Lifetime Embodied Energy: A New Value System for the ISRU Space Economy

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From Apollo to this day, mass has been a reliable and accurate proxy for space mission cost.

The Apollo architecture was optimized for minimum mass

Apollo 17 Command and Service Module over the Sea of Crises, viewed from Lunar Module. (Image: NASA)

Will we still be (literally!) shaving grams off fuel lines when we're on Mars?

Concept for a city on Mars. (Image: SpaceX)

Probably not. Our pursuit of sustainable space missions has started decoupling mass from true cost, and ISRU will accelerate this further.

Human Space Mission Architectural Decision	Last 60 years (1957-2017)	Next 30 years (2018 – 2048)	Impact on link between IMLEO and cost of space mission architecture elements
Source of payload for mission?	Earth	Earth **+ ISRU at destination**	**In-situ Resource Utilization** (ISRU) disrupts payload mass ←→ mission cost link (can 'make' payload)
Repeat visits to same planetary surface site?	No (except Apollo 12)	**Yes**	**Accumulated infrastructure** disrupts payload mass ←→ mission cost link (can 'reuse' previous payload)
Reusable launch vehicles and upper stages?	No (shuttle was uneconomic)	**Yes**	**Reusability** of booster & stages disrupts launch mass ←→ mission cost link (rocket & upper stage mass not expended)
Source of propellant for mission?	Earth	Earth **+ ISRU at destination**	**Refueling** from In-situ resources disrupts launch mass ←→ mission cost link (rocket equation is reset upon refueling)

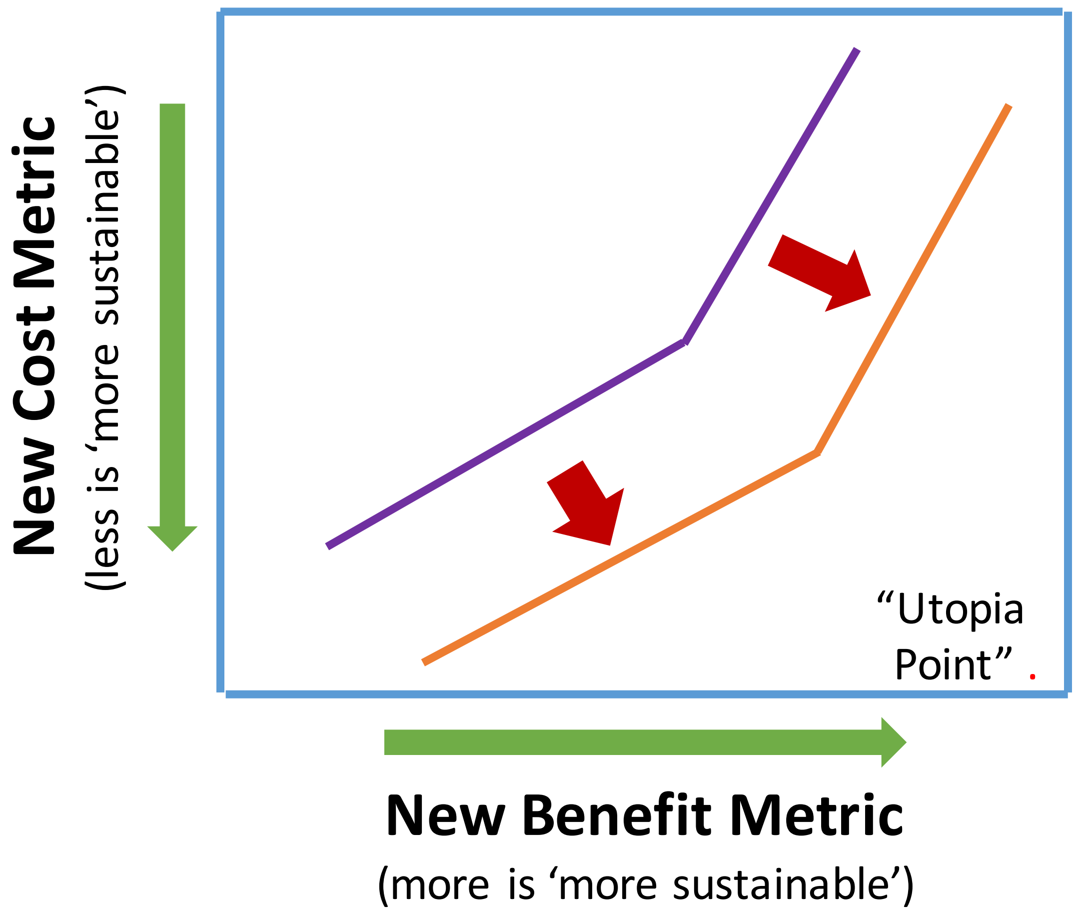
IMLEO: Initial Mass in Low Earth Orbit

Table: SM thesis (Lordos, 2018)

ISRU: In-situ Resource Utilization

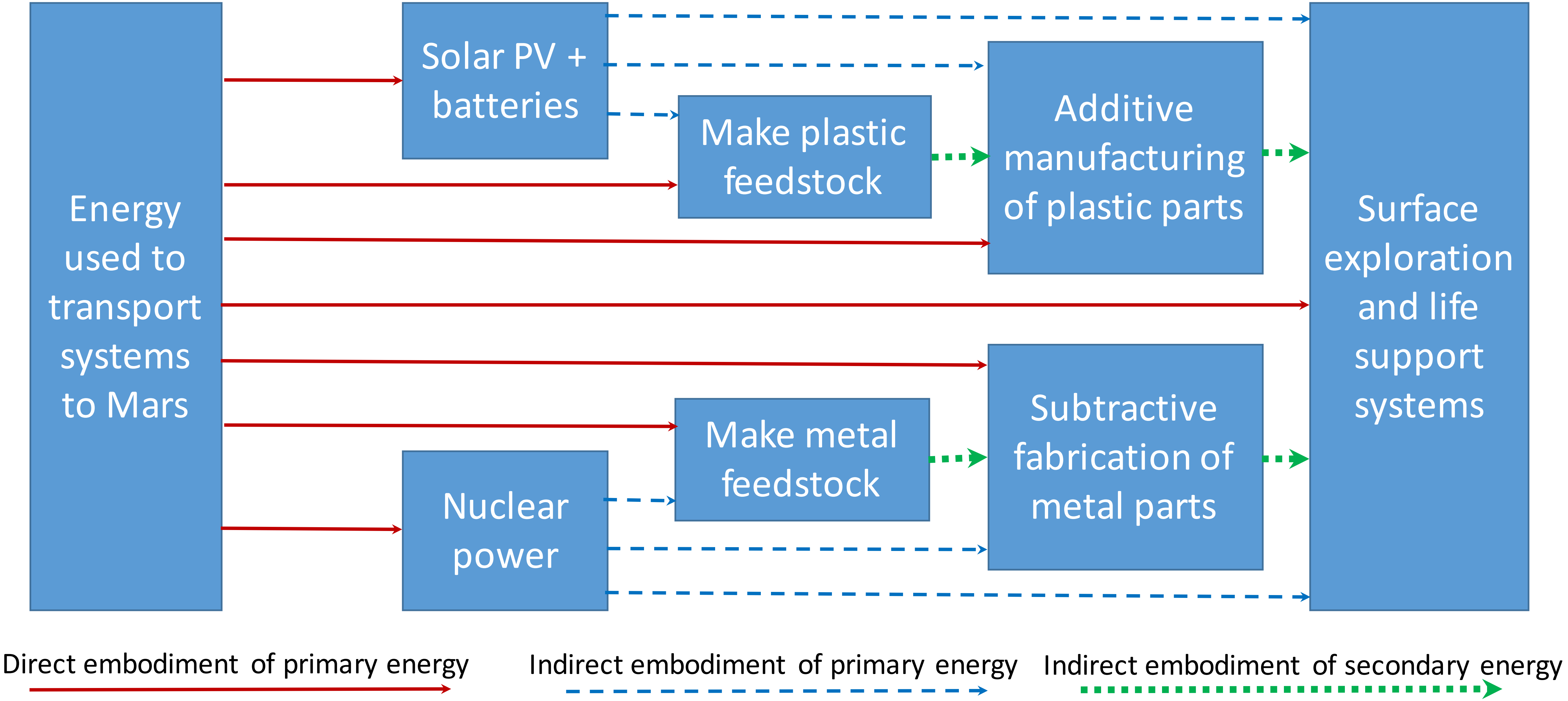
If not mass, then what? What metrics should we optimize for?

<u>Paradigm shift:</u> Align metrics with the sustainability imperative

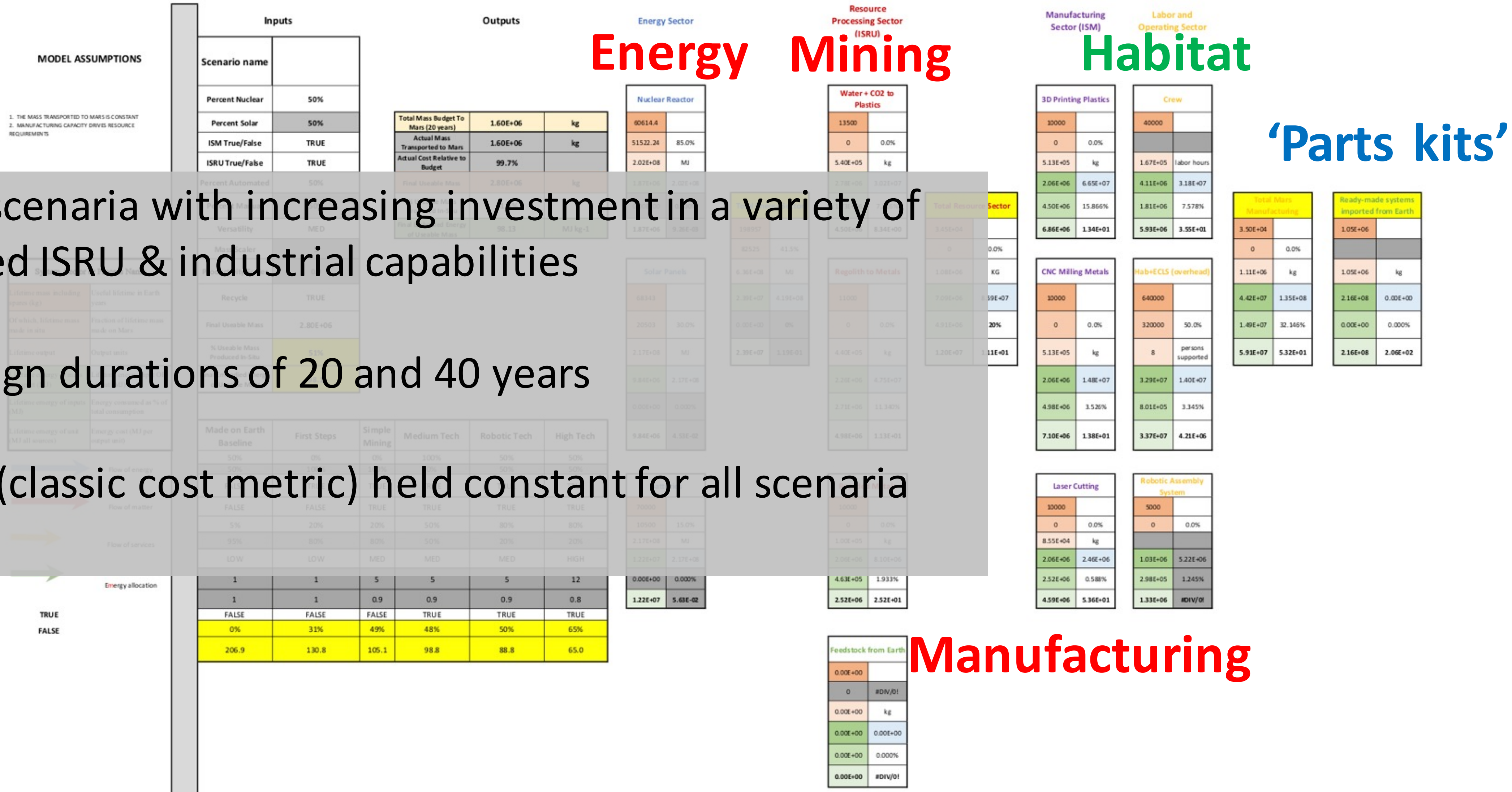


<u>Hypothesis:</u> Develop an **energy-based metric** because energy is the natural metric for work, and because work generates value and attracts cost.

Every activity relies on past use of energy. So, every line represents the 'embodiment' of energy from upstream to downstream processes.



We built a simple sectoral model to calculate LEE for a class of architectures with varying investments in ISRU capabilities.

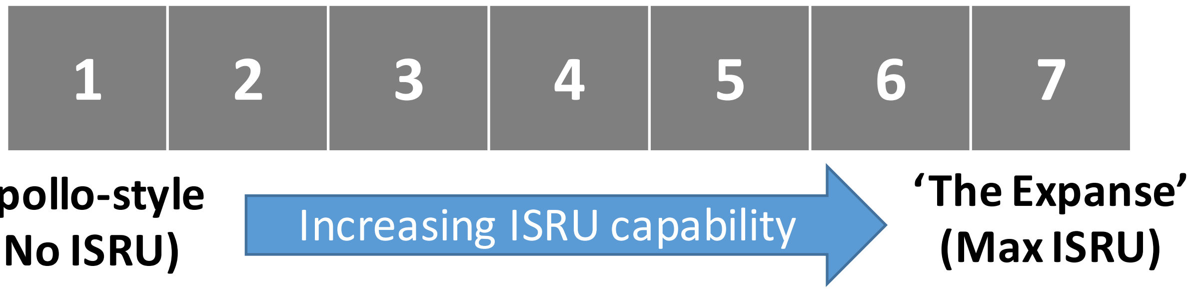


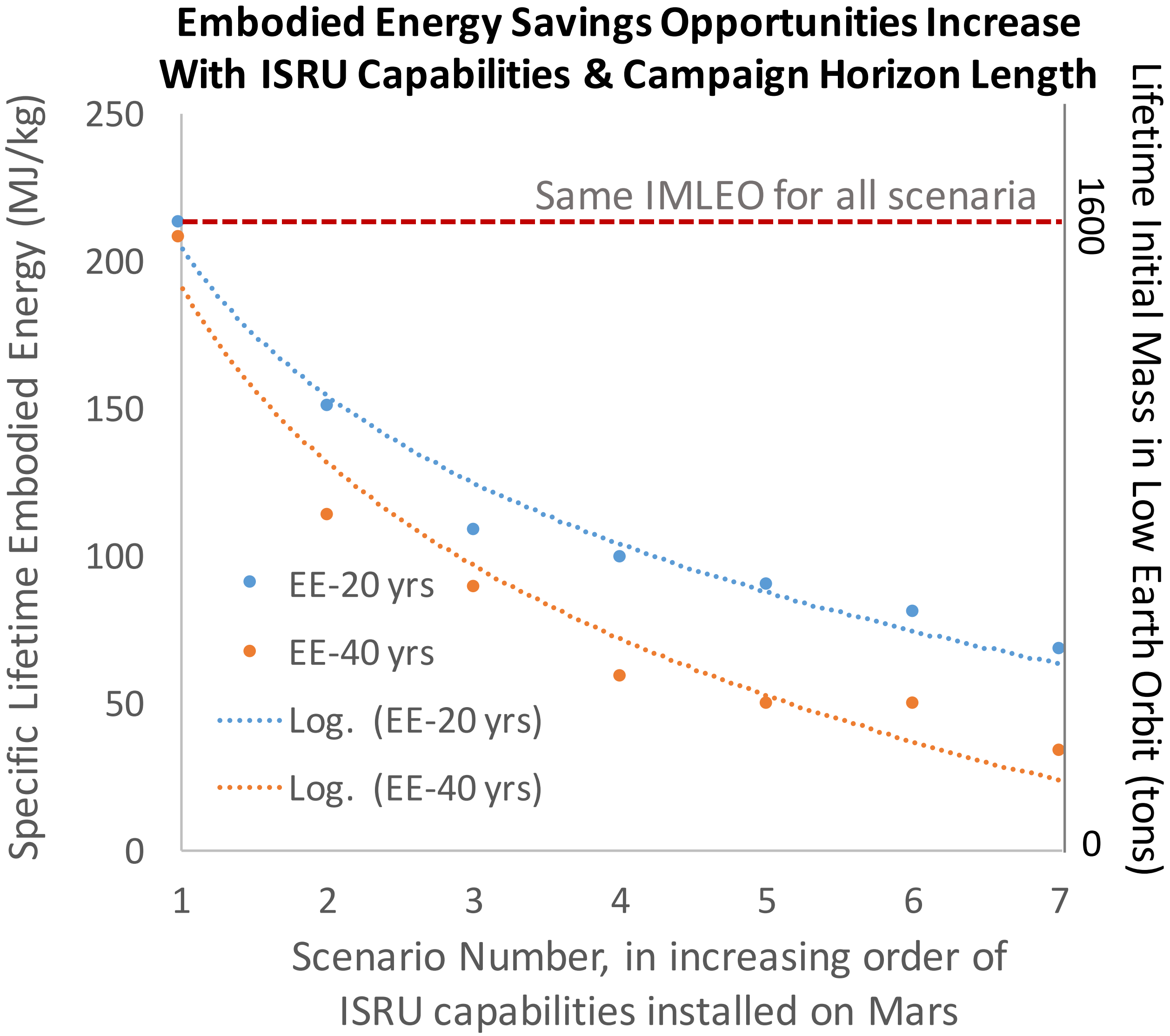
- Seven scenaria with increasing investment in a variety of modeled ISRU & industrial capabilities
- Campaign durations of 20 and 40 years
- IMLEO (classic cost metric) held constant for all scenaria

Seven campaign scenaria with *identical IMLEO cost* have significant variances in Specific Lifetime Embodied Energy (LEE/kg) cost.

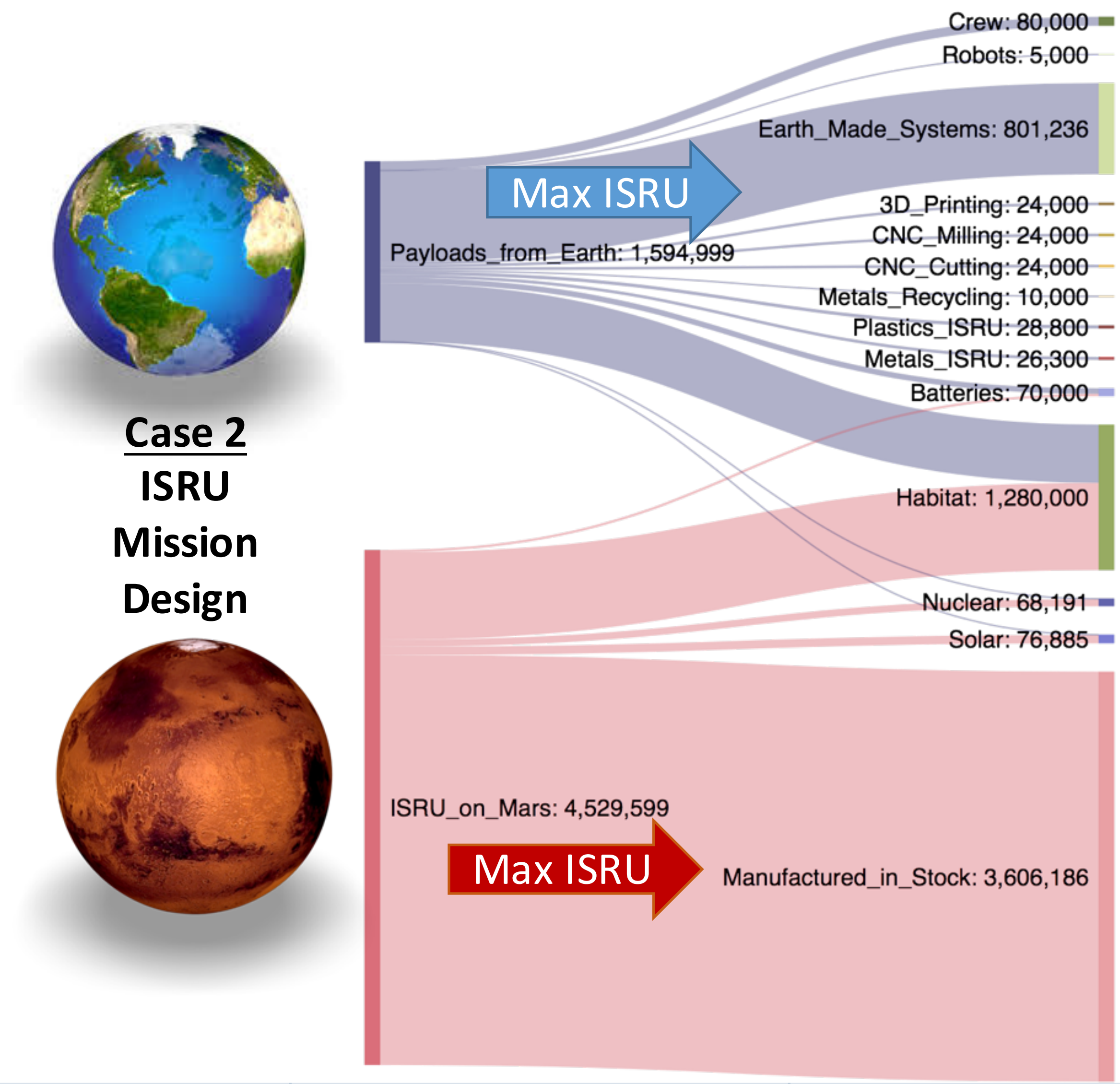
- Higher investments in Mars ISRU capabilities are associated with greater reduction in LEE/kg cost
- Longer campaign horizon (40 years vs 20 years) is associated with across the board reductions in LEE/kg cost
- A diminishing returns pattern is evident, as would be expected

<u>Seven isocost scenaria studied:</u>
<u>each has equal lifecycle IMLEO ‘cost’</u>



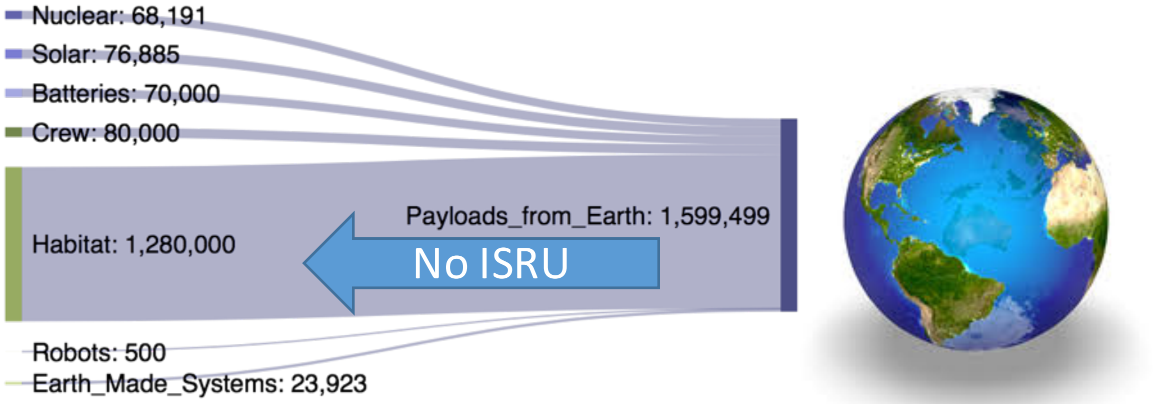


Designing surface systems for manufacturability leads to operational flexibility and enables the organic growth of habitats over time.



<u>20 Years</u>
800 tons of freed-up payload space for Earth-made Systems

<u>20 Years</u>
Same habitat mass



<u>Case 1</u>
Traditional Mission Design

<u>20 Years</u>
3600 tons of equipment manufactured on Mars

Mass flows in units of kg

What is the cost of utilizing resources? LEE facilitates trade studies of questions of value, benefit and cost in resource processing. [1], [2], [4]

Atmospheric ISRU - Mars	Questions
Scroll filter system for CO2 acquisition (Juan Agui, NASA GRC)	What will be the long-term true cost of CO_2 processing alternatives within the context of a city on Mars?
CO2 adsorption pump (Jared Berg, NASA GRC)	
Scaled-up MOXIE (Michael Hecht, MIT Haystack)	

Atmospheric & Water ISRU - Mars	Questions
Fuel production with Sabatier (Zehua Pan, CSM)	Which water processing technologies might optimally refuel spacecraft and supply other needs of a city on Mars?
Methane, Oxygen & Polyethelene (Jeff Greenblatt, Emerging Fut.)	
Poly-hydrate mining – sulfates, water (Paul Van Susante, MTU)	

Cislunar & Lunar ISRU of water, oxygen and byproducts	Questions
Lunar thermal mining (Robert Shishko, NASA JPL)	What is the net value from long term costs and benefits of alternative sets of technologies to mine water, oxygen and other byproducts from the Moon?
RASSOR for Lunar mining (Drew Smith, NASA KSC)	
Molten regolith electrolysis (Laurent Sibille, NASA KSC)	
In-space water-based fuel (Jason Aspiotis, Booz Allen)	

Note: topics sourced from meeting agenda

Lifetime Embodied Energy can be used in tradespace exploration for a system, a process or a key element of form. [1], [2], [4]

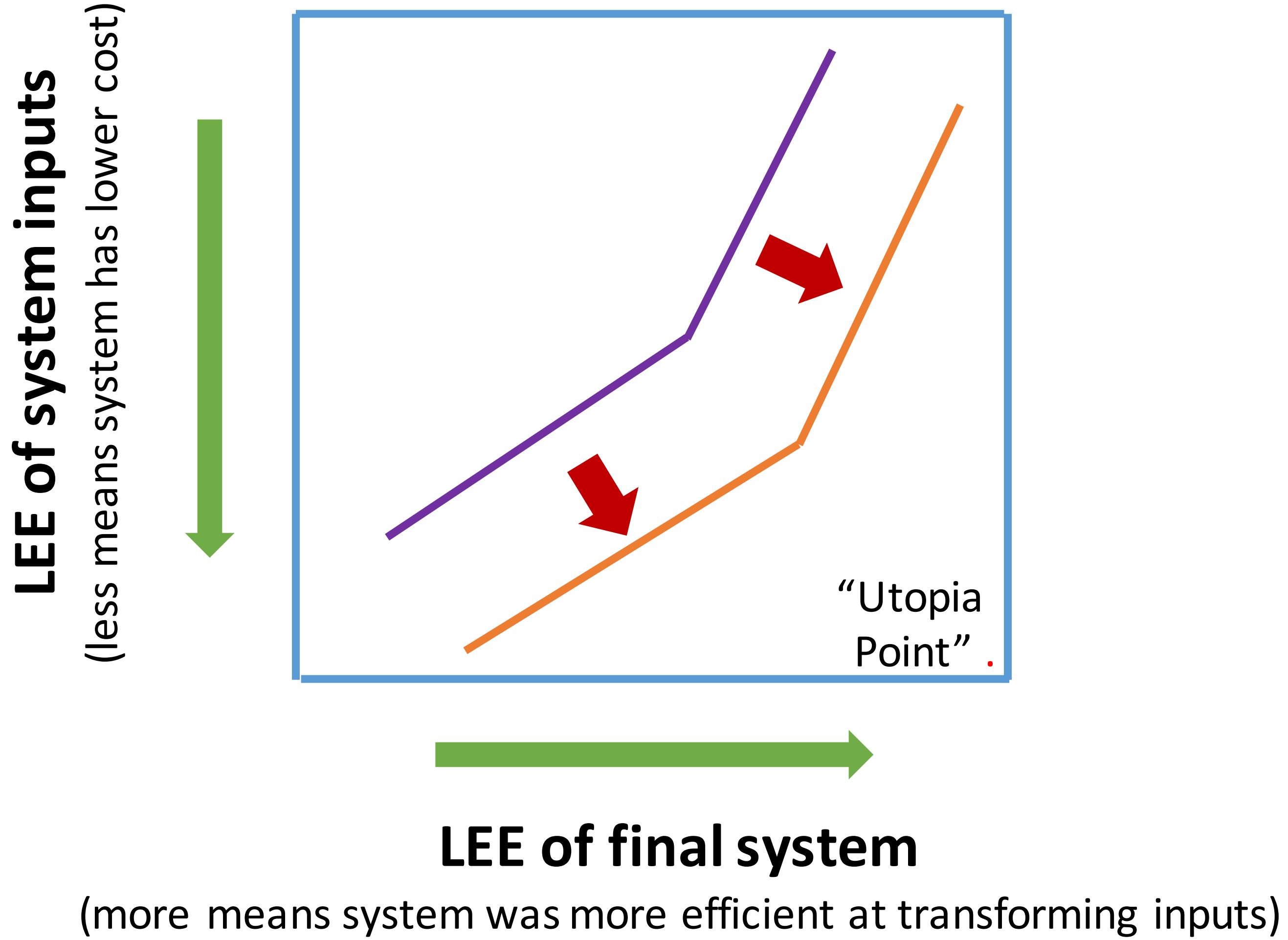
Moon Mission Architecture	Questions
Moon direct (Bob Zubrin, Pioneer Astronautics)	How much lifetime embodied energy is accumulated in Lunar infrastructure by alternative architectures?
Commercialization/settlement plan (Stanley Borowski, NASA GRC)	
Integrated robotic &human lunar exploration (David Murrow, LM)	
Robotic lunar surface operations (Brent Sherwood, NASA JPL)	

Construction on the Moon	Questions
Requirements for Lunar construction (Bob Moses, NASA LaRC)	Which ISRU construction strategies for the Moon will have the lowest impact to lifetime embodied energy cost?
ISRU system to build launch / landing pads (Elizabeth Scott, CSM)	
Moon village farm with ISRU infrastructure (Tony Muscatello,KSC)	

Mars habitats and cities	Questions
HexHab, 3D printed Mars habitat (Samuel Ximenes, Expl. Arch.)	What is the lowest-cost method for constructing 100's of Mars habitats?
K-Town, 1000 persons on Mars (Jeff Greenblatt, Emerg. Futures)	

Note: topics sourced from meeting agenda

Final takeaway: Lifetime Embodied Energy (LEE) can be used instead of dollars to account objectively for benefits and costs of space systems.



Thank you! Questions?

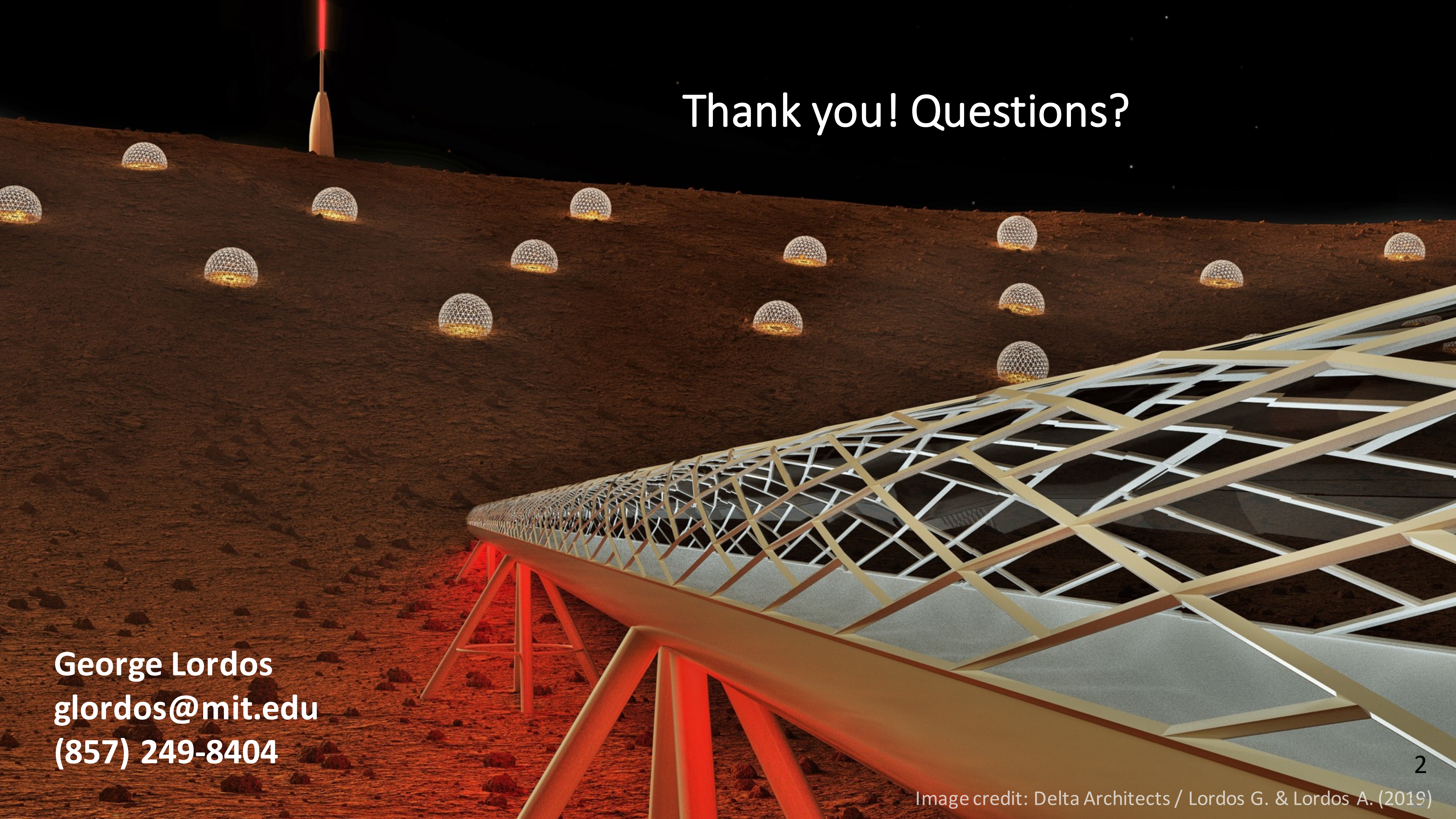


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Image credit: Delta Architects / Lordos G. & Lordos A. (2019)

References

[1] Lordos, G.C., (2018) "Towards the Sustainable Industrial Development of Mars: Comparing Novel ISRU / ISM Architectures Using Lifetime Embodied Energy", SM Thesis, Massachusetts Institite of Technology

[2] Levri, J. A., Vaccari, D. A., & Drysdale, A. E. (2000), "Theory and Application of the Equivalent System Mass Metric", 30th International Conference on Environmental Systems. Toulouse, France: ICES 2000-01-2395. https://doi.org/10.4271/2000-01-2395

[3] Ho, K., De Weck, O. L., Hoffman, J. A., & Shishko, R. (2016), "Campaign-level dynamic network modelling for spaceflight logistics for the flexible path concept", Acta Astronautica, 123, 51–61. https://doi.org/10.1016/j.actaastro.2016.03.006

[4] Odum, H. T. (1983), *Systems Ecology*, John Wiley & Sons, Inc.

Backup slides

Similarities and differences ESM - LEE

Similarities between ESM and LEE	Differences between ESM and LEE
ESM resembles an activity-based costing system	ESM still attempts to optimize mass, which in future may be decoupled from true cost
LEE also resembles an activity-based costing system	LEE optimizes work, which has a more stable and enduring coupling to true cost
ESM charges labor to subsystems by the hour	ESM uses ad-hoc 'cost leverage ratios' to incorporate benefits from ISRU
LEE also charges labor to processes by the hour	LEE can natively handle both 'business as usual', and the benefits from ISRU

More details on the 7 scenaria.

	No ISRU	2	3	4	5	6	Max ISRU
Percent Nuclear	50%	20%	0%	100%	50%	100%	50%
Percent Solar	50%	80%	100%	0%	50%	0%	50%
ISM True/False	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
ISRU True/False	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Percent Automated	5%	10%	20%	50%	80%	0%	80%
Percent Manual	95%	90%	80%	50%	20%	100%	20%
Versatility	LOW	LOW	MED	MED	MED	HIGH	HIGH
Mass Scaler	1	1	5	5	5	12	12
Productivity Scaler	1	1	0.9	0.9	0.9	0.8	0.8
Recycle	FALSE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE
Final Useable Mass	1.36E+06	1.91E+06	2.63E+06	2.90E+06	2.79E+06	4.06E+06	4.00E+06
% Useable Mass Produced In-Situ	0%	25%	52%	49%	52%	66%	67%
Final Embodied Energy of Useable Mass	212.8	150.4	108.8	99.5	89.7	80.8	68.3

Model assumptions 1 of 2 (all references refer to Lordos 2018 [1])

Assumptions	Value	Unit	Excel Name	Notes	Reference
Energy to transport 1kg of mass from Earth to Mars	205.6	MJ kg-1	MJPERKG	See Appendix I	
Energy intensity of plastics feedstock production on Mars	56	MJ kg-1	MJPLASTICS	Author estimate 10KW for 2 hours.	To be confirmed
Energy intensity of metals feedstock production on Mars	108	MJ kg-1	MJMETALS	Author estimate 30KW for 1 hour	
Energy intensity of 3D printing plastics on Mars	129.6	MJ kg-1	MJ3DPLASTIC	Author estimate 3KW for 12 hours	
Energy intensity of CNC milling metals on Mars	28.8	MJ kg-1	MJCNCMETAL	Author estimate 4KW for 2 hours	
Energy intensity of Laser cutting metals on Mars	30	MJ kg-1	MJLASER		
Energy intensity of production of consumable food	579	MJ kg-1	MJFOOD	Based on BPS system sized by S. Do 2016 (137 lights per 4 people)	Ref #4
Energy intensity of life support systems	20	MJ person-1 hour-1	MJLIFESUPPORT	See Sydney Do thesis	
Energy intensity of robotic assembly systems	18	MJ kg-1	MJROBOTS	Estimate 5KW for 1 hour	
Energy Intensity of Recycle Systems	81	MJ kg-1	MJRECYCLE	Estimate 75% of Metal Feedstock Production	

Model assumptions 2 of 2 (all references refer to Lordos 2018 [1])

Assumptions	Value	Unit	Excel Name	Notes	Reference
Logistical mass cost per human to Mars	1000	kg person-1	TRANSIT_MASS_PERSON	Including consumables in transit	Ref #1
Food consumed per person per Earth day	1.878	kg person-1 day-1	FOOD_CONS	including spoilage	Ref #2
Crew Hours Worked per person per Earth year	2087	hours person-1 year-1	HOURSPERYEAR	Working hours per year (excluding sleep, leisure)	Ref #3
Mass of habitats & ECLS per person incl spares for 20 years	80000	kg person-1	HAB_ECLSS_MASS	based on Sydney Do's Minimum Continuous Presence + BPS Case	Ref #1
Average duration of no production of solar electricity	12	hours per Sol	SOLAR_DOWNTIME_HRS	Year-round average of hours per sol with no production	Author estimate
Rocket Payload	40000	kg	PAYLOAD	based on current plans for BFS	Elon Musk, IAC 2017
# of Rocket Launches per Year	2	Launches/year	CADENCE	four launches every ~2 years = ~two launches per year	Elon Musk, IAC 2017

Model parameters 1 of 5

Parameter	Value	Unit	Excel Name	Notes
Number of crew on surface of Mars	8	persons	CREW_SIZE	persons supported by habitat.
Targeted imported Feedstock Percentage	75%	(local:total)	STOCK_IMPORT	amount of feedstock developed in-situ.
Targeted in situ mass fraction for systems "Made on Mars"	80%	(local mass:total mass)	MOM_MF	average, only for subsystems to be made on Mars. This encodes the average local mass content of all subsystems, spares etc which will be made on Mars
Fraction of crew working hours absorbed by "Made on Mars"	0%	(MoM hours:total wrkg hrs)	CREW_MOM	implicit labor productivity (output not driven by this). Changing this will change the embodied energy of habitat & crew allocated to final outputs
Min Productivity of plastic feedstock manufacturing system	200%	(output mass:system mass)	PRODPLASTICS	every year, system output = X% of system mass . Changing this will change output of raw materials, import of subassemblies & output of systems.
Min Productivity of metal feedstock manufacturing system	200%	(output mass:system mass)	PRODMETALS	every year, system output = X% of system mass . Changing this will change output of raw materials, import of subassemblies & output of systems.

Model parameters 2 of 5

Parameter	Value	Unit	Excel Name	Notes
Duration of entire campaign (=lifetime of nuclear reactor)	40	years	CAMPAIGN	A finite lifetime for the analysis. For all systems, the mass shown is cumulative lifetime mass; a 3D printer can be changed several times
Duration of mission (crew rotation every X Earth years)	4	years	CREW_ROTATION	Every X years, the crew is replaced by a new crew.
Mass of Nuclear Reactors	136382	kg	MASS_NUC	Lifetime mass, including all future spare parts. 72 Kilopower systems
Energy Output of Nuclear Reactors	0.72	MW	KILOPOWER_OUTPUT	Power output, including heat and electrical. 72 Kilopower systems
Mass Fraction of Nuclear Reactor manufacturable locally	90%	(local mass:total mass)		How much of system mass can be made with ISRU/ISM.
Mass of Water + CO2 to Plastics Resource Processing System	10000	kg	MASS_PLASTIC	Lifetime mass, including all future spare parts. Since output is linked to system mass via minimum productivity, changes here also change output
Mass Fraction of Plastics RPS manufacturable locally	0%	(local mass:total mass)		How much of system mass can be made with ISRU/ISM.

Model parameters 3 of 5

Parameter	Value	Unit	Excel Name	Notes
Mass of Regolith to Metals Resource Processing System	30000	kg	MASS_METAL	Lifetime mass, including all future spare parts. Since output is linked to system mass via minimum productivity, changes here also change output
Mass Fraction of Metals RPS manufacturable locally	0%	(local mass:total mass)		How much of system mass can be made with ISRU/ISM.
Mass of 3D Printing Manufacturing System	2000	kg	MASS_3D	Lifetime mass, including all future spare parts.
Mass Fraction of 3D Printing system manufacturable locally	0%	(local mass:total mass)		How much of system mass can be made with ISRU/ISM.
Min Productivity of 3D Priniting System	300%	(output mass:system mass)/yr		Every year, system output = X% of system mass .
Mass of CNC Milling Manufacturing System	2000	kg	MASS_CNC	Lifetime mass, including all future spare parts.
Mass Fraction of CNC Milling system manufacturable locally	0%	(local mass:total mass)		How much of system mass can be made with ISRU/ISM.
Min Productivity of CNC Milling System	300%	(output mass:system mass)/yr		Every year, system output = X% of system mass .
Mass of Robotic Assembly System	10000	kg	MASS_ROBOT	Lifetime mass, including all future spare parts.
Mass Fraction of Robotic system manufacturable locally	0%	(local mass:total mass)		How much of system mass can be made with ISRU/ISM.

Model parameters 4 of 5

Parameter	Value	Unit	Excel Name	Notes
Mass of Laser Cutting System	2000	kg	MASS_LASER	
Min Productivity of Laser Cutting System	300%			
Mass Fraction of Laser cutting system manufacturable locally	0%	(local mass:total mass)		How much of system mass can be made with ISRU/ISM.
Efficiency of 3D printing, including recycling of scrap	95%	mass_out mass_in-1	EFF3DP	out of feedstock, how much is ultimately converted to useful mass.
Efficiency of CNC milling, including recycling of scrap	95%	mass_out mass_in-1	EFFCNC	out of feedstock, how much is ultimately converted to useful mass.
Efficiency of laser cutting, including recycling of scrap	95%	mass_out mass_in-1	EFFLASER	out of feedstock, how much is ultimately converted to useful mass.
Mass of Solar Panels	153771	kg	MASS_SOLAR	Lifetime mass, including all future spare parts. Source - NASA Report. Same power as nuclear but less then half the mass
Mass of Batteries for Solar System to provide overnight cover	140000	kg	MASS_BATT	https://www.tesla.com/powerpack

Model parameters 5 of 5

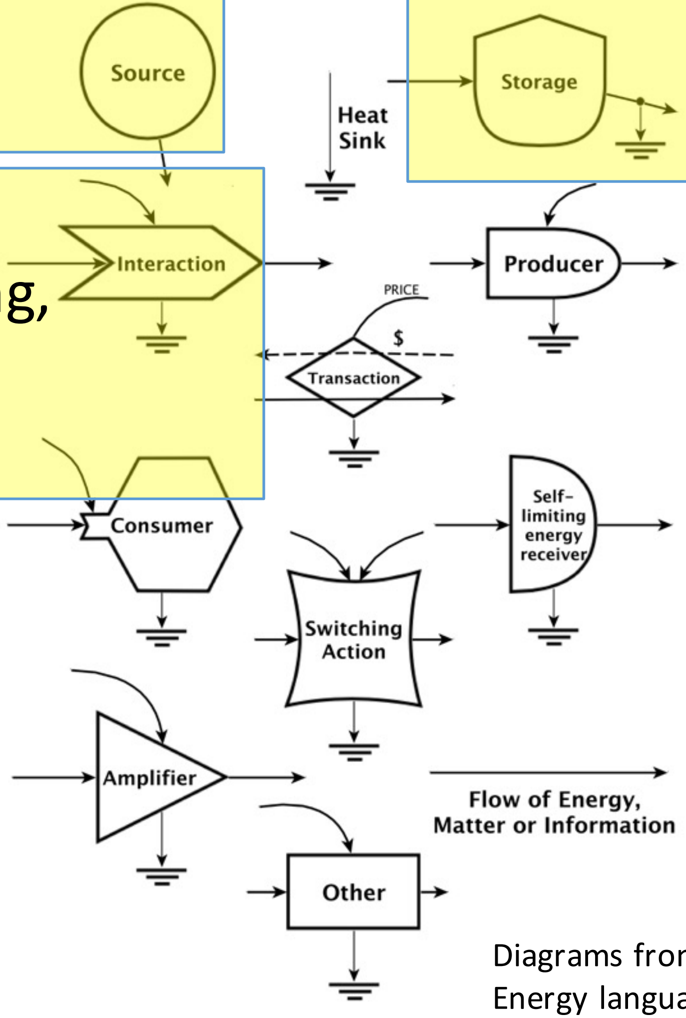
Parameter	Value	Unit	Excel Name	Notes
PEAK Energy Output of Solar Panels	1.476	MW	SOLAR_OUTPUT	Peak power output (not same as avg sustained output). System overproduces during day and charges batteries so that same output as nuclear available
Mass Fraction of Solar Panels manufacturable Locally	95%	(local mass:total mass)		How much of system mass can be made with ISRU/ISM. Linked via formula to "high versatility"
Mass Fraction of Batteries manufacturable Locally	30%	(local mass:total mass)		How much of system mass can be made with ISRU/ISM.
Mass of Recycle System	10000	kg	MASS_RECYCLE	System mass of recycling system
Min Productivity of Recycle System	50%	(output mass:system mass)	PRODRECYCLE	every year, system output = X% of system mass . Changing this will change output of raw materials, import of subassemblies & output of systems.

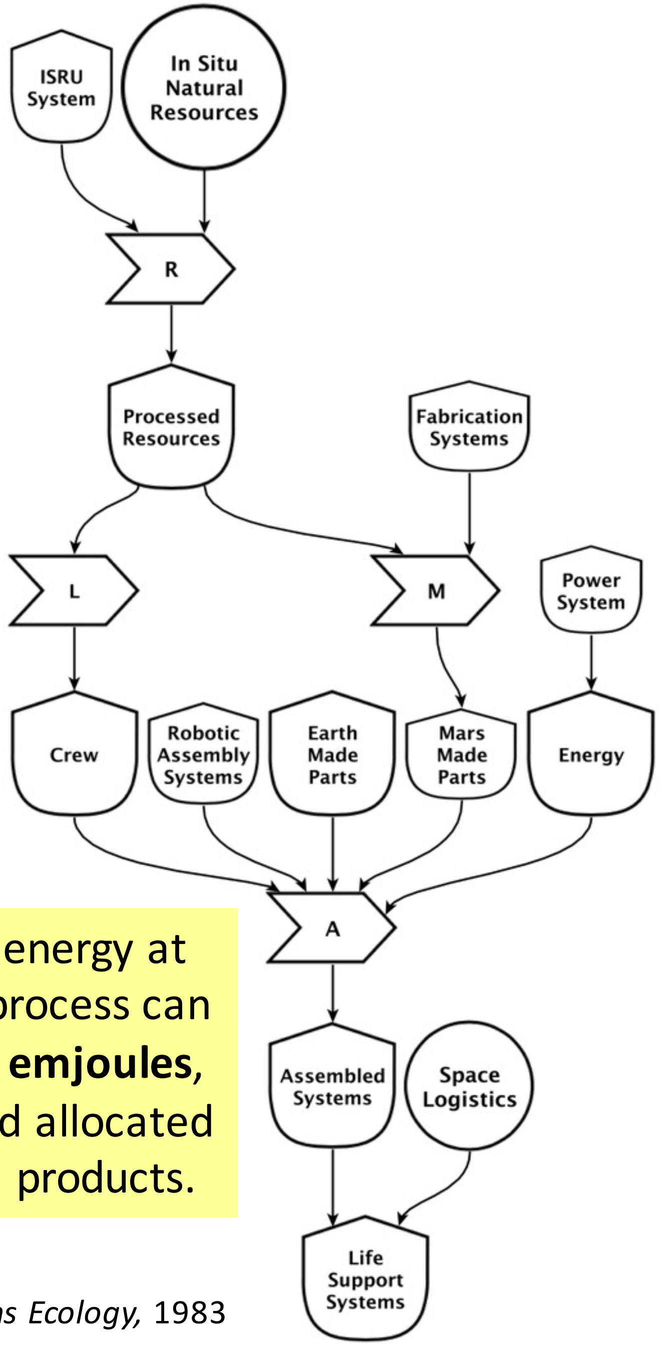
Example of flow of embodied energy through a system.

<u>Sources:</u> e.g.
In-situ natural resources on Mars

<u>Storages:</u> e.g.
Quantity of Life Support Systems

<u>Interactions:</u> e.g.
Resource processing, manufacturing, assembly.





The embodied energy at every step of a process can be measured in **emjoules**, flowed down and allocated among the final products.

Diagrams from SM thesis (Lordos, 2018)
Energy language symbols by Howard Odum, *Systems Ecology,* 1983

What is the Lifetime Embodied Energy cost of establishing a nearly self-sustaining farm?

Extra growth: trade surplus food for fertilizer

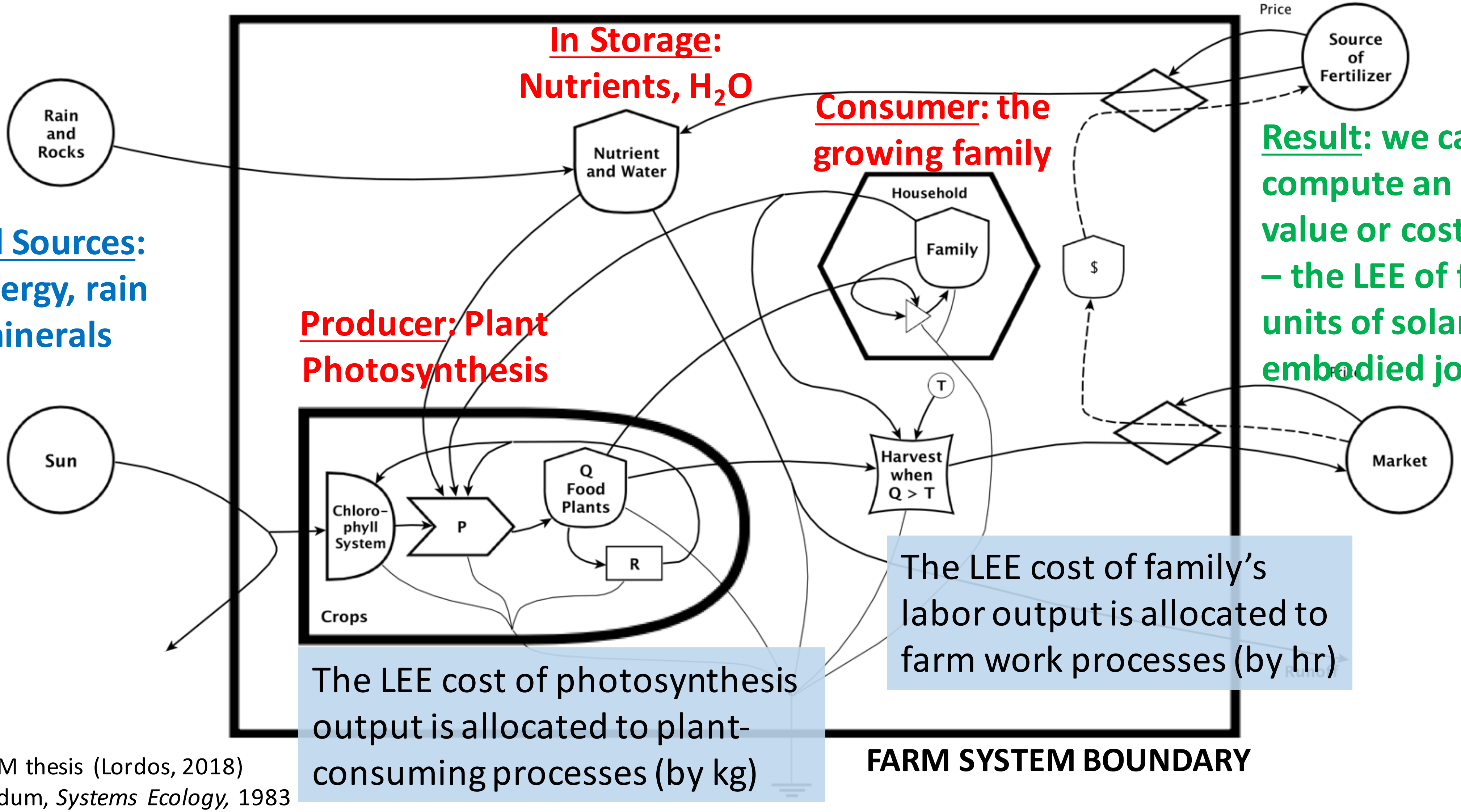
In Storage: Nutrients, H_2O

Consumer: the growing family

External Sources: Solar energy, rain and minerals

Producer: Plant Photosynthesis

Result: we can compute an objective value or cost for food – the LEE of food - in units of solar embodied joules (sej)



The LEE cost of family's labor output is allocated to farm work processes (by hr)

The LEE cost of photosynthesis output is allocated to plant-consuming processes (by kg)

Diagram from SM thesis (Lordos, 2018) after Howard Odum, *Systems Ecology*, 1983

The choice of primary energy source and system boundary are the two most critical decisions in the application of this method.

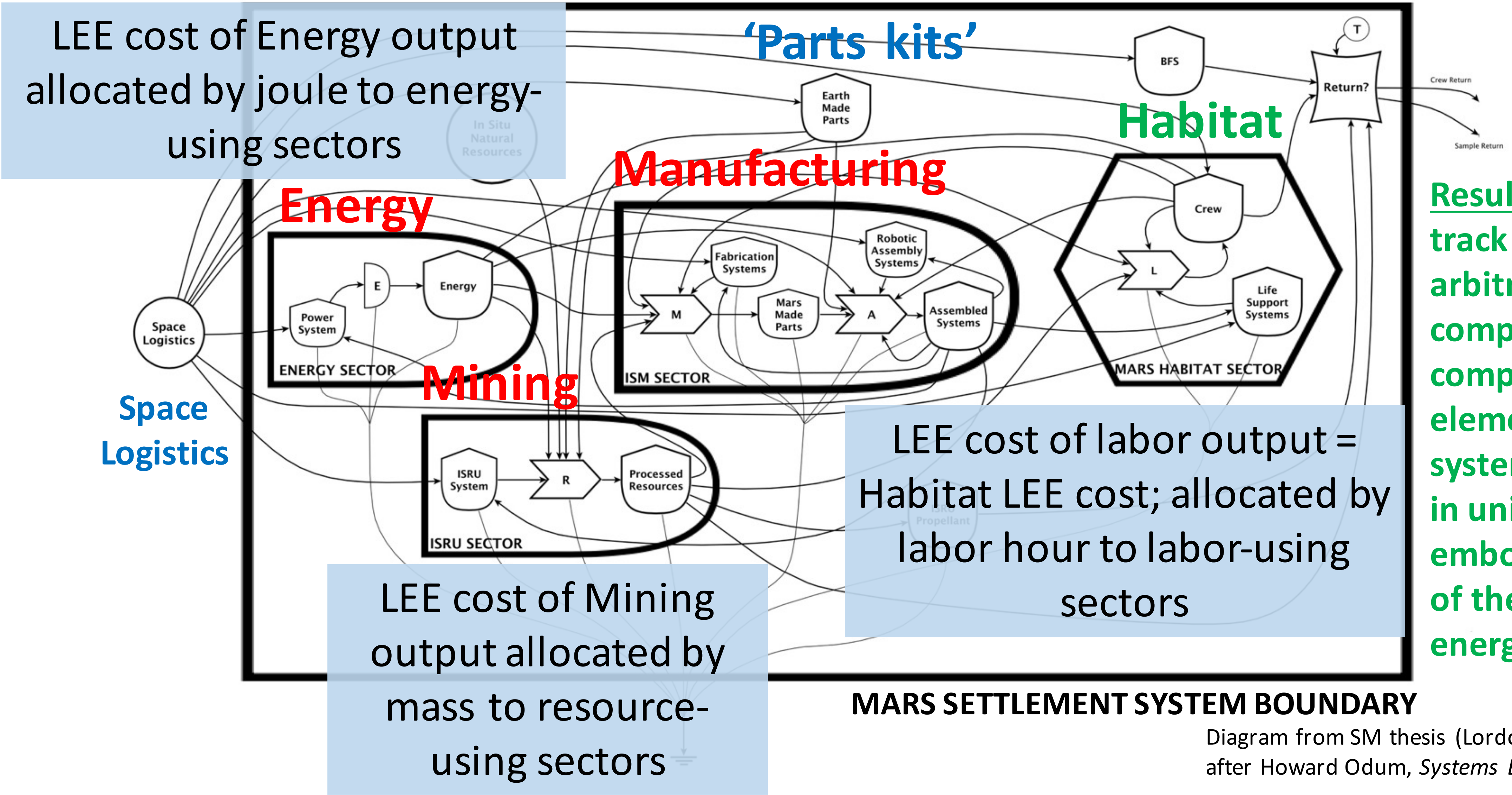


Diagram from SM thesis (Lordos, 2018)
after Howard Odum, *Systems Ecology*, 1983

Result: we can track flows to arbitrary levels of complexity and compute cost of elements within system boundary in units of embodied joules of the primary energy source

This relationship between mass and space mission cost is anchored in the one-off nature* typical of most past space missions.

Launch mass, ***M***, has been an excellent proxy for total cost, ***C***

$$\boldsymbol{C = f(M) + D}$$

C	True economic cost of mission
M	Launched mass (e.g. IMLEO, ESM)
D	Development costs (e.g. NRE)

$$\boldsymbol{D = f(M)}$$

Why was mass a good proxy for cost? 1958 – 2018

Single-use boosters and stages

One-off designs (hard to compare)

No surface asset accumulation

All payloads originated from Earth

** The extensive refurbishments required by the Space Shuttle meant that it did not depart materially from this paradigm*

IMLEO: Initial Mass in Low Earth Orbit   NRE: Non-Recurring Engineering cost   ESM: Equivalent System Mass

More details on why we need a new value system for space.

Problem: current architectures for ISS, Moon, and Mars are ***not*** on a path for sustainability.

(1) The settlement's inhabitants shall be 'living off the land'.

- **More** compatible design elements
  - **ISRU** of metals, silicates, plastics
  - **Manufacturable** ECLSS and habitats
  - **Labor-saving** technologies
  - **Efficiency** in material and energy use

- **Less** compatible design elements
  - **Overly costly** resource logistical plan
  - **Prefabricated** ECLSS, habitats from Earth
  - Over-reliance on **scarce** human labor
  - Processes that **don't scale** efficiently

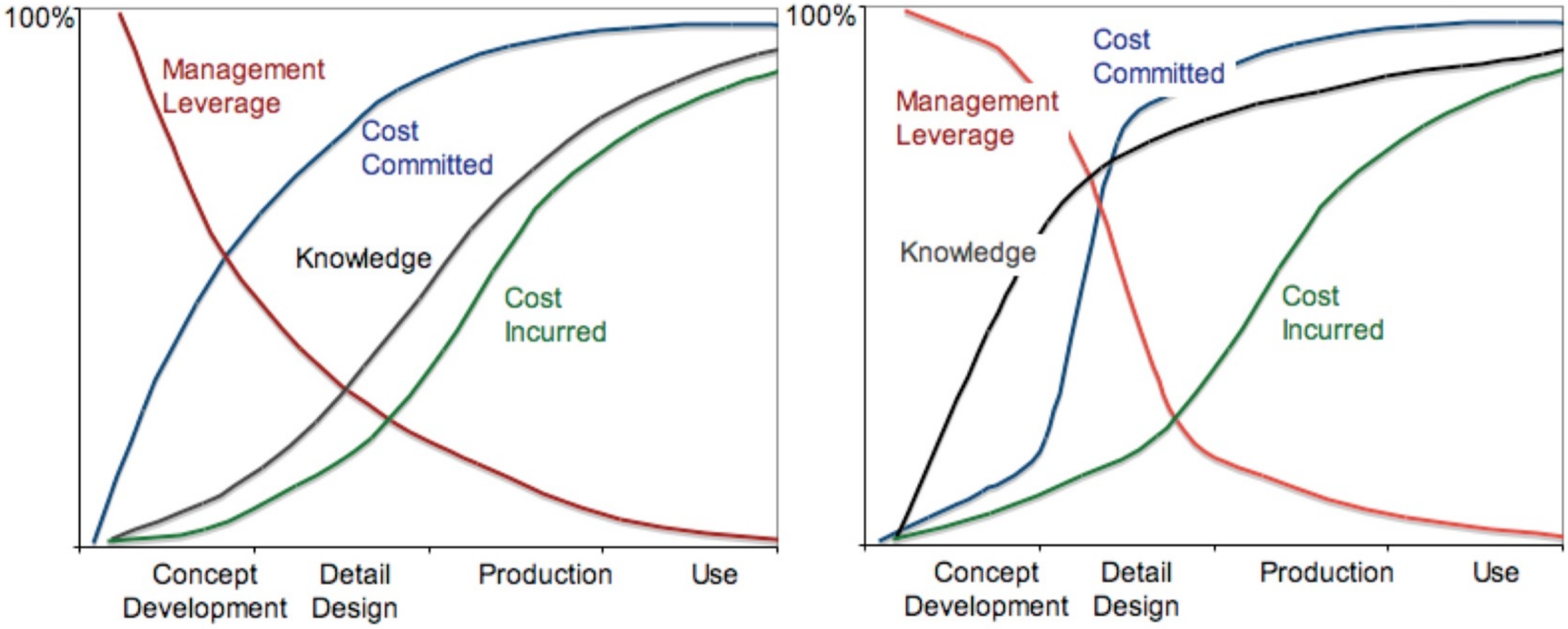
(2) The settlement shall be designed to be resilient to external disturbances.

- **More** compatible design elements
  - Focus on robust **function**, not robust form
  - Focus on **capabilities**, not on solutions
  - Large missions (**many** identical teams)

- **Less** compatible design elements
  - **Over-engineered** system form, hard to adapt
  - Unhealthy reliance on **spare parts** from Earth
  - Small missions (**one** team)

ISRU: In-situ Resource Utilization ECLSS: Environmental Control & Life Support Systems ISS: International Space Station

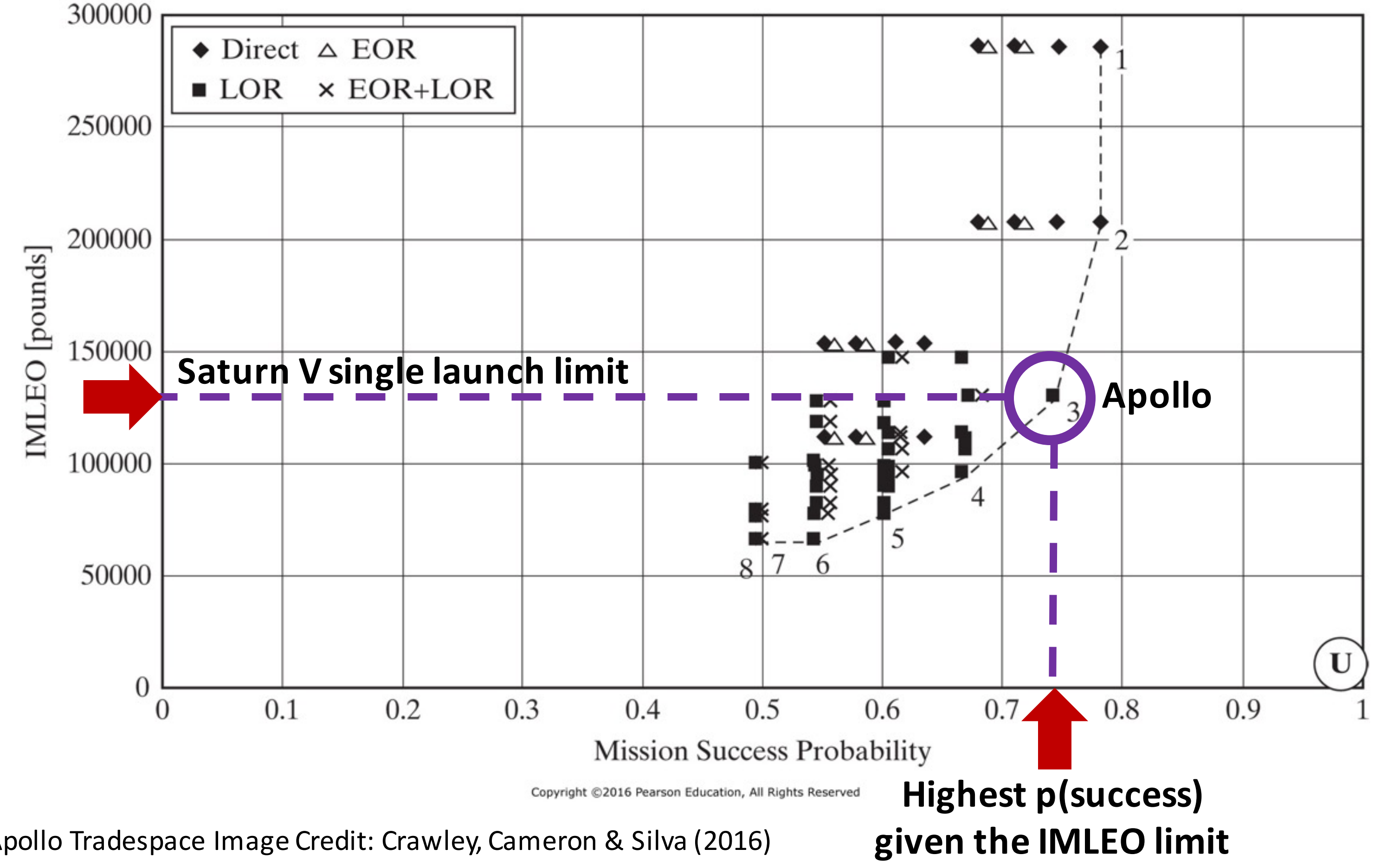
Tradespace exploration, undertaken during concept development when leverage is at a maximum, improves cost-benefit outcomes.



Traditional (left) versus more recent (right) distributions of resources during a system development lifecycle (Figure credit: Benjamin A. Corbin, MIT Doctoral thesis, 2015)

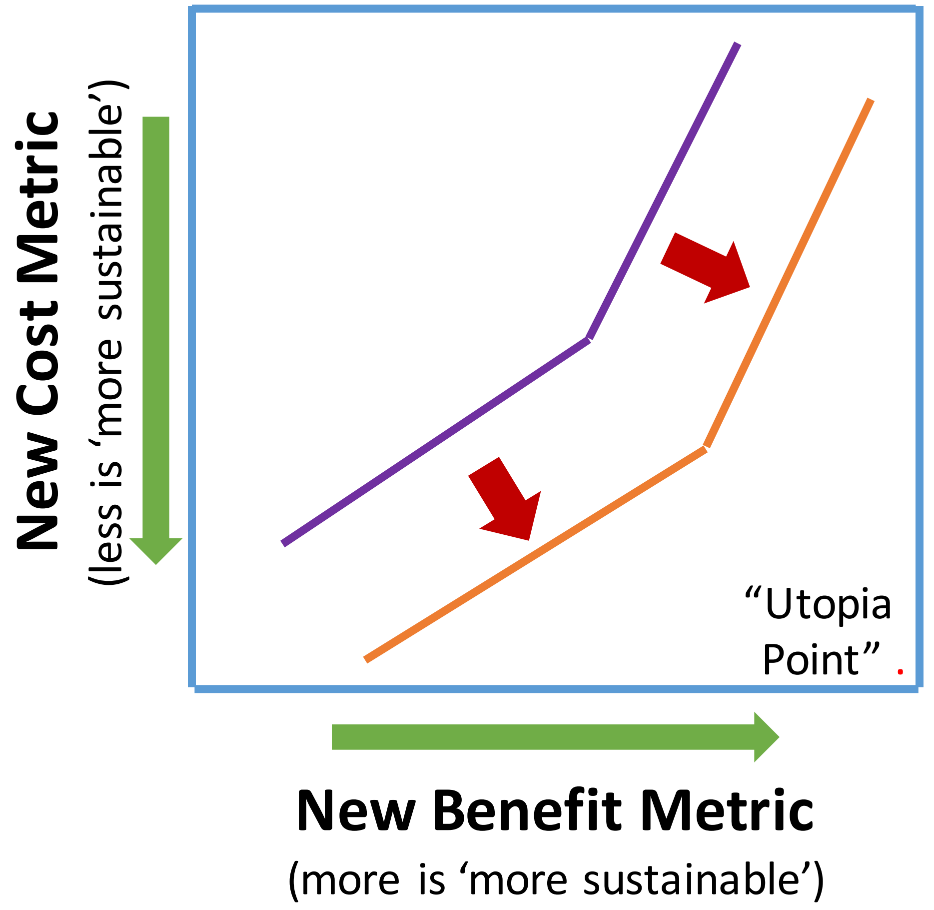
We will need new metrics for tradespace exploration.

The Apollo Lunar Orbit Rendezvous Decision
IMLEO vs Mission Success Probability



Apollo Tradespace Image Credit: Crawley, Cameron & Silva (2016)

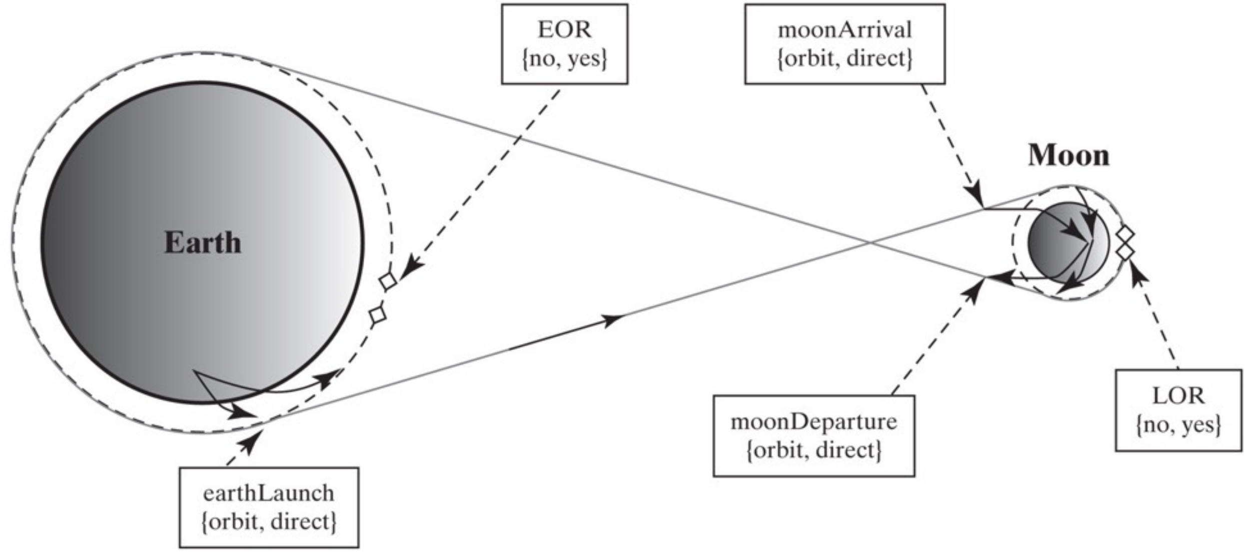
Paradigm shift: align metrics with the sustainability imperative



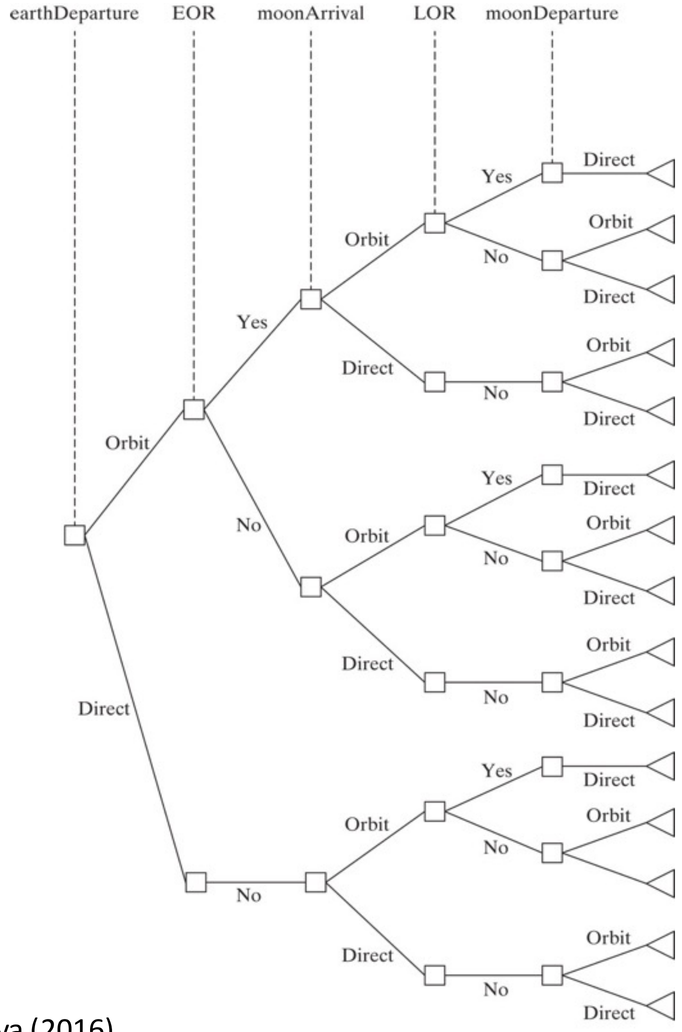
To create the Apollo tradespace plot we saw earlier, we start by generating and modeling *all* feasible architectures.

Morphological Matrix

shortID	Decision	units	alt A	alt B	alt C	alt D
EOR	Earth Orbit Rendezvous	none	no	yes		
earthLaunch	Earth Launch Type	none	orbit	direct		
LOR	Lunar Orbit Rendezvous	none	no	yes		
moonArrival	Arrival At Moon	none	orbit	direct		
moonDeparture	Departure From Moon	none	orbit	direct		
cmCrew	Command Module Crew	people	2	3		
lmCrew	Lunar Module Crew	people	0	1	2	3
smFuel	Service Module Fuel	none	cryogenic	storable		
lmFuel	Lunar Module Fuel	none	NA	cryogenic	storable	



Decision Tree



All Images Credit: Crawley, Cameron & Silva (2016)