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## Case Study for Lunar ISRU Systems Utilizing Polar Water

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- NASA's Artemis plan outlines a sustainable presence at the lunar surface in the 2028 timeframe and indicates the desire to develop ISRU technology to support this
- NASA's Human Exploration Mission Directorate (HEOMD) is developing mission scenarios and timelines
  - In order to infuse ISRU into these missions, estimates are needed for ISRU systems in term of Mass, Power, and Concept of Operations
- Two resources are available for Lunar ISRU for propellant production
  - Water from the polar regions
  - Oxygen bound in the regolith minerals
- NASA's Space Technology Mission Directorate (STMD) has developed a lead-follower approach where water-ice is the lead path and O<sub>2</sub> from regolith is the follower

## The Goal of this study was to

- Perform a case study of an end-to-end ISRU ice water system; choosing baseline architecture and technology selections to determine:
  - Mass and Power estimates
  - Sensitivity to key variables associated with architecture and water deposit characteristics
- Compare the estimates for a water-ice system to those of an O<sub>2</sub> from regolith system



# Ground Rules and Assumptions

- Production requirement is based on propellant production, H<sub>2</sub> and O<sub>2</sub> with a mixture ratio of 6
  - The Oxygen requirement is stated, but hydrogen is the driving requirement, excess oxygen will be generated
- Power systems are NOT included in mass.
  - The power needs are stated, but a power solution is not included in this study.
  - Mass does not include the power plant nor any associated power transmission or conversion systems
- Packing is not addressed
  - System volume is not offered here, though much of this information is available as it relates to mass. Packaging of hardware on landers or other platforms is addressed. Therefore structural supports their masses are not included, though margin is held for this.
- Communication and command/control systems are not explicitly addressed
  - Mobility subsystems include estimates for mass & power load
- Margins held at subsystem level
- System level thermal management systems are not included
  - Subsystems/components may include radiators, insulation, and/or allocations survival heat

<b>Mixture ratio (O/F)</b>	6
<b>Total production time</b>	225 days
<b>Commissioning time</b>	48 hr
<b>Mass Margins</b>	20% growth 15% structure
<b>Power Margins</b>	20% growth
<b>Extraction Efficiency</b>	75%
<b>Maximum battery discharge</b>	80%
<b>Regolith density</b>	1.3 g/cc
<b>PSR Min/Max/Sink Temperatures</b>	50K, 120K, 85K
<b>Ridge Min/Max/Sink Temperatures</b>	100K, 300K, 152K
<b>Radiative sky temperature</b>	4K
<b>PSR Traverse multiplier for hazard avoidance</b>	1.5 x
<b>Excavator Recharge time</b>	5 hr
<b>Tanker Recharge time</b>	10 hr
<b>Battery Energy density</b>	140 Whr/kg



## High Illumination Site (“Ridge”) Propellant Production Site

### Production plant:

- Water tank
- PEM water electrolyzer
- Gas dryers
- Hydrogen Liquefaction & Storage
- Oxygen Liquefaction and Storage

### Water Tankers x2:

Extracted water is condensed (frozen) into a water tank on a mobility platform

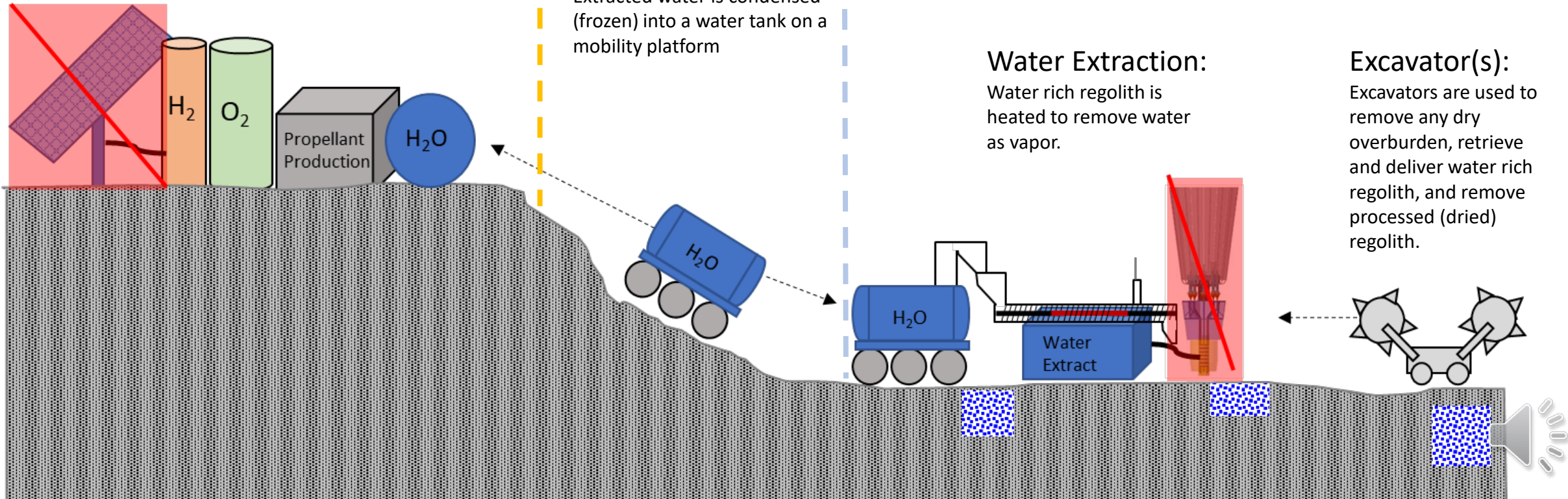
## Permanently Shadowed Region (PSR) Mine site

### Water Extraction:

Water rich regolith is heated to remove water as vapor.

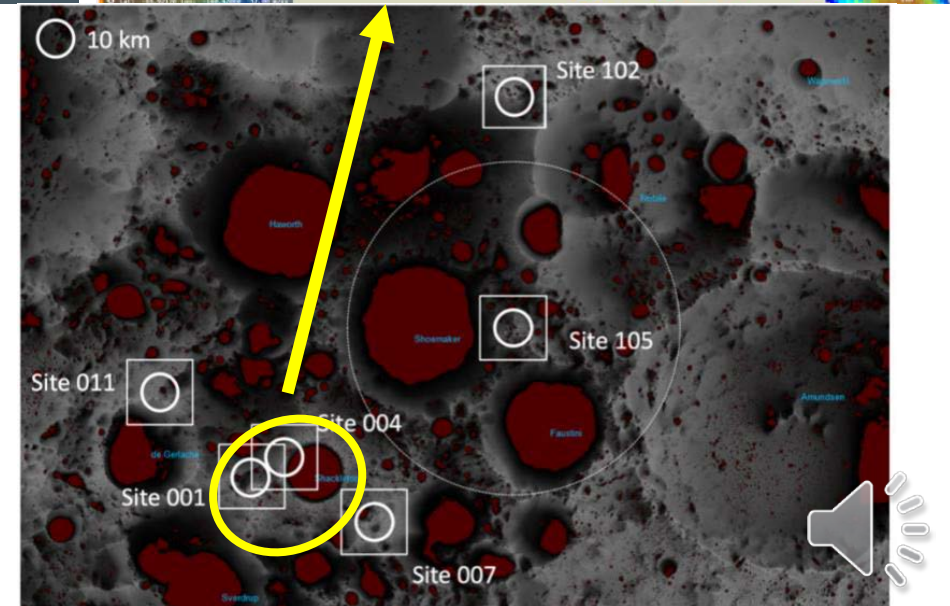
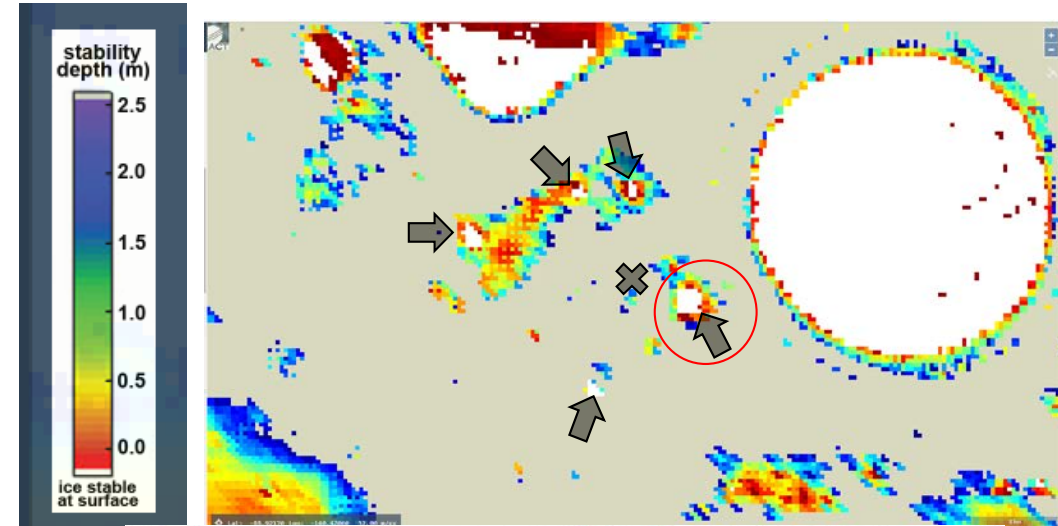
### Excavator(s):

Excavators are used to remove any dry overburden, retrieve and deliver water rich regolith, and remove processed (dried) regolith.



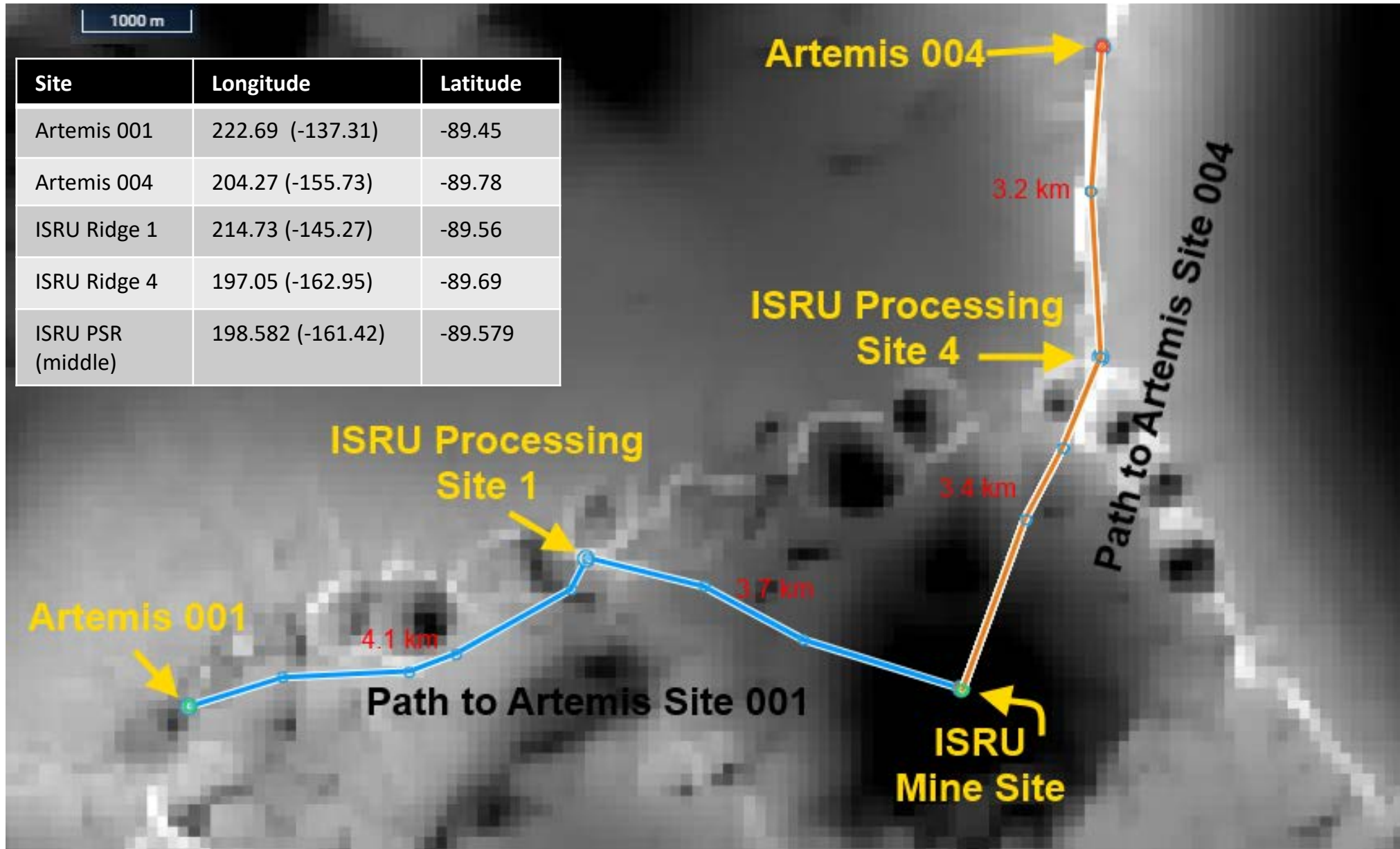
# Notional site selection

- A baseline site was selected for ISRU operations to facilitate environmental assumptions for the model including temperatures and travel distances
- A water-ice deposit for ISRU has not been located and much is still unknown extent and distribution of lunar water ice. The notional site was selected based on:
  - Notional Human Landing Sites: regions of high illumination
  - Water stability and temperature maps using LROC Quickmap software
  - Slope and traverse distance to HLS sites
- Only near surface water ice stability was considered; so mid to large permanently shadowed regions (PSRs) craters.
  - Water ice deposits of sufficient extent may exist outside these craters but were not speculated for this study



# Notional site selection

## Paths to HLS sites



# Subsystem Technologies

Subsystem technologies with empirical performance data were preferred, so the selections are not optimized and are not decisional

Subsystem	Technology	Description & Reference
Excavator	RASSOR	A dual bucket drum excavator. <sup>11</sup>
Regolith hopper	RASSOR hopper	Designed to match 1 RASSOR bucket wheel for laboratory use; 2 are used in model.
Water Extraction	Auger Dryer	An auger is used to convey regolith through a heated casing. Sizing model based on terrestrial models. <sup>12</sup>
Water Tank for water tankers	Sized: (Aluminum, 50% ullage)	Calculated based on water capacity.
Water Tanker: Mobility platform	Sized	Calculated assuming a payload ratio 1.5 where all battery mass and water tank are payload.
Fluid Transfer	DTAU + COTS water pump lookup table w/flow rate	The DTAU (Dust Tolerant Automated Umbilical) <sup>14</sup> .
Water Tank for Electrolyzer	Sized	Calculated based on water capacity.
Water Cleanup	TBD	Not currently included in model.
Electrolysis	Liquid Cathode PEM + COTS water pump lookup w/flow rate	PEM based on performance from NASA SBIR
Gas Dryer	Regenerative desiccant	JSC in house development hardware
H <sub>2</sub> Liquefaction	Cryocoolers	Modeled off COTS, includes radiator mass estimate
O <sub>2</sub> Liquefaction	Cyrocoolers	Modeled off COTS, includes radiator mass estimate
H <sub>2</sub> and O <sub>2</sub> Storage (Tanks)	Sized: Aluminum thin wall (3mm)	Calculated based on capacity.



# Baseline Case

- The baseline case for this study targeted the production of 10 mT of Oxygen for use as propellant in an O<sub>2</sub>/H<sub>2</sub> system at mixture ratio 6
  - Estimate for the amount of propellant needed to support a human scale ascent vehicle or lander; approximation based on current and previous architecture estimates
  - At this mixture ratio, using water electrolysis, hydrogen is the limiting factor: excess oxygen will be produced.

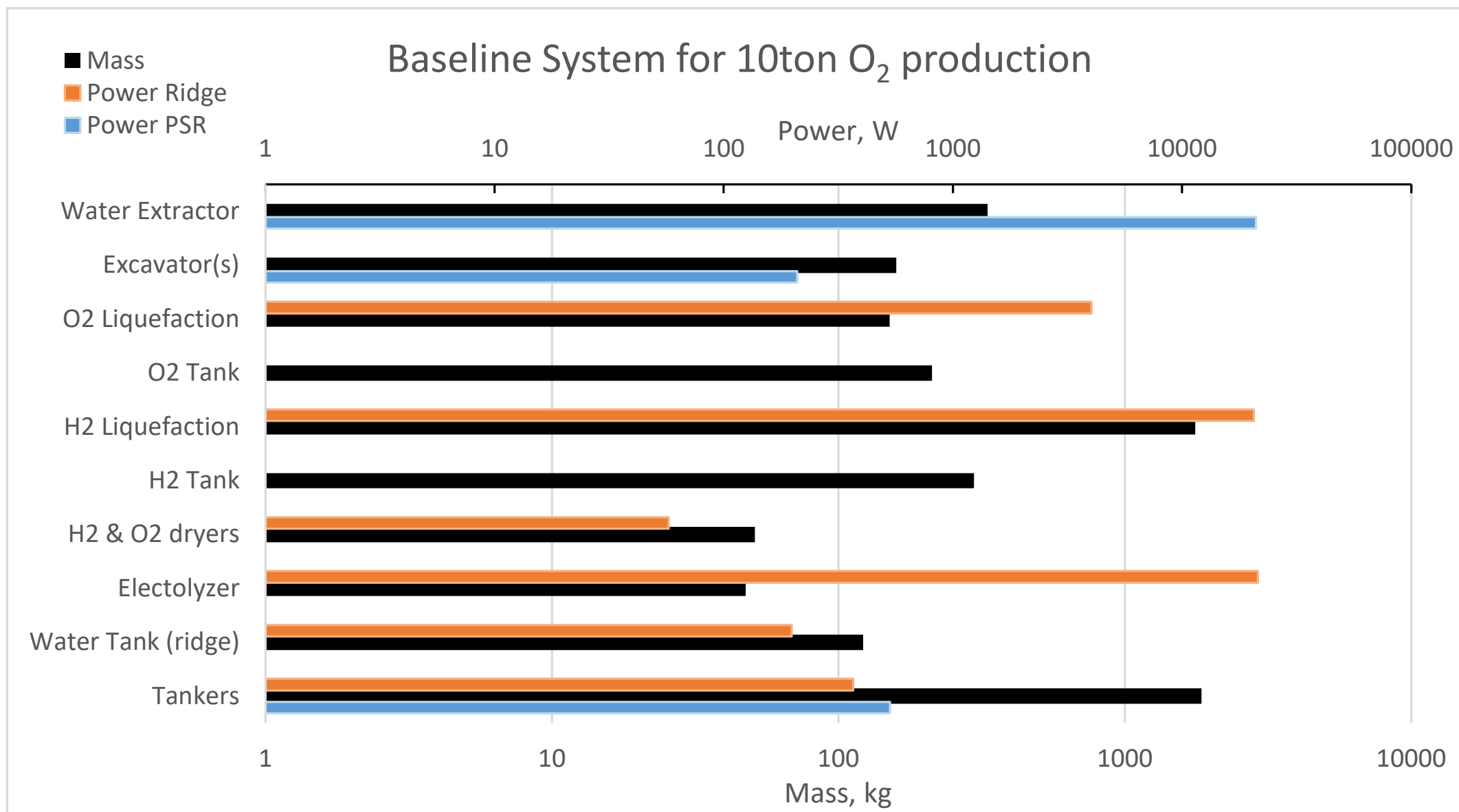
Baseline Case Key Inputs	
Water concentration	5%
Production requirement	10 mT O <sub>2</sub>
Actual production	13 mT O <sub>2</sub> 1.7 mT H <sub>2</sub>
Water required	15 mT water
Regolith required (75% extraction efficiency)	398 mT
Mine size at 30cm depth	32m x 32m
Time to water transport	10 days

Baseline case: Results	
<b>Total Mass</b>	<b>4.9 tons</b>
Ridge System	2.6 tons
Mine system	0.49 ton
2 water Tankers	1.8 ton
<b>Total power</b>	<b>68 kW</b>
Ridge Power	46 kW
Mine Power	22 kW



# Baseline Case

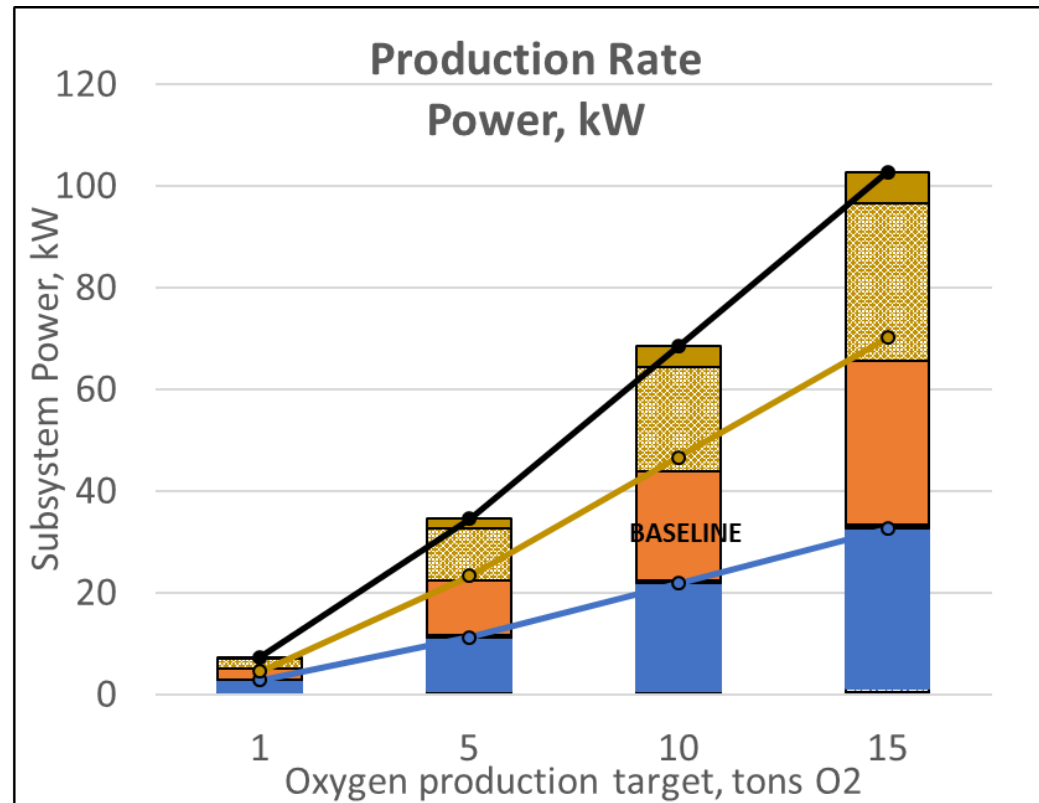
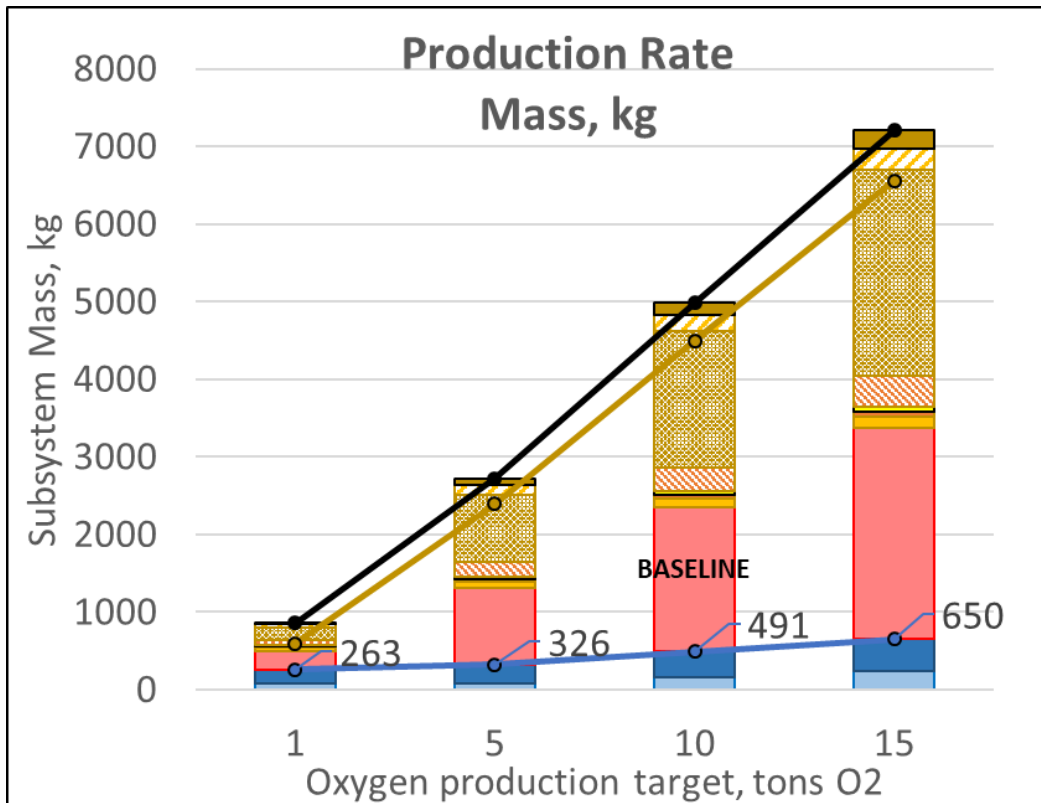
## Subsystem contributions



# Sensitivity Study

## Production requirement

- Since end-to-end production time is fixed for this study at 225 days, the system gets larger with propellant need to accommodate a larger throughput.
- A 'pilot' scale ISRU system, which is intended to be a sub-scale modular technology demonstration, is 1 mT of oxygen



#### Mine Site (PSR) SubSystems

- Water Extractor
- Excavator(s)
- Tanker Maintenance-PSR

#### Ridge Site SubSystems

- Tanker Recharge-Ridge
- Tanker (mass)
- Ridge Water tank
- Electolyzer
- H2 & O2 dryers
- H2 Tank
- H2 Liquefaction
- O2 Tank
- O2 Liquefaction

#### System Totals

- Total PSR
- Total Ridge w/tanker
- Total end-to-end

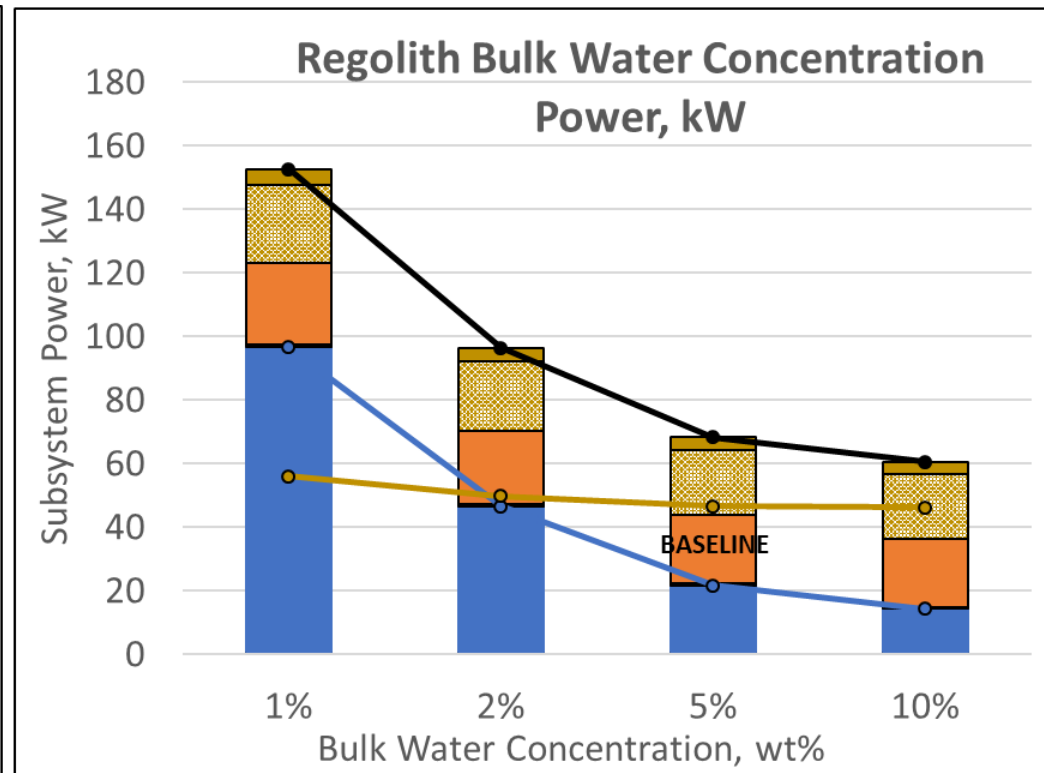
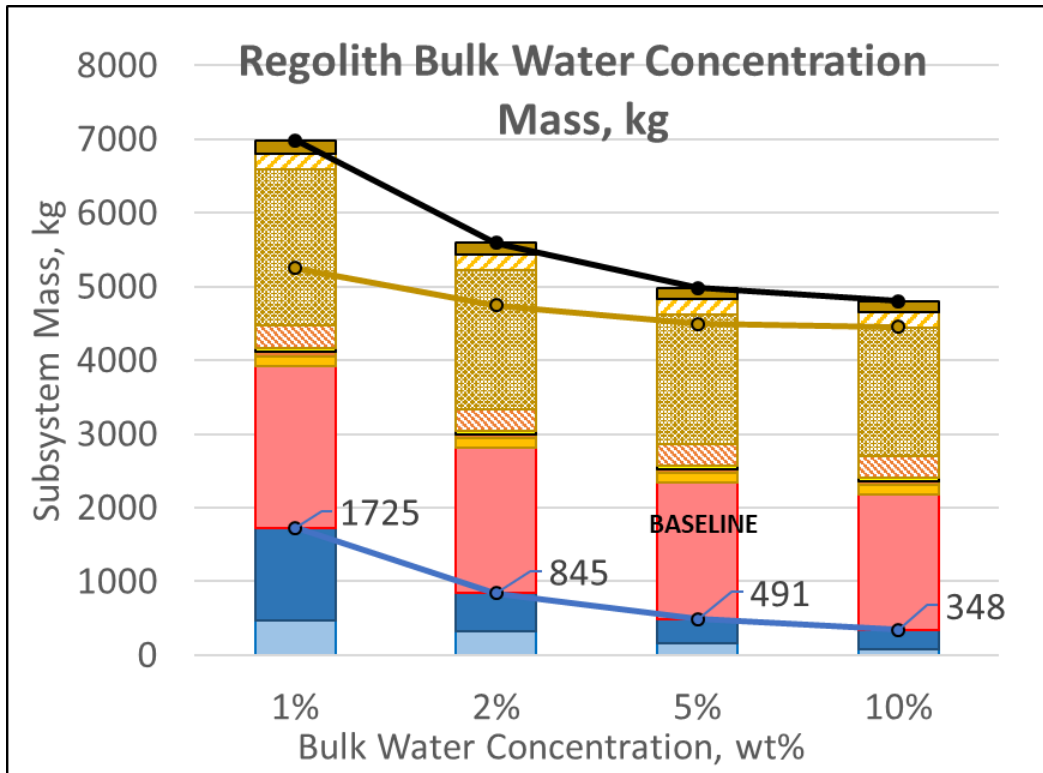


# Sensitivity Study

## Regolith bulk water concentration

Bulk water concentration is water content over the mine depth. Includes any heterogeneities

- Values chosen are consistent with possible interpretations of Neutron data
- The water extraction system drives results.
  - Water extractor subsystem reaches scalability limit, so multiple units are needed; increasing mass and power particularly at 1 wt%
  - At higher concentrations there is less impact since minimum number of units is reached
- 1wt% is unlikely to be a viable ISRU water-ice deposit (for these assumptions)



**Mine Site (PSR) SubSystems**

- Water Extractor
- Excavator(s)
- Tanker Maintenance-PSR

**Ridge Site SubSystems**

- Tanker Recharge-Ridge
- Tanker (mass)
- Ridge Water tank
- Electrolyzer
- H2 & O2 dryers
- H2 Tank
- H2 Liquefaction
- O2 Tank
- O2 Liquefaction

**System Totals**

- Total PSR
- Total Ridge w/tanker
- Total end-to-end

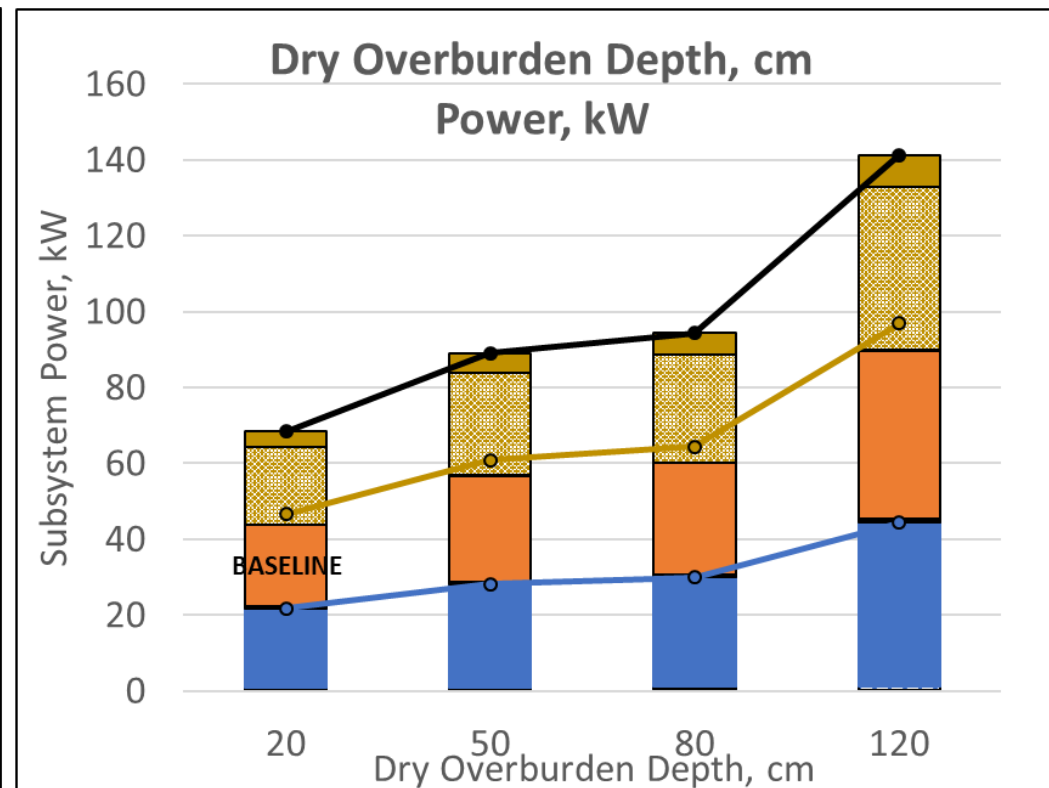
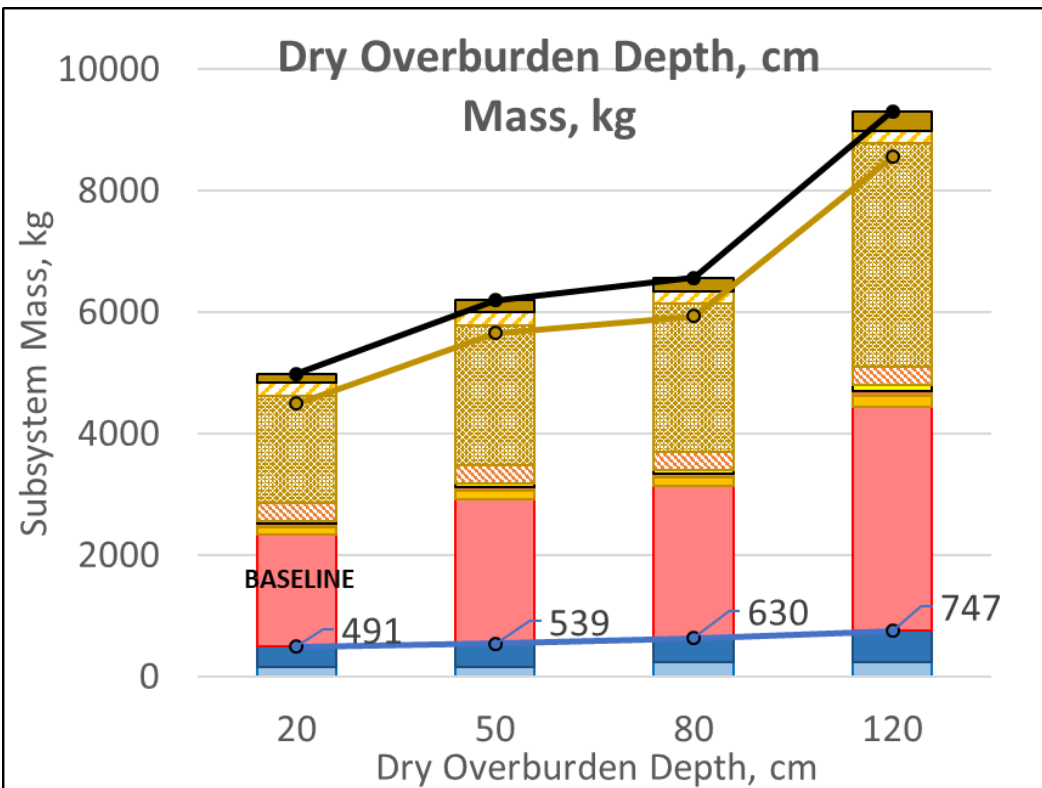


# Sensitivity Study

## Dry Overburden layer

The depth of the dry layer of desiccated regolith that is anticipated over a water-ice deposit.

- Time to remove overburden will delay water extraction and reduce the active processing time. This would increase the production rate which increases the system size.
- The model is designed to minimize excavators, hence the non-monotonic trend:
  - Both 20 cm and 50 cm overburden require 2 excavators, but 50cm overburden removal requires more time resulting in higher production rate = larger system.
  - At 80 cm, another excavator is required, but overburden removal time is similar to the 50cm case. Therefore production rate is also similar.
  - Above 1m, a similar scenario occurs, but the production rate starts to become untenable.



### Mine Site (PSR) SubSystems

- Water Extractor
- Excavator(s)
- Tanker Maintenance-PSR

### Ridge Site SubSystems

- Tanker Recharge-Ridge
- Tanker (mass)
- Ridge Water tank
- Electolyzer
- H2 & O2 dryers
- H2 Tank
- H2 Liquefaction
- O2 Tank
- O2 Liquefaction

### System Totals

- Total PSR
- Total Ridge w/tanker
- Total end-to-end

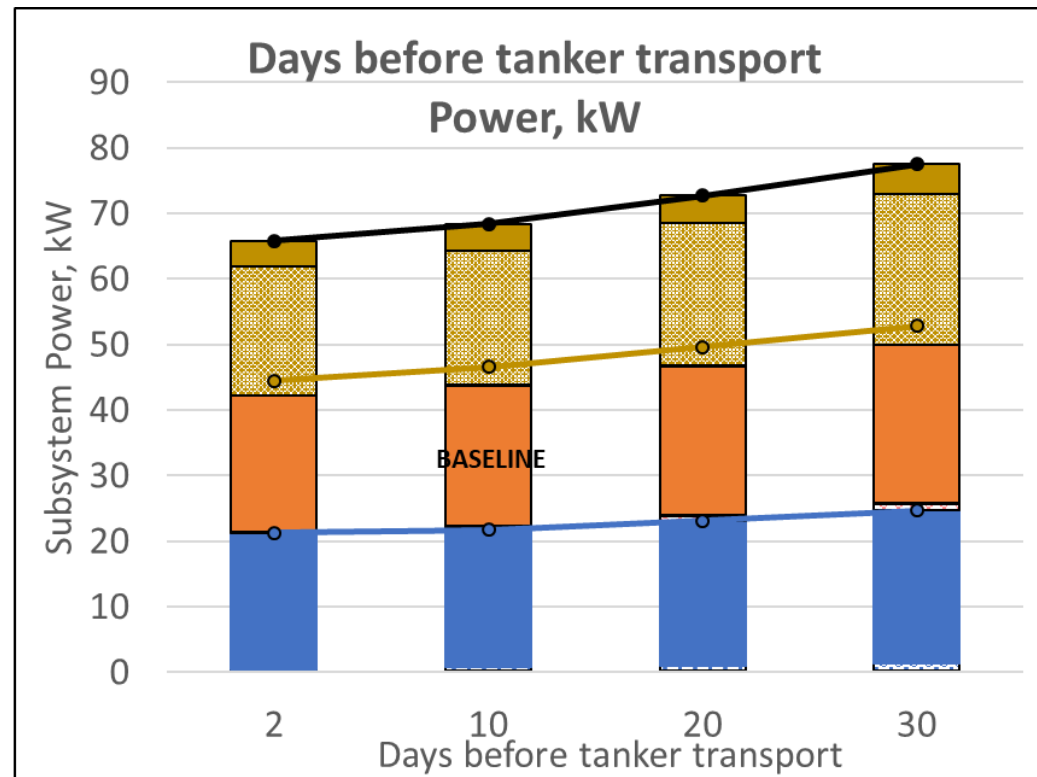
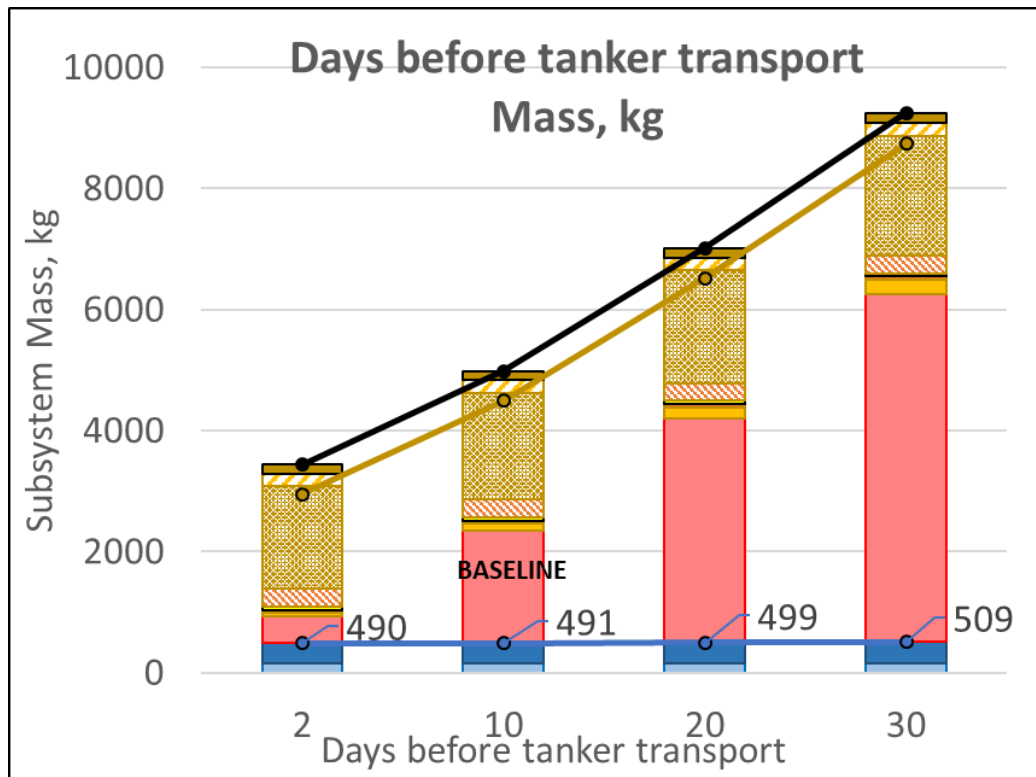


# Sensitivity Study

## Time between water transport

The time each water tanker spend collecting water; defines the number of trips each tanker must make in/out of the crater.

- Impact is primarily on mass: longer time between trips requires a larger water tank.
- However, what is not captured is the wear and risk involved in each transverse.
  - The 2 day case results in 97 trips over the total system production time, while a 30 day case is only 6 trips.
  - The baseline scenario used 10 days with 20 trips, which seemed to be a reasonable balance.
  - Difficult to judge what an “appropriate” number of traverses would be, because no planetary exploration vehicle has ever performed at this level.
    - *Distance is ~5 km each way, slopes around 16 degrees over hundreds of meters and the properties of the material are largely unknown.*



### Mine Site (PSR) SubSystems

- Water Extractor
- Excavator(s)
- Tanker Maintenance-PSR

### Ridge Site SubSystems

- Tanker Recharge-Ridge
- Tanker (mass)
- Ridge Water tank
- Electrolyzer
- H2 & O2 dryers
- H2 Tank
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- O2 Tank
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### System Totals

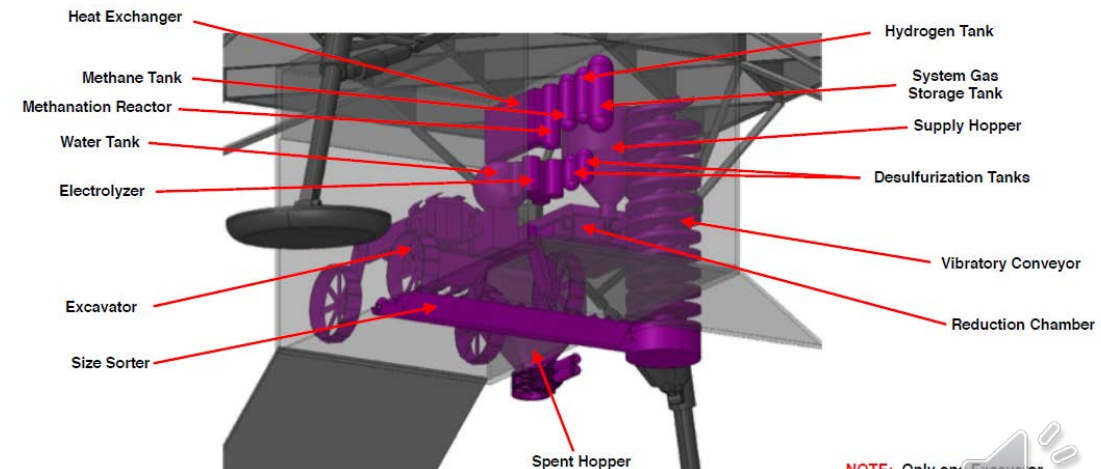
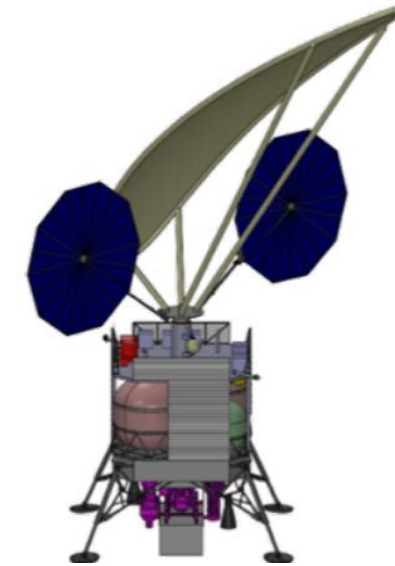
- Total PSR
- Total Ridge w/tanker
- Total end-to-end



# Comparison to O<sub>2</sub> from Regolith

## O<sub>2</sub> system

- Oxygen from regolith system from Ref. 2 with production rate of 10 mT of oxygen
- Target oxygen from the silicate minerals in the surface regolith using a Carbothermal reaction process
  - Reduction of oxides with a carbonaceous source (Methane) at temperatures in the range of 1650 -1800°C (regolith melting temperature)
  - Methane is recycled.
- Resource is ubiquitous and in readily accessible surface material.
- System assumed to be in region of high illumination and leverages direct solar heating
  - Solar concentrator for regolith melting
  - Solar array for electrical power
- This study included lander packaging



NOTE: Only one Excavator and ISRU System is shown

# Comparison to O<sub>2</sub> from Regolith

## Assumption differences

### Mass

- The ISRU system, without the lander and bus was used for the comparison
- The O<sub>2</sub> system included solar panels for power, this mass was subtracted since the water system does not include power
- The O<sub>2</sub> system requires hydrogen from earth whereas the water system produces this. An approximation of the hydrogen mass and tank was added.

### Power

- The water system power disregards thermal versus electrical power; assumes even thermal (heating) must come from electrical source
- The O<sub>2</sub> system uses a solar concentrator to supply direct heating to the regolith for reaction.

Water Ice ISRU System		O <sub>2</sub> from Regolith ISRU System	
<b>Total Mass</b>	<b>4.9 mT</b>	<b>2.7 mT</b>	
<i>Ridge System</i>	2.6 mT	<i>ISRU system</i>	0.429 mT
<i>Mine system</i>	0.49 mT	<i>H<sub>2</sub> from earth</i>	2.3 mT
<i>2 water Tankers</i>	1.8 mT		
<b>Total power</b>	<b>68 kW</b>	<b>45 kW</b>	
<i>Ridge Power</i>	46 kW	<i>Electrical</i>	11.8 kW <sub>e</sub>
<i>Mine Power</i>	22 kW	<i>Direct thermal</i>	33.3 kW <sub>t</sub>



# Comparison to O<sub>2</sub> from Regolith

## Results

Water Ice	O <sub>2</sub> from Regolith
4.9 mT	2.7 mT *each successive mission will require 2 mT of hydrogen from earth, so mass favorably is lost at 2 <sup>nd</sup> mission.
68 kW	45 kW
Resource is not yet characterized, exploration is required prior to operations to determine extent.	Resource is largely known from returned.
Highly reliant on location with accessibility challenges; likely requires higher traverse distances and some operations in an extreme environment (PSR).	The resource is very accessible and ubiquitous.
This case study requires operations at two locations.	Case study does full operations at one location.
Thermal energy for resource extraction is lower; water vaporization energy.	Thermal energy for resource extraction is high, requires melting of regolith
Use of non-electrical heat sources is challenging.	The system can use direct solar thermal heating to reduce electrical power.
Provides full propellant for vehicles. Water can also be used for other applications.	Only oxygen is provided.



- A Case study was performed for a lunar water ISRU system to examine mass, power, conops, and sensitivities in order to enable infusion into mission architectures. The system assumed:
  - ISRU operations at 2 sites: a PSR and an highly illuminated Ridge site
  - Water was transported between the two sites using 2 alternating water tanker vehicles
  - Subsystem technologies with available empirical performance data were chosen, but may not be the optimum solution
    - A surface excavator was selected, necessitating a pit-mine approach to reach water rich regolith
  - Assumptions were made regarding resource distribution; 5 wt% water (bulk over mined depth) and a 20 cm dry overburden
- The study did not include a surface power solution, but power needs are stated
  - Thermal and electrical energy requirements were not separated
- The baseline system to produce 10 mT of O<sub>2</sub> and 1.67 mT of H<sub>2</sub> in 225 days was 4.9 mT and 68 kW
  - Water concentration of 1 wt% is not considered a viable solution
  - Increasing depth of the overburden results in step changes in mass and power, one occurs at >1m that results in an untenable solution
  - Increasing the number of water transport trips results in lower mass, but increases risk and wear in an currently unquantifiable way
- Extracting Oxygen from the ubiquitous silicate minerals is a lower mass and power solution (~2.7 mT, 45 kW) for the same production requirements
  - However, each successive mission will require an additional 2 mT of H<sub>2</sub> from earth, so mass favorably is lost at 2<sup>nd</sup> mission

