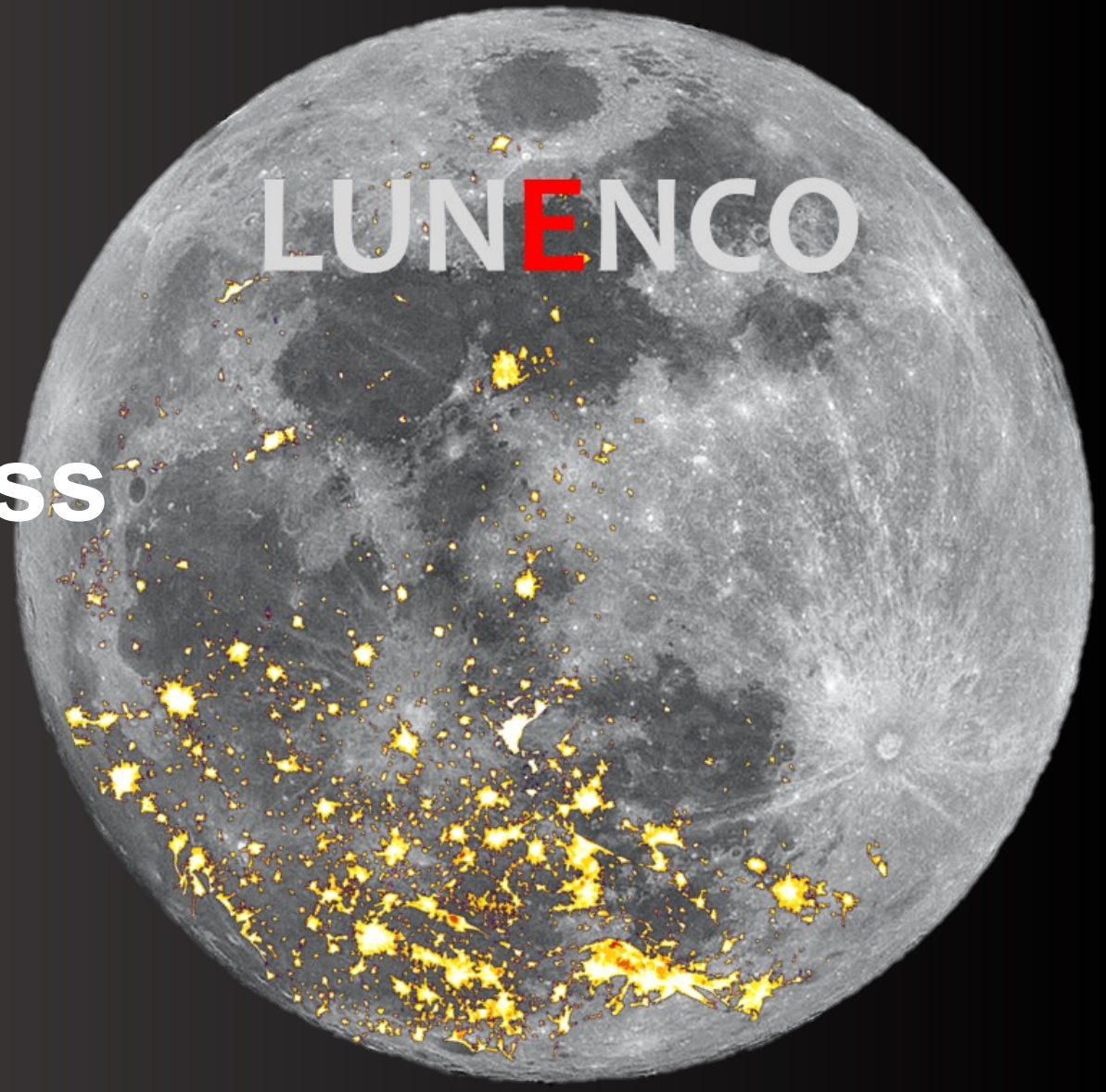
LUNENCO
The Lunar Energy Company

LUNENCO Team

Elizabeth Engeldrum • Denver, CO • Advanced Development Programs Systems Engineer • Blue Origin • 11 years, aerospace engineering • Embry-Riddle – BS, Aerospace Engineering • Embry-Riddle – MS, Aerospace Engineering • CSM – PhD Student, Space Resources • LUNENCO Role: Systems Engineering	**Nathan Davis** • Layton, UT • Senior Chemical Systems Engineer • OxEon Energy • 15 years, chemical/process engineering • Utah – BS, Chemistry • Utah – MS, Chemistry and Chemical Engineering • CSM – MS Student, Space Resources • LUNENCO Role: Systems Engineering
Gerard Lebar, Jr. • Albuquerque, NM • International Business Development Manager • Northrop Grumman (Space Systems) • 10 years, space/operations/entrepreneurship • South Carolina – BA, Political Science • Southern Methodist (SMU) - MBA, Strategy • CSM – MS Candidate, Space Resources • LUNENCO Role: Strategy and Business	**Nick Yugo, P.Eng.** • Vancouver, BC • Engineering Consultant • GeoEngineeringTech (Owner/Principal) • 10 years, mining engineering/senior consulting • Toronto – BASc, Mineral Engineering • Toronto – M.Eng, Geomechanics • CSM – MS Candidate, Space Resources • LUNENCO Role: Strategy and Business

Project Overview

- Concept: Provide power as a service on the Moon
  - Price per kWhr delivered must be advantageous to the customer
  - Deployed quickly to meet the demands of initial customers
  - Scaled to meet rising demand
- Goal: Evaluate the feasibility of a lunar power utility business
  - Potential customer base including power needs and price point
  - Development and deployment cost and potential sales revenue
  - Technical feasibility
- Approach
  - Market analysis based on planned lunar missions
  - Financial analysis including net present value, cashflows, sensitivity analysis, SWOT
  - Development of system objectives, architecture and conduct trade studies of various technical solutions ability to meet the requirements of the system



Strategy and Business

Nick Yugo
Gerard Lebar, Jr.

Customer Targets: 3 Tiers

Customers	Funding	Trend
Germany	$2.2B	+
India	$1.7B	+
Italy	$1.1B	-
Blue Origin	$1B	+
S. Korea	$657M	+
Turkey	$296M	+
UAE	$266M	-
Indonesia	$254M	+
KSA	$170M	+

Customers	Funding	Trend
France	$3.5B	+
Japan	$3.1B	+
SpaceX	$1.6B	+
UK	$977M	+
Australia	$281M	+

Customers	Funding	Trend
US	$43.9B	+
China	$7.3B	+
ESA	$5.9B	+
Russia	$3.9B	-

20XX

Tier 3

(9) Korea, Italy, Blue Origin, Germany, KSA, UAE, India, Indonesia*, and Turkey*

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Tier 2

(5) Australia, Japan, SpaceX, UK, and France*

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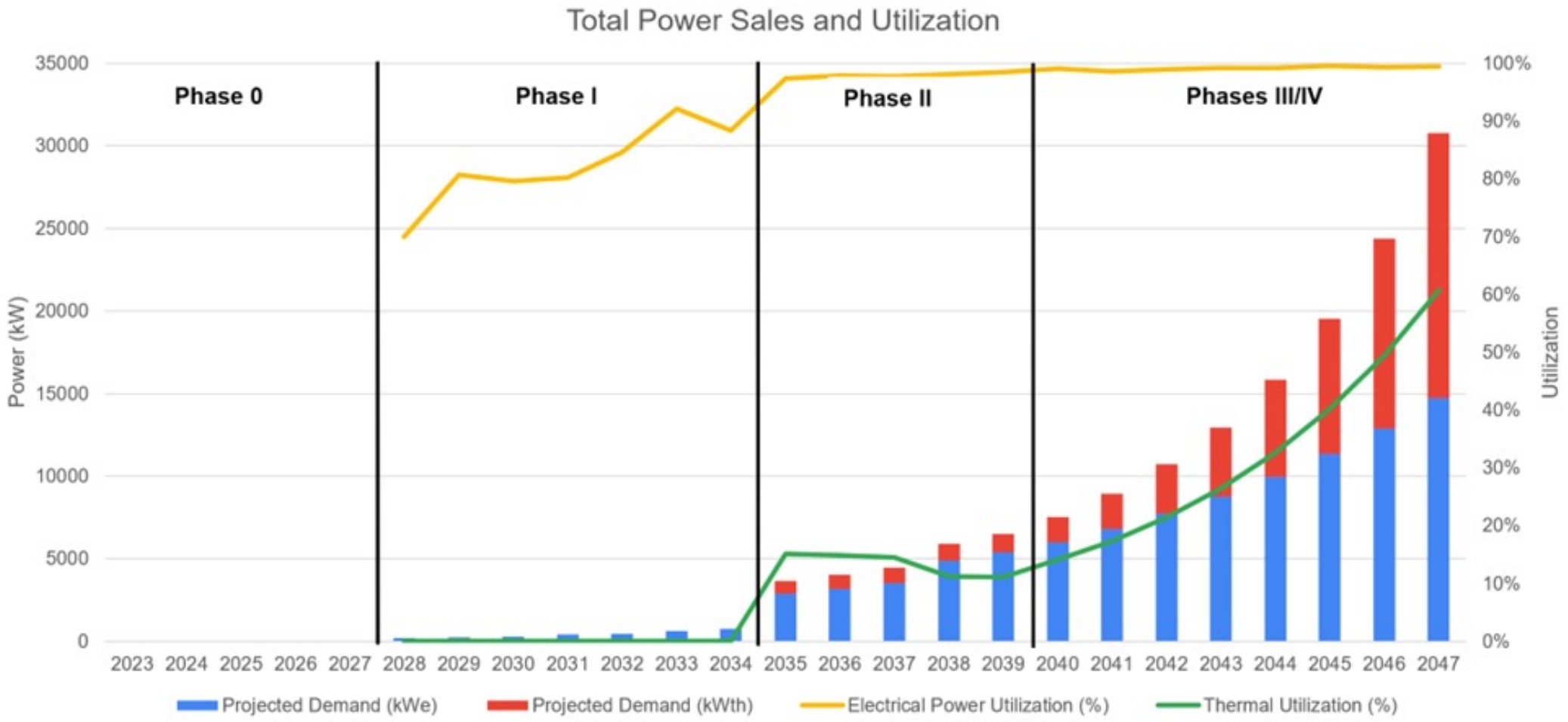
Tier 1

(4) U.S., China*, ESA, and Russia*

Production Projections



Financing Roadmap

Initial Design Concepts, Business Case

Stage 1 Financing (2022): 100% Equity Raise

$750k Secured for 3%, $25m Enterprise Value, 30x Capital Growth Potential

Stage 2 Financing (2023): Optimized Capital Raise

$7.5m Equity
$7.5m Debt
$10m Grants
$25m JV Partner

Stage 3 Financing (2024-2026): 100% Equity Raise

First Criticality 2024 (Terrestr)

First Launch 2026

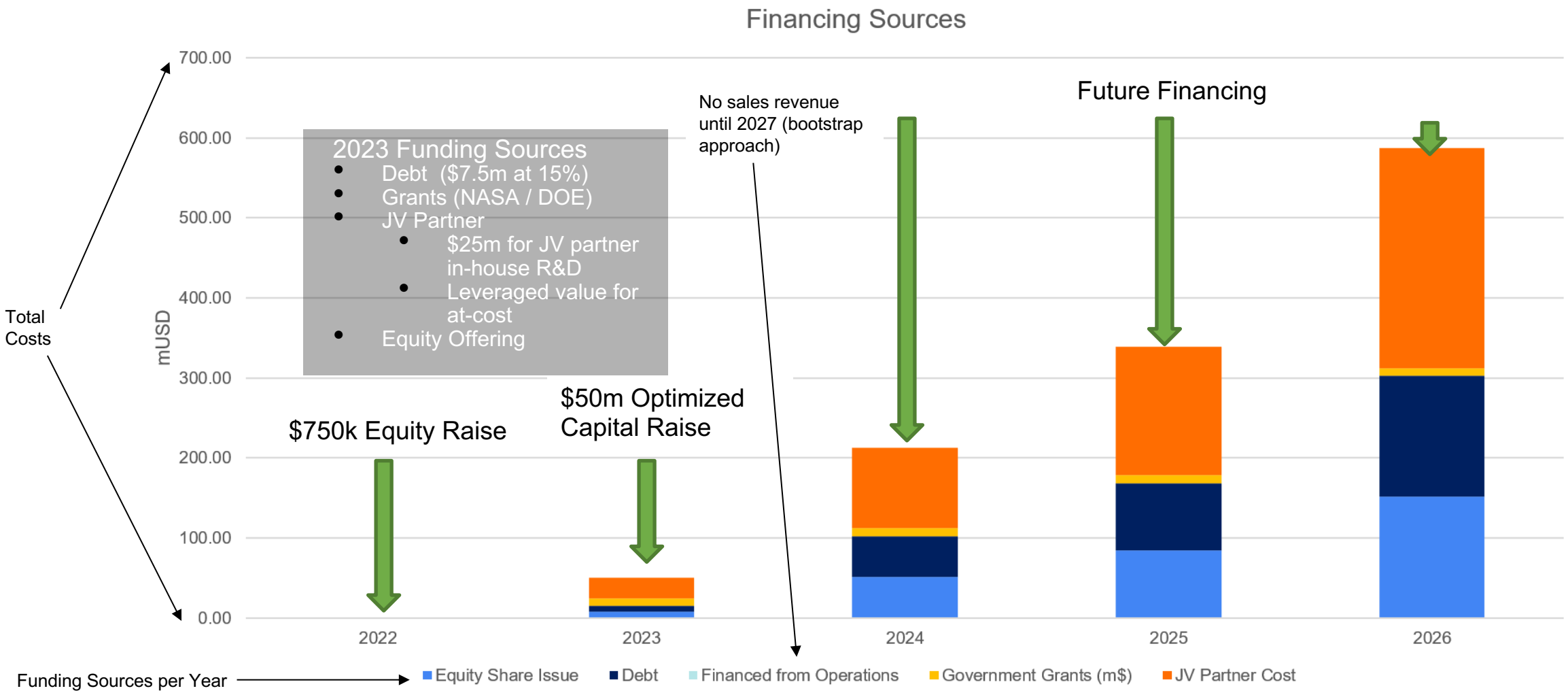
First Power 2027

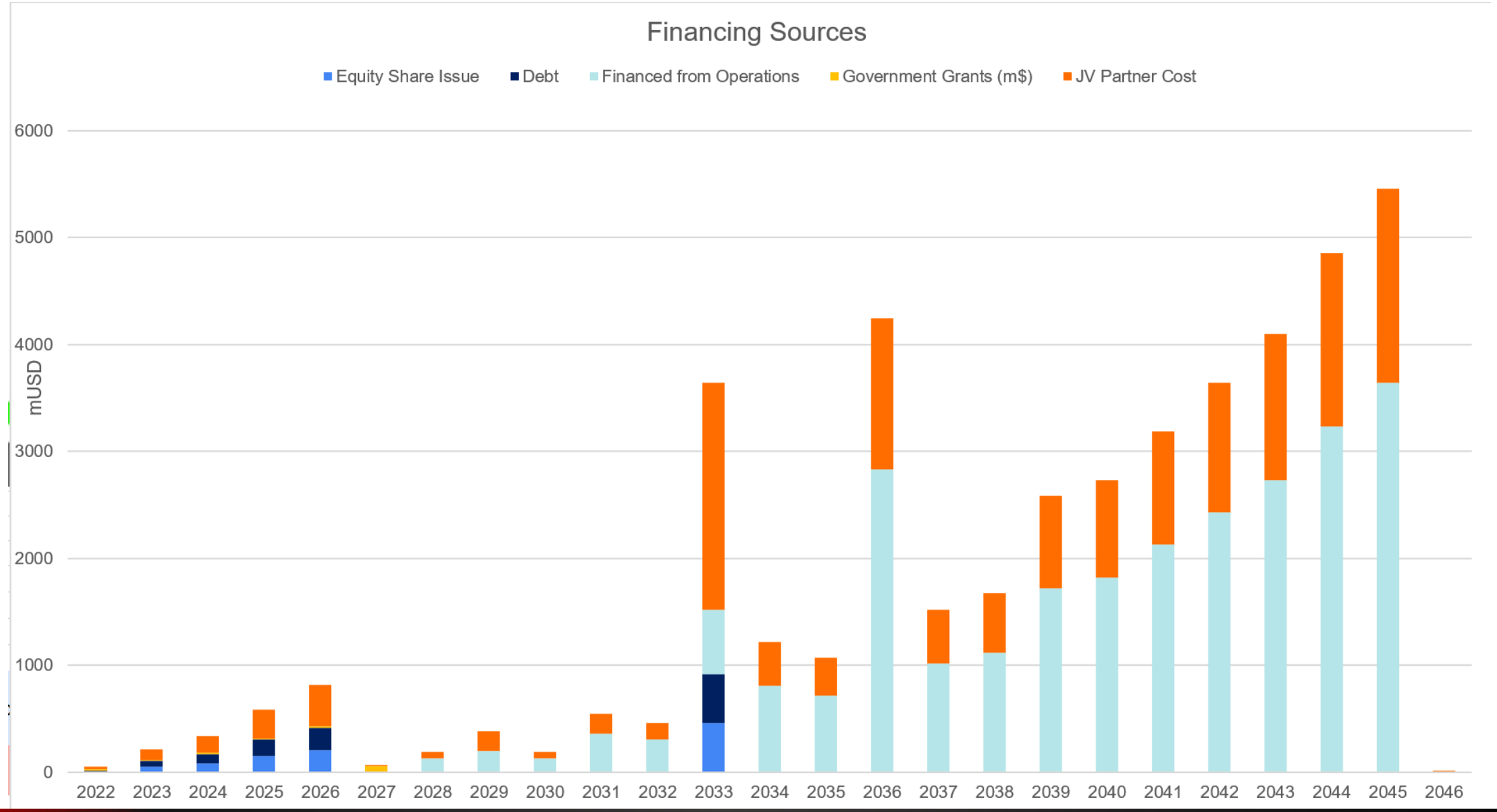
- Phased Funding Approach
- Clearly Defined Targets
- Conservative External Source funding targets

- Bootstrap Approach for future expansion beyond 2027

Near term (2022-2023) projected costs include labor (hiring plan developed), R&D into power generation system, overall system, and construction

5-Year Financing




Financing Sources
Equity Share Issue
Debt
Financed from Operations
Government Grants (m$)
JV Partner Cost
mUSD
6000
5000
4000
3000
2000
1000
0
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
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2044
2045
2046

Sales Plan – 3.0

Entity	Target Agencies/Departments	Key Stakeholders/Influencers	Target Messaging
United States	NASA (HQ); USSF	Johnson Space Center: Vanessa E. Wyche	Cost
China	China National Space Administration	Zhang Kejian	Knowledge transfer
Russia	Roscosmos - Space Systems	Dmitry Rogozin	Knowledge transfer
ESA	Concurrent Design Facility (CDF): "Moon Village"	Josef Aschbacher; Dr. David Parker	Capability
France	National Centre for Space Studies (CNES) - Sustainable Development	Jean-Yves Le Gall	Capability
Japan	Japan Aerospace Exploration Agency; Japanese Ministry of Defense	Hiroshi Yamakawa	Knowledge transfer
SpaceX	Human Spaceflight (department/div)	Michael Altenhofen	Mission enabler
UK	UK Ministry of Defence; UK Space Agency; UK Space Command	Libby Jackson	Capability
Australia	Royal Australian Air Force – Space Division; Australian Space Agency	Enrico Palermo	Knowledge transfer
Germany	German Aerospace Center (DLR) - Jülich (power research)	Anke Kaysser-Pyzalla	Capability

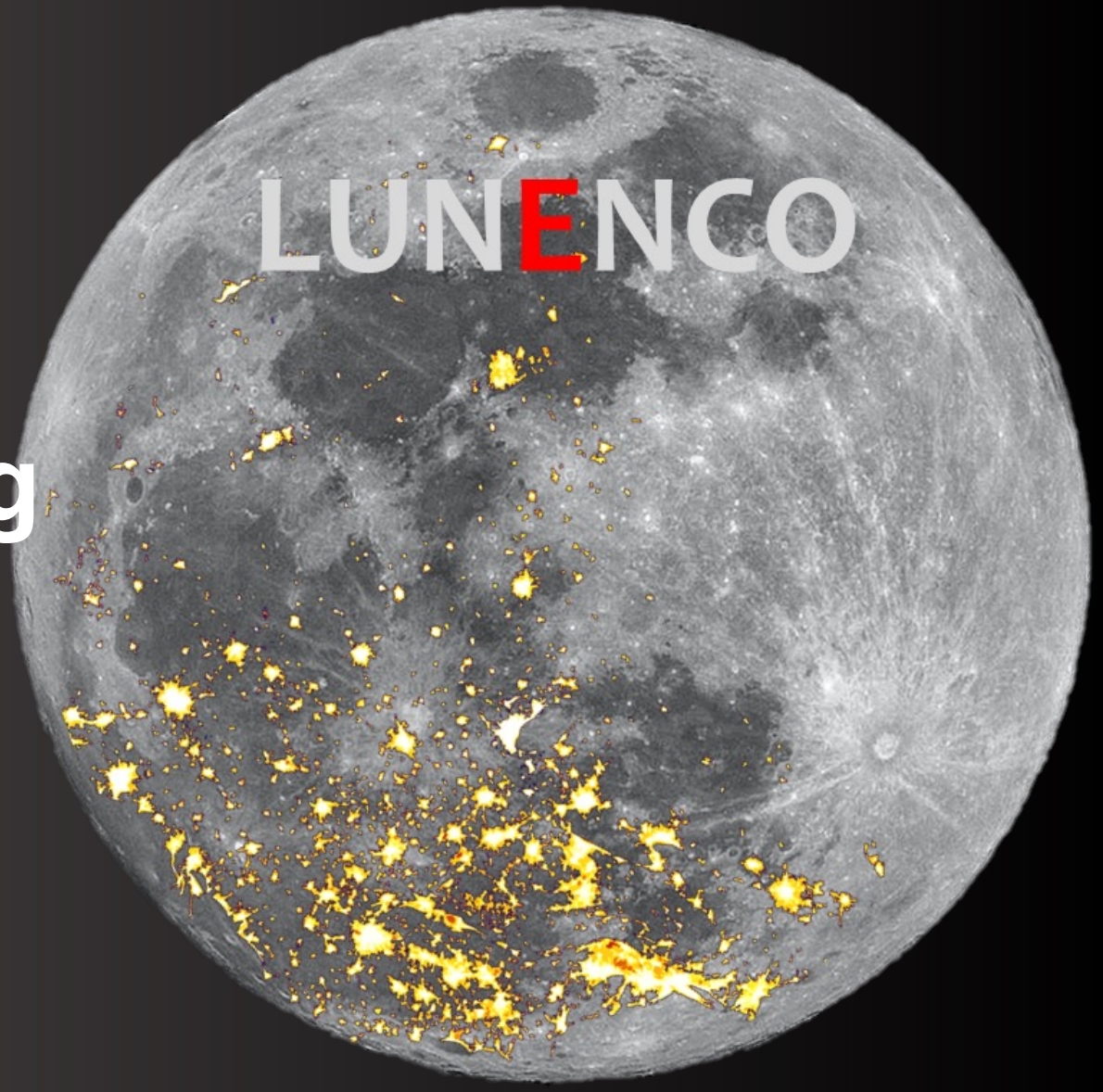
Sales Plan – 3.0

Entity	Target Agencies/Departments	Key Stakeholders/Influencers	Target Messaging
India	India Space Research Organisation - Physical Research Laboratory	Mr. R. Umamaheshwaran	Knowledge transfer
Italy	Italian Space Agency – Human Spaceflight	Simonetta Di Pippo	Capability
Blue Origin	Blue Moon (program)	Ariane Cornell	Mission enabler
Republic of Korea	Korea Aerospace Research Institute – Korean Lunar Exploration Program	Lee Sang-Ryool	Knowledge transfer
UAE	UAE Space Agency – Emirates Lunar Mission	Yousuf Hamad Alshaibani	Cost
Indonesia	National Institute of Aeronautics and Space – Propellant Laboratory	Thomas Djamaluddin	Cost
KSA	Saudi Space Commission	Majed Alonzai	Cost
Virgin Galactic	Spaceflight and Tourism Operations (divisions)	Blair Rich	Mission enabler
Caterpillar	Resource Industries Unit	Joseph E. Creed	Mission enabler
Lunar Outpost*	Lunar Terrain (program)	Julian Cyrus	Mission enabler
Origin Space Technology Co.	Space Resource Utilization – Mining (program)	Su Meng and Yu Tianhong	Capability

Initial (3-Year) Hiring Plan

Grouping	Countries	BD/Capture Hires
0	Overall Strategy	1
1	USG	2
2	SpaceX, Blue, VG, Caterpillar, Lunar	1
3	China, India, Origin Space Technology Co.	2
4	Russia	1
5	ESA, France, Germany, Italy	2
6	Australia, Indonesia	1
7	Japan, ROK	1
8	KSA, UAE	1
9	UK	1

Systems Engineering



Elizabeth Engeldrum
Nathan Davis

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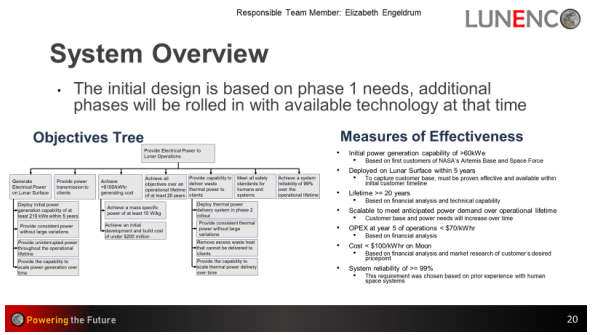
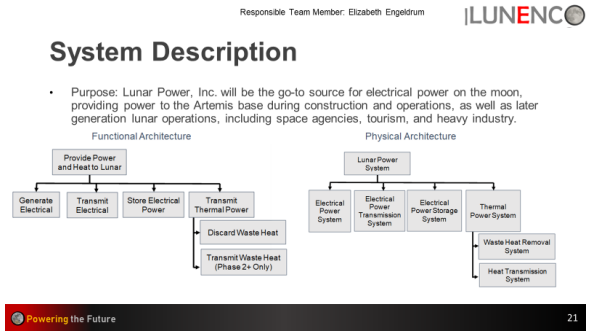
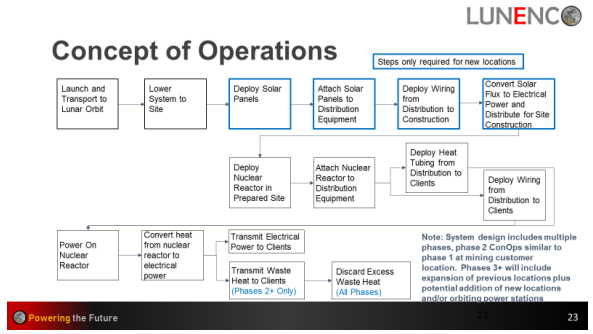
Systems Engineering Process

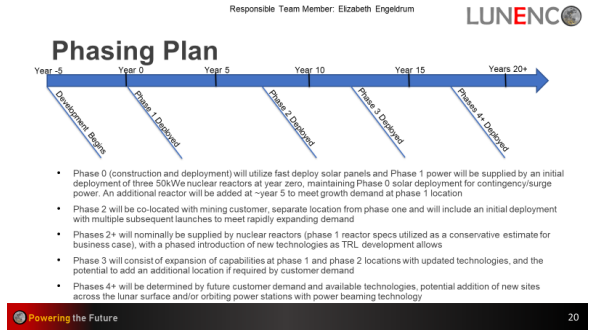
Define the System Requirements – Objectives, MOEs, Functional and Physical Architecture





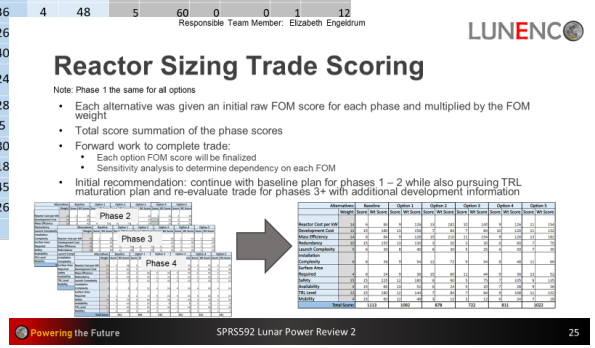
Concept of Operations Development

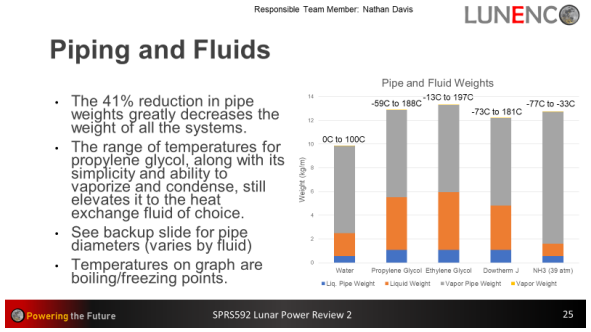




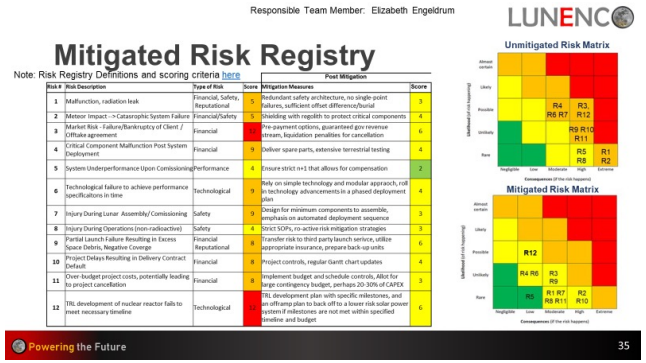
Key Trade Studies – overall technical solution, reactor sizing, heat transfer system

		Nuclear Fission Modular Reactors		Flexible Array Surface Solar Lunar Surface PV		Traditional Surface Solar Lunar Surface PV		Nuclear + Solar Surface Based		Nuclear Fission Large Reactor		Satellite Solar SSPS System		Portable Power Power Packs	
Parameter	Weight	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
Cost per kW	12	4	48	3	36	3	36	4	48	5	60	0	0	1	12
Mass Efficiency	13	3	39	3	39	2	26								
Redundancy	10	5	50	4	40	4	40								
Launch Complexity	6	3	18	4	24	4	24								
Installation Complexity	7	3	21	4	28	4	28								
Surface Area Required	5	3	15	2	10	1	5								
Safety	16	3	48	5	80	5	80								
Availability	9	5	45	2	18	2	18								
TRL	9	3	27	5	45	5	45								
Extensibility	13	5	65	3	39	2	26								
	Total	376		359		328									





Risk Identification and Mitigation



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Systems Engineering Conclusions

- LUNENCO is a **system integrator** and **utility provider**
- System deployment will be broken into phases, beginning with initial rapid deployment phase 1, including larger phases and alternative locations as demand grows
- Strategic investments into TRL development and exclusive supplier contracts are key to cornering the market early
- Technical solution trade study settled on small (~50kWe) modular nuclear fission reactors
  - Mitigate TRL risk by pursuing a parallel path solar power system development

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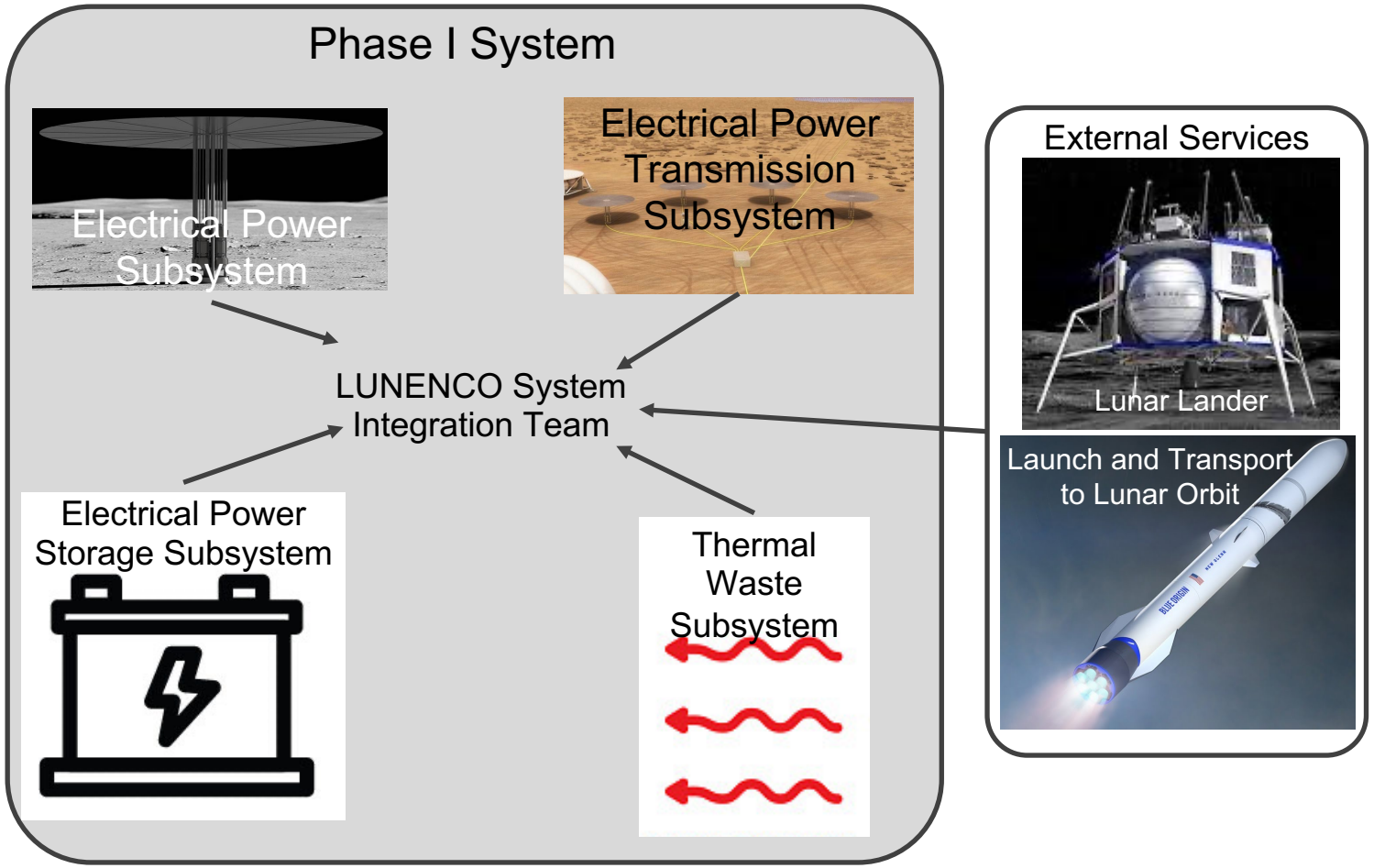
System Architecture

- Subsystems will be sourced from suppliers with expertise in each area
- Supplier selection will be through a competitive process with potential for parallel path development
- LUNENCO will purchase launch and lunar landing services from commercial providers



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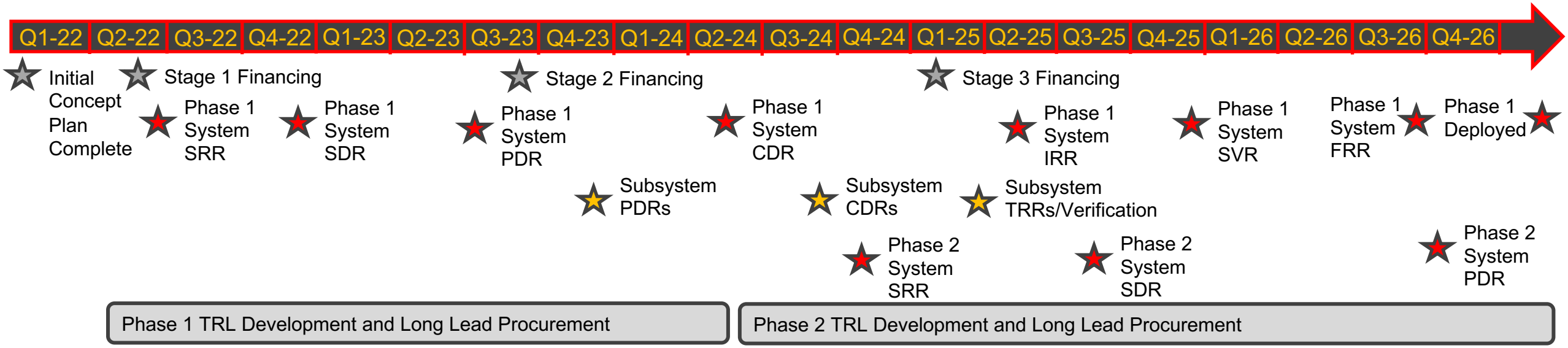
Design Review Maturity

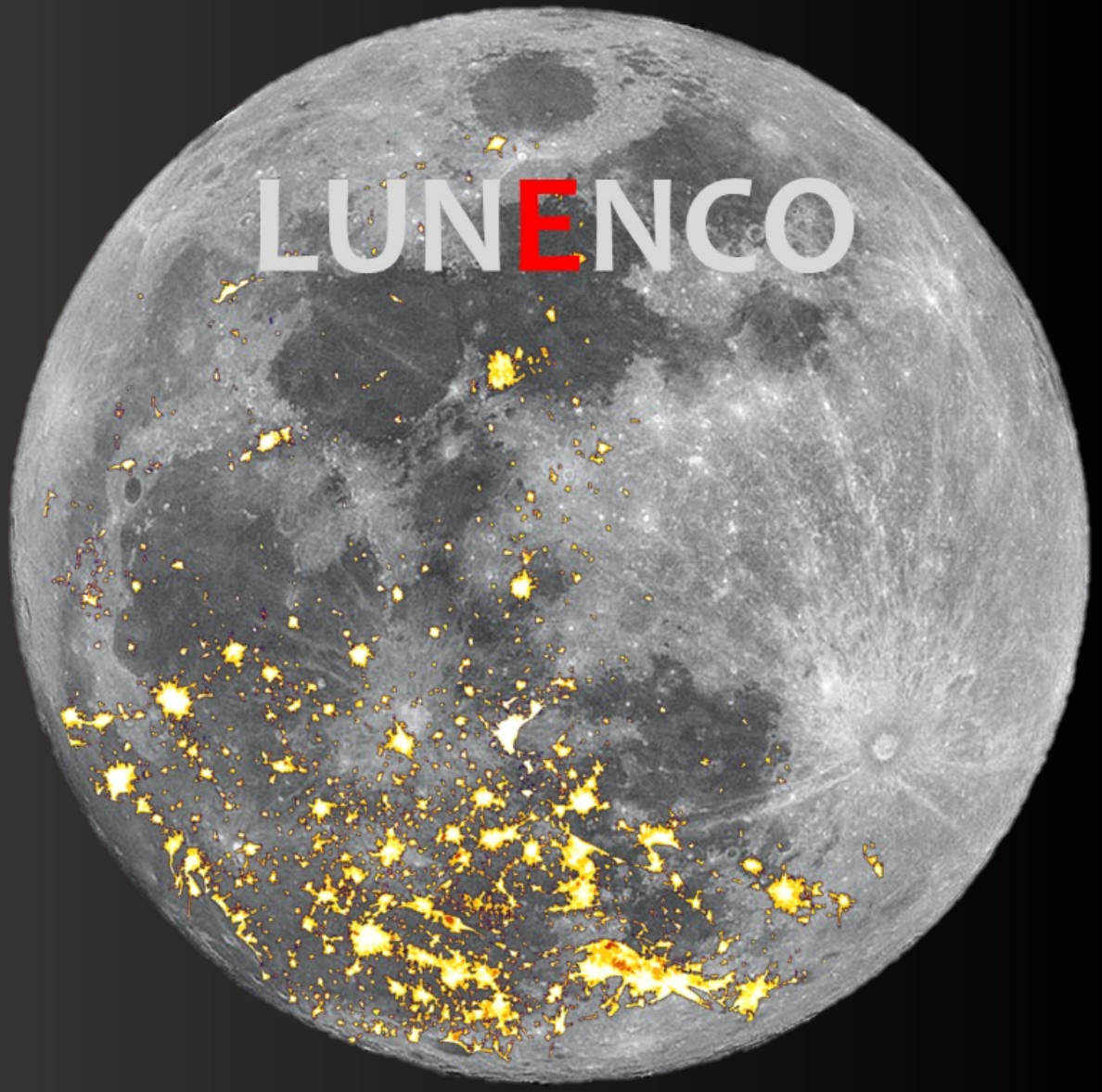
- As a start-up company LUNENCO needs to move fast but also build investor confidence with a thorough design review process
- TRL development will occur concurrently with design reviews



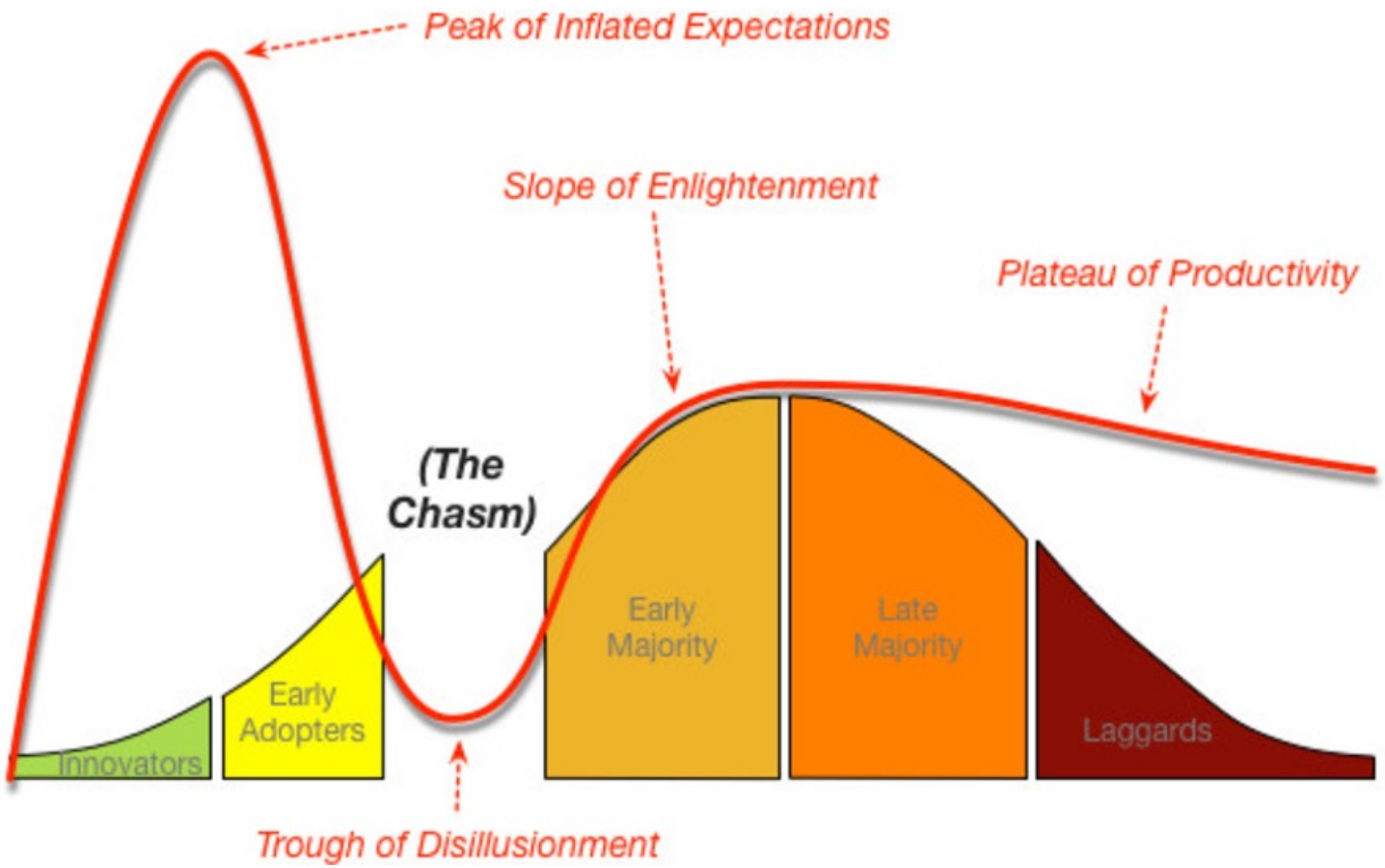
Conclusions

- Maximum projected NPV in excess of $3.7B for most optimal plan, other options modeled range from $700M - $1.7B
  - Optionality maintained throughout project life with several off-ramps that pause growth capital
- Majority of funding can be sourced from series of fund raises
- Timeline of development and deployment of system is aggressive but achievable with the right investments
- Lunar power utility comprised of modular nuclear reactors servicing electrical and thermal demand shown to be a viable business case
  - Scenarios investigated show strong economic returns with ability to adapt to market and technical conditions

Back-Up



Technology Adoption Lifecycle



Tranche 2 Investor Opportunity

- $7.5m for 7.5% of LUNENCO Inc
  - Represents only 15% of funding sources, large leverage
- Equity value of $100m from Tranche 2 share offering
  - First Tranche investors rewarded with 4x valuation growth from previous offering
  - >7x growth opportunity based on $700m+ NPV
  - Total enterprise value of Debt + Equity to date $100m + $7.5m
  - Sets up firm for “retained earnings” potential in future growth
- Right of first refusal for all subsequent share offerings
- First mover advantage

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Cash Flow Model Assumptions

	Base Case	-50%	-25%	25%	50%		Comments
Discount Rate	15%	15%	15%	15%	15%		Constant 8% for initial analysis
Reactor Unit Cost Units 1-5 (m$)	100	50	75	125	150		In addition to R&D, KRUSTY program was $20m
Reactor Unit Cost Units 5-15 (m$)	50	25	37.5	62.5	75		Assumes economies of scale
Reactor Unit Cost Units 16+ (m$)	30	15	22.5	37.5	45		Assumes economies of scale
Reactor Launch Cost (m$)	51	25.5	38.25	63.75	76.5		Scaled SpaceX 1000kg to LEO using mass and deltaV
Delivered Fuel Cost per Reactor per year (m$)	0.1	0.05	0.075	0.125	0.15		10-year fuel cycle HEU, $1m/refuel
Lunar Staff OPEX per person per year (m$)	1	0.5	0.75	1.25	1.5		$1m per lunar staff average total burden
Terrestrial Staff per person per year (m$)	0.25	0.125	0.188	0.313	0.375		$250k per terrestrial staff average total burden
Sale Price $/kWhr Years 1-5	100.00	50	75	125	150		Fixed price pre-launch agreements
Sale Price $/kWhr Years 6-10	90.00	45	67.5	112.5	135		Market-maker ability, reduction driven by vendor
Sale Price $/kWhr Years 11-20	80.00	40	60	100	120		Market-maker ability, reduction driven by vendor
Waste Heat Price $/kW-hr	50.00	25	37.5	62.5	75		Checks to ensure <50% waste heat is utilized for sale to account for losses

$361mUSD total gross cost to NASA / Space Force over initial 5-year operating period compared with $11+ bUSD (3%) Artemis budget through 2025

https://oig.nasa.gov/docs/IG-21-018.pdf

Base Case		-50%	-25%	25%	50%		Comments	Base
15%		15%	15%	15%	15%		Constant 8% for initial analysis	8%
100		50	75	125	150		In addition to R&D, KRUSTY program was $20m	100
50		25	37.5	62.5	75		Assumes economies of scale	50
30		15	22.5	37.5	45		Assumes economies of scale	30
51		25.5	38.25	63.75	76.5		Scaled SpaceX 1000kg to LEO using mass and deltaV	51
0.1		0.05	0.075	0.125	0.15		10-year fuel cycle HEU, $1m/refuel	0.1
1		0.5	0.75	1.25	1.5		$1m per lunar staff average total burden	1
0.25		0.125	0.1875	0.3125	0.375		$250k per terrestrial staff average total burden	0.25
100.00		50	75	125	150		Fixed price pre-launch agreements	100.00
90.00		45	67.5	112.5	135		Market-maker ability, reduction driven by vendor	90.00
80.00		40	60	100	120		Market-maker ability, reduction driven by vendor	80.00
50.00		25	37.5	62.5	75		Checks to ensure <50% waste heat is utilized for sale to account for losses	50.00

Total		Development					Production																			
	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047
	-6	-5	-4	-3	-2	-1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		0	0	0	0	0	210	242	279	401	466	645	751	2875	3180	3521	4906	5418	5993	6802	7724	8777	9978	11350	12918	14712
							6	6	7	10	11	14	17	59	65	72	100	110	121	138	156	177	201	228	260	296
							90	58	71	99	84	55	99	75	70	79	94	82	57	98	76	73	72	50	82	88
							70%	81%	80%	80%	85%	92%	88%	97%	98%	98%	98%	99%	99%	99%	99%	99%	99%	100%	99%	99%
							536	536	625	893	982	1250	1518	5268	5804	6429	8929	9821	10804	12321	13929	15804	17946	20357	23214	26429
		0	0	0	0	0	0	0	0	0	0	0	0	800	864	933	1008	1088	1175	1317	1475	1651	1850	2072	2320	2599
							0%	0%	0%	0%	0%	0%	0%	15%	15%	15%	11%	11%	11%	11%	11%	10%	10%	10%	10%	10%
		0	0	0	1	2	0	1	3	1	3	3	42	6	7	28	10	11	17	18	21	24	27	32	36	0
886,049		0	0	0	0	0	1,840	2,120	2,443	3,517	4,078	5,650	6,579	25,184	27,853	30,847	42,973	47,464	52,496	59,585	67,665	76,882	87,404	99,423	113,163	128,881
							0	0	0	0	0	0	0													
88,605		**0**	**0**	**0**	**0**	**0**	**184**	**212**	**244**	**352**	**408**	**565**	**658**	**2518**	**2785**	**3085**	**4297**	**4746**	**5250**	**5958**	**6766**	**7688**	**8740**	**9942**	**11316**	**12888**
							0.6	0.6	0.7	1	1.1	1.4	1.7	5.9	6.5	7.2	10	11	12.1	13.8	15.6	17.7	20.1	22.8	26	29.6
							11	11	12	15	16	19	22	64	70	77	105	115	126	143	161	182	206	233	265	301
		20	50	75	150	150	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
		5	12.5	18.75	37.5	37.5	41	41	42	45	46	49	52	94	100	107	135	145	156	173	191	212	236	263	295	331
3,053		**5**	**13**	**19**	**38**	**38**	**42**	**42**	**43**	**46**	**47**	**50**	**54**	**100**	**107**	**114**	**145**	**156**	**168**	**187**	**207**	**230**	**256**	**286**	**321**	**361**
		0	**0**	**0**	**0**	**0**	**142**	**170**	**202**	**306**	**361**	**515**	**604**	**2419**	**2679**	**2971**	**4152**	**4590**	**5082**	**5772**	**6560**	**7459**	**8484**	**9657**	**10995**	**12528**
				20	50	75	5	25	65	25	65	65	845	125	145	565	205	225	345	365	425	485	545	645	725	5
6,045		0	0	20	50	75	5	25	65	25	65	65	845	125	145	565	205	225	345	365	425	485	545	645	725	5
1,550	**0.75**	50	200	300	500	500																				
9,160						100	0	50	150	50	150	90	1260	380	210	840	300	330	510	540	630	720	810	960	1080	0
14,892						102	0	51	153	51	153	153	2142	306	357	1428	510	561	867	918	1071	1224	1377	1632	1836	0
31,647	**0.75**	**50**	**200**	**320**	**550**	**777**	**5**	**126**	**368**	**126**	**368**	**308**	**4247**	**811**	**712**	**2833**	**1015**	**1116**	**1722**	**1823**	**2126**	**2429**	**2732**	**3237**	**3641**	**5**
	0.75	**7.5**	**51.25**	**84.375**	**151.3**	**208**	**0**	**0**	**0**	**0**	**0**	**0**	**458**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
		7.5	**51.25**	**84.375**	**151.3**	**208**	**0**	**0**		**0**		**0**	**457.513124**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	0	**0**	**0**	**0**	**0**	**0**	**5**	**126**	**202**	**126**	**361**	**308**	**604**	**811**	**712**	**2833**	**1015**	**1116**	**1722**	**1823**	**2126**	**2429**	**2732**	**3237**	**3641**	**5**
	0.75	**15**	**102.5**	**168.75**	**302.5**	**416**	**5**	**126**	**202**	**126**	**361**	**308**	**1519**	**811**	**712**	**2833**	**1015**	**1116**	**1722**	**1823**	**2126**	**2429**	**2732**	**3237**	**3641**	**5**
		10	**10**	**10**	**10**	**10**	**50**																			
		25	**100**	**160**	**275**	**388.5**	**3**	**63**	**184**	**63**	**184**	**154**	**2124**	**406**	**356**	**1417**	**508**	**558**	**861**	**912**	**1063**	**1215**	**1366**	**1619**	**1821**	**3**
	0	**35**	**110**	**170**	**285**	**398.5**	**53**	**63**	**184**	**63**	**184**	**154**	**2124**	**406**	**356**	**1417**	**508**	**558**	**861**	**912**	**1063**	**1215**	**1366**	**1619**	**1821**	**3**
53,887		-55	-213	-339	-588	-815	137	44	-166	180	-7	207	-3643	1608	1967	138	3137	3474	3360	3949	4434	5030	5752	6420	7354	12523
		-55	-197	-290	-466	-599	87	26	-90	90	-3	89	-1447	591	670	43	916	939	841	915	951	999	1058	1093	1160	1829
1,725																										
21%																										

LUNENCO

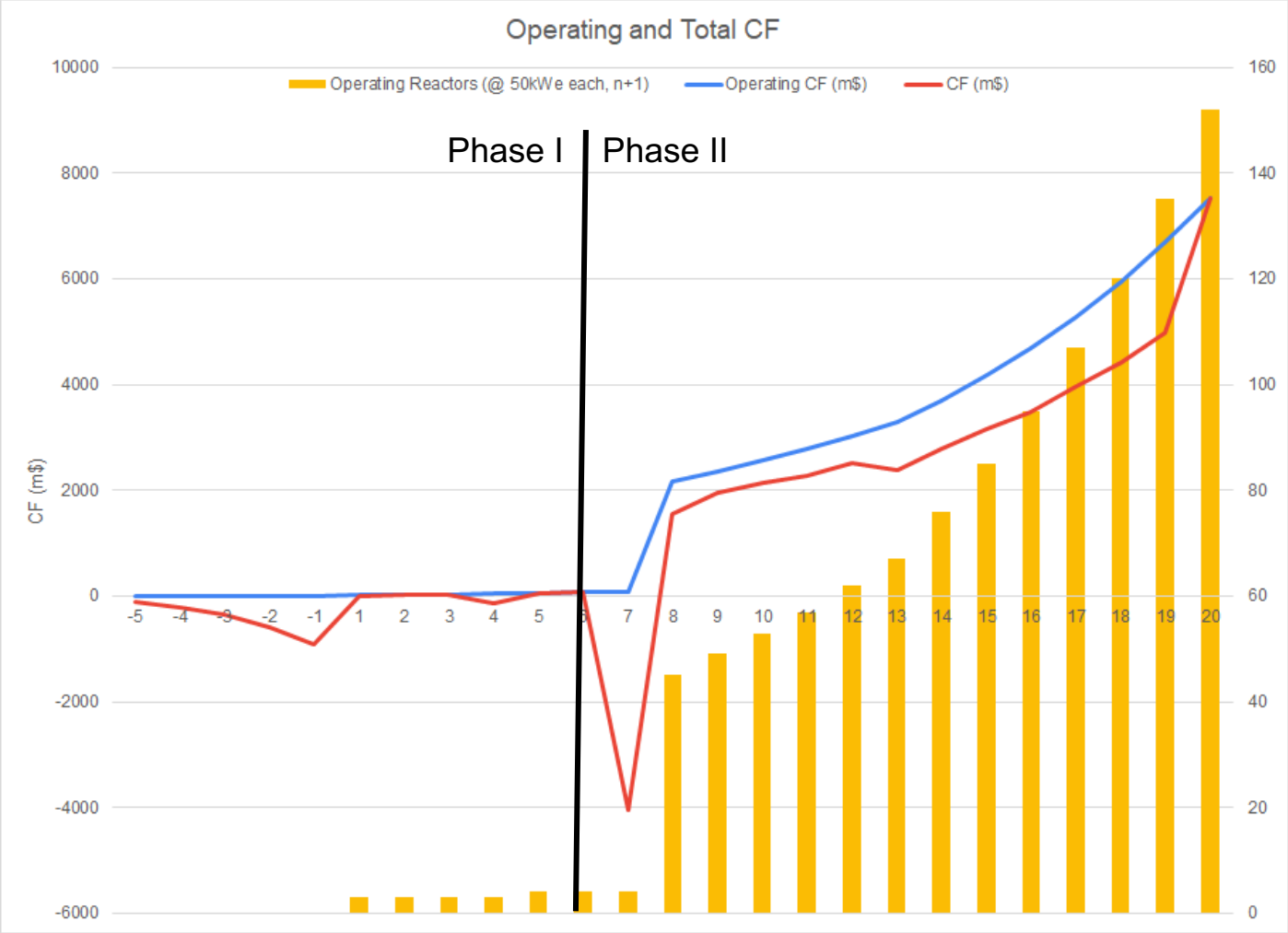
Updated CF Model With Thermal Revenue

	Total	Development					Production																			
Year		**-5**	**-4**	**-3**	**-2**	**-1**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**2**
Projected Demand (kW_e)		0	0	0	0	0	60	70	81	93	108	125	146	2169	2356	2560	2784	3028	3295	3706	4168	4690	5277	5939	6685	752
Operating Reactors (@ 50kWe each, n+1)							3	3	3	3	4	4	4	45	49	53	57	62	67	76	85	95	107	120	135	15
Reserve Power (kWe)							90	81	69	57	92	75	54	81	94	90	66	72	55	94	82	60	73	61	65	7
Electrical Power Utilization (%)							40%	46%	54%	62%	54%	63%	73%	96%	96%	97%	98%	98%	98%	98%	98%	99%	99%	99%	99%	99
Available Thermal Power kW (28% Eff, 50% usebale)							268	268	268	268	357	357	357	4018	4375	4732	5089	5536	5982	6786	7589	8482	9554	10714	12054	1357
Projected Demand (kW_{th})		0	0	0	0	0	0	0	0	0	0	0	0	800	864	933	1008	1088	1175	1317	1475	1651	1850	2072	2320	259
Thermal Utilization (%))							0%	0%	0%	0%	0%	0%	0%	20%	20%	20%	20%	20%	20%	19%	19%	19%	19%	19%	19%	19
Build & Launch		0	0	0	1	2	0	0	0	1	0	0	41	4	4	4	5	5	9	9	10	12	13	15	17	
Total Annual MW-hrs_e sold	**480,633**	0	0	0	0	0	526	609	705	818	948	1,099	1,275	18,999	20,638	22,428	24,385	26,524	28,867	32,464	36,515	41,080	46,225	52,024	58,564	65,94
Total Annual MW-hrs_th sold							0	0	0	0	0	0	0	7,008	7,569	8,174	8,828	9,534	10,297	11,533	12,917	14,467	16,203	18,147	20,325	22,76
Gross Revenue (m$)	**56,452**	**0**	**0**	**0**	**0**	**0**	**53**	**61**	**71**	**82**	**95**	**110**	**127**	**2250**	**2442**	**2652**	**2880**	**3129**	**3402**	**3823**	**4297**	**4831**	**5433**	**6110**	**6873**	**773**
Reactor Opex (Fuel, m$)							0.3	0.3	0.3	0.3	0.4	0.4	0.4	4.5	4.9	5.3	5.7	6.2	6.7	7.6	8.5	9.5	10.7	12	13.5	15.
Lunar Operating Staff							8	8	8	8	9	9	9	50	54	58	62	67	72	81	90	100	112	125	140	15
Earth Staff		20	50	75	150	150	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	12
OPEX Labor Cost (m$)		5	12.5	18.75	37.5	37.5	38	38	38	38	39	39	39	80	84	88	92	97	102	111	120	130	142	155	170	18
OPEX (m$)	**2,033**	**5**	**13**	**19**	**38**	**38**	**38**	**38**	**38**	**38**	**39**	**39**	**39**	**85**	**89**	**93**	**98**	**103**	**109**	**119**	**129**	**140**	**153**	**167**	**184**	**20**
Operating CF (m$)		**0**	**0**	**0**	**0**	**0**	**14**	**23**	**32**	**43**	**55**	**70**	**88**	**2166**	**2353**	**2558**	**2782**	**3026**	**3293**	**3704**	**4169**	**4692**	**5280**	**5943**	**6689**	**753**
Lunar Construction Staff				20	50	75	5	5	5	25	5	5	825	85	85	85	105	105	185	185	205	245	265	305	345	
CAPEX Labor Cost (m$)	**3,225**	0	0	20	50	75	5	5	5	25	5	5	825	85	85	85	105	105	185	185	205	245	265	305	345	
R&D (m$)	**1,600**	100	200	300	500	500																				
Sustaing Capital (New Reactors)	**4,940**					200	0	0	0	100	0	0	1230	320	120	120	150	150	270	270	300	360	390	450	510	
Sustaing Capital (Launch Costs)	**7,701**					102	0	0	0	51	0	0	2091	204	204	204	255	255	459	459	510	612	663	765	867	
CAPEX Total (m$)	**17,466**	**100**	**200**	**320**	**550**	**877**	**5**	**5**	**5**	**176**	**5**	**5**	**4146**	**609**	**409**	**409**	**510**	**510**	**914**	**914**	**1015**	**1217**	**1318**	**1520**	**1722**	
CF (m$)	**36,935**	-105	-213	-339	-588	-915	9	18	27	-133	50	65	-4058	1557	1944	2149	2272	2516	2379	2790	3154	3475	3962	4423	4967	752
DCF (m$)		-105	-197	-290	-466	-672	6	10	15	-66	23	28	-1611	572	662	678	663	680	595	647	677	690	729	753	783	109
NPV (m$)	**782**																									
IRR	**18%**																									

NPV without thermal mining: $226mUSD at 16% IRR

Sensitivity Analysis and Cashflows

Scenario	NPV (mUSD)	IRR
Base No Thermal	226	16%
Thermal Revenue	782	18%
Unit Costs +50%	-242	-
Unit Costs -50%	1806	23%
Revenue +50%	2698	24%
Revenue -50%	-1134	-
"Blue Sky" Demand*	1078	19%



2023 Expenditures Outlook

OPEX:

- Null as defined by GAAP, full cost capitalization prior to commercial production

CAPEX

- $5m labor costs
  - $1.5m for 5 company personnel
  - $3.5m consulting (technical specialists, legal, marketing)
- $45m R&D Costs
  - $25m direct at-cost expenses for JV partner (nuclear end)
  - $10m aerospace (mechanical engineering for non nuclear components, thermal systems)
  - $10m construction research (construction methods, tools & techniques, desert trials)

Launch Operations

Launch systems developed for Artemis Program will be available commercially or in private-public partnerships with NASA to deploy infrastructure

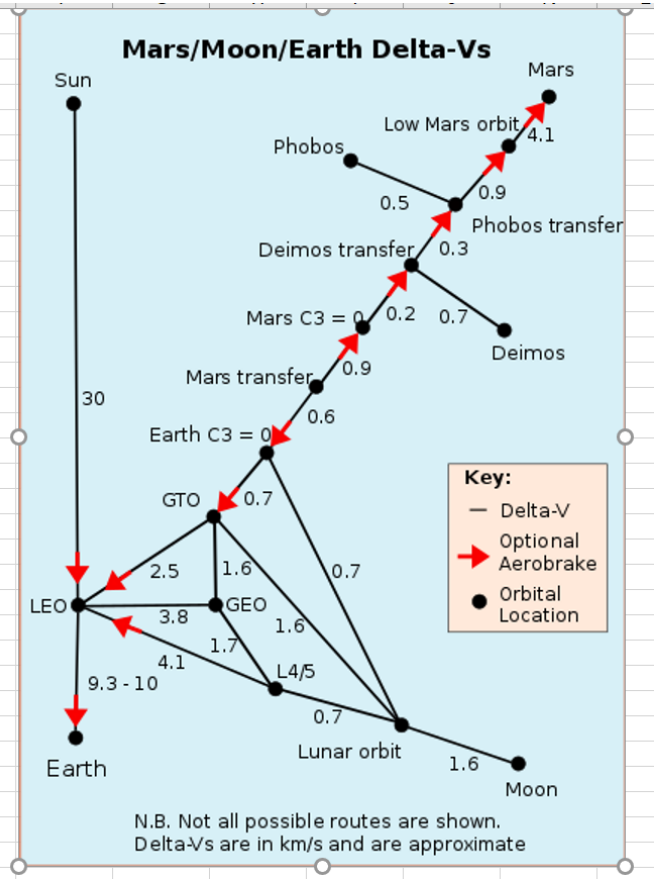
Initial launch mass for reactors in phase 1:
3 x 7500 kg

Assumed launch costs during operations:
6,800 $/kg (Per kg landed on lunar surface)
(SpaceX Starship)

Responsible Team Member: Alex Genzel

Launch Cost Estimates

mass	SpaceX LEO	dV
1000	$ 4,150,000	10
1	$ 4,150	10
7500	$ 31,125,000	10
7500	$ 3,112,500	1
7500	$ 51,045,000	16.4
1	$ 6,806	7.4



SpaceX, https://rideshare.spacex.com/search?orbitClassification=1&launchDate=2029-03-07&payloadMass=1000
DeltaV Map, https://upload.wikimedia.org/wikipedia/commons/thumb/7/74/Delta-Vs_for_inner_Solar_System.svg/400px-Delta-Vs_for_inner_Solar_System.svg.png

Power Projections

TABLE I. Pylon System in Different Locations

Design	Power [kW_e]	Mass [kg]	Heat Reject.	T_{hot}/T_{cold} [K]
Pylon-Space	150	4100	Rad.	1150/430
Pylon-Moon	150	4500	Rad.	1150/430
Pylon-Mars	320	4300	Conv.	1150/290

Eades,M. et al. (2019). **The Pylon: Commercial LEU Nuclear Fission Power for Lunar, Martian, and Deep Stace Applications.** American Nuclear Society. http://anstd.ans.org/NETS-2019-Papers/Track-4--Space-Reactors/abstract-129-0.pdf

Habitat Summary

The power required (table 2) for nominal outpost operations is ~ 9.4 kW (without a 30% growth). The power required for the outpost while crew is not on-board during a quiescent mode is ~ 3.2 kW. The thermal conditioning required for air-cooled and cold-plated cooling is ~ 3.5 kW and 5.8 kW respectively. The mass properties are shown in table 3. The outpost configuration total mass to the surface is ~ 16,561 kg for the three outpost habitation units.

Table 2, LS-12.0 Outpost Power & Thermal Loads

Note: **without** the 30% growth	PCM	PEM	PLM	Total Power & Thermal, W
Outpost Power Active, We	6992	1471	1018	9481
Outpost Quiescent Power, We	1017	1207	1006	3230
Outpost Air-Cooled Thermal, W_t	2756	454	261	3471
Outpost Cold-Plated Thermal, W_t	4237	817	757	5811

Kennedy, K.J. et al. (2009). **Constellation Architecture Team-Lunar Scenario 12.0 Habitation Overview.** NASA.https://ntrs.nasa.gov/api/citations/20100003415/downloads/20100003415.pdf

Lunar Mining

Commercial Lunar Propellant Architecture

A Collaborative Study of Lunar Propellant Production

To achieve production demand with this method, 2.8 megawatts of power is required (2 megawatts electrical and 0.8 megawatts thermal). The majority of the electrical power will be needed in the processing plant, where water is broken down into hydrogen and oxygen. This substantial amount of power can come from solar panels, sunlight reflected directly to the extraction site, or nuclear power. Because the bottoms of the polar craters are permanently shadowed, captured solar

STRENGTHS

- Positive NPV with base-load electric only demand
- Market-leading approach
- No exotic technologies
- Robust system reliability and reserve capacity

WEAKNESSES

- High upfront CAPEX requirements
- First-mover risk
- Licensing, regulatory requirements for nuclear materials

OPPORTUNITIES

- Utilize "waste heat" as additional income-generating cashflow stream
- Vertical integration into mining operations
- License technology for remote terrestrial use

THREATS

- Competition from SSPS (long-term 10+ years)
- Vertical integration from miners
- Delayed revenue stream due to third-party delays (Artemis, private lunar miners)

Updated CF Model Without Thermal Revenue

	Total	Development					Production																			
Year		**-5**	**-4**	**-3**	**-2**	**-1**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Projected Demand (kW_e)		0	0	0	0	0	60	70	81	93	108	125	146	2169	2356	2560	2784	3028	3295	3706	4168	4690	5277	5939	6685	7528
Operating Reactors (@ 50kWe each, n+1)							3	3	3	3	4	4	4	45	49	53	57	62	67	76	85	95	107	120	135	152
Reserve Power (kWe)							90	81	69	57	92	75	54	81	94	90	66	72	55	94	82	60	73	61	65	72
Electrical Power Utilization (%)							40%	46%	54%	62%	54%	63%	73%	96%	96%	97%	98%	98%	98%	98%	98%	99%	99%	99%	99%	99%
Available Thermal Power kW (28% Eff, 50% usebale)							268	268	268	268	357	357	357	4018	4375	4732	5089	5536	5982	6786	7589	8482	9554	10714	12054	13571
Projected Demand (kW_{th})		0	0	0	0	0	0	0	0	0	0	0	0	800	864	933	1008	1088	1175	1317	1475	1651	1850	2072	2320	2599
Thermal Utilization (%))							0%	0%	0%	0%	0%	0%	0%	20%	20%	20%	20%	20%	20%	19%	19%	19%	19%	19%	19%	19%
Build & Launch		0	0	0	1	2	0	0	0	1	0	0	41	4	4	4	5	5	9	9	10	12	13	15	17	0
Total Annual MW-hrs_e sold	**480,633**	0	0	0	0	0	526	609	705	818	948	1,099	1,275	18,999	20,638	22,428	24,385	26,524	28,867	32,464	36,515	41,080	46,225	52,024	58,564	65,941
Total Annual MW-hrs_th sold							0	0	0	0	0	0	0													
Gross Revenue (m$)	**48,063**	**0**	**0**	**0**	**0**	**0**	**53**	**61**	**71**	**82**	**95**	**110**	**127**	**1900**	**2064**	**2243**	**2438**	**2652**	**2887**	**3246**	**3652**	**4108**	**4622**	**5202**	**5856**	**6594**
Reactor Opex (Fuel, m$)							0.3	0.3	0.3	0.3	0.4	0.4	0.4	4.5	4.9	5.3	5.7	6.2	6.7	7.6	8.5	9.5	10.7	12	13.5	15.2
Lunar Operating Staff							8	8	8	8	9	9	9	50	54	58	62	67	72	81	90	100	112	125	140	157
Earth Staff		20	50	75	150	150	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
OPEX Labor Cost (m$)		5	12.5	18.75	37.5	37.5	38	38	38	38	39	39	39	80	84	88	92	97	102	111	120	130	142	155	170	187
OPEX (m$)	**2,033**	**5**	**13**	**19**	**38**	**38**	**38**	**38**	**38**	**38**	**39**	**39**	**39**	**85**	**89**	**93**	**98**	**103**	**109**	**119**	**129**	**140**	**153**	**167**	**184**	**202**
Operating CF (m$)		**0**	**0**	**0**	**0**	**0**	**14**	**23**	**32**	**43**	**55**	**70**	**88**	**1815**	**1975**	**2150**	**2341**	**2549**	**2778**	**3128**	**3523**	**3969**	**4470**	**5035**	**5673**	**6392**
Lunar Construction Staff				20	50	75	5	5	5	25	5	5	825	85	85	85	105	105	185	185	205	245	265	305	345	5
CAPEX Labor Cost (m$)	**3,225**	0	0	20	50	75	5	5	5	25	5	5	825	85	85	85	105	105	185	185	205	245	265	305	345	5
R&D (m$)	**1,600**	100	200	300	500	500																				
Sustaing Capital (New Reactors)	**4,940**					200	0	0	0	100	0	0	1230	320	120	120	150	150	270	270	300	360	390	450	510	0
Sustaing Capital (Launch Costs)	**7,701**					102	0	0	0	51	0	0	2091	204	204	204	255	255	459	459	510	612	663	765	867	0
CAPEX Total (m$)	**17,466**	**100**	**200**	**320**	**550**	**877**	**5**	**5**	**5**	**176**	**5**	**5**	**4146**	**609**	**409**	**409**	**510**	**510**	**914**	**914**	**1015**	**1217**	**1318**	**1520**	**1722**	**5**
CF (m$)	**28,546**	-105	-213	-339	-588	-915	9	18	27	-133	50	65	-4058	1206	1566	1741	1831	2039	1864	2214	2508	2752	3152	3515	3951	6387
DCF (m$)		-105	-197	-290	-466	-672	6	10	15	-66	23	28	-1611	444	533	549	534	551	466	513	538	547	580	599	623	933
NPV (m$)	**226**																									
IRR	**16%**																									

Historical Costs

Past Space Reactor Programs

13 Programs, ~$18 Billion Spent, 1 Flight Reactor 55 years ago

Decade	Project	Estimated Cost	Cost Today	Reactors Tested	Flight Units
60s-70s	SNAP	~$380M	$2.40B	~6	1
60s-70s	Rover/NERVA	~$2B	$12.00B	~20	0
70s-80s	SPAR	~$10M	$0.06B	0	0
80s-90s	SP-100	~$1B	$2.50B	0	0
80s-90s	MMW program	~$50M	$0.13B	0	0
90s-00s	NEBA (bimodal)	~$5M	$0.01B	0	0
90s-00s	Topaz	~$50M	$0.09B	0	0
90s-00s	SNTP/Timberwind	~$200M	$0.34B	0	0
00s-10s	Affordable Rx Prog.	~$5M	$0.01B	0	0
00s-10s	JIMO	~$400M	$0.53B	0	0
10s-20s	NCPS/NTP	~$80M	$0.08B	0	0
10s-20s	FSP	~$24M	$0.03B	0	0
10s-20s	KiloPower	$20M	$0.02B	1	0
Total			**~$18.4B**	**~27**	**1**

King, J. (2021). SPRS598 Space Fission Power Systems Class Notes

Baseload Demand

Customers	Annual Growth Rate																									
		-5	-4	-3	-2	-1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Total kWe Demand		0	0	0	0	0	60	70	81	93	108	125	146	169	196	227	264	307	357	415	482	561	653	760	885	1031
Group 1																										
NASA - Artemis	**15%**						50	58	66	76	87	101	116	133	153	176	202	233	268	308	354	407	468	538	619	712
Space Force - Military (comms initially, base, Planetary	**20%**						10	12	14	17	21	25	30	36	43	52	62	74	89	107	128	154	185	222	266	319
ESA	**7%**																									

Blue Sky Demand

Customers	Annual Growth Rate	-5	-4	-3	-2	-1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Total kWe Demand		0	0	0	0	0	60	70	81	173	303	463	548	2649	2928	3243	4597	5079	5620	6395	7282	8299	9466	10805	12346	14118
Total kWth Demand		0	0	0	0	0	0	0	0	0	0	0	0	800	864	933	1008	1088	1175	1317	1475	1651	1850	2072	2320	2599
Tier 1																										
NASA - Artemis	**15%**						50	58	66	76	87	101	116	133	153	176	202	233	268	308	354	407	468	538	619	712
Space Force - Military (comms initially, base, Planetary De	**20%**						10	12	14	17	21	25	30	36	43	52	62	74	89	107	128	154	185	222	266	319
ESA	**7%**										50	60	72	86	104	124	149	179	215	258	310	372	446	535	642	770
Russia	**5%**										50	60	72	86	104	124	149	179	215	258	310	372	446	535	642	770
China	**10%**																									
Tier 2																										
ASA (Austrailia)	**5%**									20	23	26	30	35	40	46	53	61	70	81	93	107	123	142	163	187
JAXA	**3%**									20	24	29	35	41	50	60	72	86	103	124	149	178	214	257	308	370
SpaceX	**30%**									20	24	29	35	41	50	60	72	86	103	124	149	178	214	257	308	370
UK Space Agency	**5%**									20	24	29	35	41	50	60	72	86	103	124	149	178	214	257	308	370
France	**5%**																									
Tier 3																										
KARI (Korea)	**4%**											15	17	20	23	26	30	35	40	46	53	61	70	80	92	106
ASI (Italian)	**4%**											15	18	22	26	31	37	45	54	64	77	93	111	134	160	193
Blue Origin	**10%**											15	18	22	26	31	37	45	54	64	77	93	111	134	160	193
DLR (Germany)	**3%**											15	18	22	26	31	37	45	54	64	77	93	111	134	160	193
SSC (Saudi)	**1%**											15	17	20	23	26	30	35	40	46	53	61	70	80	92	106
UAESA (UAE)	**1%**											15	18	22	26	31	37	45	54	64	77	93	111	134	160	193
ISRO (India)	**4%**											15	18	22	26	31	37	45	54	64	77	93	111	134	160	193
Initial Commerical Demand (First Movers)	**8% for 5 years, 12% after**													2000	2160	2333	2519	2721	2939	3291	3686	4129	4624	5179	5800	6496
Initial Commerical Demand (First Movers) kW_th														800	864	933	1008	1088	1175	1317	1475	1651	1850	2072	2320	2599
Subsequent Commerical Demand (Early Adopters)	**12% for 5 years, 25% after**																500	540	583	653	732	819	918	1028	1151	1289
Mainstream Commerical Demand (Early Early Majority)	**20% for 5 years, 30% after**																500	540	583	653	732	819	918	1028	1151	1289

Market Analysis Sources

- Russia/China cooperation: China, Russia reveal roadmap for international moon base - SpaceNews
- Technology Adoption Lifecycle: Crossing the Chasm in Technology Adoption Life Cycle EXPLAINED | B2U (business-to-you.com)
- Funding Profiles:
- 2020: March 2021 - Government Space Budgets Surge Despite Global Pandemic | Via Satellite (satellitetoday.com)
- 2018: Op-ed | Global government space budgets continues multiyear rebound - SpaceNews
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- ESA awards study contracts for lunar communications and navigation systems – SpaceNews
- ESA - ESA advances its plan for satellites around the Moon
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- 'It's important we go together': time for Australian flag to fly on the moon, Nasa says | Space | The Guardian
- Japan: Japan is joining the push to return to the moon | TheHill
- SpaceX: Is SpaceX Really Worth $74 Billion? (forbes.com)
- Elon Musk's SpaceX raised $850 million at $419.99 a share (cnbc.com)
- What Is Driving SpaceX's Revenues & Valuation? | Trefis
- SpaceX - Missions: Moon
- SpaceX Wins NASA $2.9 Billion Contract to Build Moon Lander - The New York Times (nytimes.com)
- UK: Project Artemis: UK signs up to Nasa's Moon exploration principles - BBC News
- UK Space Agency hopes first woman on moon mission will make it key player | Space | The Guardian
- France: France may join Russia and China in effort to build lunar research station - Global Construction Review
- Official: China's moon probe will carry French, Russian gear (apnews.com)
- Korea: South Korea signs Artemis Accords, aims for moon by 2030 | Space
- Blue Origin: Jeff Bezos Interview With Axel Springer CEO on Amazon, Blue Origin, Family (businessinsider.com)
- Blue Origin protest over $2.9B lunar lander contract slapped down - Puget Sound Business Journal (bizjournals.com)
- Jeff Bezos offers $2B to NASA to add Blue Origin in moon trip plans (usatoday.com)
- Germany: Aerospace: Germany and Israel are intending to go to the moon together (deutschland.de)
- KSA: Saudi Arabia to boost space funding with eye on Moon and Mars (thenationalnews.com)
- UAE: UAE to send rover to the Moon in 2022 (phys.org)
- UAE reveals long-term Moon exploration plan at global space conference (thenationalnews.com)
- India: Chandrayaan-3: India plans third Moon mission - BBC News
- Chandrayaan-1: India's First Mission to the Moon | Space
- Indonesia: Blast off: Space minnow Indonesia eyes celestial success - Science & Tech - The Jakarta Post
- Utilization of Space Resources: Indonesia's Perspective | SpaceTech Asia
- Turkey: Turkey aims to send rocket to moon in three years, land lunar rover by 2030 | Space

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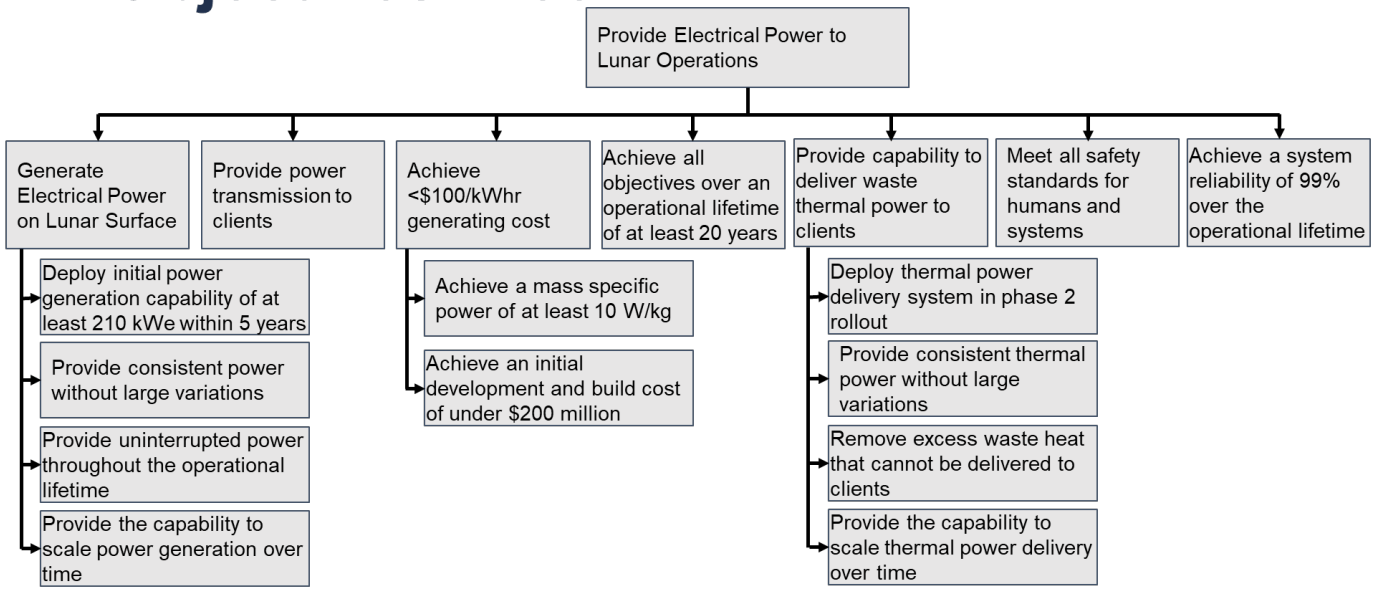
System Overview

- The initial design is based on phase 1 needs, additional phases will be rolled in with available technology at that time

Objectives Tree



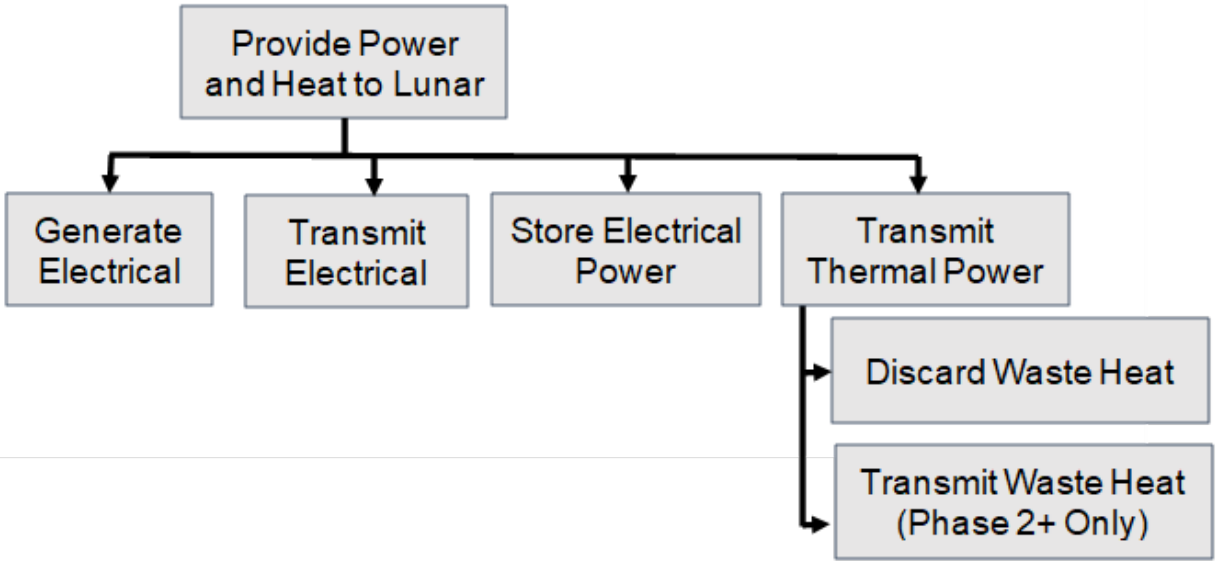
Measures of Effectiveness

- Initial power generation capability of >60kWe
  - Based on first customers of NASA's Artemis Base and Space Force
- Deployed on Lunar Surface within 5 years
  - To capture customer base, must be proven effective and available within initial customer timeline
- Lifetime >= 20 years
  - Based on financial analysis and technical capability
- Scalable to meet anticipated power demand over operational lifetime
  - Customer base and power needs will increase over time
- OPEX at year 5 of operations < $70/kWhr
  - Based on financial analysis
- Cost < $100/kWhr on Moon
  - Based on financial analysis and market research of customer's desired pricepoint
- System reliability of >= 99%
  - This requirement was chosen based on prior experience with human space systems

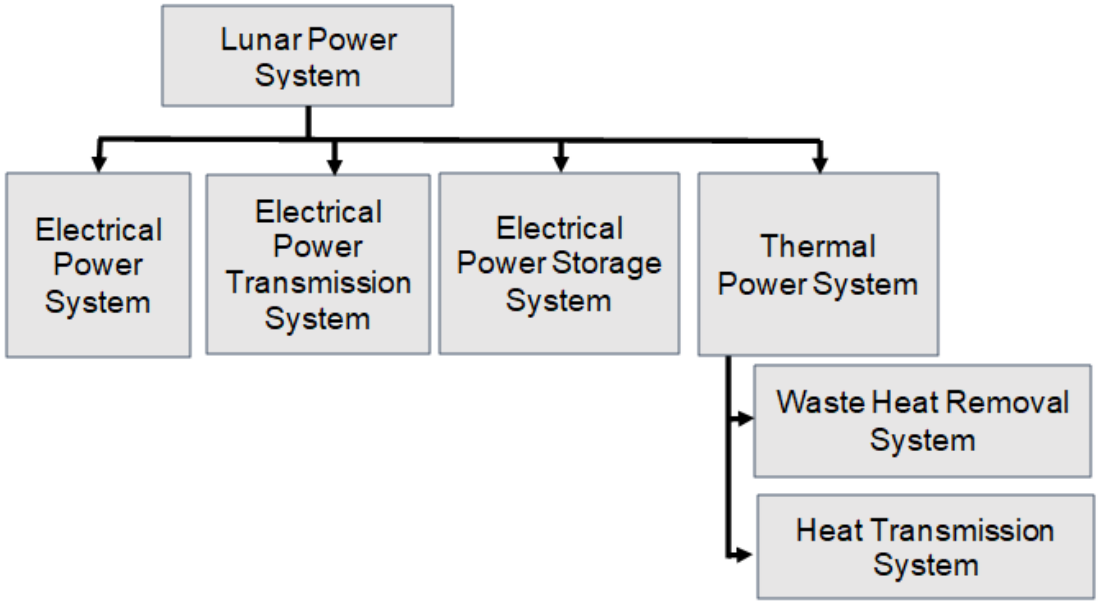
System Description

- Purpose: Lunar Power, Inc. will be the go-to source for electrical power on the moon, providing power to the Artemis base during construction and operations, as well as later generation lunar operations, including space agencies, tourism, and heavy industry.

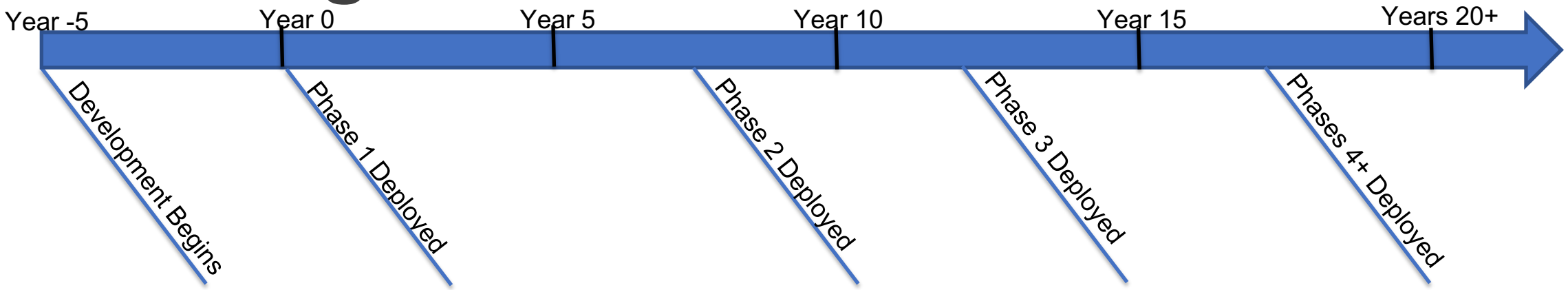
Functional Architecture



Physical Architecture

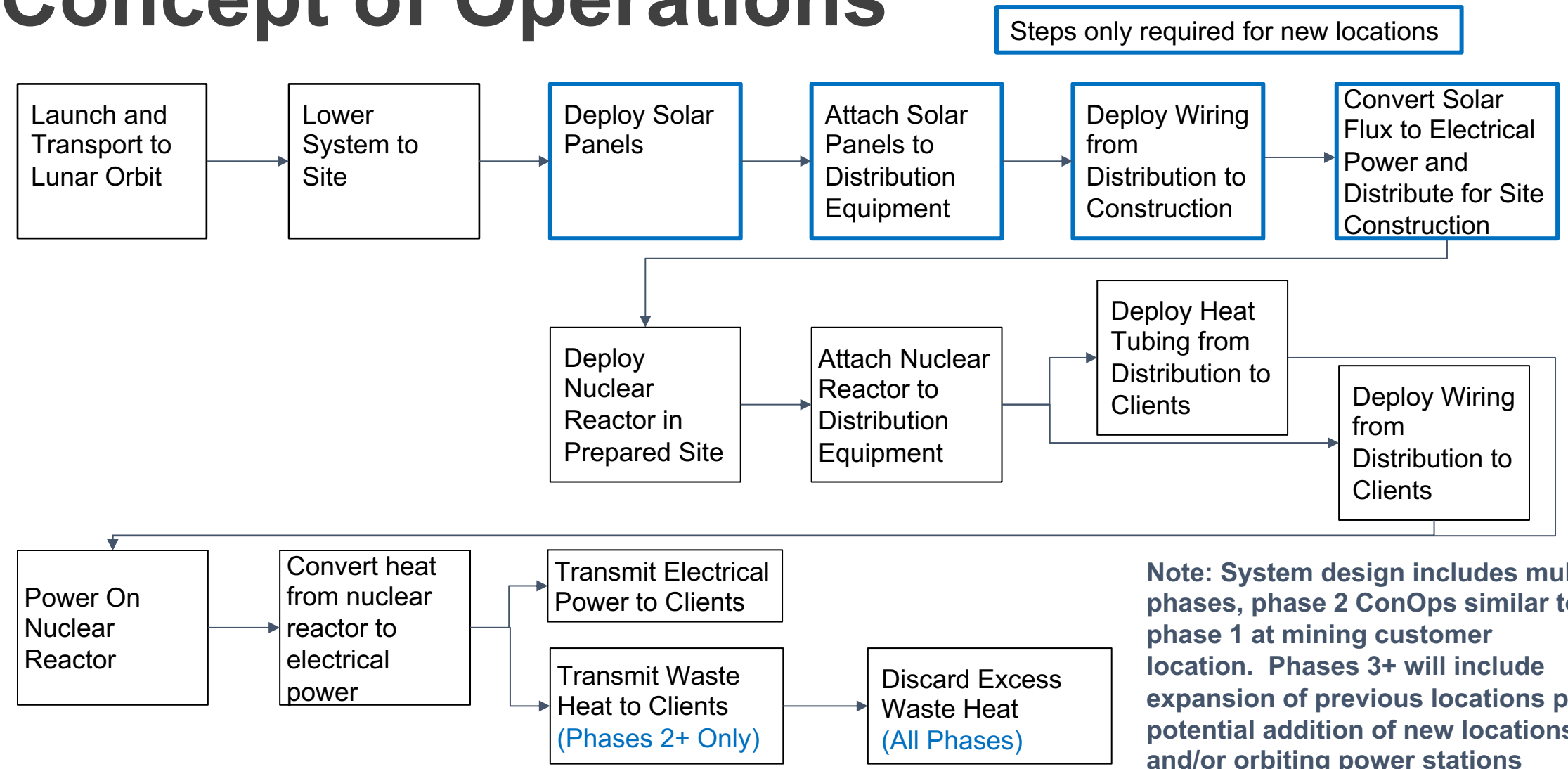


Phasing Plan



- Phase 0 (construction and deployment) will utilize fast deploy solar panels and Phase 1 power will be supplied by an initial deployment of three 50kWe nuclear reactors at year zero, maintaining Phase 0 solar deployment for contingency/surge power. An additional reactor will be added at ~year 5 to meet growth demand at phase 1 location
- Phase 2 will be co-located with mining customer, separate location from phase one and will include an initial deployment with multiple subsequent launches to meet rapidly expanding demand
- Phases 2+ will nominally be supplied by nuclear reactors (phase 1 reactor specs utilized as a conservative estimate for business case), with a phased introduction of new technologies as TRL development allows
- Phase 3 will consist of expansion of capabilities at phase 1 and phase 2 locations with updated technologies, and the potential to add an additional location if required by customer demand
- Phases 4+ will be determined by future customer demand and available technologies, potential addition of new sites across the lunar surface and/or orbiting power stations with power beaming technology

Concept of Operations



Note: System design includes multiple phases, phase 2 ConOps similar to phase 1 at mining customer location. Phases 3+ will include expansion of previous locations plus potential addition of new locations and/or orbiting power stations

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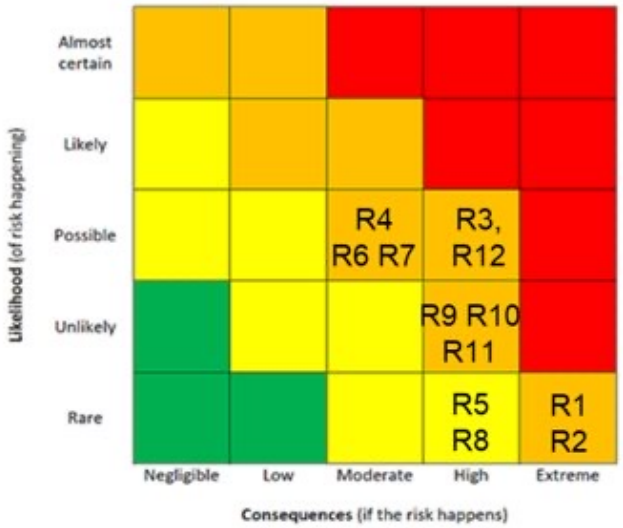
Mitigated Risk Registry

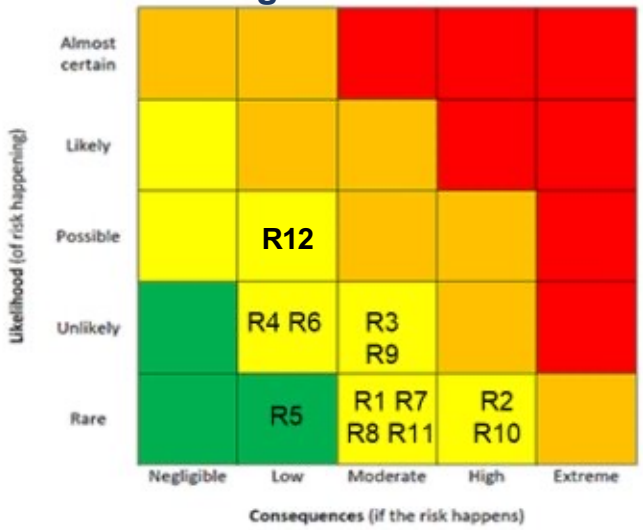
Note: Risk Registry Definitions and scoring criteria here

Risk #	Risk Description	Type of Risk	Score	Post Mitigation: Mitigation Measures	Post Mitigation: Score
1	Malfunction, radiation leak	Financial, Safety, Reputational	5	Redundant safety architecture, no single-point failures, sufficient offset difference/burial	3
2	Meteor Impact --> Catasrophic System Failure	Financial/Safety	5	Shielding with regolith to protect critical components	4
3	Market Risk - Failure/Bankruptcy of Client / Offtake agreement	Financial	12	Pre-payment options, guaranteed gov revenue stream, liquidation penalities for cancellation	6
4	Critical Component Malfunction Post System Deployment	Financial	9	Deliver spare parts, extensive terrestrial testing	4
5	System Underperformance Upon Comissioning	Performance	4	Ensure strict n+1 that allows for compensation	2
6	Technological failure to achieve performance specificaitons in time	Technological	9	Rely on simple technology and modular appraoch, roll in technology advancements in a phased deployment plan	4
7	Injury During Lunar Assembly/ Comissioning	Safety	9	Design for minimum components to assemble, emphasis on automated deployment sequence	3
8	Injury During Operations (non-radioactive)	Safety	4	Strict SOPs, ro-active risk mitigation strategies	3
9	Partial Launch Failure Resulting in Excess Space Debris, Negative Coverge	Financial Reputational	8	Transfer risk to third party launch serivce, utilize appropriate insurance, prepare back-up units	6
10	Project Delays Resulting in Delivery Contract Default	Financial	8	Project controls, regular Gantt chart updates	4
11	Over-budget project costs, potentially leading to project cancellation	Financial	8	Implement budget and schedule controls, Allot for large contingency budget, perhaps 20-30% of CAPEX	3
12	TRL development of nuclear reactor fails to meet necessary timeline	Technological	12	TRL development plan with specific milestones, and an offramp plan to back off to a lower risk solar power system if milestones are not met within specified timeline and budget	6

Unmitigated Risk Matrix



Mitigated Risk Matrix



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Risk Registry Definitions

Risk Liklihood Definition					
	Rare	**Unlikely**	**Possbile**	**Likely**	**Almost Certain**
Score	1	2	3	4	5
Probability	**<0.01**	**0.01-0.10**	**0.11-0.40**	**0.44-0.64**	**>0.65**

Risk Consequence Definition					
	Negligible	**Low**	**Moderate**	**High**	**Extreme**
Score	1	2	3	4	5
Financial	< $1m	$1m-$25m	$25m-$100m	$100-$500m	>$500m
Reputational	Minor Incident, Non-reportable	Minor Incident, Reportable, No Media Coverage	Reportable Incident, Local Media	Major Incident, National Media	Major Incident, Interational Media
Safety	Minor Impacts, No Medical Inervention	First Aid Required	Medical Intervention Required	Severe Medical Intervention or Evacuation Required	1 or More Fatality
Schedule	Recoverable Impacts to Critical Path	Non-Recoverable Impact, Does not Effect Critical Path	< 60 Day Impact, Effects Critical Path	< 6 Month Impact, Effects Critical Path	> 6 Month Impact, Effects Critical Path
Technical	Negligible Impact to Requirements	Minor Impact to Requirements	Moderate Impact to Requirements	Severe Impact to Requirements	System Redesign Required

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Full Analysis of Alternatives (Phase 1 Only)

Note: Full Figure of Merit Definitions and scoring criteria here

		Nuclear Fission		Flexible Array Surface Solar		Traditional Surface Solar		Nuclear + Solar		Nuclear Fission		Satellite Solar		Portable Power	
		Modular Reactors		Lunar Surface PV		Lunar Surface PV		Surface Based		Large Reactor		SSPS System		Power Packs	
Parameter	Weight	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
Cost per kW	12	4	48	3	36	3	36	4	48	5	60	0	0	1	12
Mass Efficiency	13	3	39	3	39	2	26	3	39	5	65	0	0		0
Redundancy	10	5	50	4	40	4	40	5	50	0	0	3	30	5	50
Launch Complexity	6	3	18	4	24	4	24	3	18	3	18	2	12	1	6
Installation Complexity	7	3	21	4	28	4	28	2	14	4	28	0	0	1	7
Surface Area Required	5	3	15	2	10	1	5	3	15	4	20	5	25	4	20
Safety	16	3	48	5	80	5	80	3	48	2	32	5	80	3	48
Availability	9	5	45	2	18	2	18	5	45	5	45	3	27	4	36
TRL	9	3	27	5	45	5	45	3	27	1	9	0	0	3	27
Extensibility	13	5	65	3	39	2	26	4	52	5	65	5	65	1	13
	Total	376		359		328		356		342		239		219	

Options removed from consideration for phase 1 due to low TRL/inability to meet phase 1 schedule required by business case:

- **Nuclear Fission Large Reactor**
- **Satellite Solar Power (Beamed to Surface)**

Options removed from consideration for phase 1 due to mass inefficiency:

- **Portable Power Packs**

NOTE: These options are still under consideration for phases 2+

Notes:

- **Figures of merit selected based on business case**
- **Pairwise comparison used to determine scoring and weights of figures of merit**
- **Scoring and weights based on phase 1 only. Since phase 1 is intended for a human lunar base, astronaut safety takes precedence**
- **Off-ramp plan to higher TRL system in place based on development milestones for selected system**

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Figure of Merit Definition - AoA

		Score					
Figure of Merit	**Definition**	**0**	**1**	**2**	**3**	**4**	**5**
Cost per kW	Total generating cost per kW of power delivered on the Moon, including development, design and build, launch, installation, and operations.	> $200/kWhr	< $200/kWhr	< $150/kWhr	< $100/kWhr	< $75/kWhr	< $50/kWhr
Mass Efficiency	Watts per kilogram of system mass	< 1 W/kg	> 1 W/kg	> 4 W/kg	> 7 W/kg	>10 W/kg	> 20 W/kg
Redundancy	Capability of the system to continue production after a major system fault resulting in the loss of power generation capabilities	Single Failure Results in Total System Failure	Single Failure Results in Severe Capability Reduction	Single Failure Results in Significant Capability Reduction	Single Failure Results in Moderate Capability Reduction	Single Failure Results in Minor Capability Reduction	Single Failure Results in No Capability Reduction
Launch Complexity	Launch considerations including limited compatible launch vehicle options versus the capability to launch on multiple rockets, number of launches required, launch and ground safety concerns, and additional regulations and security controls	Extreme Considerations	Significant Considerations	Major Considerations	Moderate Considerations	Minor Considerations	Negligible Considerations
Installation Complexity	Considerations related to installation of the evaluated option on the lunar surface including the amount of human intervention required for installation and whether in person or remote support is needed, as well as how much site preparation is required.	Intensive On-site Human Intervention, Extreme Site Prep	Minimal On-site Human Intervention, Significant Site Prep	Intensive Remote Intervention, Major Site Prep	Moderate Remote Intervention, Moderate Site Prep	Minimal Remote Intervention, Minor Site Prep	Fully Automated Deployment, Minimal Site Prep
Surface Area Required	Relative amount of lunar surface area required	Extreme Lunar Surface Area Required	Significant Lunar Surface Area Required	Major Lunar Surface Area Required	Moderate Lunar Surface Area Required	Minor Lunar Surface Area Required	Negligible Lunar Surface Area
Safety	Safety risk to human missions on the lunar surface	Extreme Safety Risk	Significant Safety Risk	Major Safety Risk	Moderate Safety Risk	Minor Safety Risk	Negligible Safety Risk
Availability	Amount of time that the system is unavailable due to various outages	Outages >50% of time	Outages <50% of time	Outages <33% of time	Outages <25% of time	Outages <10% of time	No outages
TRL Level	Amount of TRL development necessarily and ability to develop in time to meet the Phase 1 timeline	Key technologies < TRL 3, 10+ years of development	Significant TRL development needed, not ready within 5 years	Moderate TRL development needed, possibly ready within 5 years	All technologies > TRL 5, ready within 5 years	All technologies > TRL 7, ready within 5 years	All technologies TRL 9
Extensibility	Number of technologies developed for Phase 1 that can be utilized on a larger scale in future phases	Not extensible to future phases	Some Extensibility	Limited Extensibility	Majority of Technologies Extensible	Most Technologies Extensible	Technologies Fully Extensible

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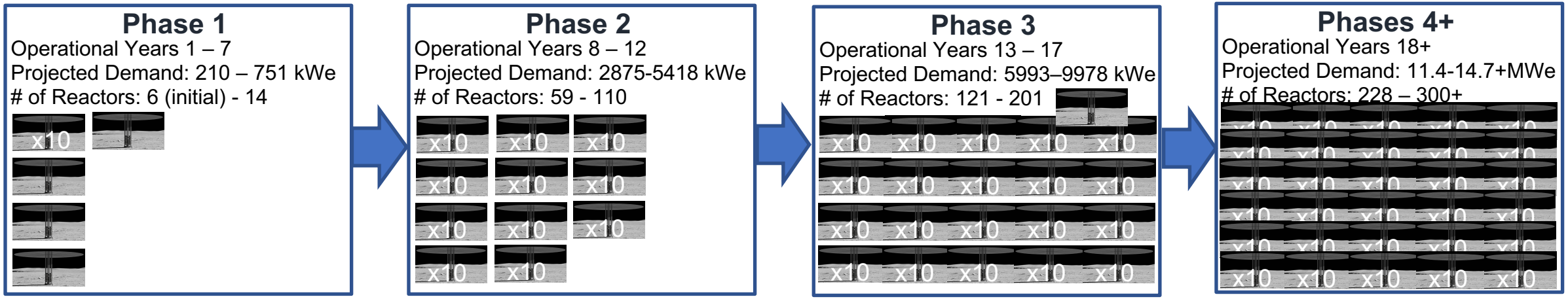
Reactor Sizing Trade Study

- Baseline ConOps for LUNENCO power system is to add more 50 kWe reactors as the demand grows, adding additional locations as necessary
  - Takes advantage of economy of scale, mass production savings
  - 50 kWe reactor is small compared to demand, not mass efficient



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Reactor Sizing Trade Study

Note: Full Figure of Merit Definitions and scoring criteria here

- Trade study intended to determine the best balance between development cost, risk, and mass efficiency
  - Questions to answer include: when (if at all) to switch to larger reactors, how large reactors to use?
- FOMs include:
  - Reactor build cost
  - Development cost
  - Redundancy
  - Launch complexity
  - Installation complexity
  - Surface area required
  - Safety
  - Availability
  - TRL
  - Mobility
- FOM Weighting determined by pairwise comparison
- Each option will be scored for each phase against the FOMs

Alternative	Description
Baseline	Phases 1+: 50kWe Reactors
Phase 2 Large Reactor Upgrade	Phase 1: 50kWe Reactors Phase 2+: 100kWe (TBD) Reactors
Phase 2 Mega Reactor Upgrade	Phase 1: 50kWe Reactors Phase 2+: 1MWe (TBD) Reactors
Phase 2 Large Reactor, Phase 3 Mega Reactor	Phase 1: 50kWe Reactors Phase 2: 100kWe (TBD) Reactors Phase 3+: 1MWe (TBD) Reactors
Phase 2 Large Reactor, Phase 4 Mega Reactor	Phase 1: 50kWe Reactors Phase 2-3: 100kWe (TBD) Reactors Phase 4+: 1MWe (TBD) Reactors
Phase 3 Mega Reactor Upgrade	Phases 1-2: 50kWe Reactors Phase 3+: 1MWe (TBD) Reactors

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Reactor Sizing Trade Scoring

Note: Phase 1 the same for all options

- Each alternative was given an initial raw FOM score for each phase and multiplied by the FOM weight
- Total score summation of the phase scores
- Forward work to complete trade:
  - Each option FOM score will be finalized
  - Sensitivity analysis to determine dependency on each FOM
- Initial recommendation: continue with baseline plan for phases 1 – 2 while also pursuing TRL maturation plan and re-evaluate trade for phases 3+ with additional development information

Phase 2

Alternatives:		Baseline		Option 1		Option 2		Option 3		Option 4		Option 5	
	Weight	Score	Wt Score	Score	Wt Score	Score	Wt Score	Score	Wt Score	Score	Wt Score	Score	Wt Score
Reactor Cost per kW	14	2	28						14	1	14	2	28
Development Cost	12	5	60						12	1	12	5	60
Mass Efficiency	14	3	42	4	56	5	70	1	14	1	14	3	42

Phase 3

Alternatives:		Baseline		Option 1		Option 2		Option 3		Option 4		Option 5	
	Weight	Score	Wt Score	Score	Wt Score	Score	Wt Score	Score	Wt Score	Score	Wt Score	Score	Wt Score
Redundancy													
Launch Complexity													
Installation Complexity	Reactor Cost per kW	14	2	28					56	3	42	4	56
Surface Area Required	Development Cost	12	5	60					24	5	60	2	24
Safety	Mass Efficiency	14	2	28	3	42	5	70	5	70	3	42	5	70
Availability	Redundancy	10	5	50	4	40	1	10	1	10	4	40	1	10
TRL Level														
Mobility														
To														

Phase 4

Alternatives:		Baseline		Option 1		Option 2		Option 3		Option 4		Option 5	
	Weight	Score	Wt Score	Score	Wt Score	Score	Wt Score	Score	Wt Score	Score	Wt Score	Score	Wt Score
Launch Compl													
Installation Complexity													
Surface Area Required	Reactor Cost per kW	14	2	28	3				70	5	70	5	70
Safety	Development Cost	12	5	60	5				48	4	48	4	48
Availability	Mass Efficiency	14	1	14	2	28	5	70	5	70	5	70	5	70
TRL Level	Redundancy	10	5	50	5	50	1	10	1	10	1	10	1	10
Mobility	Launch Complexity	5	1	5	2	10	2	10	2	10	2	10	2	10
	Installation Complexity	6	1	6	2	12	4	24	4	24	4	24	4	24
	Surface Area Required	4	1	4	2	8	5	20	5	20	5	20	5	20
	Safety	15	5	75	4	60	2	30	2	30	2	30	2	30
	Availability	4	5	20	5	20	2	8	2	8	2	8	2	8
	TRL Level	12	5	60	5	60	4	48	4	48	4	48	4	48
	Mobility	4	5	20	4	16	1	4	1	4	1	4	1	4
	Total Score:		342		366		342		342		342		342

Alternatives:		Baseline		Option 1		Option 2		Option 3		Option 4		Option 5	
	Weight	Score	Wt Score	Score	Wt Score	Score	Wt Score	Score	Wt Score	Score	Wt Score	Score	Wt Score
Reactor Cost per kW	14	6	84	9	126	13	182	10	140	9	126	11	154
Development Cost	12	15	180	13	156	7	84	7	84	10	120	11	132
Mass Efficiency	14	6	84	9	126	15	210	11	154	9	126	13	182
Redundancy	10	15	150	13	130	3	30	3	30	6	60	7	70
Launch Complexity	5	6	30	8	40	6	30	5	25	6	30	7	35
Installation Complexity	6	6	36	9	54	12	72	9	54	8	48	11	66
Surface Area Required	4	6	24	9	36	15	60	11	44	9	36	13	52
Safety	15	15	225	12	180	6	90	5	75	7	105	9	135
Availability	4	15	60	13	52	6	24	5	20	7	28	9	36
TRL Level	12	15	180	12	144	7	84	7	84	9	108	11	132
Mobility	4	15	60	12	48	3	12	3	12	6	24	7	28
Total Score:		1113		1092		878		722		811		1022	

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Figure of Merit Definition – Reactor Sizing Trade

			Score					
Figure of Merit	**Definition**	**Weight**	**0**	**1**	**2**	**3**	**4**	**5**
Reactor Cost per kW	Total reactor build cost per kW delivered	14	> $3M/kW	< $3M/kW	< $2M/kW	< $1M/kW	< $750k/kW	< $500k/kW
Development Cost	Total reactor development cost	12	> $1B	< $1B	< $500M	< $250M	< $100M	< $50M
Mass Efficiency	Watts per kilogram of reactor mass	14	< 1 W/kg	> 1 W/kg	> 4 W/kg	> 7 W/kg	>10 W/kg	> 20 W/kg
Redundancy	Capability of the system to continue production after a major system fault resulting in the loss of power generation capabilities	10	Single Failure Results in Total System Failure	Single Failure Results in Severe Capability Reduction	Single Failure Results in Significant Capability Reduction	Single Failure Results in Moderate Capability Reduction	Single Failure Results in Minor Capability Reduction	Single Failure Results in No Capability Reduction
Launch Complexity	Launch considerations including limited compatible launch vehicle options versus the capability to launch on multiple rockets, number of launches required, launch and ground safety concerns, and additional regulations and security controls	5	Extreme Considerations	Significant Considerations	Major Considerations	Moderate Considerations	Minor Considerations	Negligible Considerations
Installation Complexity	Considerations related to installation of the evaluated option on the lunar surface including the amount of human intervention required for installation and whether in person or remote support is needed, as well as how much site preparation is required.	6	Intensive On-site Human Intervention, Extreme Site Prep	Minimal On-site Human Intervention, Significant Site Prep	Intensive Remote Intervention, Major Site Prep	Moderate Remote Intervention, Moderate Site Prep	Minimal Remote Intervention, Minor Site Prep	Fully Automated Deployment, Minimal Site Prep
Surface Area Required	Relative amount of lunar surface area required	4	Extreme Lunar Surface Area Required	Significant Lunar Surface Area Required	Major Lunar Surface Area Required	Moderate Lunar Surface Area Required	Minor Lunar Surface Area Required	Negligible Lunar Surface Area
Safety	Safety risk to human missions on the lunar surface	15	Extreme Safety Risk	Significant Safety Risk	Major Safety Risk	Moderate Safety Risk	Minor Safety Risk	Negligible Safety Risk
Availability	Amount of time that the system is unavailable due to various outages	4	Outages >50% of time	Outages <50% of time	Outages <33% of time	Outages <25% of time	Outages <10% of time	No outages
TRL Level	Amount of TRL development necessarily and ability to develop in time to meet the L2+ timeline	12	Key technologies < TRL 3, 10+ years of development	Significant TRL development needed, not ready within 5 years	Moderate TRL development needed, possibly ready within 5 years	All technologies > TRL 5, ready within 5 years	All technologies > TRL 7, ready within 5 years	All technologies TRL 9
Mobility	Ability to be easily redeployed to new location	4	Cannot be moved	Mobile with extreme operations impact	Mobile with major operations impact	Mobile with moderate operations impact	Mobile with minor operations impact	Extremely mobile

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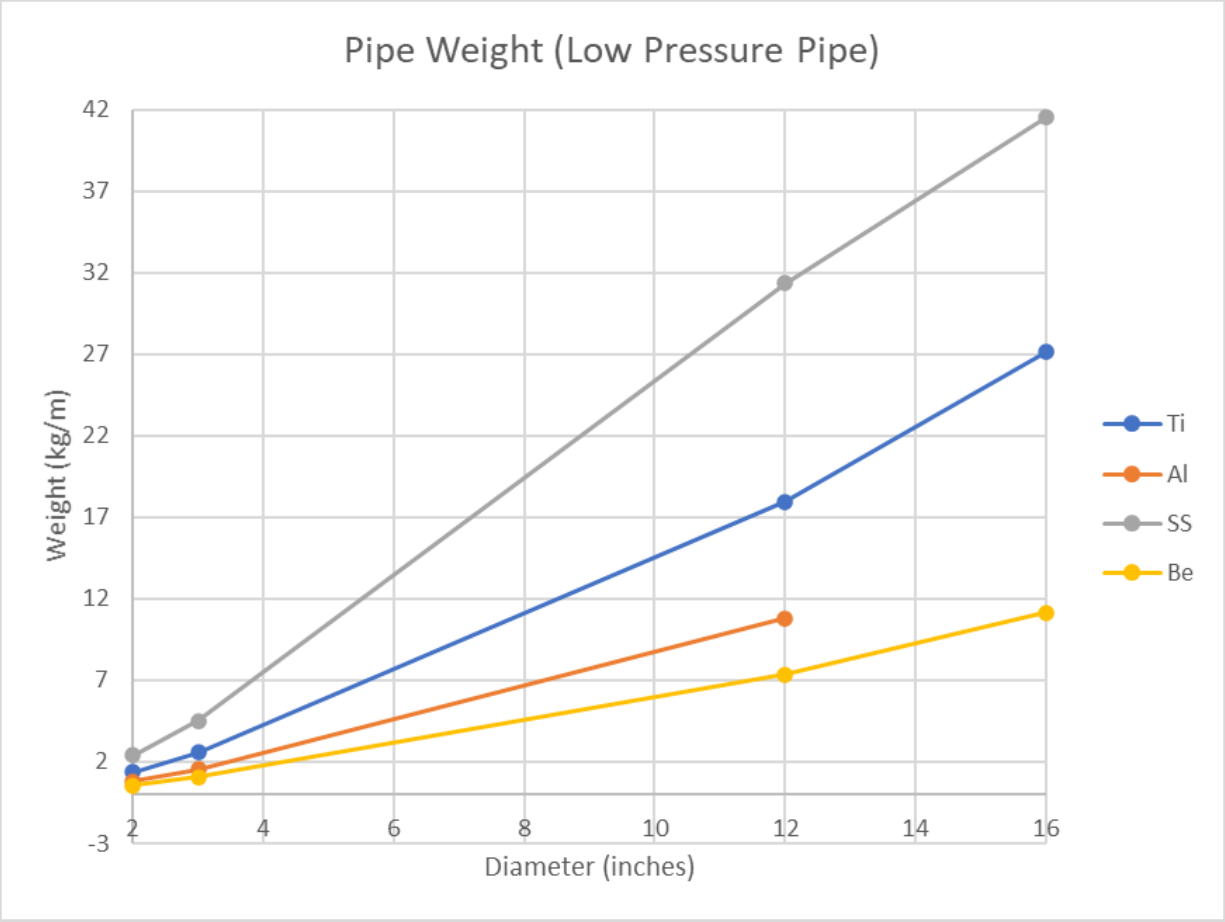
Heat Exchange System Trade Overview

- Purpose of the trade was to select a heat exchange pipe material and fluid to maximize performance while minimizing landed lunar mass
- Options considered included various combinations of pipe materials and fluids
- Pipe Materials:
  - Titanium
  - Aluminum
  - Stainless Steel
  - Beryllium
- Working Fluids:
  - Water
  - Propylene Glycol
  - Dowtherm J
  - NH3

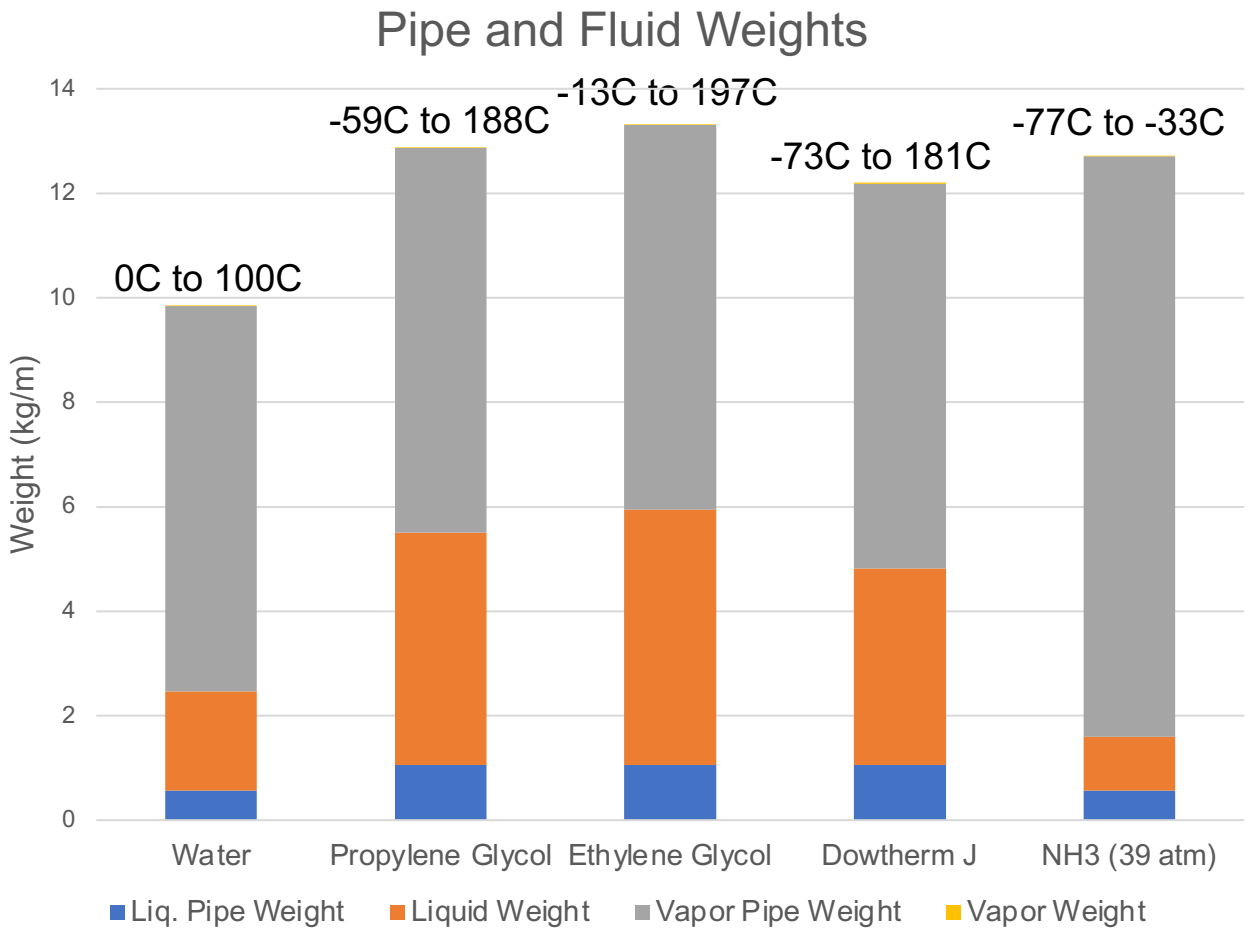
Piping – Beryllium is King

- Titanium pipe is the standard for weight and pressure rating to replace stainless steel.
- However, Beryllium weighs 41% of Titanium but has similar tensile strengths.
- Beryllium will work for all the desired temperature ranges of the heat system.



Piping and Fluids

- The 41% reduction in pipe weights greatly decreases the weight of all the systems.
- The range of temperatures for propylene glycol, along with its simplicity and ability to vaporize and condense, still elevates it to the heat exchange fluid of choice.
- See backup slide for pipe diameters (varies by fluid)
- Temperatures on graph are boiling/freezing points.



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Heat Exchange System Trade Conclusion

- Beryllium piping will be used throughout the heat exchange system.
  - Machined Beryllium is $1,800 per kg and machined Titanium is $318 per kg. The mass savings is more than worth switching due to reduced launch costs.
- Propylene glycol will be used as the heat exchange fluid, as a liquid from the heat demand to the reactor, and as a gas from the reactor to the heat demand.

	Weight	Material Cost	Launch Cost	Total
Distance: 800m	**(kg)**	**($MM)**	**($MM)**	**($MM)**
Titanium	32,882	10.5	223.6	234
Beryllium	13,481	24.3	91.7	116