National Aeronautics and Space Administration

Benefits of Mars ISRU Regolith Water Processing: A case study for the NASA Evolvable Mars Campaign

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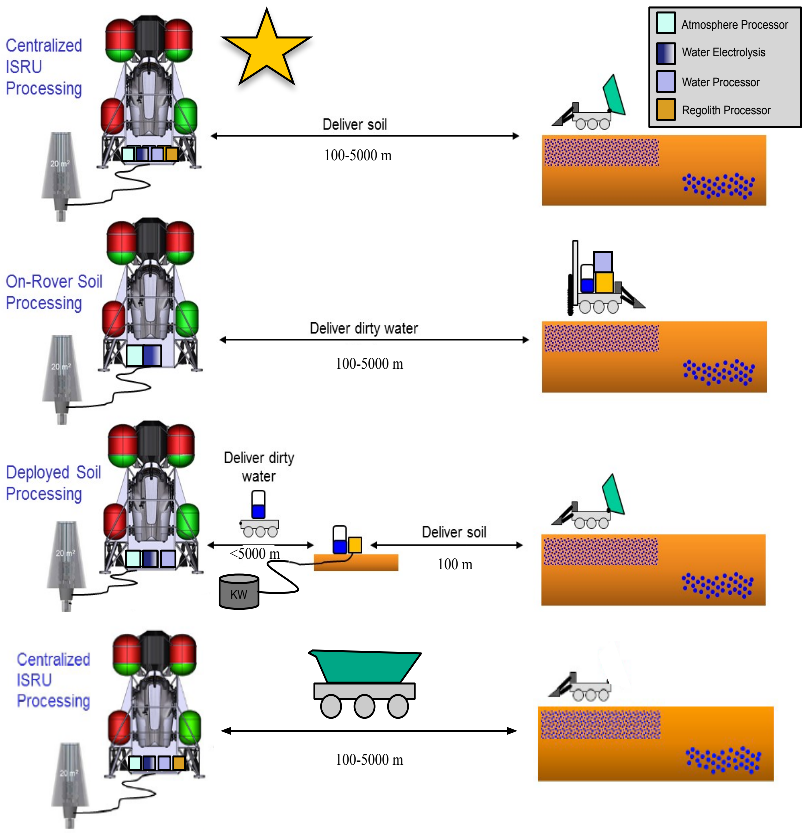
Motivation

- **ISRU of Mars resources was baselined in 2009 Design Reference Architecture (DRA) 5.0, but only for Oxygen production using atmospheric CO_2**
  - The Methane (LCH_4) needed for ascent propulsion of the Mars Ascent Vehicle (MAV) would need to be brought from Earth
- **HOWEVER: Extracting water from the Martian Regolith enables the production of both Oxygen and Methane from Mars resources**
  - Water resources could also be used for other applications including: Life support, radiation shielding, plant growth, etc
  - Water extraction was not baselined in DRA5.0 due to perceived difficulties and complexity in processing regolith
- **The NASA Evolvable Mars Campaign (EMC) requested studies to look at the quantitative benefits and trades of using Mars water ISRU**
  - Phase 1: Examined architecture scenarios for regolith water retrieval. Completed October 2015
  - Phase 2: Deep dive of one architecture concept to look at end-to-end system size, mass, power of a LCH_4/LO_2 ISRU production system

Approach

- **Water bearing regolith is retrieved using a mobile excavator and delivered to a centralized ISRU processing plant.**
- **ISRU processing plant is co-located with the Lander and MAV.**
- **Use current EMC projections to define ISRU production needs**
- **Generate a system model to roll up mass & power of a full ISRU system and enable parametric trade studies.**
  - Use previous studies and technology development programs to select baseline subsystems/components for this study
  - Use existing hardware with mass/power/ performance to provide a basis for subsystem level trades in future studies
  - Whenever possible used reference-able (published) numbers for traceability, as opposed to 'real-time' working numbers.



Top level production requirements

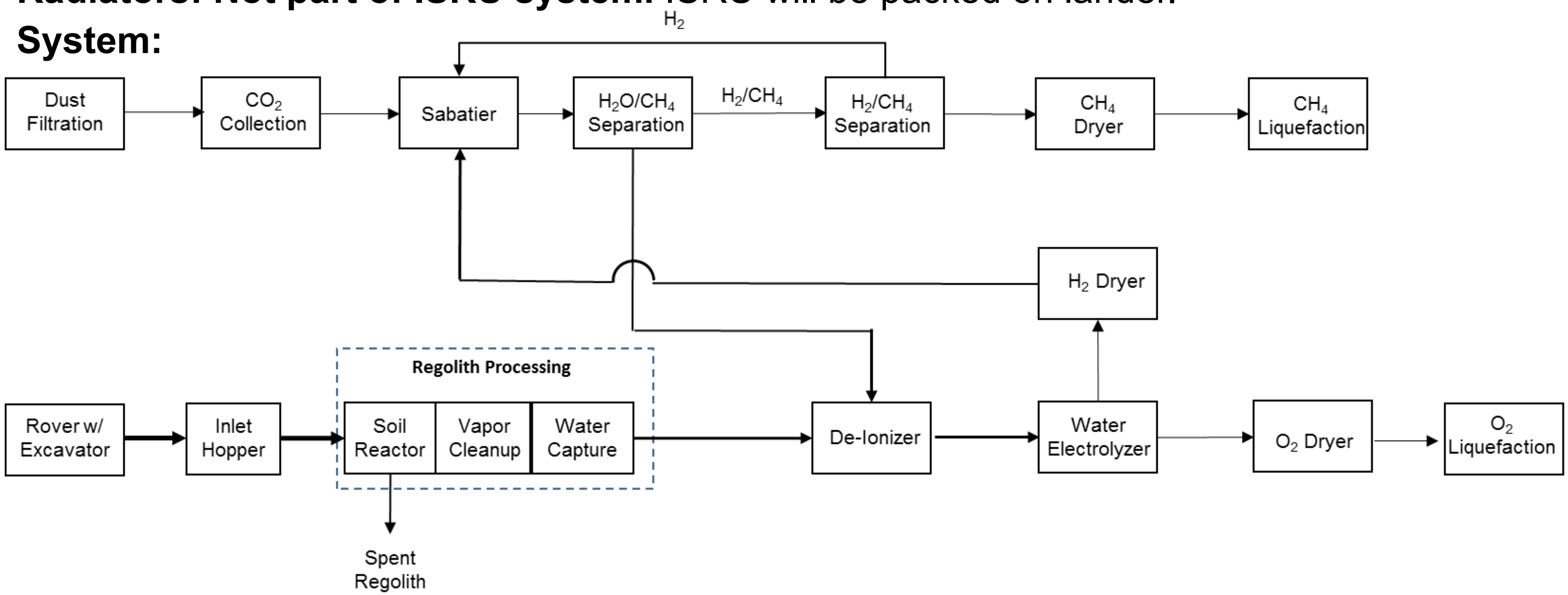
- **Propellant mass needs taken from most recently published MAV study:**
  - Polsgrove, T. et al. (2015), AIAA2015-4416
- **MAV engines operate at mixture ratios (oxygen:methane) between 3:1 and 3.5:1, whereas the Sabatier reactor produces at a 4:1 ratio. Therefore:**
  - **Methane production is the driving requirement**
  - **Excess Oxygen will be produced**
- **Production rate based on a mission timeline of 480 days (16 months)**
  - ISRU system arrives one launch opportunity ahead of humans
  - MAV must be fully fueled before human departure from earth

26 month launch opportunity
– 9 month transit time
– 1 month margin
16 months

		Total mass needed	Rate at 480days continuous operation
Requirement:	CH_4	6978 kg	0.61 kg/hr
Reactants needed to meet requirement:	H_2O	15701 kg (785,050 kg 2% soil)	1.36 kg/hr (68.2 kg/hr soil@2%)
	CO_2	19190 kg	1.67 kg/hr
Results in:	O_2	27912 kg total (22728 kg propellant, 1906 kg Life support, 3278 kg leftover)	2.43 kg/hr

Assumptions

- **Production Rate driver: 6978 kg of Methane needed + 0.5% margin**
  - Methane is the driver since excess oxygen will be produced using Sabatier process
- **Time of ISRU production: 480 day operation, 24hr/day**
- **Soil Water resource (baseline): Water from surface regolith = hydrates** Ubiquitous (location independent), Available in surface material (subsurface excavation not required), Lower resource yield is more of a worse case for water extraction system
- **Liquefaction: Takes place in the MAV tanks.** ISRU system only includes mass/power for crycoolers needed to liquefy. MAV responsible for tanks and zero boil-off systems
- **Power Source: Not part of ISRU system.** Assumes a fission reactor will be needed for human presence, ISRU will use reactor when humans are not present. (TBD- negotiations to occur as power needs are identified)
- **Radiators: Not part of ISRU system.** ISRU will be packed on lander.
- **System:**



Subsystem Selection for this study

Subsystem	Components	Heritage
Excavation	RASSOR 2.0 excavator concept prototype	KSC hardware (2015 Phase 1)
Soil Processing	Size Sorter / Auger Conveyor reactor	JSC design concept (2015 Phase)
	Soil hopper/Size Sorter prototype	KSC hardware –sized & tested
	Vapor cleanup	Nafion, COTS
	Water collection: Coldtrap	JSC design concept
CO2 Acquisition	Cryocooler	Cryotel GT, COTS, KSC cold head
Sabatier	Microchannel Sabatier	Battelle PNNL (SRP study)
	CH4/H2O separator	-sized-
	CH4/H2 separator	Hamilton Sunstrand (MIST)
Electrolysis	PEM electrolysis stack, Cathode feed	Giner Inc., COTS (HESTIA)
	Deionizer	GE, COTS
	H2/H2O separator	-sized-
	Inlet pump	Micropump, COTS
	Regenerative Gas drier, desiccant	JSC hardware
Liquefaction	Cryocooler	Cryotel GT, COTS
	~~Tanks~~	~~-sized-~~

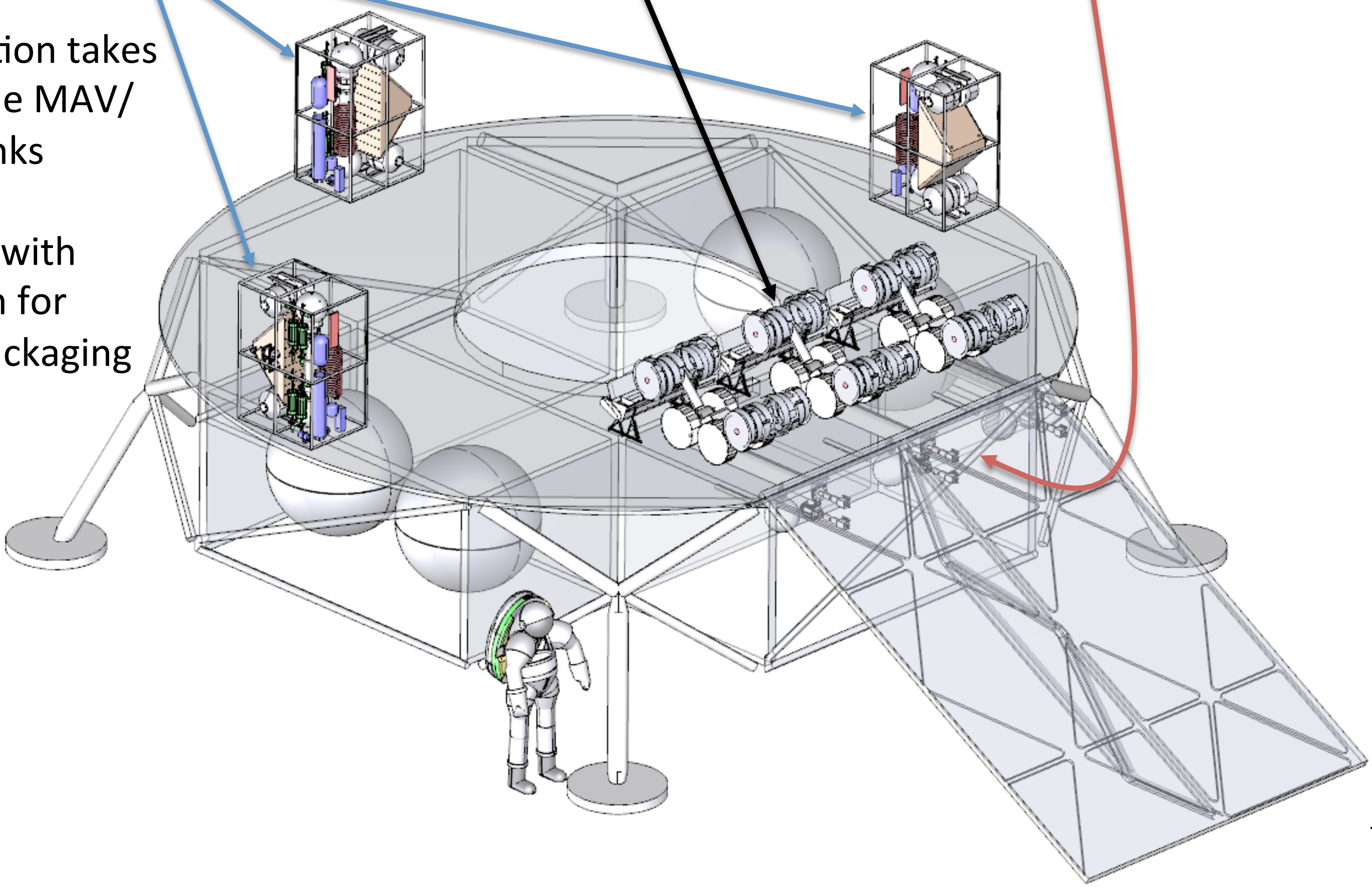
Sizing: LO_2 and LCH_4 ISRU System

Approach: Production requirement met by 3 independent ISRU systems including:

3 Propellant production (atmosphere processing/water electrolysis) modules	3 mobile RASSOR excavators	3 regolith processing (water production) modules

*Liquefaction takes place in the MAV/ Lander tanks

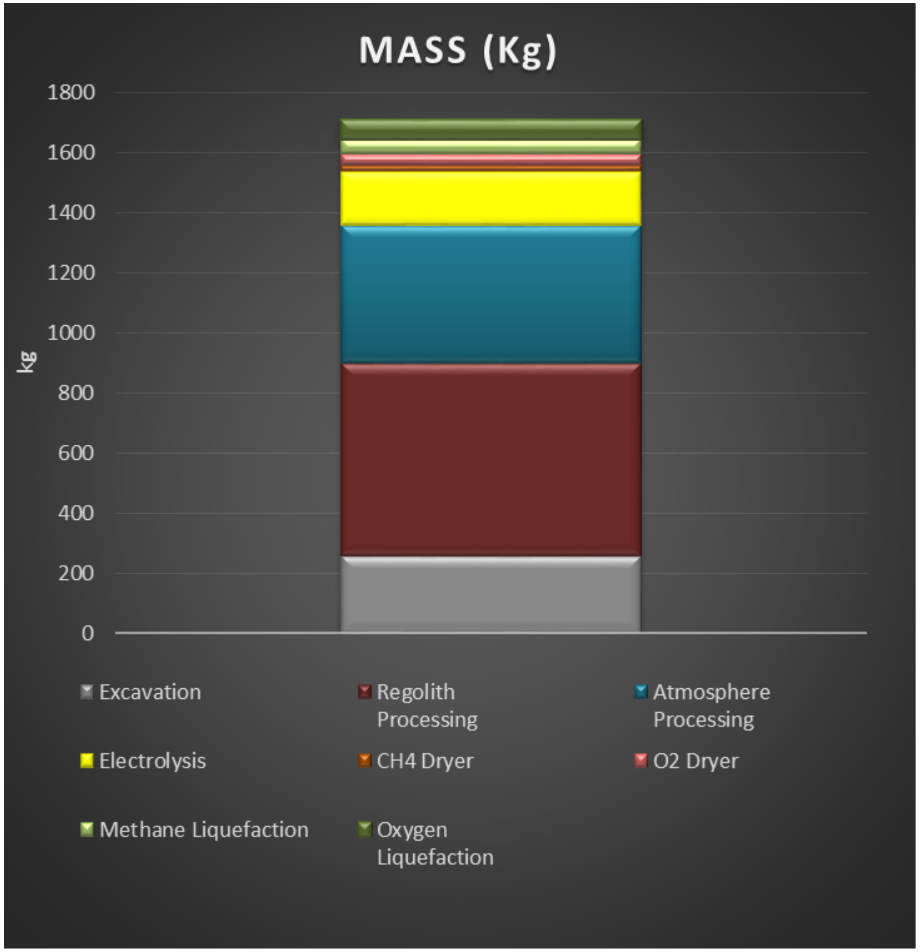
*Working with MAV team for current packaging

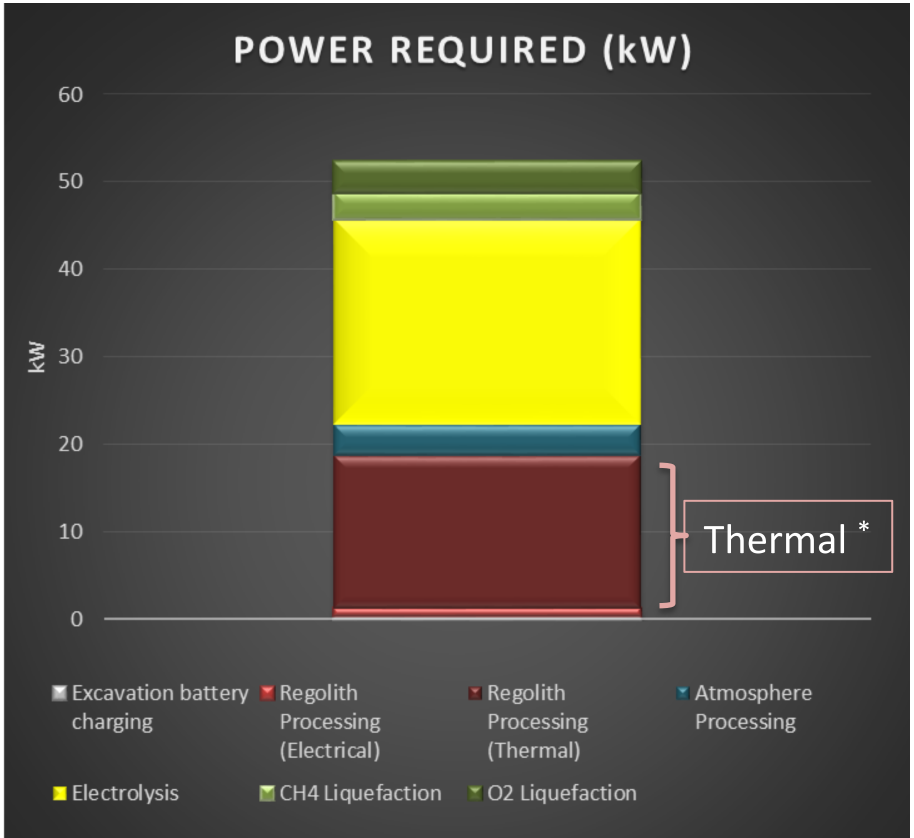


Total ISRU system (3 modules)

Baseline case, Assumptions:

3 independent ISRU systems each producing 40% of the needed products, 15% mass added for structure, 20% margin added to power and mass, Garden variety (common globally on Mars surface) regolith with 1.26wt% water processed at 300C





* Large thermal energy requirement may create an opportunity to link with FSP for heat recuperation

Total Mass: 1708 kg

Total Power: 52 kW

Regolith needs for Baseline case

	Total needed for mission		Amount needed **per module** (assuming 3 independent modules)		Amount needed **per module per day**		Delivery capabilities **per Rassor per day*** (using baseline assumptions)
Mass of Regolith	1500 MT	→	500 MT	→	1.04 MT	compare	2.3 MT
# of Rassor batches	14797 batches		4932 batches		11 batches		23 batches

Using the current assumptions 1 Rassor excavator per module is more than sufficient to meet production needs.

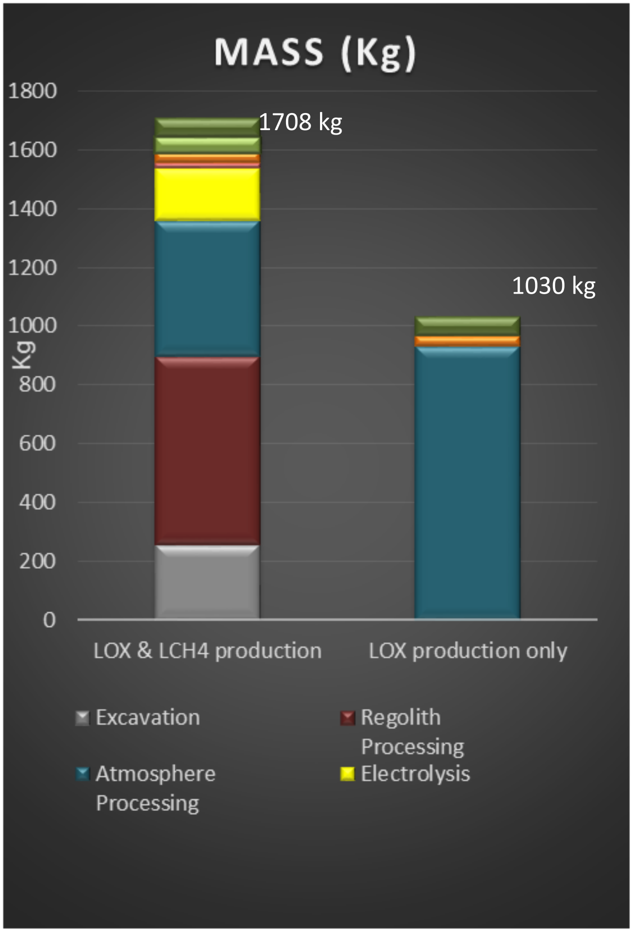
(If assumptions are changed, the system model is designed to adjust the number of excavators needed and this would be reflected in mass/power)

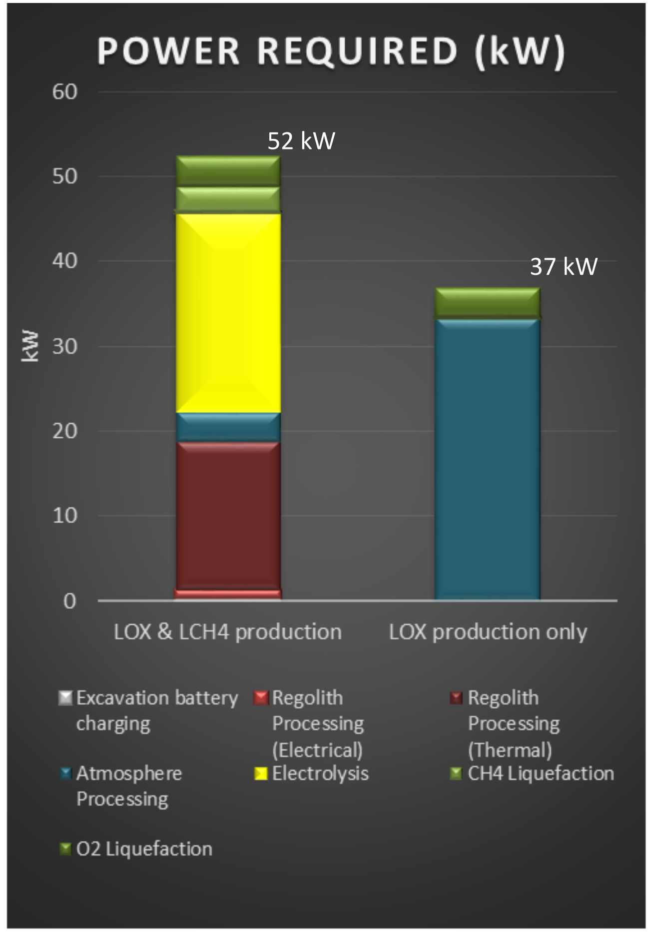
*Assumptions:

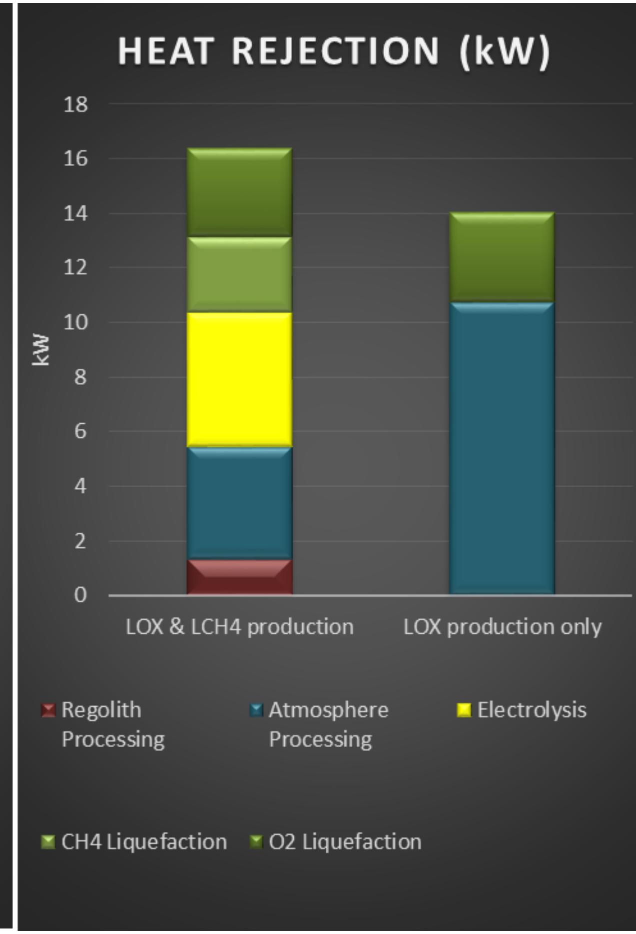
- Conops: 5 hrs = 5 batches + battery recharge (Assuming the resource is 100m away, the rover travels at 0.26 m/s, and excavation time from laboratory tests.)
- Each Rassor batch delivers 9.7% of the needed regolith per day per module. (Based on volumetric capacity of Rassor bucket and regolith bulk density of 1.9g/cc as suggested by MWIP team, Rassor can delivery 100kg per batch)

Comparison to Oxygen-Only ISRU plant

- **Assumptions: 3 independent ISRU systems each producing 40% of the needed products, 15% mass added for structure, 20% margin added to power and mass.**
- O_2-only system assumes a cryofreezer for CO2 extraction and Solid Oxide Electrolysis for conversion







66% higher mass

42% higher power

17% more waste heat

M-WIP - Definition of Reference Reserve Cases

Essential Attribute	Deposit Type: A. Ice	B. Poly-hydrated Sulfate	C. Clay	D. Typical Regolith (Gale)
Depth to top of deposit (stripping ratio)	3 m	0 m	0 m	0 m
geometry, size	bulk	bulk	bulk	bulk
Mechanical character of overburdern	sand	NA	NA	NA
Concentration and state of water-bearing phase within the minable volume				
–Phase 1	90% ice	40% gypsum[1]	40% smectite[2]	23.5% basaltic glass[3]
–Phase 2	--	3.0% allophane[4]	3.0% allophane[4]	3.0% allophane[4]
–Phase 3	--	3.0% akaganeite[5]	3.0% akaganeite[5]	3.0% akaganeite[5]
–Phase 4	--	3.0% smectite[2]	3.0% akaganeite[5]	3.0% bassanite[6]
–Phase 5	--	--	--	3.0% smectite[2]
Geotechnical properties				
–large-scale properties ("minability"), e.g. competence, hardness	competent--hard	sand--easy	sand--easy	sand--easy
–fine-scale properties ("processability") , e.g. competence, mineralogy	no crushing needed	no crushing needed	no crushing needed	no crushing needed
The nature and scale of heterogeneity	variation in impurities	±30% in concentration	±30% in concentration	±30% in concentration

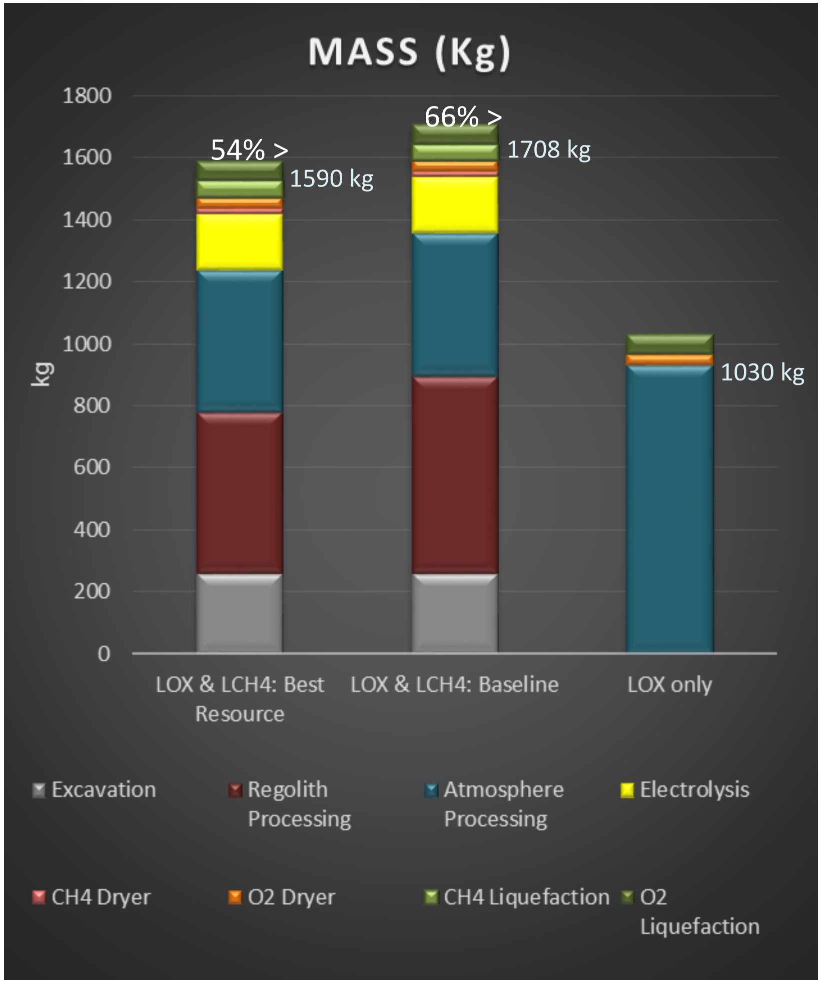
1. ~20 wt% water, 100-150°C
2. ~4 wt% water, 300°C
3. ~1 wt% water, >500°C
4. ~20 wt% water, 90°C
5. ~12 wt% water, 250°C
6. ~6 wt% water, 150°C

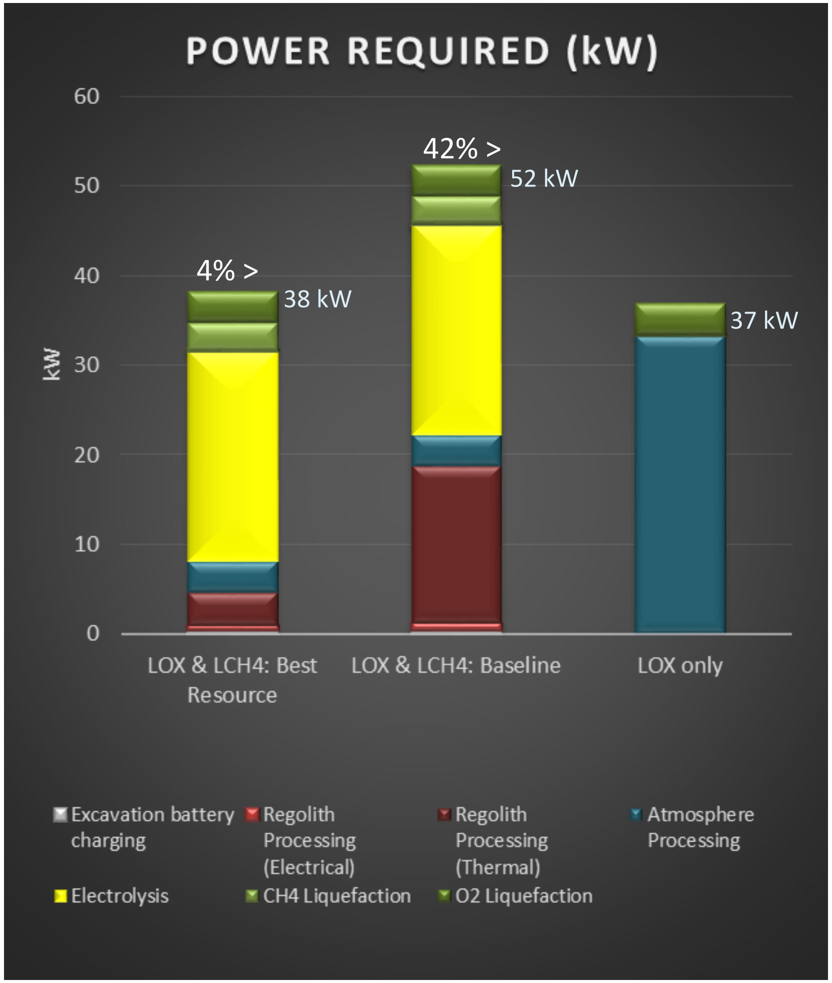
The M-WIP (Mars Water ISRU Planning) study is lead by SMD/Mars Program office and involves academy and industry members. The ISRU team has been working closely with these team to identify impacts of Mars resources and their location, and the data still needed to best define them.

- The MWIP team report is projected for released March 31,2016
- Information from the MWIP team has been incorporated into this study and visa/versa
- Other information from the MWIP team that will be leveraged for future work includes
  Distance of resource versus excavation efficiency and Depth of resource versus overburden removal (trade)
- This slide shows the reference case resource possibilities. Case D was baselined in this Lox/LCH4 study. The following trades show the impact of Case B (best case granular deposit)

Trade: higher yield regolith

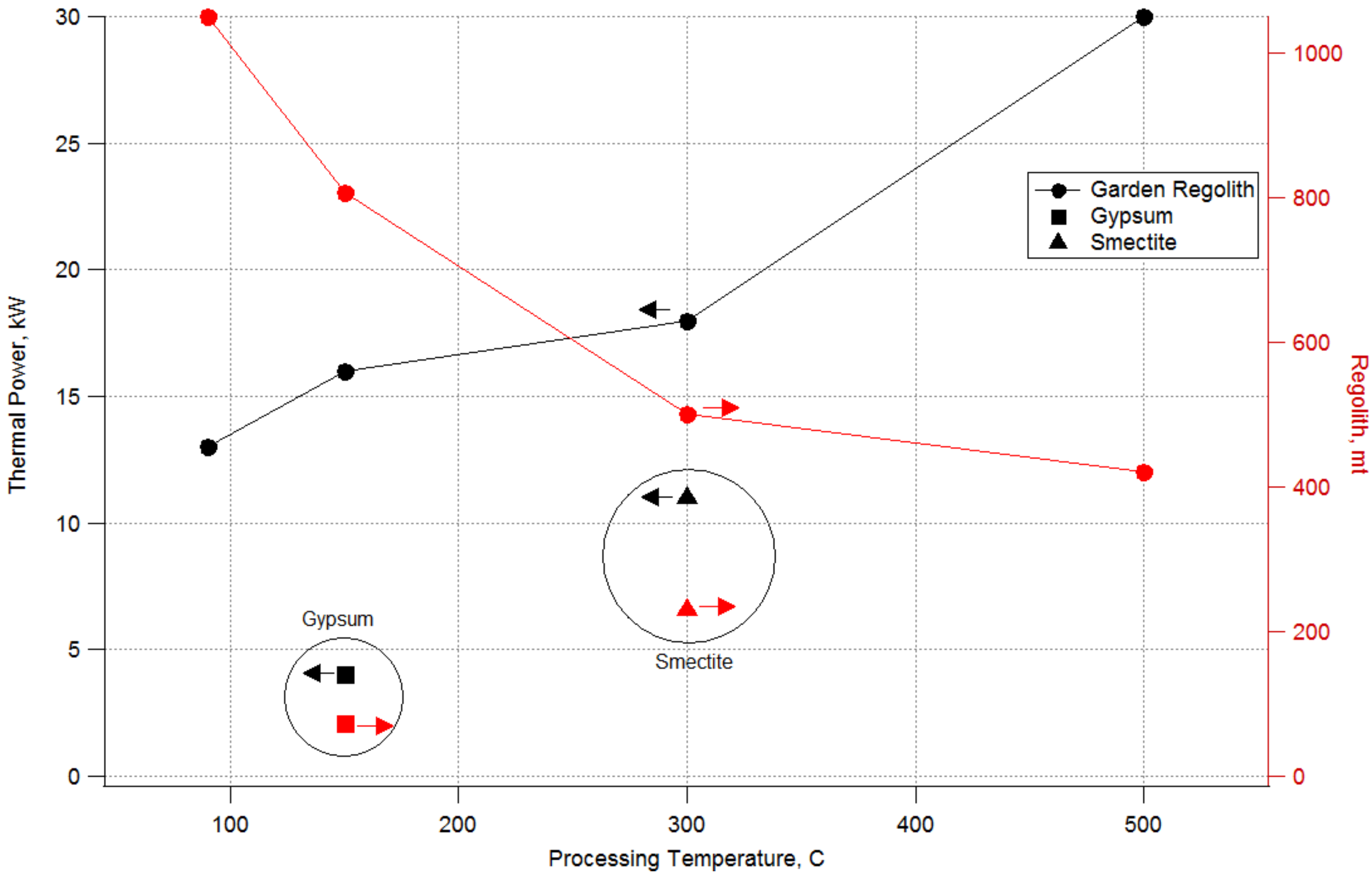
- **The MWIP team has identified Reference cases for soil-water resources. The best case is that of a Gypsum deposit which has 8 wt% water releasing at 150C.**
  - The percentages on the graphs show the increase over the LOX-only case
  - Targeting water-Rich deposits offers marginal mass improvement, but significant power reduction



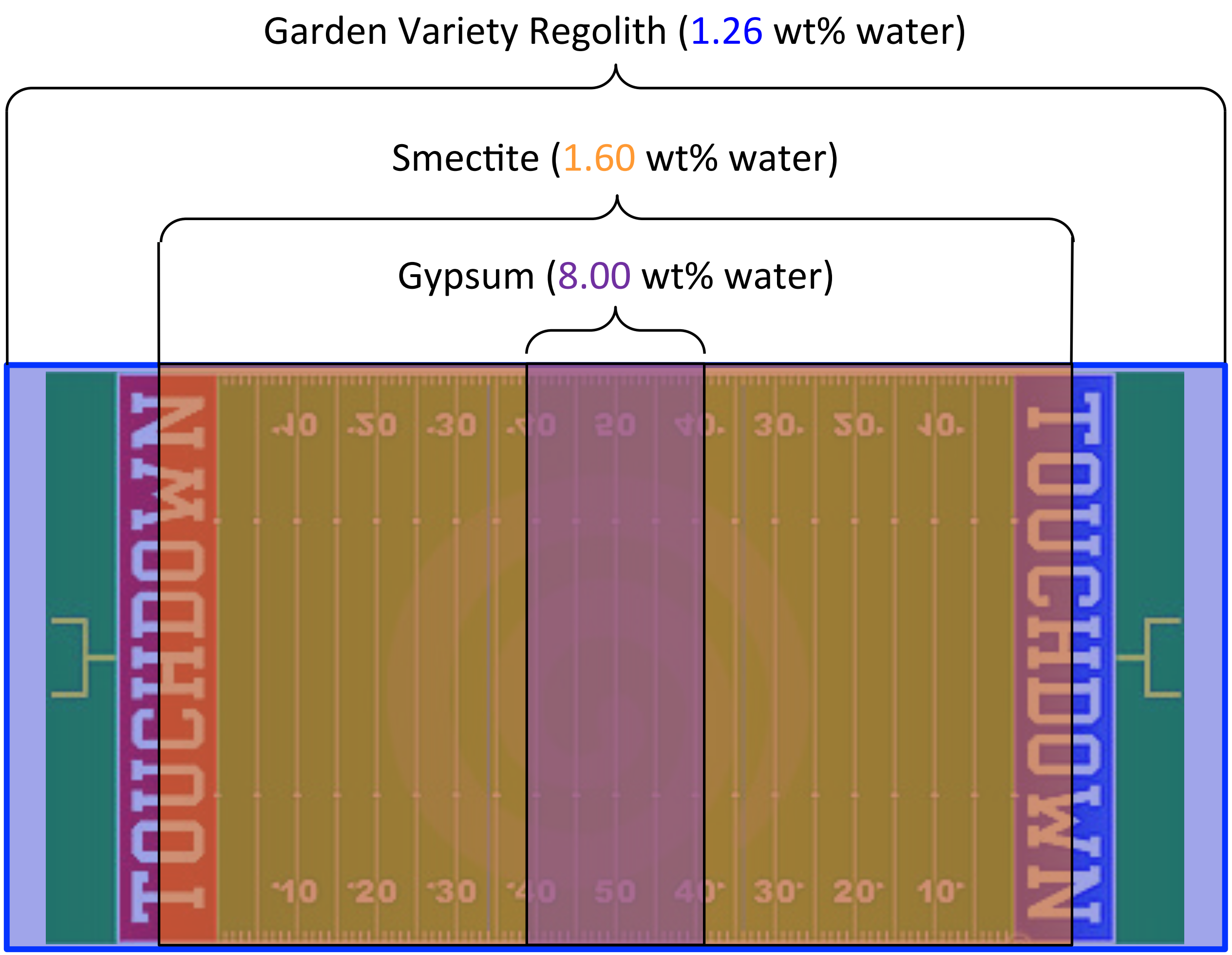


Trade: higher yield regolith

- **The real benefit of targeting higher yield regolith is the power saving**
  - Less regolith to heat
  - Heating at a lower temperature



Human Mission Mars Soil Excavation for Water

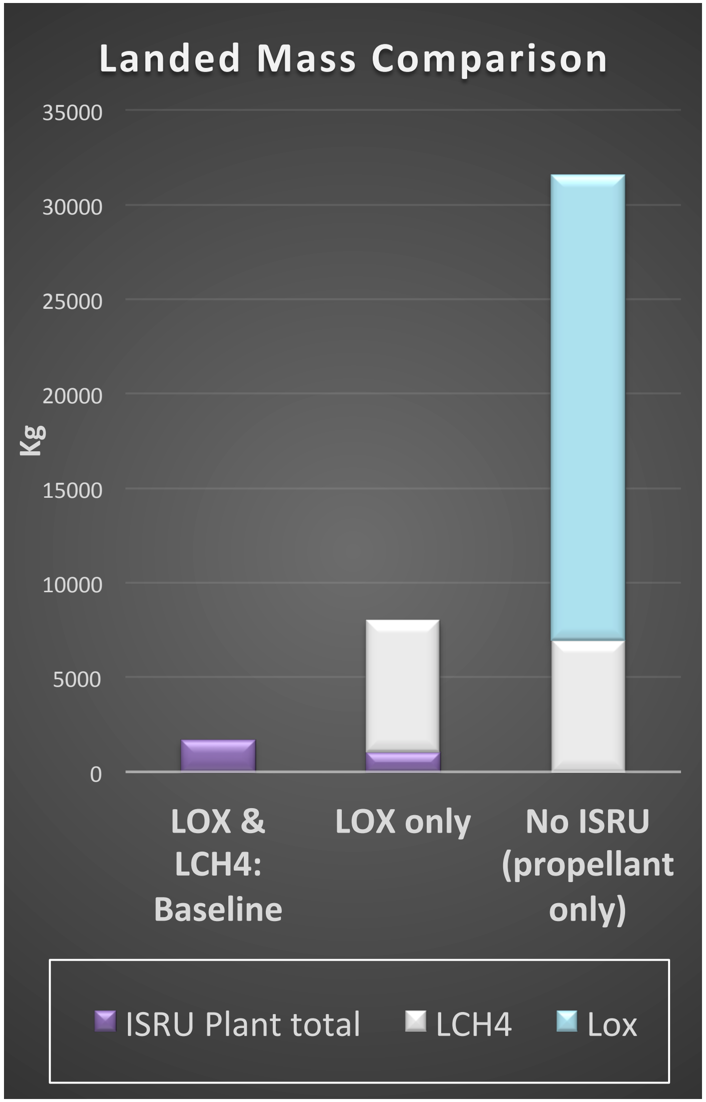


Surface area required per mobile excavator with the following assumptions:

- 3 mobile excavators used
- Each excavator provides 40% of required water
- Excavation depth = ~5cm (2.0 in)

Mass comparisons

ISRU system Mass Comparison			
The ISRU system leverages the power and radiator systems that are pre-positioned by the lander for human systems. So these are not explicitly part of the ISRU system.			
	Hardware Mass, mt	**Total Mass, mt** (ISRU Hardware + Propellant from Earth)	**Ratio: Propellant produced per kg of landed mass**
Case 1 ISRU for LO_2 & LCH_4: Sulfates	1.6	1.6	22.1
Case 2 ISRU for LO_2 & LCH_4: Regolith	1.7	1.7	20.5
Case 3 ISRU for LO_2 only (no water)	1.0	8.0 (1mt hardware + 7mt Methane)	3.1
Case 4 Propellant only (no ISRU)	NA	31.6 (24mt Oxygen + 7mt Methane)	NA



Conclusions

For every kilogram of landed mass

(hardware mass + including terrestrial propellants):

- A LO_2/LCH_4 ISRU system can produce 20 kg of propellant
- A LO_2-only ISRU system can produce 3 kg of propellant

Harnessing the Mars regolith water for ISRU offers a **6x improvement** over Mars ISRU atmosphere processing alone.

- *These calculations only account for the mass of the propellant that is needed in the MAV. They do not account for the additional propellant mass which would be required to deliver that MAV propellant to Mars from LEO. Thus the advantage of a combined ISRU LOX/Methane production system would be greater than indicated.*
- *Component/Technology trades in the ISRU end-to-end system may also offer an improvement*

This results in about mass savings in LEO on the order of 10kg for every kg of mars produced propellant

Targeting Water-rich landing sites (eg Gypsum deposits) offers only a marginal mass benefit, but reduces the power such that it is comparable to the LO_2-only case (30% less power than the baseline regolith case).

Back up

Mars Regolith-Water Processing Study improvements

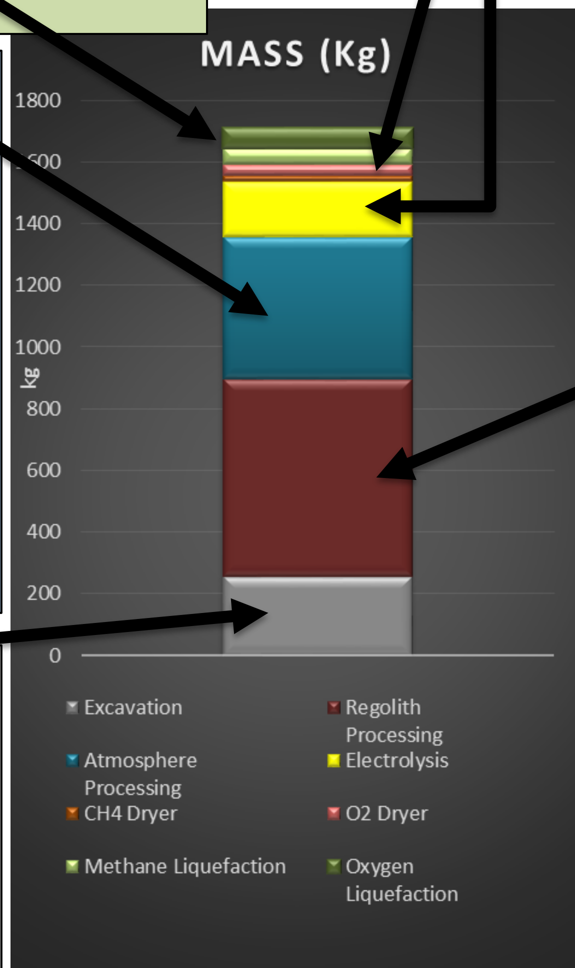
- **Update regolith mineral properties for more accurate heat requirement calculations**
- **Currently no soil beneficiating or size sorting. Will need to adjust total regolith requirements if either is implemented.**
  – Examine benefits of adding this feature
- **Update/size soil hoppers and size sorters.** Currently using soil hoppers based on Rassor laboratory hopper. Packaging location and con-ops could alter the hopper needs.
- **Trade cryofreezers (CO_2 acquisition and Liquefaction)**
  – Cryofreezer units sized for the full flow rate vs multiple modular units
  – Con-ops could be examined to make better use of atmospheric conditions for thermal management
  – Continue to seek higher efficiency cyrocooler options
- **Flow system impacts:** streamline pressure/flow rate inputs across subsystems and add margin for line losses. Examine impacts of operating pressures across subsystems

Operational Assumptions

Liquefaction: (CH$_4$ liquefaction, O$_2$ liquefaction)
The ISRU liquefaction system only accounts for cryocoolers needed to liquefy the propellants. Liquefaction is assumed to occur in MAV ascent tanks so Tank mass and liquid maintenance is accounted for in MAV.
O$_2$ at 60K 15psi, CH$_4$ at 100K 50psi

Driers: (CH$_4$ drier, O$_2$ drier)
Regenerative desiccant systems remove excess water prior to liquefaction. Some product is lost during regeneration, but this margin accounted for in production rate.

Atmospheric processing: (CO$_2$ cyrofreezer, Sabatier reactor, gas separators)
CO$_2$ acquisition is a batch process so 2 systems operate in parallel so one is freezing CO$_2$ while the other is heating & venting to the Sabatier. The Sabatier is an exothermic reaction so one time power draw then self-sustaining. Products go through 2 separation systems to remove water product and excess H$_2$…both are recycled back to Sabatier.
Cryocoolers for CO$_2$ capture 4per module, CO$_2$ gas at 50psia to drive system.



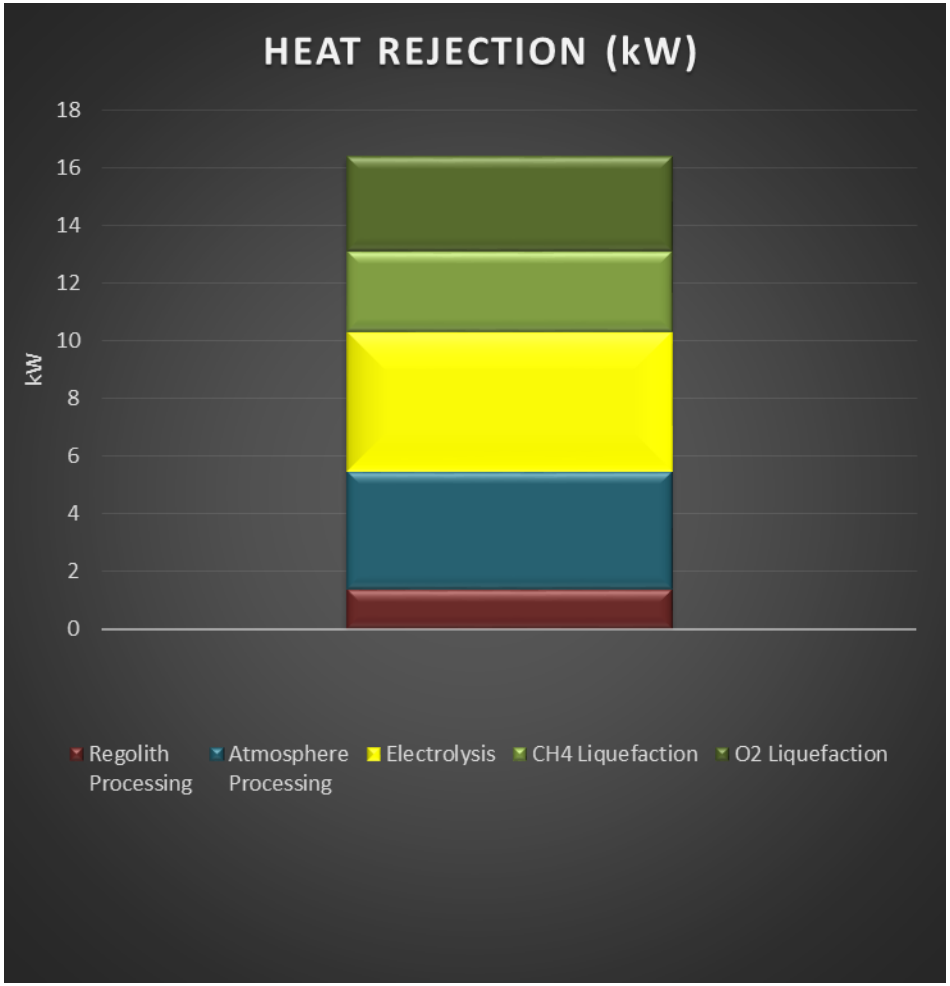
Electrolysis: (DeIonizer, PEM stack, pumps, H$_2$/H$_2$O separator tank)
Cathode feed PEM stack feed by regolith water and water from Sabatier reactor.
PEM: 1 stack (+1 spare) per module, 71 cells, baseline operation at 1.8V

Regolith processing: (hoppers, reactor, water vapor cleanup, water capture)
Rovers deliver to hopper/size sorter which meters regolith to the screw conveyor reactor to maintain continuous reaction. Water vapor periodically builds pressure to 20psia and vents to condenser for capture as liquid.
Reactor: 1 per module
Water condenser w/ passive cooling at operation saturation temp (300K)

Excavator: (rovers only)
Rovers operate 24/7 to maintain needed H2O production rate: battery recharge time and traverse time included in rate calcs.
Rassor, 1 per module, Traveling 100m at 0.26m/s,
Capacity 0.05m^3 per batch (80kg)

Heat rejection to radiators – total ISRU system (3 modules)

We are currently working with the MAV team to specify ISRU radiator needs.
Heat rejection is being tracked for each subsystem so that trades can be identified.



- The heat rejection from the regolith processing is low since most of the heat that is input goes into the regolith and is disposed of with the spent regolith. The only heat rejection required is that of the heated water vapor that is released from the regolith.
- The heat rejection from Liquefaction systems and from the majority of the Atmospheric processing is from cyrocoolers.
- The Electrolysis heat rejection is from the electrical heating of the PEM stack

Top level production requirements

Reference	O2 requirement	O2 Requirement Derived from	CH4 Requirement	Ch4 Requirement Derived from
Linne/Sanders 2015/DRA5	25000 kg	22985 kg ascent propellant + 1906 kg life support	6250 kg	Based on O2 requirement- 4:1 Sabatier production
MAV: Polsgrove AIAASpace2015	22728 kg	14986kg propellant + residuals + reserves	6978 kg	4282 kg propellant + residuals, reserves, bias, autogeneous pressurant

		Total mass needed	Rate at 480days continuous operation
Requirement:	CH4	6978 kg	0.61 kg/hr
Reactants needed to meet requirement:	H_2O	15701 kg (785,050 kg 2% soil)	1.36 kg/hr (68.2 kg/hr soil@2%)
	CO_2	19190 kg	1.67 kg/hr
Results in:	O_2	27912 kg total (22728 kg propellant, 1906 kg Life support, 3278 kg leftover)	2.43 kg/hr

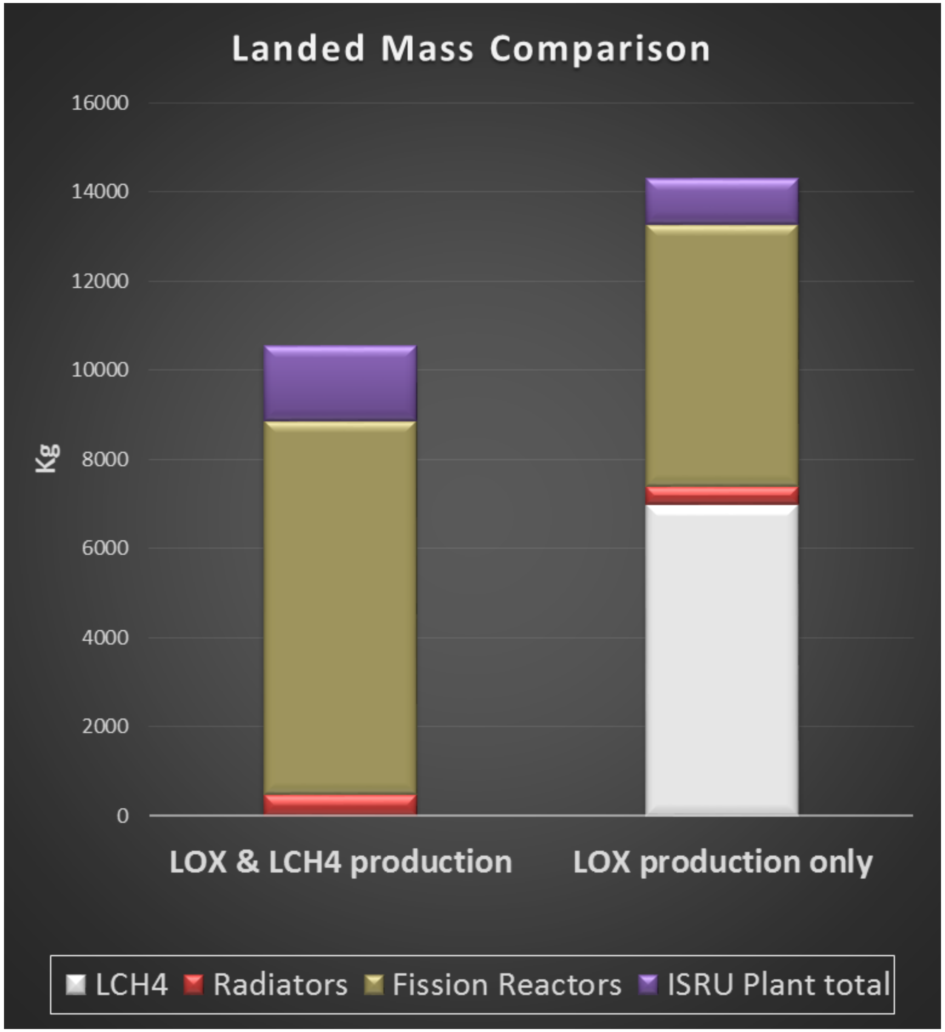
Methane production is the driving requirement.

Propellant mass needs taken from most recently published MAV study.

Excess Oxygen will be produced

Landed Mass comparison

- **Assumptions: Fission reactor assumed at 160 kg/kW (Kilopower units). Radiator approximation using Ref* (not the current MAV radiator)**

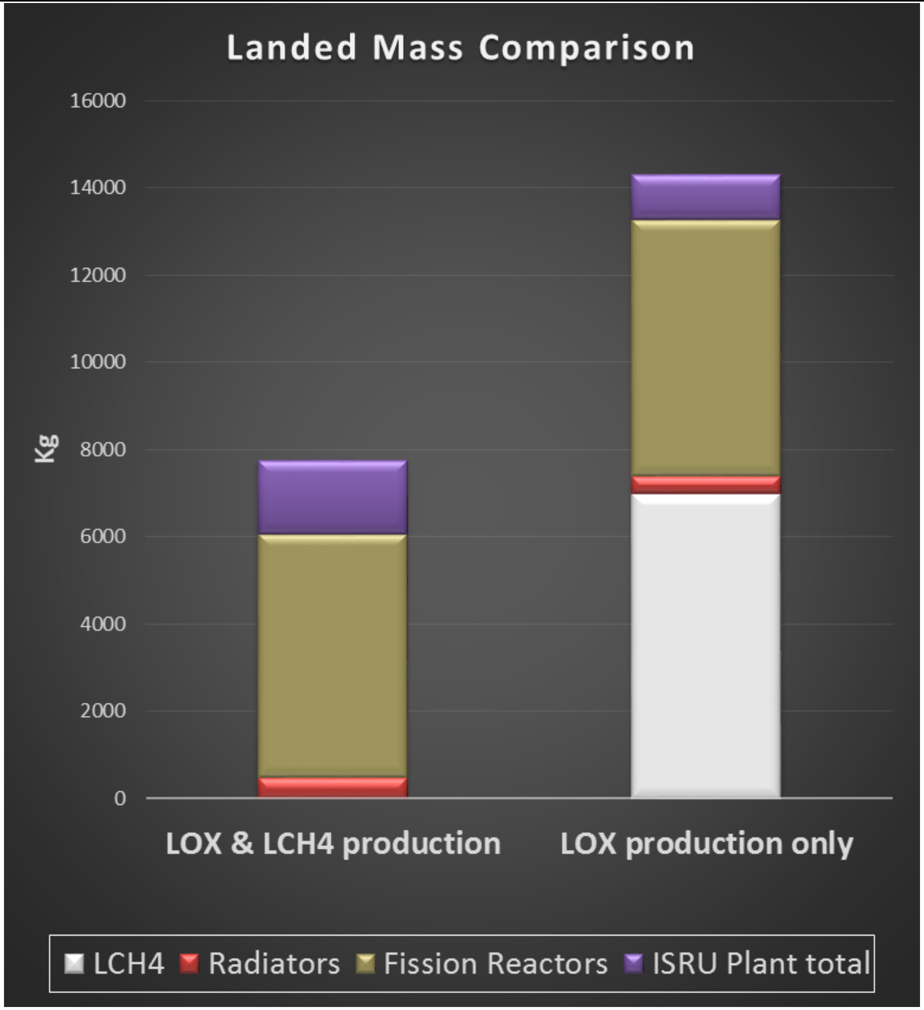


- **In both these systems Oxygen is produced via ISRU**
- **The LOX/LCH_4 production plant requires 26% less landed mass than the LOx-only plant <u>with</u> MAV methane brought from Earth.**
- **The Methane landed mass**
  - Accounts for 50% of the landed mass of a LOx-only ISRU system
  - A landed LOx/LCH_4 production plant only has 26% greater mass than the required Methane mass alone

*Hauser, Johnson, & Sutherlin, AIAA 2016-0721, AIAA SciTech 2016.

Landed Mass comparison with heat recuperation

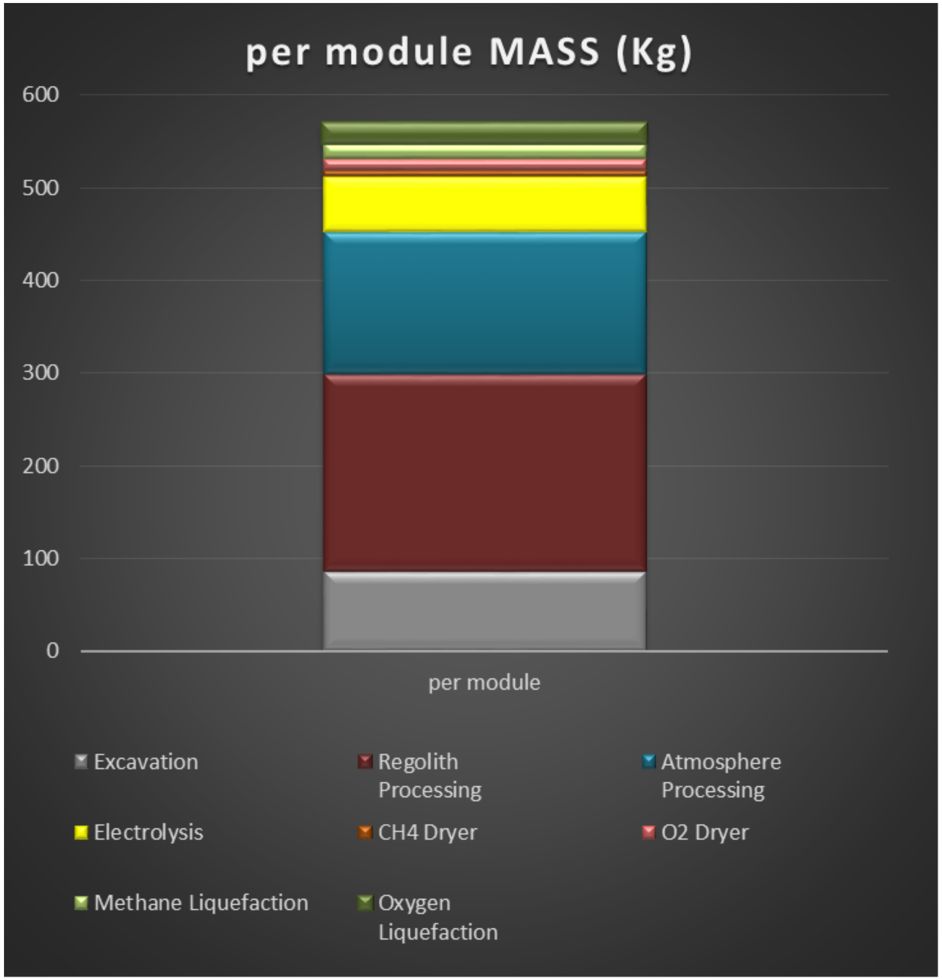
These fission power numbers do NOT include the thermal heat needed for regolith processing.
Assumption: Waste heat from the Fission reactor can be used for regolith heating reduces ISRU plant mass

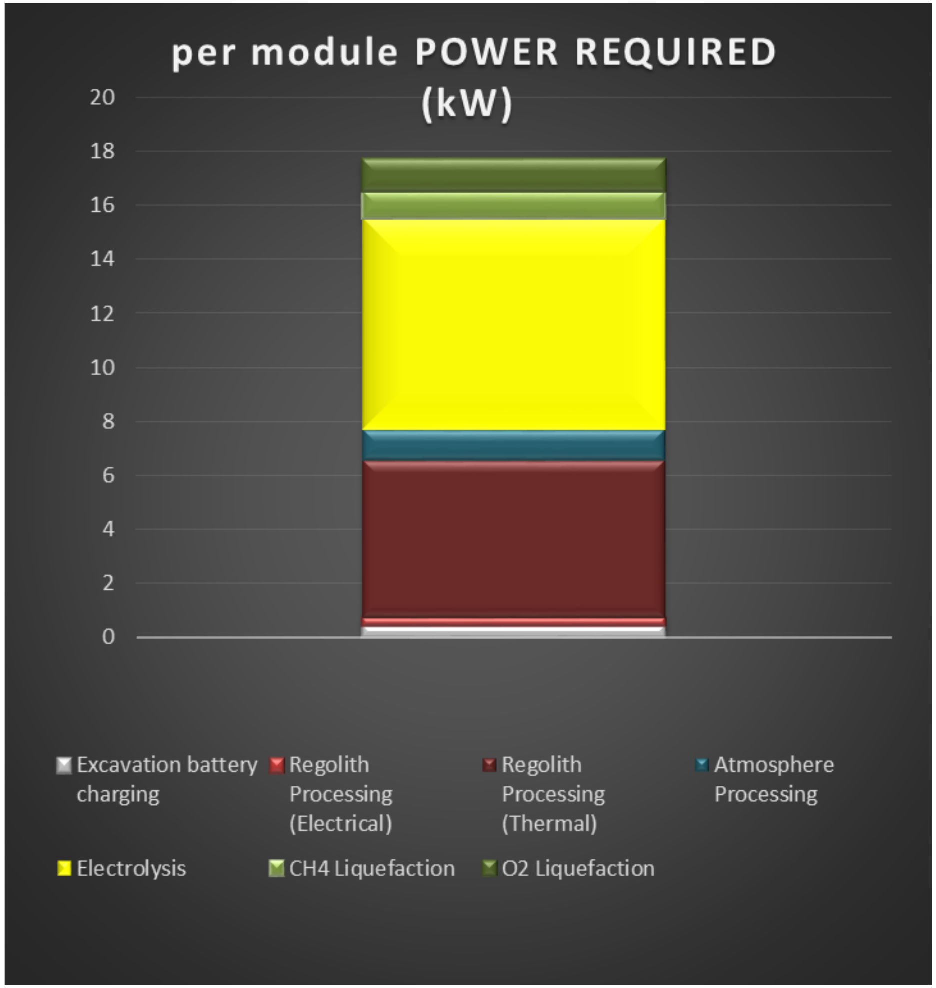


- **In both these systems Oxygen is produced via ISRU**
- **The LOX/LCH_4 production plant requires 26% less landed mass than the LOx-only plant with MAV methane brought from Earth.**
- **The Methane landed mass**
  - Accounts for 50% of the landed mass of a LOx-only ISRU system
  - A landed LOx/LCH_4 production plant only has 11% greater mass than the required Methane mass alone

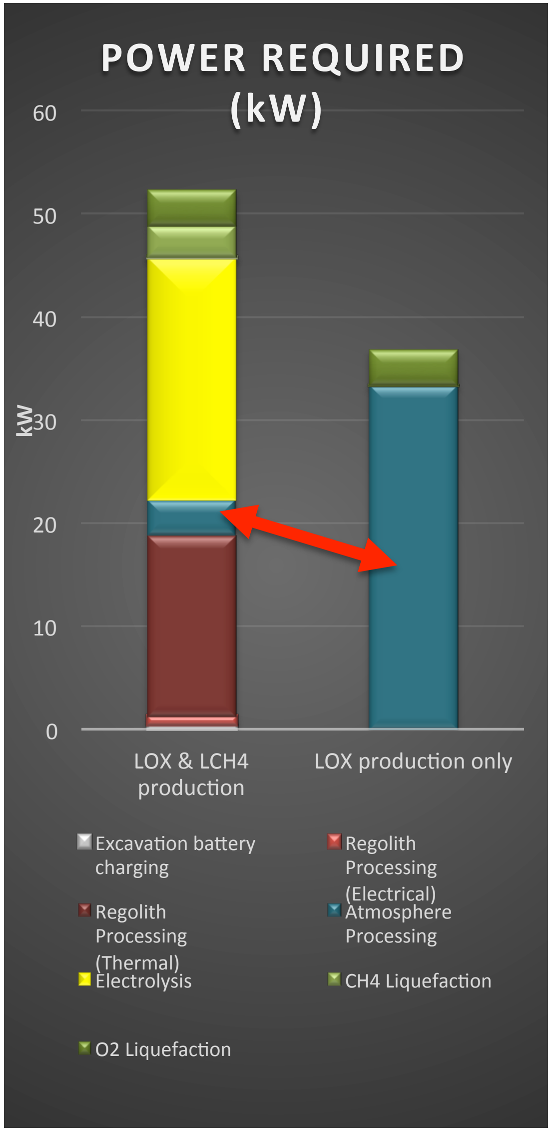
Backup: Per module mass & Power

- **Baseline case, Assumptions: 3 independent ISRU systems each producing 40% of the needed products, 15% mass added for structure, 20% margin added to power and mass, Garden variety (surface) regolith with 1.26wt% water processed at 300C**





Atmospheric Production: Power comparison



<u>Why are these atmospheric production requirements so different?</u>

- **SOE ($2CO_2 \Rightarrow CO + O_2$)**
- **Sabatier ($2H_2O+CO_2 \Rightarrow 2O_2+CH_4$)**

- **The Solid Oxide Electrolysis (SOE) used in LOX-only is an endothermic reaction whereas the Sabatier is exothermic. Thus the Sabatier only requires a startup power input and then is self sustaining. The SOE requires continuous heating to sustain the reaction, thus a higher power requirement.**
- **More CO_2 is required in the Lox-only case: 72% more CO_2 is needed from the atmosphere, requiring a larger acquisition device (freezer)**