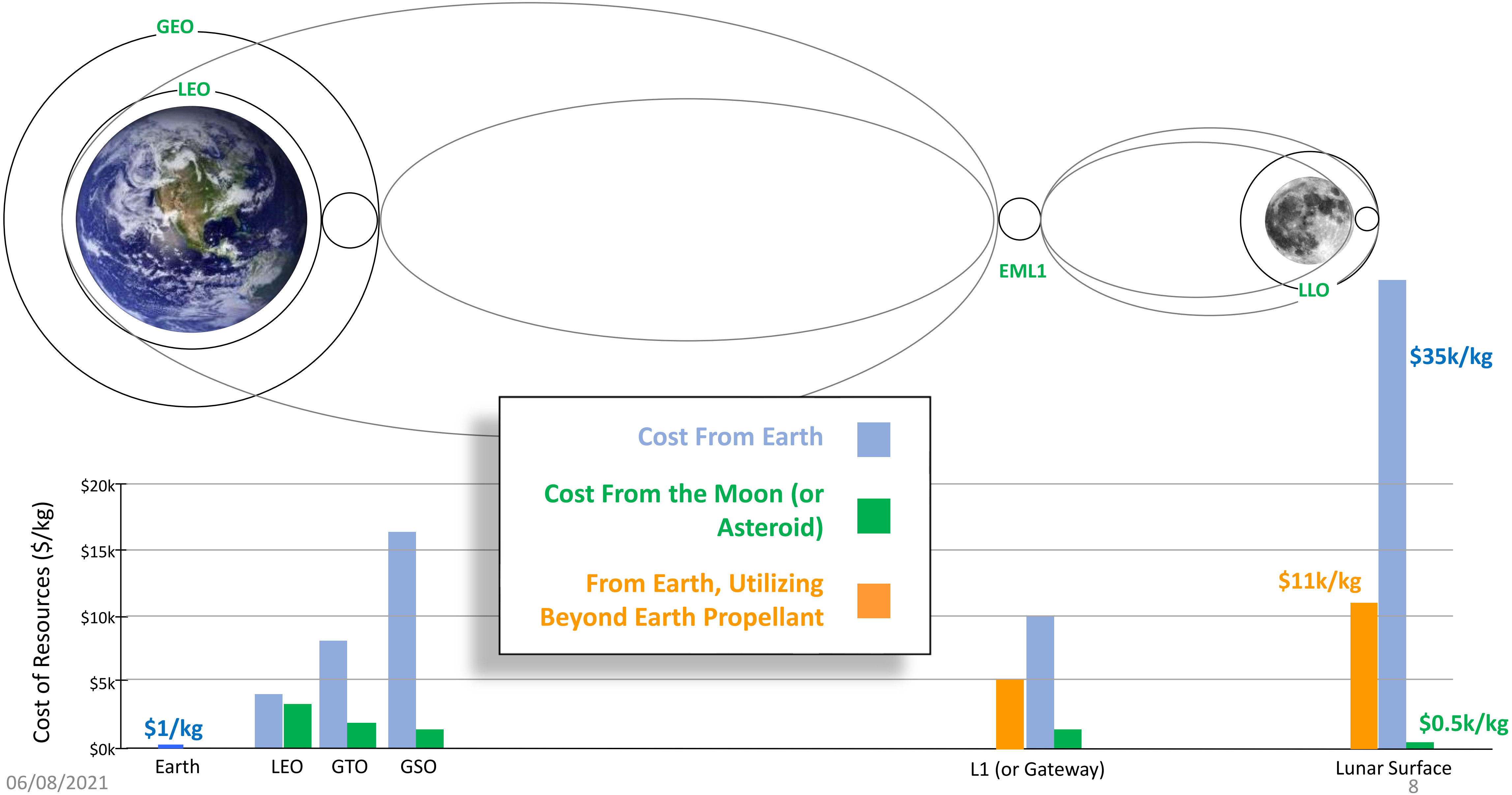
Demand Scenarios



Demand Scenarios



Costs of Propellant in Cislunar Space



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Production System Architecture

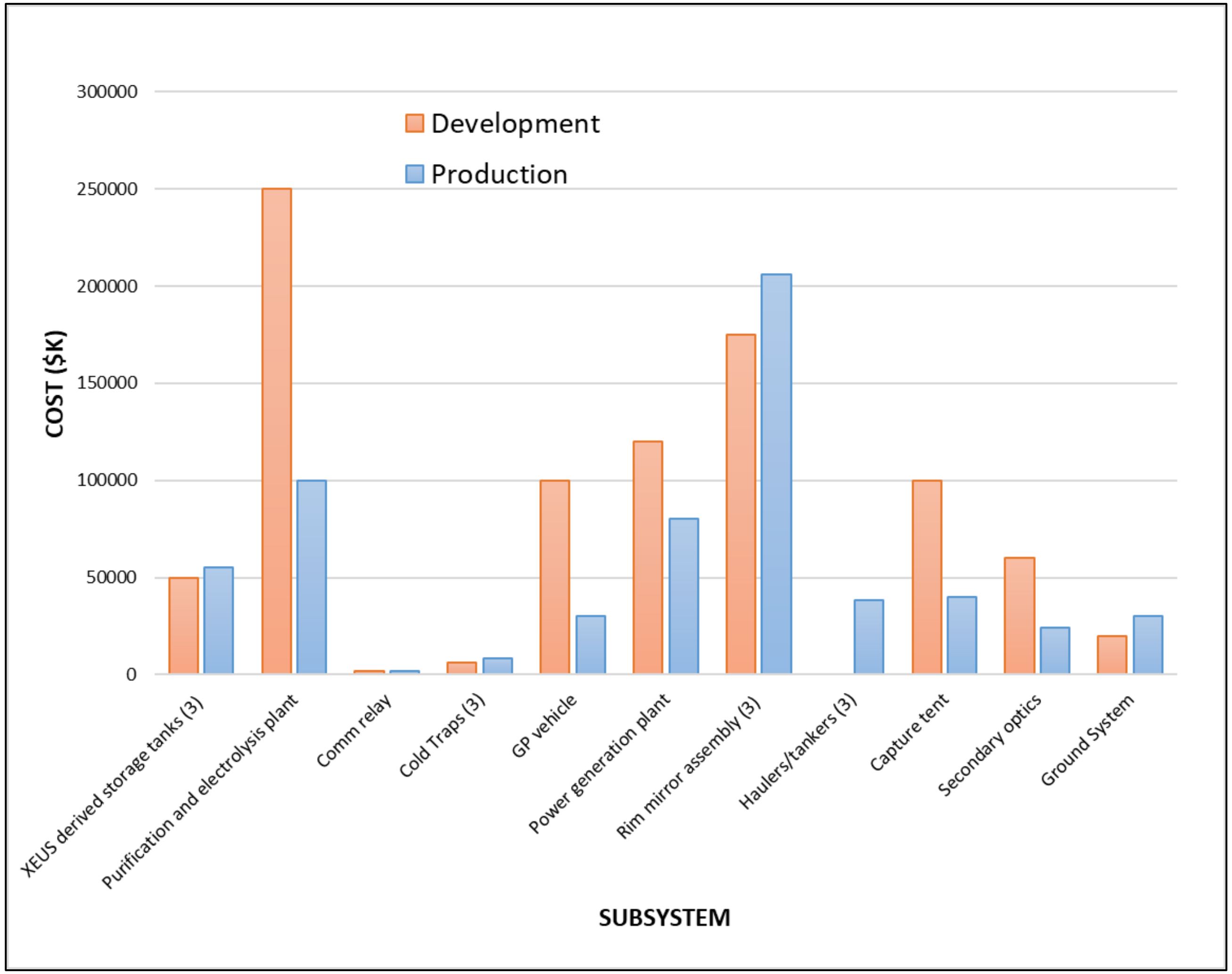
- Propellant production system
  - Ice extraction system
    - Capture Tent
    - Cold Traps
    - Secondary Optics
  - Mobility systems
    - General Purpose Vehicle
    - Ice hauler
  - Propellant processing system
    - Purification & Electrolysis system
    - Liquification system
  - Storage systems
  - Solar energy system
  - Power system
  - Communication system
  - Ground System

Based on Thermal Mining NIAC study:
https://space.mines.edu/wp-content/uploads/sites/134/2020/03/Thermal-Mining-NIAC-Phase-I-final-report.pdf

System Cost Model

- Costs estimated for Scenario 1, Commercial Only
- Scaled by production rate for Scenarios 2 & 3

Cost Element	Cost ($M)
Development	883
Production	614
Launch	1,062
Total	2,559



Public Private Partnership

- Developing lunar water resources can be enabled by government (NASA) policies and actions
    - Resource exploration
    - Technology development (risk reduction)
    - Co-investment in initial capability
    - Initial customer
- Public-Private partnership constructs increase the returns to a commercial lunar propellant company sufficient to attract private investment
    - Private capital reduces government outlays while establishing a capability that NASA needs
- Positive returns for both the public and private parties
    - Access to low cost lunar propellant reduces long term NASA costs
    - NASA investment reduces up front cash well (debt) and provides early NASA commitment
    - NASA propellant purchases provide reliable revenue stream for the private company

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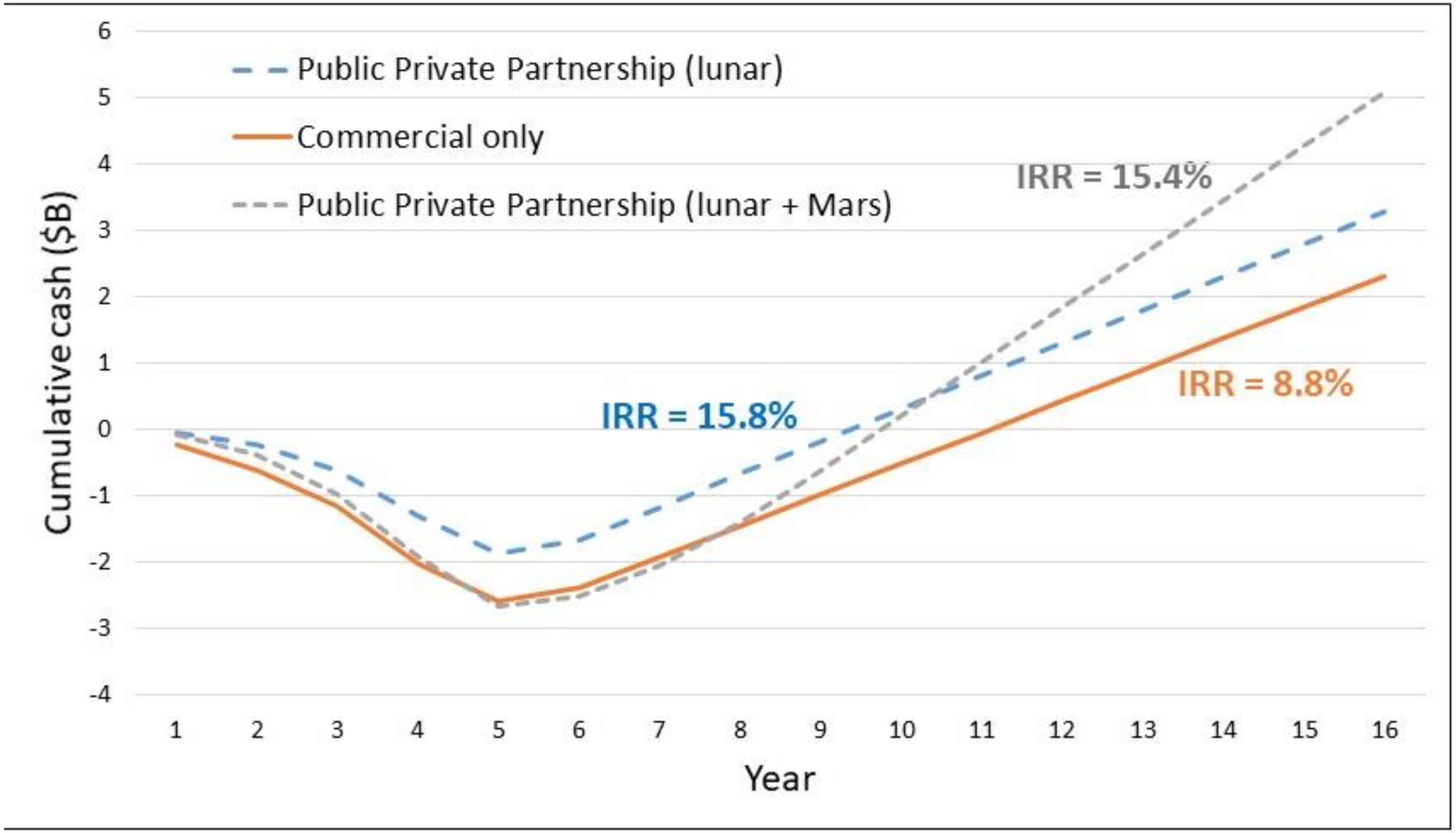
Business Case Results

Parameter	Scenario 1 (Commercial Only)	Scenario 2 (Commercial + NASA Lunar)	Scenario 3 (Commercial + NASA Lunar + Mars)
Production rate (mT/yr)	1100	1158	1882
Development cost ($M)	883.0	929.6	1435.1
Production cost ($M)	613.5	645.8	997.0
Transportation cost ($M)	1062.0	1062	1370
Operations cost ($M/yr)	78.6	82.7	127.7
NASA investment ($M)	0	800	1200
Price ($/kg)	500	500	500
Revenue ($M/yr)	550	579	971
IRR (%)	8.8	15.8	15.4

Cash Flows



Public Private Partnership (lunar)
Commercial only
Public Private Partnership (lunar + Mars)
IRR = 15.4%
IRR = 15.8%
IRR = 8.8%
Cumulative cash ($B)
6
5
4
3
2
1
0
-1
-2
-3
-4
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Year

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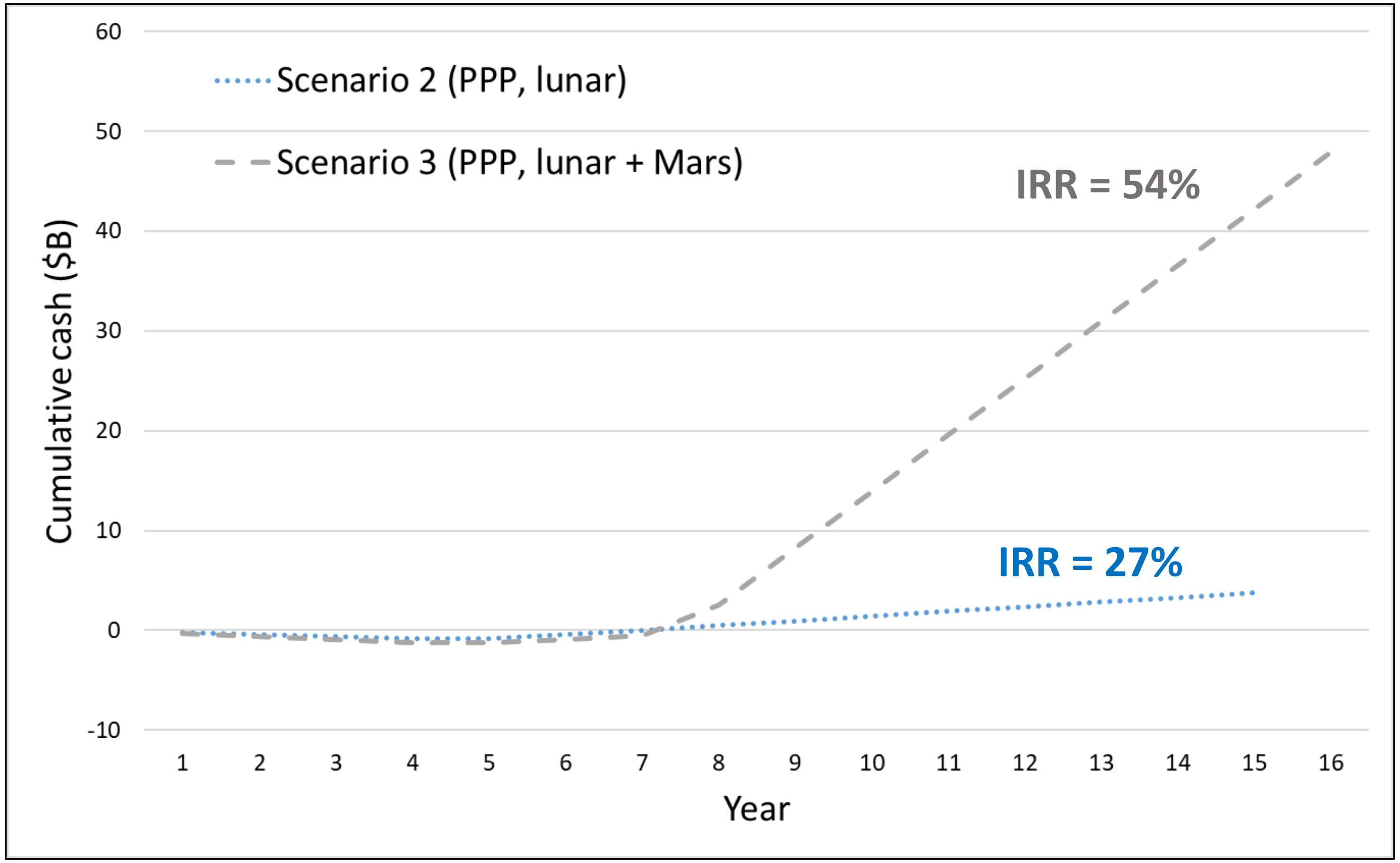
NASA Savings

- Scenario 2
  - Investment = $800M
  - Savings = $473M/yr
- Scenario 3
  - Investment = $1200M
  - Savings = $473M/yr + $5185M/yr Mars
  - **$12B savings per Mars mission**



Comparison to Jones et al. (2019)

Factor	Jones et al.	Thermal Mining	Comments/Rationale
Propellant price in cislunar space	$101,000/kg	$1100/kg	Factor of 92 difference.
Business model	Government only	PPP	Commercial investment amortized over the 10-year life of the operation.
Delivery vehicle mass fraction	0.26	0.11	Mass fraction corresponding to the Altair human lander. XEUS based on cargo only Centaur derivative.
Delivery to the Moon	SLS	Commercial	Commercial launch readily available, commercial landing in development.
Plant efficiency (kg annual propellant production per kg plant mass, excluding power)	8.4	62.0	Thermal Mining avoids excavation, targets surface ice. Jones is based on molten regolith electrolysis.
Power source	Nuclear (75kg/kW)	Reflected sunlight (5.8kg/kW)	Reflected sunlight very mass efficient. Nuclear number high by factor of 4.
Power efficiency	Based on molten regolith electrolysis (48kW/T/yr	1.8kW/T/yr	Molten regolith electrolysis is a poor proxy for ice extraction, producing only oxygen and requiring temperatures of 2200K (vs 220K for Thermal Mining).

Questions?

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