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Habitation-Driven Demand as a Catalyst for Lunar ISRU Deployment

SPACE RESOURCES ROUNDTABLE XXVI – JUNE 2-5, 2026

AUTHORS: J. E. JOHNSON, G. SOWERS, A. ABBUD-MADRID

The Value of Lunar-derived Oxygen and Water for an Early Habitation Customer

Space and Planetary Resources Journal (Manuscript submitted for publication)

James E. Johnson

Ph.D. Candidate – Space Resources Program

COLORADO SCHOOL OF MINES

Advisor: Dr. Angel Abbud-Madrid

Co-advisor: Dr. George Sowers

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Introduction


Credit: NASA

GUIDING PRINCIPLES

- Phasing toward sustained human presence
- Early habitats rely on consumable resupply
- Concurrent demonstration of ISRU
- Greater ISRU customer insight is needed

Could early habitation demand be a catalyst for a lunar ISRU economy?

Habitation consumable demand

Resupply lifecycle cost

VS.

ISRU lifecycle cost

=

Intrinsic value vs. production cost

Intrinsic value represents a deferred logistics cost

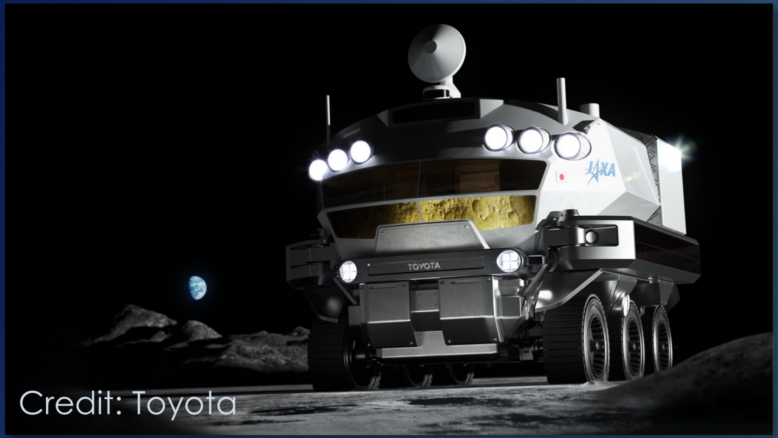
Architectures:

- Minimum
- Baseline (expected)
- Maximum

Case Studies:

- Water only
- Oxygen only
- Combination

Early Lunar Habitation


Credit: Toyota

- NASA's Initial Moon Base Habitation
  - JAXA Pressurized Rover (PR)
  - ASI Multi-Purpose Habitation (MPH) Module
  - 10-yr system life, starting early 2030's
  - Both habitats leverage open-loop environmental control and life support systems (ECLSS)

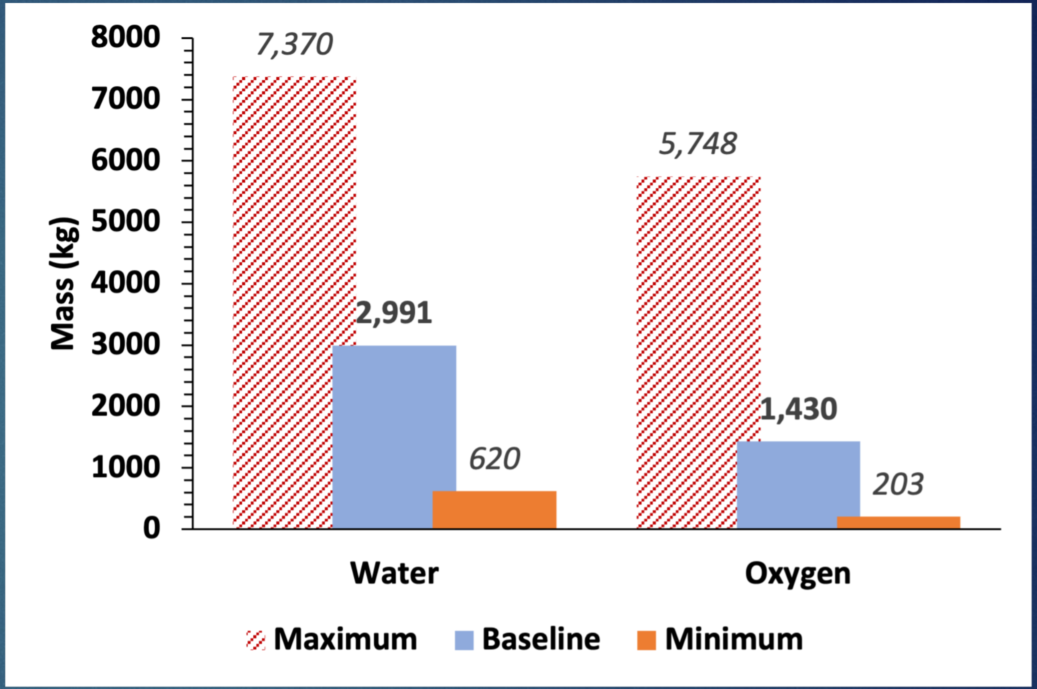

Credit: ASI

- Mission architecture & habitat design affect demand
  - Crew size (2-4 crew)
  - Mission duration (7-28 days)
  - Mission cadence (1 flight/yr)
  - Extravehicular activities (EVA)
    - Duration (4-8 hours)
    - Cadence (2-5 per week)
  - Airlock design (14-76 m^3)

Habitation Demand

Oxygen Demands
- EVA
- Metabolic
- Leakage

Water Demands
- Drinking
- Food Preparation
- Hygiene
- Flush
- Sampling
- Medical/Contingency
- EVA Cooling



Expected 10-yr lifetime baseline demand for early Moon Base habitats:

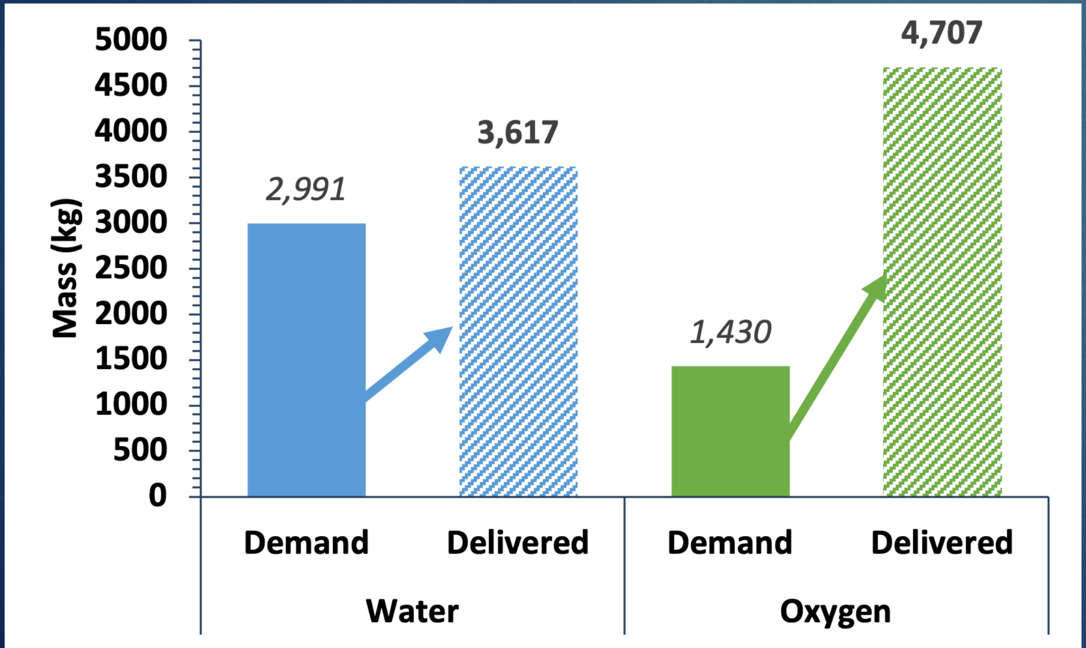
- **$H_2O \cong$ 2.9 t** → Driven by duration, crew size & EVA
- **$O_2 \cong$ 1.4 t** → Driven by duration, EVA & crew size

Logistical Impacts of Resupply

Oxygen Tanks

Water Bags

Packaging



4.4 metric tons of demand can become ~8.3 metric tons delivered mass

Lifecycle Cost (LCC) & Value Estimation

Design, Development, Test & Evaluation (DDT&E) + Production Costs

+

Transportation Costs

+

Operations Costs

=

Total LCC

Intrinsic value vs. production cost

- Median of three parametric cost models:
  - Advanced Missions Cost Model (AMCM)
  - Project Cost Estimating Capability (PCEC)
  - Industry Cost Factors + learning curve

- Commercial Lunar Payload Services ~$1M/kg
- SpaceX advertised delivery cost $100k/kg
- Lower delivery cost = lower intrinsic value

- DDT&E + Production "wrap factors" range 5.25-15%
- Static estimate of 5.5% DDT&E + Production
- Lower operations cost = lower intrinsic value

- Total LCC costs adjusted to FY26 dollars
- Median LCC informs intrinsic value vs. production cost

$$P_{cons} \approx \frac{M_{LCC}}{m_{wet}}$$

- Median LCC ÷ consumable delivered or produced
- Resulting values *inform* business case development

Intrinsic Value Results

Oxygen-only Resupply Architecture

Category	Metric	Minimum	Baseline	Maximum
Oxygen Demand & Mass (kg)	Lifetime oxygen demand	202.7	1,429.7	5,748.1
	Additional oxygen for full tanks	153.3	350.3	303.9
	Dry mass per oxygen tank	51.6	53.7	55.8
	Dry mass per package	3.38	4.83	6.28
	Lifetime delivered mass	905.8	4,706.5	16,605.6
Quantities (units)	Number of oxygen tanks	10	50	170
	Number of packages	10	50	170
Total Lifecycle Cost ($MFY26)	AMCM estimate	$237	$875	$2,542
	PCEC estimate	$110	$496	$1,726
	Industry estimate	$102	$510	$1,774
	Median estimate	$110	$510	$1,774
Intrinsic Value ($k/kg FY26)	Value per kg oxygen delivered	$310	$287	$293

- Median intrinsic values **significantly exceed** preceding lunar ISRU propellant business cases:
  - Charania & DePasquale (2007) = $35,300/kg
  - Kornuta et al. (2019) = $500-$7,500/kg
  - Sowers (2021) = $500/kg

Oxygen	Water	Combination
$297k/kg	**$121k/kg**	**$189k/kg**

Oxygen holds greater value due to current logistical inefficiencies

Comparison with ISRU Production

- Representative pilot-plant concepts analyzed for production cost
  - Concept masses adjusted for a habitation customer
  - Recurring spare delivery assumed at 10% system mass per year of operation

Oxygen-only ISRU Architectures

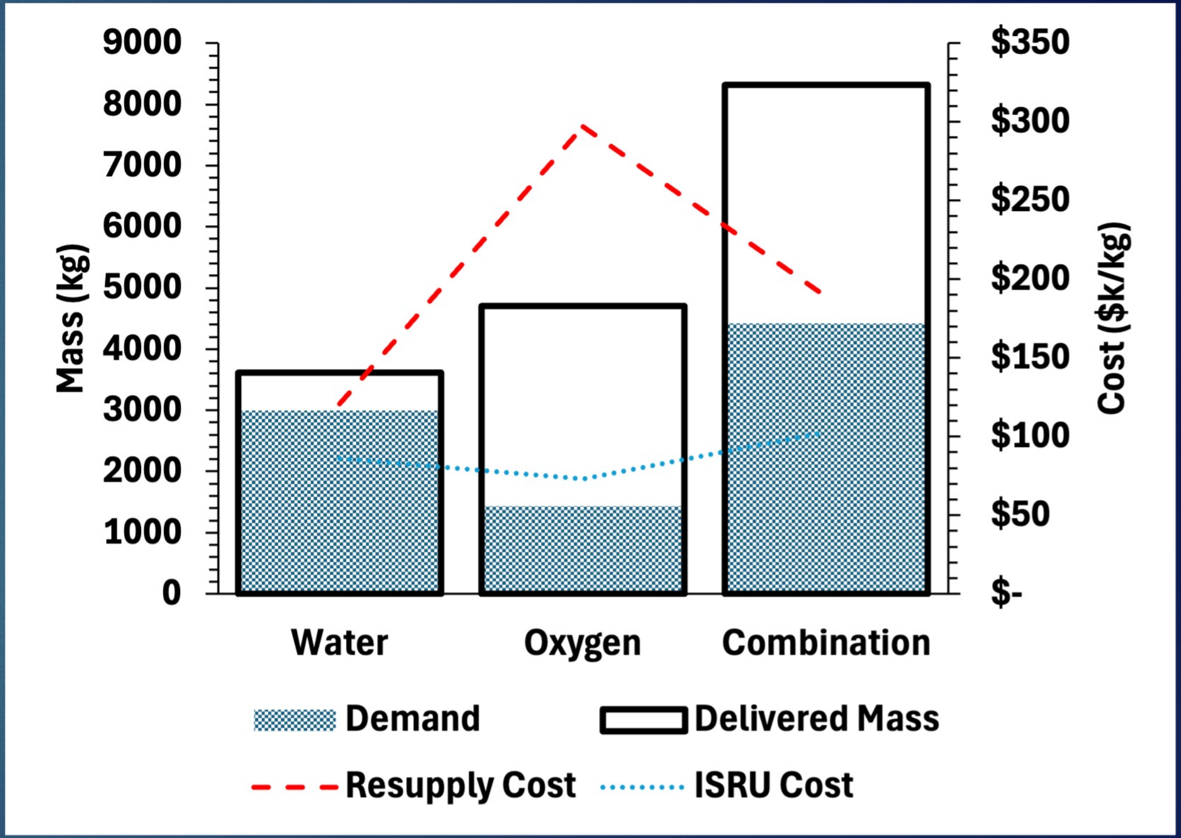
Category	Metric	Water Ice	Carbothermal	Molten Salt Electrolysis (MSE)
System Mass & Production Quantity (kg)	System mass	1,039	1,026	1,292
	Recurring spares mass per year	104	103	129
	Lifetime delivered mass	2,078	2,052	2,584
	Lifetime produced oxygen	10,000		11,550
Total Lifecycle Cost ($MFY26)	AMCM estimate	$2,610	$2,588	$3,033
	PCEC estimate	$705	$696	$886
	Industry estimate	$350	$345	$435
	Median estimate	$705	$696	$886
Production cost ($k/kg)	Cost per kg oxygen produced	$71	$70	$77

Oxygen production may exhibit the greatest profitability for early lunar habitation consumables

Oxygen	Water	Combination
$73k/kg	**$86k/kg**	**$103k/kg**

Conclusions

- Early habitation creates meaningful near-term in-situ consumable demand
- Logistical inefficiencies drive an extremely high intrinsic value
- Oxygen is especially valuable
- Eventual inclusion of regenerative life support systems will reduce demand, making this a time-limited opportunity



Habitation may be a near-term customer that catalyzes the ISRU economy

James E. Johnson
Ph.D. Candidate – Space Resources Program
COLORADO SCHOOL OF MINES
jejohnso@mines.edu

Thank You!

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1. Establish reliable access
2. Establish initial infrastructure
3. Enable long-duration exploration

Early habitat operations & ISRU demonstrations will likely overlap

Credit: NASA

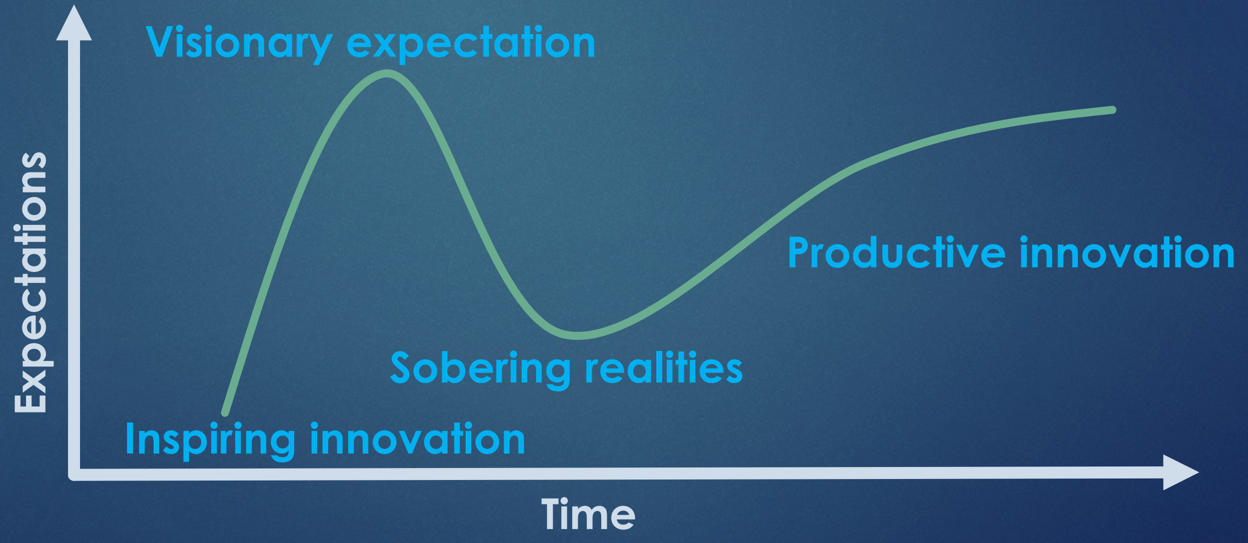
Strategic Implications

Early habitation may:

- Incentivize ISRU maturation
- Provide initial operational experience
- Accelerate commercial investment
- Create a pathway toward propellant & other economies

But:

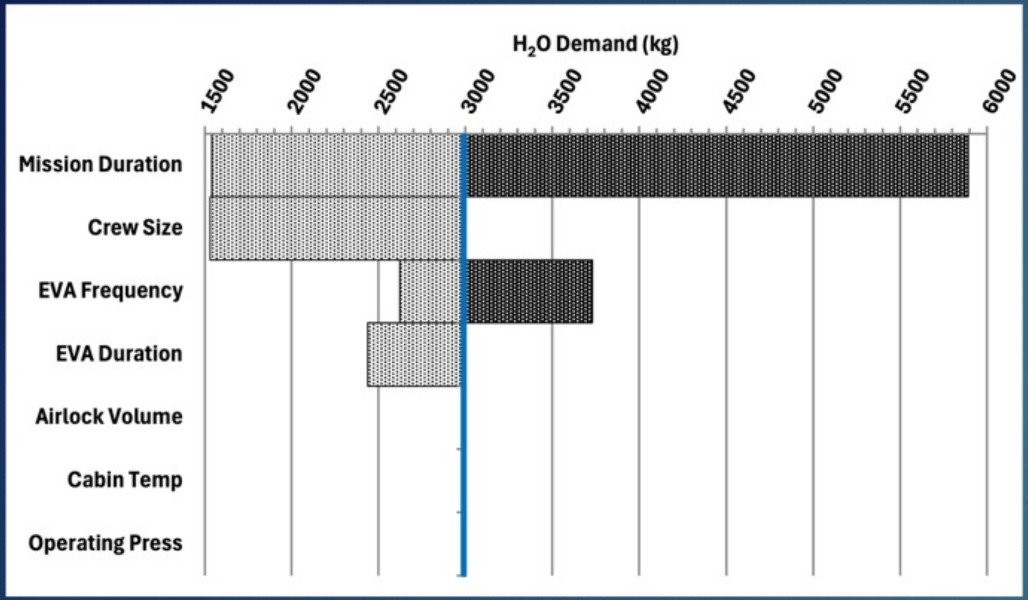
- Opportunity may be temporary
- Regenerative ECLSS reduces demand
- Transportation cost reductions will shift breakeven



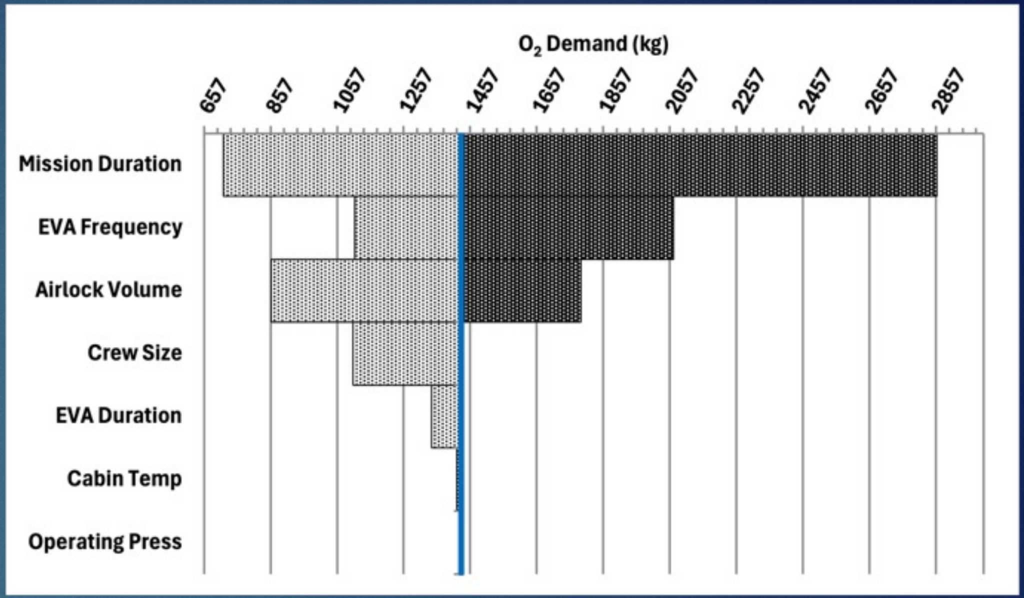
Habitation may be the "technology bridge" that gets ISRU operational

Demand Sensitivities

Water Demand



Oxygen Demand



- Demand drivers:
  - Mission duration
  - Crew size
  - EVA (frequency & duration)

- Demand drivers:
  - Mission duration
  - EVA (frequency & airlock volume)
  - Crew size
  - EVA duration
  - Cabin temperature & operating pressure

DDT&E + Production Cost Estimation Overview

- Parametric DDT&E estimation is based upon mass, complexity & coefficients

$$C = k \cdot aW^b$$

- AMCM database predicated on pre-1999 government spaceflight projects

$$C = \alpha Q^{\beta} \cdot M^{\Xi} \cdot \delta^{S} \cdot \varepsilon^{\left(\frac{1}{(IOC-1900)}\right)} \cdot B^{\phi} \cdot \Upsilon^{D}$$

- PCEC is an updated version of the preceding NASA/Air Force Cost Model (NAFCOM) and allows subsystem-specific cost estimating relationships
  - Excel plug-in downloadable from NASA's Software Catalog
- Industry cost factors enable rough order magnitude (ROM) estimation which can be further refined by applying a learning curve for repeat unit production
  - Initial unit DDT&E cost ≅ \$63 k/kg
  - Production unit cost ≅ \$25.5 k/kg

Learning curve: $\bar{X}_n = X \cdot \frac{1}{n} \sum_{i=1}^{n} i^b$

- All costs inflation-adjusted to FY26 (Jan) dollars

AMCM Variables & Assumptions

Regression Coefficients
$\alpha, \beta, \Xi, \delta, \varepsilon, \phi, \Upsilon$

Advanced Missions Cost Model (AMCM) =

$$System\ Cost = \alpha Q^{\beta} M^{\Xi} \delta^{S} \varepsilon^{\left(\frac{1}{IOC-1900}\right)} B^{\phi} \gamma^{D}$$

Unit Quantity (*Q*) | Mass (*M*) | Specification (*S*) *Human Habitats (2.13)* | Year (*IOC*) *2032* | Block (*B*) | Difficulty (*D*)

Coefficient	Value
α	5.65×10^{-4}
β	0.5941
Ξ	0.6604
δ	80.599
ε	3.8085×10^{-55}
ϕ	-0.3553
Υ	1.5691

Coefficients extracted from Guerra & Shishko (1999)

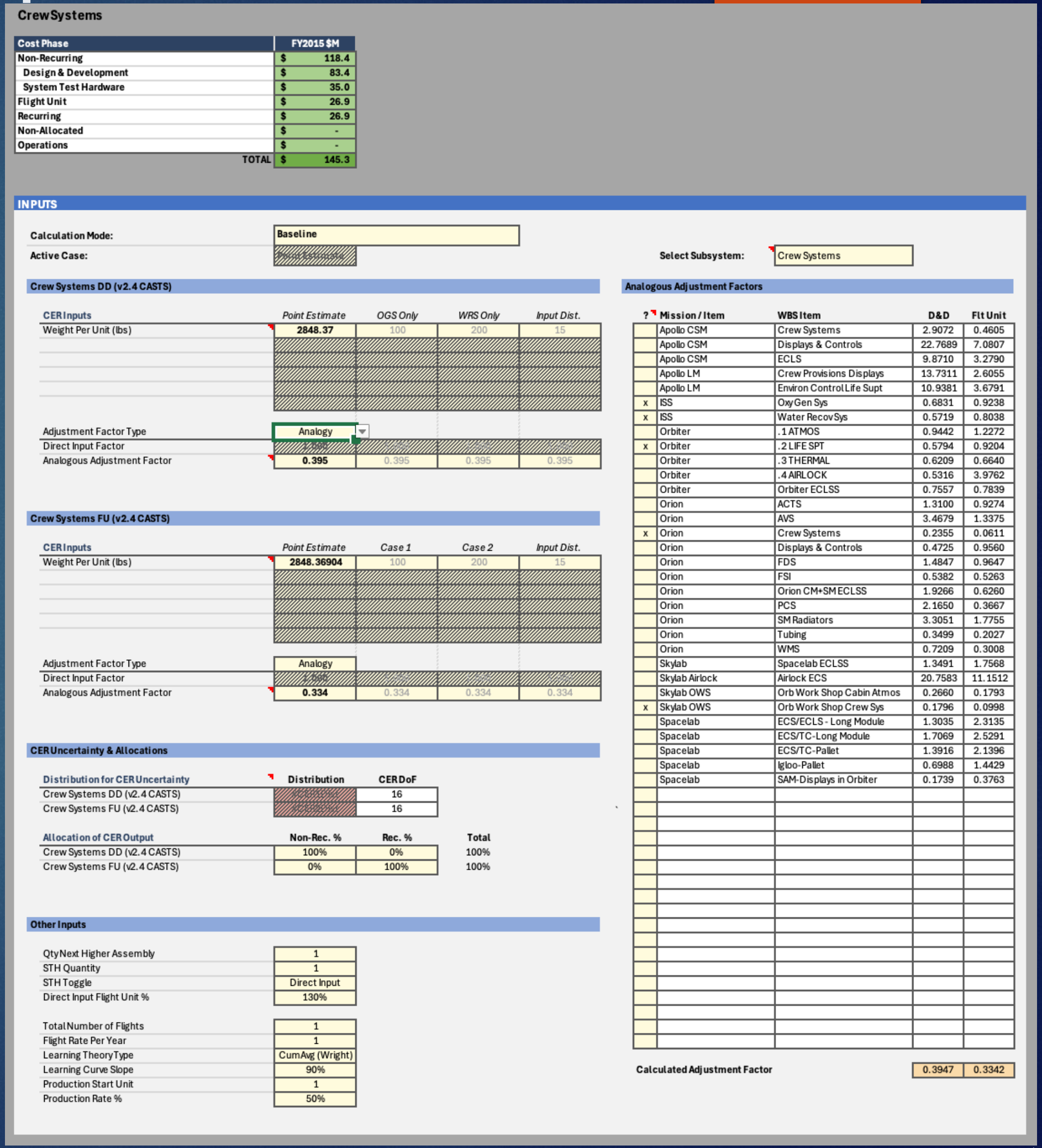
System	Variables	Values	Rationale
Earth-based Resupply	(*Q*) quantities	Variable/dependent	*As calculated*
	(*B*) block	5th iteration (5)	*Estimated ISS upgrade*
	(*D*) difficulty	Extremely Easy (-2.5)	*ISS-heritage*
Pilot ISRU	(*Q*) quantities	2	*1 flight + 1 qual*
	(*B*) block	1st iteration (1)	*Novel system*
	(*D*) difficulty	Slightly Difficult (0.5)	*Novel w/ground testing*

Resulting costs are in 1999 dollars, requiring inflating adjustment

PCEC Variables & Assumptions

- PCEC is an updated version of the preceding NASA/Air Force Cost Model (NAFCOM) and allows subsystem-specific cost estimating relationships
  - Excel plug-in from NASA's Software Catalog
  - Results in FY15 dollars
- Applied Crew and Space Transportation Systems (CASTS) v2.4 library and Crew Systems Cost Estimating Relationships

Variable	Earth-based Resupply	ISRU Pilot Systems
Flight Unit %	130%	130%
Flights	10	1
Rate	1	1
Theory	CumAvg (Wright)	CumAvg (Wright)
Slope	90%	90%
Production Start Unit	5	1
Production Rate %	50%	50%



Crew Systems

Cost Phase	FY2015 $M
Non-Recurring	$ 118.4
Design & Development	$ 83.4
System Test Hardware	$ 35.0
Flight Unit	$ 26.9
Recurring	$ 26.9
Non-Allocated	$ -
Operations	$ -
TOTAL	$ 145.3

INPUTS

Calculation Mode: Baseline
Active Case: Point Estimate
Select Subsystem: Crew Systems

Crew Systems DD (v2.4 CASTS)

CER Inputs	Point Estimate	OGS Only	WRS Only	Input Dist.
Weight Per Unit (lbs)	2848.37	100	200	15
Adjustment Factor Type	Analogy			
Direct Input Factor				
Analogous Adjustment Factor	0.395	0.395	0.395	0.395

Crew Systems FU (v2.4 CASTS)

CER Inputs	Point Estimate	Case 1	Case 2	Input Dist.
Weight Per Unit (lbs)	2848.36904	100	200	15
Adjustment Factor Type	Analogy			
Direct Input Factor				
Analogous Adjustment Factor	0.334	0.334	0.334	0.334

CER Uncertainty & Allocations

Distribution for CER Uncertainty	Distribution	CER DoF
Crew Systems DD (v2.4 CASTS)		16
Crew Systems FU (v2.4 CASTS)		16

Allocation of CER Output	Non-Rec. %	Rec. %	Total
Crew Systems DD (v2.4 CASTS)	100%	0%	100%
Crew Systems FU (v2.4 CASTS)	0%	100%	100%

Other Inputs

Qty Next Higher Assembly	1
STH Quantity	1
STH Toggle	Direct Input
Direct Input Flight Unit %	130%
Total Number of Flights	1
Flight Rate Per Year	1
Learning Theory Type	CumAvg (Wright)
Learning Curve Slope	90%
Production Start Unit	1
Production Rate %	50%

Analogous Adjustment Factors

?	Mission / Item	WBS Item	D&D	Flt Unit
	Apollo CSM	Crew Systems	2.9072	0.4605
	Apollo CSM	Displays & Controls	22.7689	7.0807
	Apollo CSM	ECLS	9.8710	3.2790
	Apollo LM	Crew Provisions Displays	13.7311	2.6055
	Apollo LM	Environ Control Life Supt	10.9381	3.6791
x	ISS	Oxy Gen Sys	0.6831	0.9238
x	ISS	Water Recov Sys	0.5719	0.8038
	Orbiter	.1 ATMOS	0.9442	1.2272
x	Orbiter	.2 LIFE SPT	0.5794	0.9204
	Orbiter	.3 THERMAL	0.6209	0.6640
	Orbiter	.4 AIRLOCK	0.5316	3.9762
	Orbiter	Orbiter ECLSS	0.7557	0.7839
	Orion	ACTS	1.3100	0.9274
	Orion	AVS	3.4679	1.3375
x	Orion	Crew Systems	0.2355	0.0611
	Orion	Displays & Controls	0.4725	0.9560
	Orion	FDS	1.4847	0.9647
	Orion	FSI	0.5382	0.5263
	Orion	Orion CM+SM ECLSS	1.9266	0.6260
	Orion	PCS	2.1650	0.3667
	Orion	SM Radiators	3.3051	1.7755
	Orion	Tubing	0.3499	0.2027
	Orion	WMS	0.7209	0.3008
	Skylab	Spacelab ECLSS	1.3491	1.7568
	Skylab Airlock	Airlock ECS	20.7583	11.1512
	Skylab OWS	Orb Work Shop Cabin Atmos	0.2660	0.1793
x	Skylab OWS	Orb Work Shop Crew Sys	0.1796	0.0998
	Spacelab	ECS/ECLS - Long Module	1.3035	2.3135
	Spacelab	ECS/TC-Long Module	1.7069	2.5291
	Spacelab	ECS/TC-Pallet	1.3916	2.1396
	Spacelab	Igloo-Pallet	0.6988	1.4429
	Spacelab	SAM-Displays in Orbiter	0.1739	0.3763
	Calculated Adjustment Factor		0.3947	0.3342

Industry Cost Factor Approach

$$C = k \cdot XM$$

- *k* is an optional complexity factor
- *X* is industry-based cost factor
- *M* is system mass (in kg)

- Industry cost factors enable rough order magnitude (ROM) estimation which can be further refined by applying a learning curve for repeat unit production
  - Initial unit DDT&E cost ≅ \$63 k/kg
  - Production unit cost ≅ \$25.5 k/kg
  - Factors are inflation-adjusted to FY26 dollars from Sowers (2021)
- Learning rate of 0.9 applied for repeat unit production
  - 10% cost reduction every time cumulative production doubles
  - Rate considered aerospace industry standard

$$\bar{X}_n = X \cdot \frac{1}{n}\sum_{i=1}^{n} i^b$$

Deriving Intrinsic Value

Demand/impact assessed for following cases:

- Minimum
- Baseline
- Maximum

Demand/ production
- Calculate habitation oxygen & water demand

Logistical impacts
- Calculate dry mass & quantities for oxygen & water delivery

DDT&E cost
- Calculate design, development, test & evaluation costs

Lifecycle cost (LCC)
- Calculate full LCC, inclusive of transportation & operations

Intrinsic value
- Derive avoided LCC of an Earth-based resupply paradigm

Early Lunar ISRU Assumptions

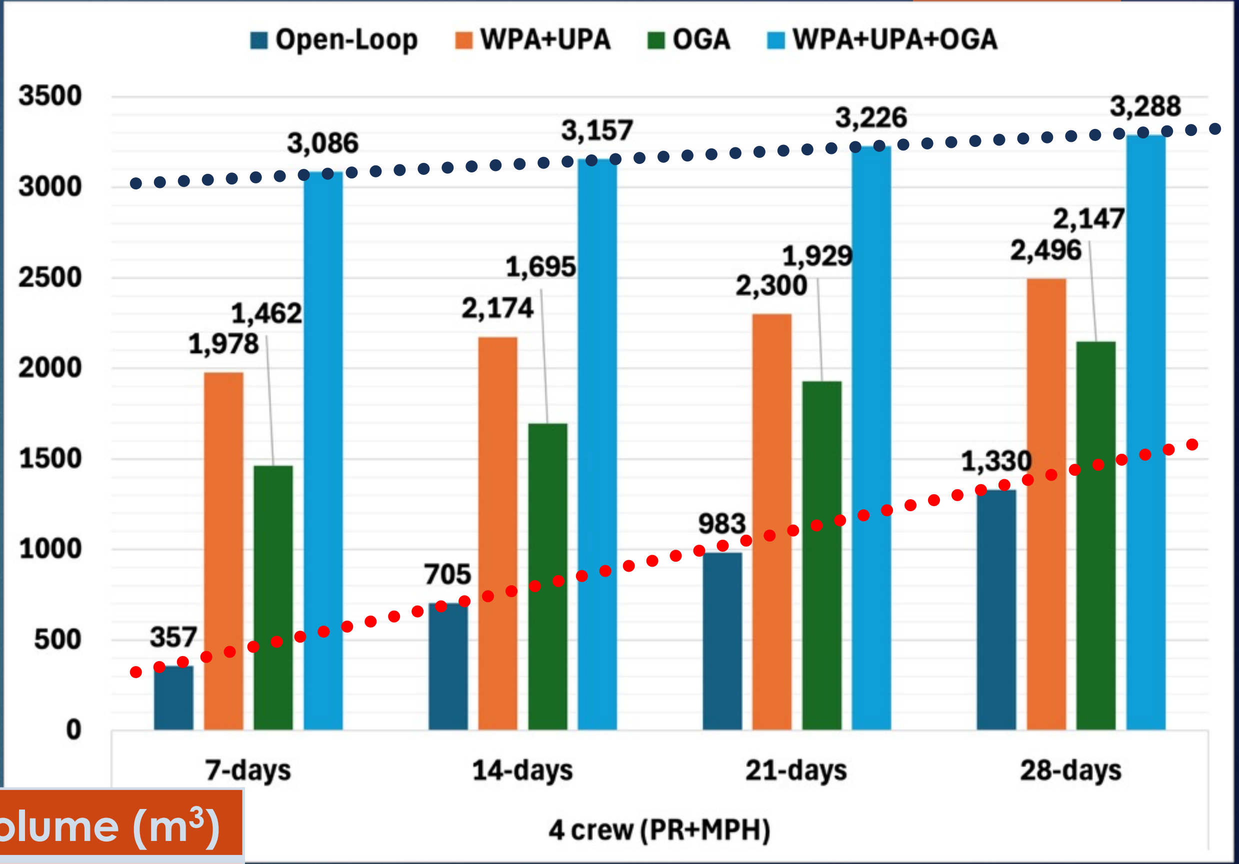
- Experiments → demonstrations → **pilot-scale production** → full-scale production
  - Pilot-scale production rates of ~1 t/yr O_2 (~1.1 t/yr H_2O)
- Representative pilot-scale concepts may need tailoring for a habitation customer
  - Liquefaction is not required
  - O_2 compression (~3,000-6,000 psia) + water processing
- ISRU maintenance/sparing assumed at 10% dry mass/year

Parameter or Subsystem	**Water Ice[1]**	**Carbothermal[2]**	**Molten Salt Electrolysis[3]**
Production rate (kg O_2/yr)	1,000		1,155
Baseline concept mass (kg)	1,164	946	1,172
Included subsystems			
Liquefaction (kg)	245	40	0
Electrolyzer (kg)	84	53	0
Additional subsystems[4]			
High-pressure oxygen compressor (kg)	120		
Water processor assembly (kg)	528		N/A
Adjusted total system mass			
Oxygen only (kg)	1,039	1,026	1,292
Water only (kg)	1,363	1,434	N/A
Water + oxygen (kg)	1,567	1,554	N/A

[1] Linne et al. (2020); [2] Sanders et al. (2022); [3] Birch et al. (2026); [4] Stromgren et al. (2022)

Regenerative Life Support Impacts

- Major factors in regenerative LSS analysis
  - Pressurized volume
  - Power
  - Thermal
- Reliability & maintenance not modelled
- OGA assumes recurring H_2O demand
- WPA+UPA assumes recurring O_2 demand
- WPA+UPA+OGA has limited recurring H_2O demand

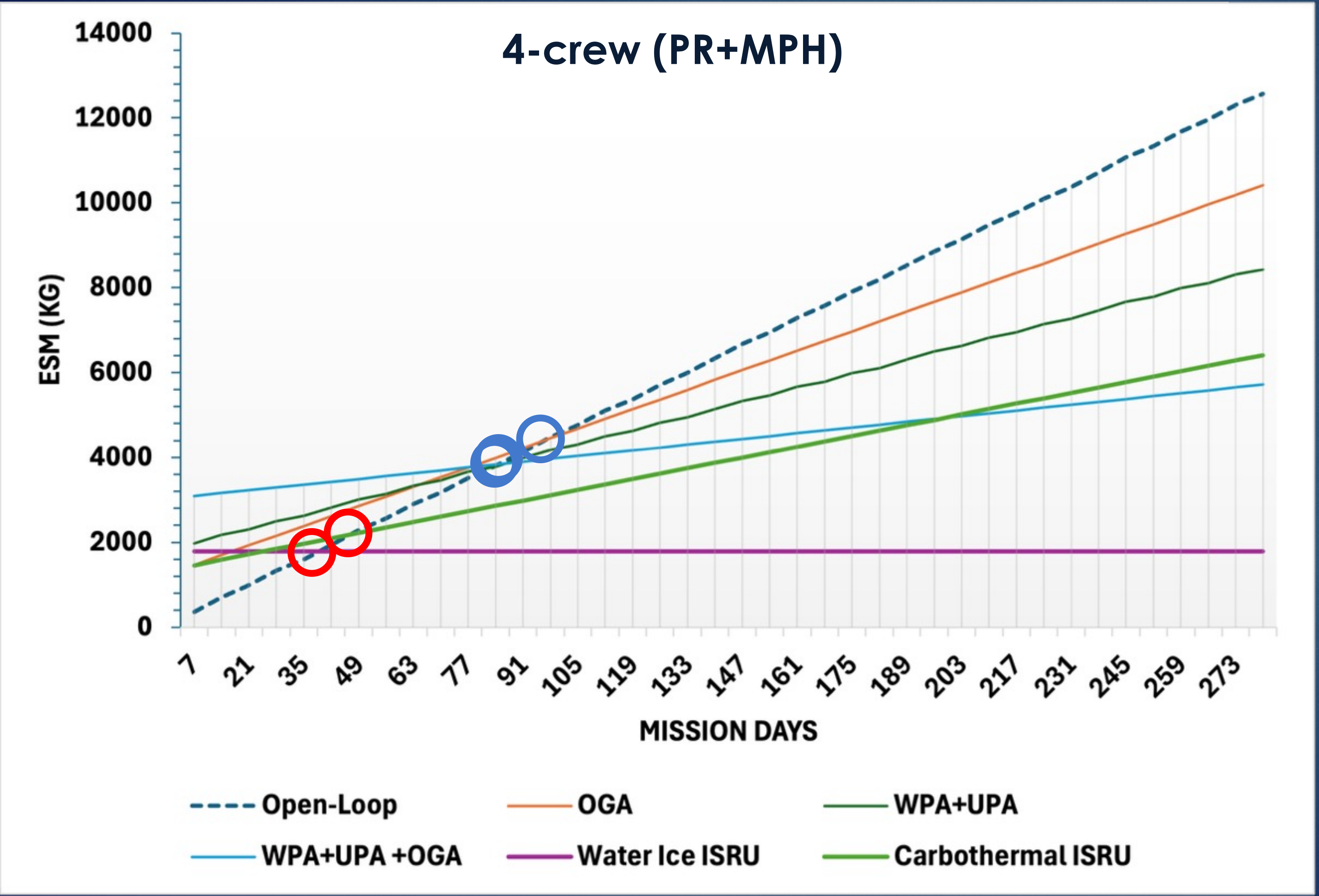


System	Mass (kg)	Power (W)	Volume (m^3)
Oxygen Generation Assy. (OGA)	676	3573	1.57
Water Processor Assy. (WPA)	1385	343	3.14
Urine Processor Assy. (UPA)		424	
TOTAL	**2,061**	**4,340**	**4.71**

Regenerative systems reduce *consumable* resupply mass by ~26-48%

Regenerative Life Support Breakeven

Equivalent system mass (ESM) results



Breakeven points w/Earth resupply:
ISRU ○ < Regenerative ECLS ○

- ISRU mass advantages arise:
  - 70-81 days (2-crew PR Only)
  - 40-49 days (4-crew PR+MPH)
- Regenerative ECLS mass advantages arise between 84-168 days
- ISRU may provide mass advantages before regenerative ECLS
- Larger crew and greater mission duration shift breakeven points earlier

Water Architecture Results

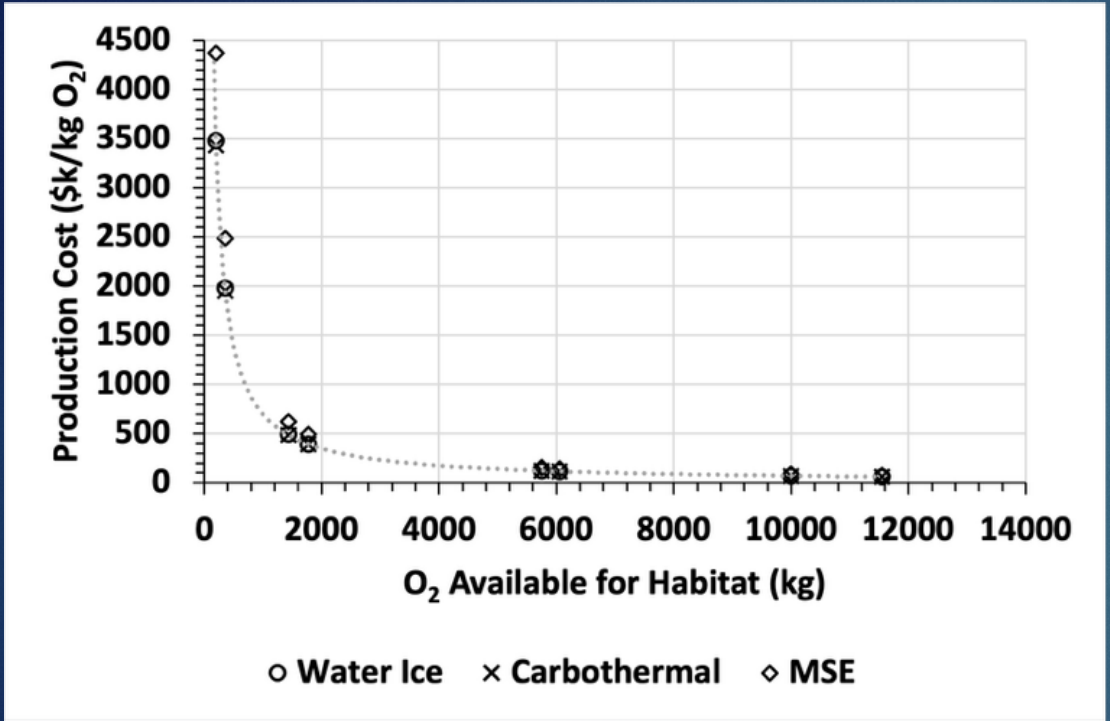
Category	Metric	Minimum	Baseline	Maximum
Water Demand & Mass (kg)	Lifetime water demand	620.4	2,990.8	7,370.0
	Additional water for full bags	30.6	47.2	8.0
	Dry mass per water bag	0.85	1.22	1.59
	Dry mass per package	5.71	8.16	10.61
	Lifetime delivered mass	733.6	3,616.8	9,191.8
Quantities (units)	Number of water bags	30	140	340
	Number of packages	10	50	120
Total Lifecycle Cost ($MFY26)	AMCM estimate	$119	$509	$1,215
	PCEC estimate	$75	$366	$930
	Industry estimate	$75	$369	$939
	Median estimate	$75	$369	$939
Intrinsic Value ($k/kg)	Value per kg water delivered	$116	$121	$127

Combined Architecture Results

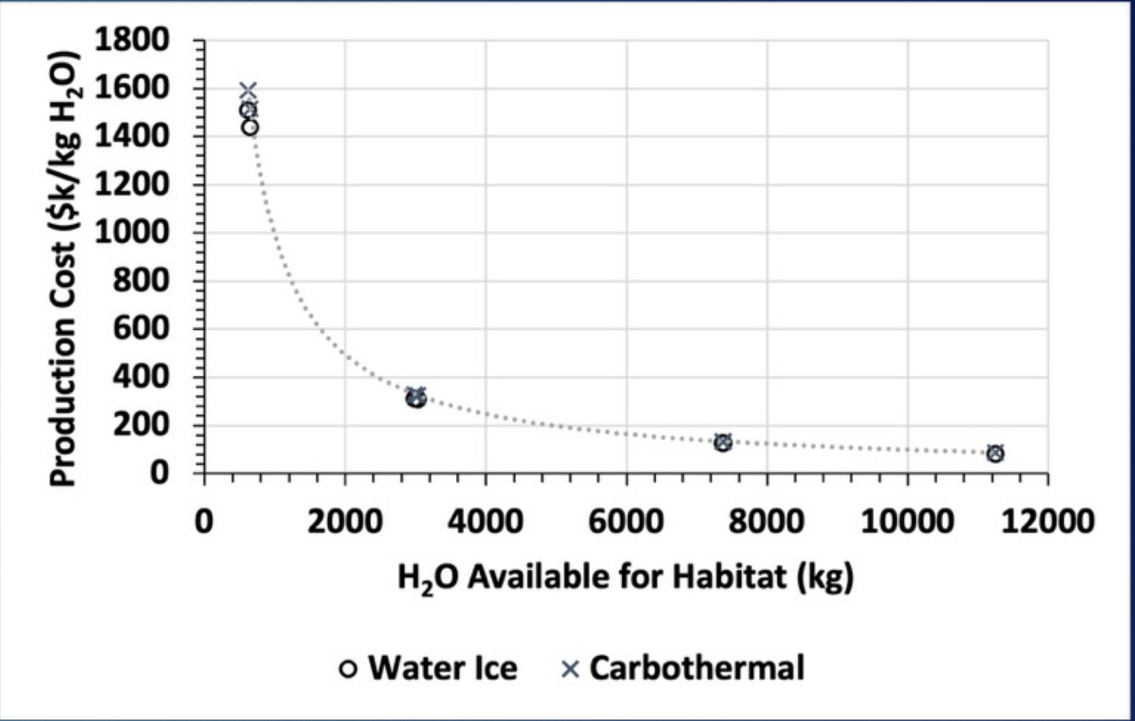
Category	Metric	Minimum	Baseline	Maximum
Combined Demand & Mass (kg)	Lifetime demand	823.1	4,420.5	13,118.1
	Additional oxygen + water	183.9	397.5	311.9
	Dry mass per oxygen tank	51.6	53.7	55.8
	Dry mass per water bag	0.85	1.22	1.59
	Dry mass per package	4.55	6.50	8.45
	Lifetime delivered mass	1,455.6	7,926.3	25,595.2
Quantities (units)	Number of oxygen tanks	10	50	170
	Number of water bags	30	140	340
	Number of packages	20	100	290
Total Lifecycle Cost ($MFY26)	AMCM estimate	$344	$1,345	$3,687
	PCEC estimate	$184	$860	$2,668
	Industry estimate	$176	$878	$2,722
	Median estimate	$184	$878	$2,722
Intrinsic Value ($k/kg FY26)	Value per kg oxygen + water delivered	$183	$182	$203

Economies of Scale

Total Oxygen vs. Median Production Cost



Total Water vs. Median Production Cost



- Just as with larger-scale ISRU production, economies of scale take affect
- The economy of scale for water production is less extreme due to higher lifecycle production cost/kg compared to oxygen