Case Studies for Lunar ISRU Systems Utilizing Polar Water

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In-Situ Resource Utilization (ISRU) is key to long term presence at any extraterrestrial destination. Current NASA direction is to achieve a sustainable presence on the lunar surface by 2028. Mission plans currently target the lunar South Pole to leverage the extended periods of solar illumination and allow for potential access to water ice in the permanently shadowed areas around the poles. With water, it is possible to produce both fuel and oxidizer to fully refuel a vehicle. In order to address ISRU infusion into mission planning, a study of an end-to-end ISRU propellant production system was initiated to assess ISRU architectures and obtain mass and power estimates. The results of this case study will be presented.

For this study, The ISRU system architecture involved two sites; the mine site in a shadowed crater where water ice is excavated and extracted from the regolith and the propellant production site at an illuminated ridge where the water is processed into liquefied O_2 and H_2 propellants. Fixed hardware would be emplaced at each site, with two alternating water tankers to transport water between them. Notional lunar sites were identified for this architecture for baseline environmental parameters. Technology solutions for each subsystem were selected based on those with the highest fidelity models or those that have empirical laboratory data to anchor to. While power needs were identified for each location, a power solution was not prescribed, therefore the masses presented do not include surface power systems.

The baseline case in this study assumed that 10 mT of oxygen, along with enough hydrogen to support a propulsion mixture ratio of 6, must be produced in 225 days. Therefore 15 mT of water would need to be collected and processed. The baseline solution resulted in a system mass of 5 mT and a total required power of 68 kW. The majority of the mass was split between the propellant production system (at the illuminated ridge) and the two water tankers; 2.6 mT and 1.8 mT respectively. The majority of the required power was with three subsystems at approximately 20 kW each: hydrogen liquefaction, electrolysis, and the water extractor subsystem. Trades for four key variables were also presented, namely production rate, water concentration, dry overburden depth, and number of water transport trips. The baseline water system was compared to an ISRU system that targets only oxygen from the minerals in the surface regolith. A carbothermal reduction reactor system was used for this comparison. The use of direct solar thermal energy to process the regolith and the ease of access of the resource resulted in significantly lower values for the oxygen case: approximately 2.7 mT and 11.8 kW. However, the mass trade would favor the water case over successive missions where the hydrogen up-mass of 2 mT per mission will accrue against the oxygen system.

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I. Nomenclature

Con-Ops	=	Concept of Operations
COTS	=	Commercial Off The Shelf
HLS	=	Human Landing System
ISRU	=	In-Situ Resource Utilization
PSR	=	Permanently Shadowed Region
LCROSS	=	Lunar Crater Observation and Sensing Satellite
LROC	=	Lunar Reconnaissance Orbiter Camera
mT	=	metric Tons
PEM	=	Polymer electrolyte membrane
SBIR	=	Small Business Innovation Research
VIPER	=	Volatiles Investigating Polar Exploration Rover

II. Introduction

NASA's current Artemis plan outlines a return to the moon by 2024 and achieving a sustainable surface presence in the 2028 timeframe[1]. A key part of sustainability is In-Situ Resource Utilization (ISRU), which is the practice of using local resources to provide mission consumables. NASA's mission plans currently target the lunar South Pole to leverage the extended periods of solar illumination. But this location also allows for potential ISRU of water ice, which has been identified in the permanently shadowed areas around the poles. With water, it is possible to produce both fuel and oxidizer to fully refuel a lander or ascent vehicle. Water also has a variety of other potential uses, such as for life support applications and power; but the initial focus for mission studies is propellants only, as this is the primary consumable. In order to address ISRU infusion into mission planning, a study of an end-to-end water based ISRU system for propellant production was initiated to assess several ISRU architectures and concepts of operations (con-ops), and obtain mass and power estimates. These estimates feed into broader mission plans and help target technology development needs.

Since the details of the mission architectures, and how ISRU will be infused, are still in discussion the trade space is still open. Technology options, site selection, availability of supporting systems, and operational concepts are still in flux. The study presented here is one case study. The assumptions used, and the baselines selected for this case study should not be taken as decisional. Rather, the objective was to look at the sensitivity of the system to key variables and look for any break points, or limits, where the system may become untenable. Some of these variables involve the definition of the water deposit itself. While water has been identified at the lunar poles, there is very limited information regarding the concentration, extent, and form of that water. Thus another goal of this study was to help define the ISRU need criteria for a viable lunar water deposit. Just because water exists at a location does not mean it is useful; its quantity and accessibility have to meet use criteria such that the water deposit constitutes a water "reserve"[2].

With that in mind, water is not the only resource available for propellant ISRU on the lunar surface. Oxygen bound in the crystalline structure of minerals is a ubiquitous resource across the moon; as much as 40% of the lunar regolith is bound oxygen. The processes used to extract the oxygen tend to be higher energy reactions than water extraction, but this is traded against challenges of accessing the specific locations where water resides in significant quantities. NASA is carrying both options until more is known about the water. A comparison of baseline water and oxygen from regolith ISRU systems will be offered at the end of this document.

III. Approach

The primary goal of this study was to develop mass and power estimates for a lunar water ISRU system to help feed into mission scale planning. Various con-ops trades naturally fell out of the modeling process. While volumetric estimates (packaging) will not be covered here, dimensions of many subsystems are available in the model as part of the sizing process. Results from an earlier version of this model were used for a Compass study performed in early 2020 for a 'pilot' scale ISRU water system and will be covered in another manuscript at this forum (Ref. 3).

The model itself was built in Excel to leverage previous work (component/subsystem modules) and for ease of use for team members. The core of the model was based on a similar Mars ISRU Case study[4]; some of the component modules (e.g. electrolyzer, liquefaction, etc) were kept largely intact (with adjusted inputs) as these are similar technology needs. The modules are largely empirically-based so that performance data from existing technologies could be used to anchor mass and power numbers. While the baselined technologies may not be the optimum choice in the long-run, performance data and development status were favored over optimization. The selected technologies are from in-house technology development, NASA solicited technology development efforts, or relevant off-the-shelf technologies. A list of these will be offered in a following section.

The system defined here is ISRU-specific system hardware only. While power generation is absolutely pivotal to any ISRU infrastructure, this case study does not include surface power systems. Rather, estimates will be provided for the power needs so that power architectures can be traded. Likewise, consideration was not explicitly given to communications architectures. While the ISRU system is assumed to be autonomous, additional mass and power may be needed to implement this. A following section will outline assumptions, and define the margins held to address them. The ISRU system produces liquefied propellant (O_2 and H_2) and stores it. However, delivery of this propellant to its user (e.g. landing/ascent vehicles) is not addressed here.

The end-to-end ISRU system was divided into three primary systems; the water mining system, the water tanker, and the propellant production system. The water mining system includes any hardware used to access and extract water from the lunar regolith. This hardware is assumed to be located at the mine site. The water tanker carries the water from the mine site to the propellant production system. The propellant production system includes any hardware need to process the water into its usable form; H_2 and O_2 propellants. Particularly since some of these processes require significant power (electrolysis, liquefaction), this system is located at a site with long periods of high illumination so that solar power can be leveraged. Since the Human Landing Systems (HLS) would also be located at an illuminated site, ISRU products would also be more accessible to their user.

A. Assumptions

Table 1 outlines some of the top level parameters used for all the trade cases included here. The main assumption is that the water would be used to produce propellant at an oxygen/hydrogen mixture ratio of 6. Therefore, electrolyzing water will result in excess oxygen, so hydrogen is the driving factor. Production requirements are stated in terms of the amount of oxygen needed for the ascent/lander vehicle. This was done for ease of comparison to the oxygen-only from regolith option. This means that if 10 mT of oxygen is required for vehicle propellant, a total of 1.7 mT of hydrogen is required to match that mixture ratio. To produce this amount of hydrogen, 15 mT of water would be required, resulting in 13 mT of oxygen, so an excess of 3 mT of oxygen would be produced.

One of the biggest drivers of the ISRU system is the amount of time available for production. It is assumed that and end-to-end ISRU system would have 225 days to produce propellants. This number was based on a COMPASS study[5] where 225 days was defined as the period of continuous illumination in this polar region. This time is reduced by the 'commissioning' time (deployment/start-up time). Mass margins are held at the subsystem level. This includes a growth margin as well as additional margin to cover structure and packaging which can't be defined until more is known about launch/lander vehicles for the ISRU systems. All masses and powers stated in this manuscript include the margin. Losses in the water extraction and capture process (e.g. sublimation during excavation, line losses, etc) are captured in the extraction efficiency parameter, which is set at 75%. So if the in-ground water content of the regolith is 5 wt%, the effective usable concentration is 3.75 wt%. The mobility platforms (water tankers, excavators) are assumed to run on batteries which are allowed to discharge 80% (i.e. battery capacity is de-rated by 20%). Battery consumption rates drive much of the con-ops time lines. Other assumptions listed in Table 1 include temperatures at the different sites, assumed times for battery recharge (which are times when the mobility platforms are inactive), and energy density for battery mass calculations.

Table 1. Ground rule assumptions for the model.

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

B. Site selection: Baseline

In order to develop the baseline con-ops and identify the key parameters, it was necessary to choose a baseline lunar site for ISRU system implementation. The selection of this site is by no means decisional, particularly since there are many unknowns regarding the extent of lunar water deposits. Until new information is gained (e.g. ground based reconnaissance like VIPER[6]) an ISRU lunar water reserve can't be identified.

Two main assumptions went into the baseline site selection. The first is that the location of the ISRU system must be co-located with, or near-to, a potential Human Landing Systems (HLS) site. When this study began in 2019 there were no specific HLS sites identified. However, regions of high illumination at the lunar South Pole, particularly the Shackleton - de Gerlache Ridge, in favor. Since then, the Artemis campaign has identified a broader set of specific sites, as shown in Fig. 1, where Site 001 is on the Shackleton - de Gerlache Ridge. The second assumption is that an acceptable water deposit would be located in a permanently shadowed crater of significant size. In other words, a traverse over a significant distance and slope would be needed to access the water. Small, micro-cold traps, or areas of temporary illumination where water may exist in some quantity, were not considered for this study. The Lunar Reconnaissance Orbiter Camera (LROC) Quickmap software (https://quickmap.lroc.asu.edu/) was used to identify areas where ice stability and maximum temperature were favorable to ice retention near the surface. Figure 2 shows the Shackleton - de Garlache Ridge with the Diviner instrument overlay for Ice stability. The "X" in this image is a highly illuminated location on Shackleton - de Garlache Ridge which was used as the initial assumption for water use location. The arrows show five potential water deposit sites where the circled location was selected as the baseline. Among the five options, the baseline location is a larger crater (classified as a permanently shadowed region, or PSR) which could indicate a potential for a sizeable water deposit. The elevation profiles (generated in Quickmap) indicated a traverse into this crater had maximum slopes under 20 deg and was among the shortest distances to the prospective Ridge location. Note that the large ice stability region in Fig. 2 is Shackleton crater, which was not considered a viable ISRU site due to steep slopes (>30°) and long traverse distances.

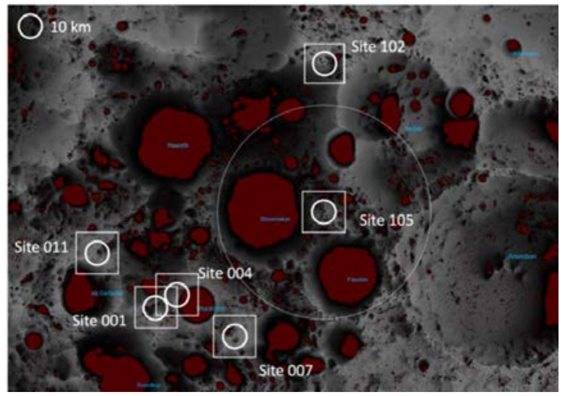

Figure 1. Potential HLS landing sites as defined in the Artemis plan[1]. This study focuses on Sites 001 and 004.

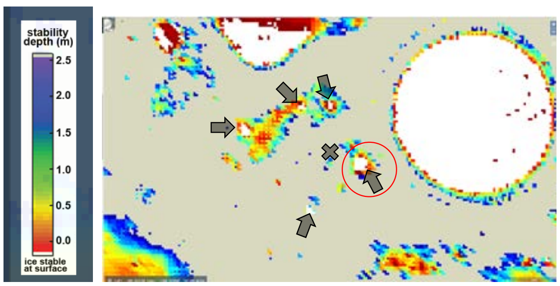

Figure 2. Ice stability depth in the notional ISRU site region. Arrows indicate potential shallow ice stability regions that were traded for accessibility. The "x" is ISRU ridge site for 001.

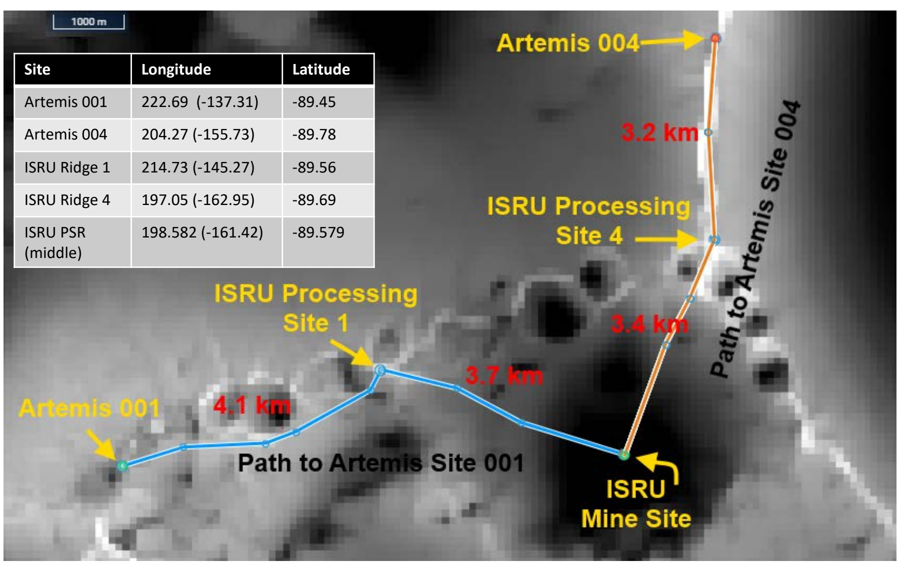

Figure 3. Traverse paths from the notional ISRU mine site. Distances are marked in red.

Using the baselined PSR as the ISRU water 'mine' location, Fig. 3 shows locations of some notional traverse paths to the two Artemis sites that could utilize this mine. The ISRU ridge sites are where the propellant production system would be. The ISRU ridge sites are not co-located with the HLS sites so that ISRU operations would not interfere with HLS activities, to reduce water delivery distances, and to keep the ISRU system independent of landings/ascents which may occur at different locations. All of the sites except Ridge Site 1 are based on coordinates in Ref. 7, which ranks high illumination sites in this area. Ridge Site 1 was selected as a midpoint between Artemis 001 and the PSR, with high illumination based on the LROC illumination layer in Quickmap. Figure 4 shows the traverse plots (elevation and slope) for both paths starting at the mine site and ending at the Artemis sites. Note that the model assumes a 1.5 times multiplier for all traverse distances to account for path finding over the slopes and around local obstacles (small craters and boulders). So a 3.5 km traverse distance in Figures 3 and 4, becomes 5.2 km in the model.

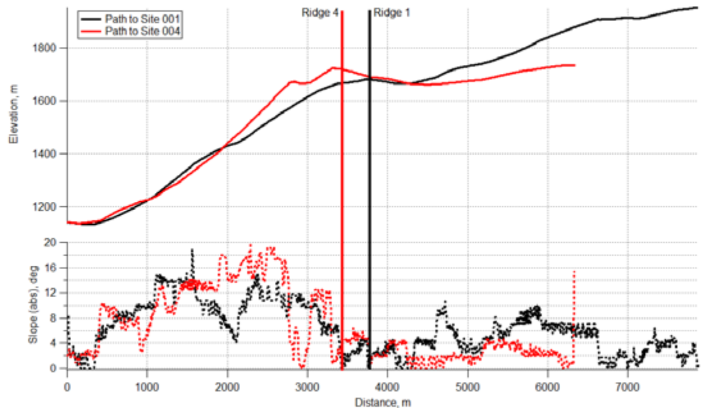

Figure 4. The traverse path profiles in terms of elevation (top) and slopes (bottom) over the distance, starting at the mine site.

C. System Concept of Operations

The overall concept of operations (Con-ops) involves three systems, the operations at the mine site (water excavation and extraction), operations at the ridge site (propellant production), and the water transport vehicles (tankers) that runs between them. Figure 5 shows the overall con-ops.

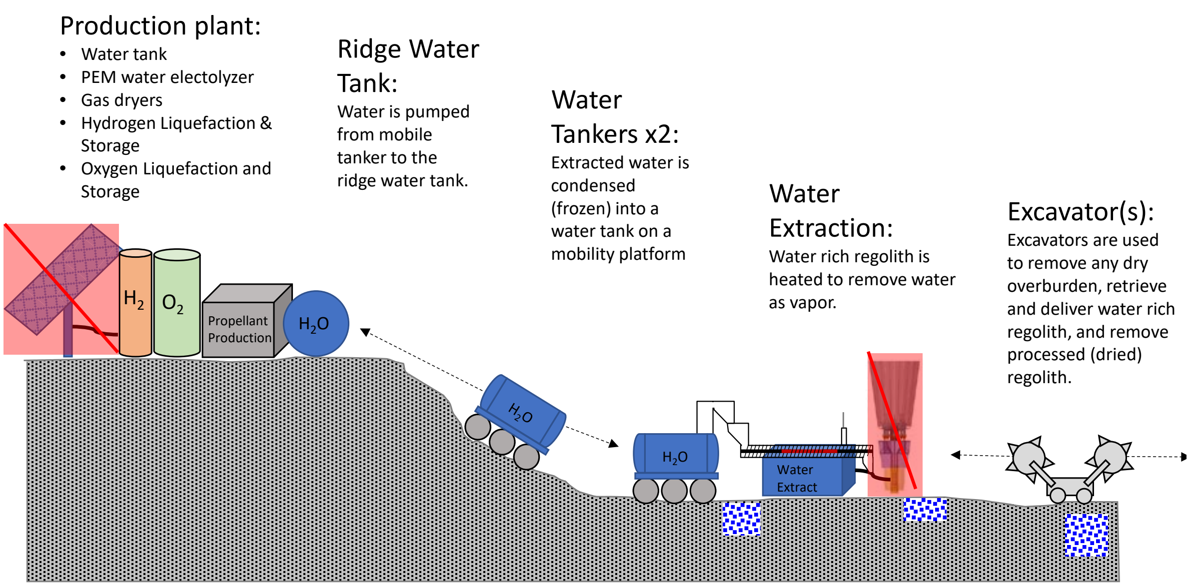

Figure 5. The ISRU architecture used in this trade study. Tentative power systems are shown for completeness, but were not included in the model.

At the mine site, water-ice rich regolith is removed using excavator(s) and delivered to water extractor(s) that are located at a fixed site. A pit-mine approach was baselined for this study, where the surface excavator(s) remove a dry overburden layer to reach resource rich material. Alternative options include mobile water processors[8] and in-situ processors[9]. It should be noted that a mobile processor was traded early using a 12.7 cm diameter, 1 m deep heated core drill from Ref. 8. While this scenario may be acceptable for small production requirements; propellant requirements for a human scale vehicle (10 mT of oxygen) would require on the order of 20,000 drill holes, assuming regolith with 5 wt% water over the entire drill depth. Particularly since drill bit life span is on the order of 100 holes, this option did not trade well in the initial trade study.

Within the mine site, there are 3 locations of interest (Fig. 6): the water ice mine site, the tailings site where dry material is deposited, and the water extraction site where water is extracted from the regolith. The water extraction site is also where the excavator recharge station would be located, as this is where the power source would be needed. During overburden removal, the excavator(s) travel between the mine and tailings sites. Occasional trips to the extraction site are made when recharge is required. During active water processing, the excavator(s) travel in a triangle. Fresh material is retrieved from the water ice mine site and delivered to the water extractor. Dried material is removed from the water extractor and delivered to the tailings site before returning to the mine site. The distance between the mine site and extraction site is assumed to be 100m. The distance between the tailings and mine sites depends on the size of the mine. Considering a mine with ramps for access (Fig. 6, Ref. 10), the tailings site distance is equal to half the mine length plus 10 m. The number of excavators is calculated based on processing time available, travel times, and quantity of regolith needed (kg/hr). Since overburden removal must occur before water extraction can start, a larger overburden reduces the amount of time available for water extraction & processing. Therefore an iterative loop is used to optimize the number of excavators against overburden and processing needs. Regolith delivery to the water extractor is on-demand and constant. So delivery occurs just when the soil hopper is depleted. The number of excavators also takes into account this time constraint, along with time needed for excavator battery recharge (currently fixed at 5 hr). While there is no explicit contingency time held (e.g. if an excavator fails), the on-demand delivery rate is typically not fully equal to the excavator round trip time, so the excavators typically have to wait before delivering into the hopper. This additional time is accounted for in excavator battery consumption.

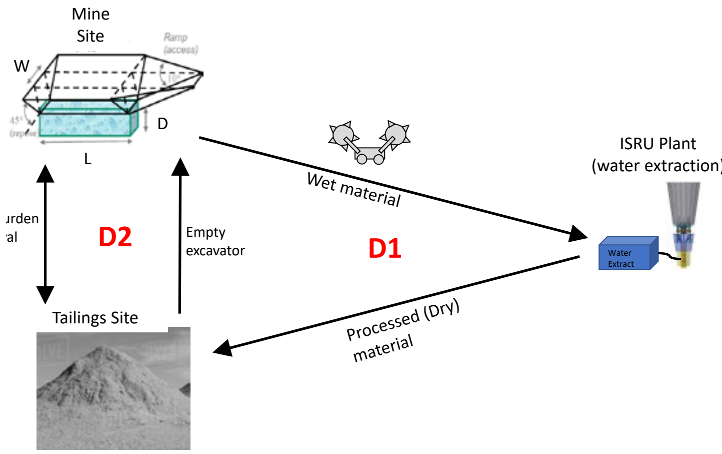

Figure 6. Mine site traverse operations, where D2 is traversed during overburden removal and the D1 triangle is processing operations. An example power system is shown at the extraction site for completeness.

The extracted water is captured directly into the water tank on the tanker. This means that 2 water tankers are required so that one remains with the water extractor, while the other delivers water to the water processor system. Fig. 7 shows the top level operation timeline for the water delivery. The size of the tank, and thus the size of the tanker platform itself, is based on how long the tanker spends collecting water at the mine site before transport. This is a top level input. Taking advantage of the low temperature at the mine site, water vapor leaves the water extractor and is allowed to freeze on the inside of the tank. Therefore, power is not required to maintain water state in the tank. Once the filled tanker reaches the ridge site, the water is allowed to thaw using solar gain. While the Compass study[3] of a pilot scale ISRU system included a radiator to control this heat transfer process, that option is not included here. The spherical tank is uncontrolled, with radiative losses calculated based on the environmental exposure. Once thawed, the water is pumped as liquid into the propellant production system water tank. As in Fig. 7, water processing at the ridge site does not start until after the first water tank is thawed and transferred. An additional delay is added to ensure that water processing is not interrupted, so water delivery is not on-demand. The water tank attached to the propellant production system is sized for this extra capacity. Note that while water processing at the ridge site starts later than the water extraction in the PSR, the water extraction ends sooner. Water extraction ends when the last tank is filled so that last tank can be processed at the ridge site within the 225 day time limit. The water extraction rate and the water processing rate typically end up very similar even though the individual timelines are not identical.

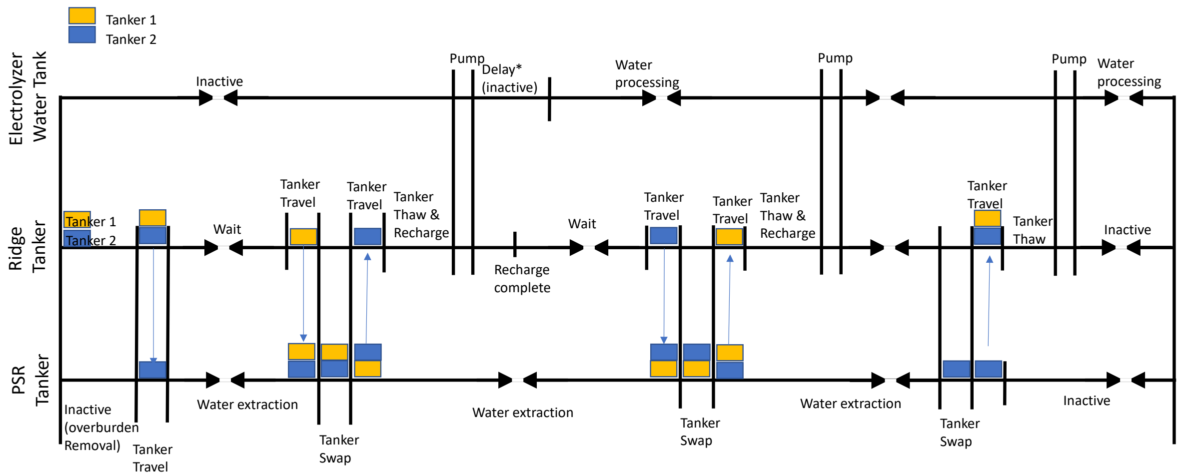

Figure 7. A graphical representation of the con-ops for the ISRU system. This highlights the movement of the water tankers which drive the production processes.

D. Technology selection: Baseline

Table 2 lists all of the technologies that were used in the model for each subsystem. As mentioned, technologies with empirical performance data were preferred, so the selections are not optimized and are not decisional. The excavator is the RASSOR vehicle[11]. This technology was designed for excavation in low gravity, using dual bucketwheels to offset the gravity forces. The digging implement is a bucketwheel, which is a surface excavation technique. This means a trenching, or pit mine approach is required for subsurface access. While performance data exists for operation in lunar simulants, including with ice, its limitations at higher water concentration (e.g. approaching saturation and higher) are unproven. The excavator delivers to a hopper, which size sorts and meters the regolith into the water extractor via a conveyance auger at its bottom. The baseline unit is a laboratory system, not optimized for flight in terms of mass or power. Two hoppers are needed to accommodate both bucketwheels for the regolith processing rates required here. The mass and power for these hoppers are included in the water extraction subsystem. The water extraction subsystem is the same design used in Ref. 4 and is based on a detailed sizing model built using Ref. 12. The model was adjusted for lunar conditions including soil properties and operational environment. Breadboard hardware has been built[13] so that model validation can occur with lunar simulants.

The water tanker (a water tank on a mobility platform) parameters are fully calculated. The tanker is not based on an existing system, rather the model is to be used to define the requirements. The tank itself captures water by freezing the incoming vapor. It is sized based on water capacity with a 50% ullage. Freezing and reheating is accomplished via radiation from/to the tank surface. The mobility platform that carries the tank is sized based on a payload mass ratio of 1.5. The battery mass and the water tank are considered payload, as well as an assumed communication and navigation system mass. An calculation determines battery capacity needed for the travel time. Since battery consumption is impacted by the battery mass itself, this is an iterative calculation. The tanker only draws on the battery during the traverse and recharges and draws maintenance power both at the mine site and the ridge site. The tanker also has a dust tolerant umbilical[14] for power and fluid connections at both sites. The passive portion of this umbilical is on the tanker while the active portion is on the extractor and propellant production subsystems.

At the propellant production system, a fixed water tank is sized to hold more than the tanker capacity to ensure no interruption of processing. A commercial off the shelf (COTS) pump and motor are selected based on a lookup table for flow rate. This same look up table is also used for the electrolysis system pumps. Electrolysis is accomplished using a polymer electrolyte membrane (PEM) liquid cathode feed. Note that no water cleanup systems are currently captured explicitly in this model. The criteria of such a unit is still unknown as water contaminants are yet to be defined. However, evaluation is currently underway using predictions from Ref. 15 and Ref. 16. Desiccant gas dryer subsystems are included on both the O_2 and H_2 streams to separate any remaining water prior to liquefaction. These units are modeled off breadboard regenerative dryer systems in development at NASA. The liquefaction subsystems both use a series of cyrocooler models to determine mass and power requirements. Hydrogen liquefaction in particular, is a major system power driver. The NASA cryo-fluid management group supplied the hydrogen liquefaction portion of the model. At set conditions, the mass and power varies linearly with production rate, so the results of this model were curve fit for integration into this trade study. The radiator temperature was set to 300K, which is the lowest mass solution. Finally, the propellant storage tanks were sized assuming aluminum walls. No additional power is included for storage maintenance since liquefaction would take place directly in the tanks.

Table 2. The different subsystems and the technologies selected for use in this case study.

Subsystem	Technology	Description & Reference
Excavator	RASSOR	A dual bucket drum excavator.[11]
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.[12]
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) [14].
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_2 Liquefaction	Cryocoolers	Modeled off COTS, includes radiator mass estimate
O_2 Liquefaction	Cyrocoolers	Modeled off COTS, includes radiator mass estimate
H_2 and O_2 Storage (Tanks)	Sized: Aluminum thin wall (3mm)	Calculated based on capacity.

IV. Results

The follow case studies address the impact of some of the key model inputs. Since the use-case for an ISRU system is still being defined, and since there is still much unknown about the water-ice deposits, these case studies are intended to show the sensitivity of the system to these inputs. The results will be presented as bar graphs showing mass and power of each subsystem to highlight the primary contributors. The bars are color-coded to match which system they are a part of. For mass they are grouped: mining system (blues), water transport (reds), or propellant production system (orange). This mass division helps show what may be needed in terms of lander/deployment requirements at each location. The water transport tankers could be landed with either system, but are included in the ridge system mass for the bar graph summaries below. In terms of power, the subsystems are grouped by the location where the power is required, mine (PSR) or propellant production (Ridge). Note that the water transport ("tanker") requires power at both locations, since there is always one tanker at each location. Again, no power solution is specified here, only the amount of power needed at the two locations is shown.

A. Key Inputs

The following is a description of the key inputs along with the values for the baseline (control) case. The baseline inputs are also shown in Table 3.

1) Production Requirement: This is the total product required by the system at the end of the specified time frame. For this study, the total production time is fixed at 225 days, so a larger production requirement means a higher production rate, resulting in a larger system. The baseline value is 10mT of oxygen.

2) Regolith Water concentration: This, along with the extraction efficiency, effectively defines the yield per gram of regolith. A higher concentration means less regolith needs to be processed. The water concentration defined here is the bulk water concentration of the regolith by mass (wt%). So if the water is patchy over the mine area, this is the average concentration over the mined mass. The baseline value is 5 wt% (Ref. 15).
3) Overburden depth: A dry layer of desiccated regolith is anticipated over a water-ice deposit[17]. For the pit mine excavation technique used here, 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 baseline overburden depth is 20 cm.
4) Time before water transport: This time defines the number of trips required to/from the mine site. The more time between water transports means fewer trips for the tankers but also requires larger tankers. Qualitatively, fewer trips is likely desirable from lifespan (wear) and risk standpoint, but from a mass/power standpoint this preference isn't born out quantitatively. The baseline is 10 days between transports, which results in about 20 trips.
5) Mine depth: This is the mined depth of the water-ice rich regolith deposit, not including overburden depth. In this model, the area of the mine is assumed to be square. A shallower mine would require a larger surface area to meet total regolith requirement. The baseline mine depth is 30 cm.

Table 3: Key inputs for the baseline case.

Water concentration	5%
Production requirement	10 mT O2
Actual production	13 mT O2, 1.7 mT H2
Water required	15 mT water
Regolith required (75% extraction efficiency)	398 mT
Mine size at 30cm depth	32m x 32m
Time before water transport	10 days

B. Baseline case results

The mass and power results for the baseline case are shown in Table 4 and Fig. 8 (note the logarithmic scales to capture the wide range of magnitude for the different subsystems). This case assumes a production requirement of 10 mT of oxygen propellant, with enough hydrogen to support the mixture ratio of 6. This is an estimate for the amount of propellant needed to support a human scale ascent vehicle or lander. Without a specific lander or ascent vehicle to base this on, 10 mT of oxygen is an approximation based on current and previous architecture estimates[18].

The primary mass drivers are the two water tankers and the hydrogen liquefaction subsystem. As mentioned in the previous section, the amount of time the tank spends at the mine will impact the tanker size. In the baseline scenario

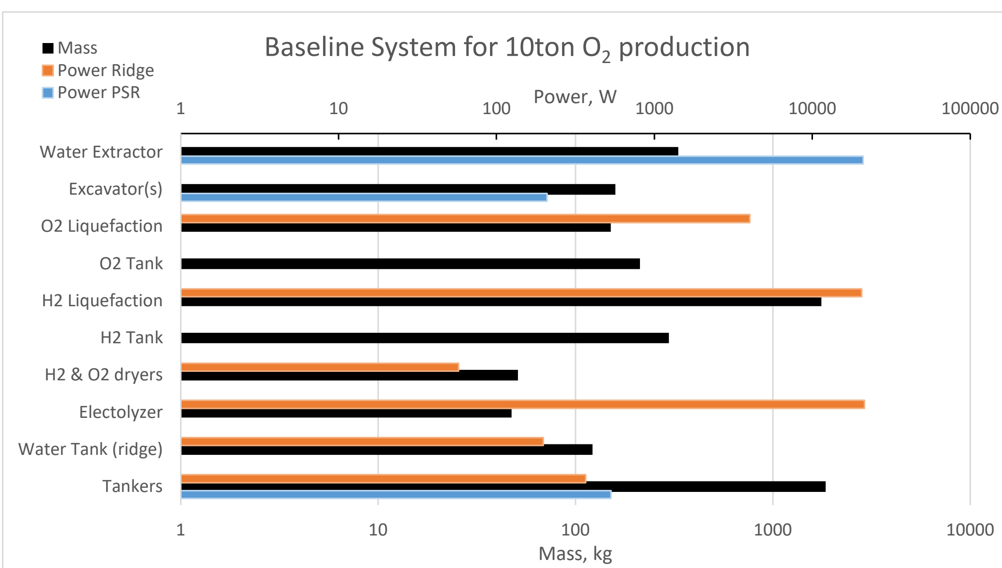

Figure 8. Mass (corresponding to bottom axis) and power (corresponding to top axis) for each subsystem in the baseline case. Note the logarithmic scales.

it spends 10 days collecting water at the mine site, so it has to carry about 800 kg of water per trip. Other options considered included using a single tanker where the mine system would need to remain dormant during transport, and an option using a single mobility platform that picked up and swapped water tanks between the locations. The former did not trade well due to the mismatch in operational timing of the propellant production and mine systems, and ultimately did not save much mass because the water capacity per trip was higher. The latter option required 3 water tanks total as well as hardware at each side to aid in the swap.

The primary power drivers are the hydrogen liquefaction subsystem, the electrolyzer, and the water extractor. The water extraction subsystem is a conceptual system, and there are still many unknowns in terms of efficiencies and regolith parameters. Continued technology development should solidify and, hopefully, reduce this estimate.

Both mass and power drivers have one subsystem in common; the hydrogen liquefaction subsystem. This is an area of interest for continued technology development. Performing the liquefaction at the mine site, in other words at a very cold shadowed region, has been suggested as a way to improve this. However, note it is the radiative environment that influences this, and whether you are in the PSR or at the sunlight ridge, the radiator would be oriented to view the sky at 4K.

Table 4. Tabular results for the baseline case.

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

C. Key Trades

Figure 9 shows the impact of the key variables listed in section IV-A. Mass and power results are shown by subsystem. The baseline system results from section IV-B are shown, and identified, in each of the graphs for comparison. Only one variable was changed for each plot series in Fig. 9, otherwise the baseline values were used.

The obvious key factor influencing the size of the system is how much propellant it needs to produce. This variable is shown in Fig. 9A. 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.

Fig. 9B shows the impact of regolith water concentration. The values chosen are consistent with the neutron data[15] when considering the unknown heterogeneity over depth. The transition between 1% and 2% for both mass and power is most notable. This indicates a breakpoint, where 1% water content is less likely to be a viable ISRU solution. Note that the driver of this transition is the mine (PSR) system, particularly in the power profile; the propellant production (ridge) system is largely unchanged. The amount of regolith needed for a 1% case is nearly 2000 tons. To meet this, multiple water extractor units are required (where their per-unit size exceeds the scalability limit, so more units are added), which results in a higher power and mass. Above 5% the system numbers start to level out since the minimum number of units is reached.

The impact of overburden depth is shown in Fig. 9C. The effects here are a bit more complex. The number of excavators is balanced against production needs and overburden removal time. The model is designed to minimize excavators. For example, both 20 cm and 50 cm overburden require 2 excavators. However, 50cm overburden requires more time to remove so there is less time available for production. Therefore the rest of the subsystems are scaled up to meet a higher production rate. 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.

The amount of time between water transports in Fig. 9D mainly impacts the size of the water tanker. Therefore the impact is primarily on mass, longer time between trips requires a larger water tank. From a mass standpoint, the less time the better. However, what is not captured here is the number of traverses the tanker needs to make in and out of the PSR, and the wear and risk involved in each transverse. For example, 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. However, it is difficult to judge what an appropriate number of traverses would be, because no planetary exploration vehicle has ever performed at this level. The distance is around 5 km each way, the terrain involves slopes around 16 degrees over hundreds of meters (Fig. 4), and the properties of the material (especially in the PSR) are largely unknown. The operations are assumed to be fully autonomous, which increases complexity and risk even more.

While not shown graphically, it is worthwhile to note the impact of a few other factors. Mine depth was noted as a key variable in Section IV-A. A deeper mine results in less surface area, but would require deeper trenching. The model assumes that the overburden is removed and access ramps (Fig. 6) are created prior to any delivery of water-ice rich material. But for deeper mines, ramp building must continue as the water is mined. The model is currently not setup to capture this. The second factor of note is the distance of water transport, or the distance between the mine site and ridge site. Again, the model does not capture the impact of wear and risk to the mobility platforms. From a mass and power standpoint the distance does not have a significant impact until the travel time starts to interfere with the production times. The tanker must spend enough time at the ridge to melt the water and recharge the battery. A longer trip time would necessitate fewer tanker trips (and thus a larger tanker) in order to still maintain the overall con-ops. For the baseline scenario this starts to have a significant impact on mass and power at around 50 km, which would involve a roundtrip of 100 km for 20 trips.

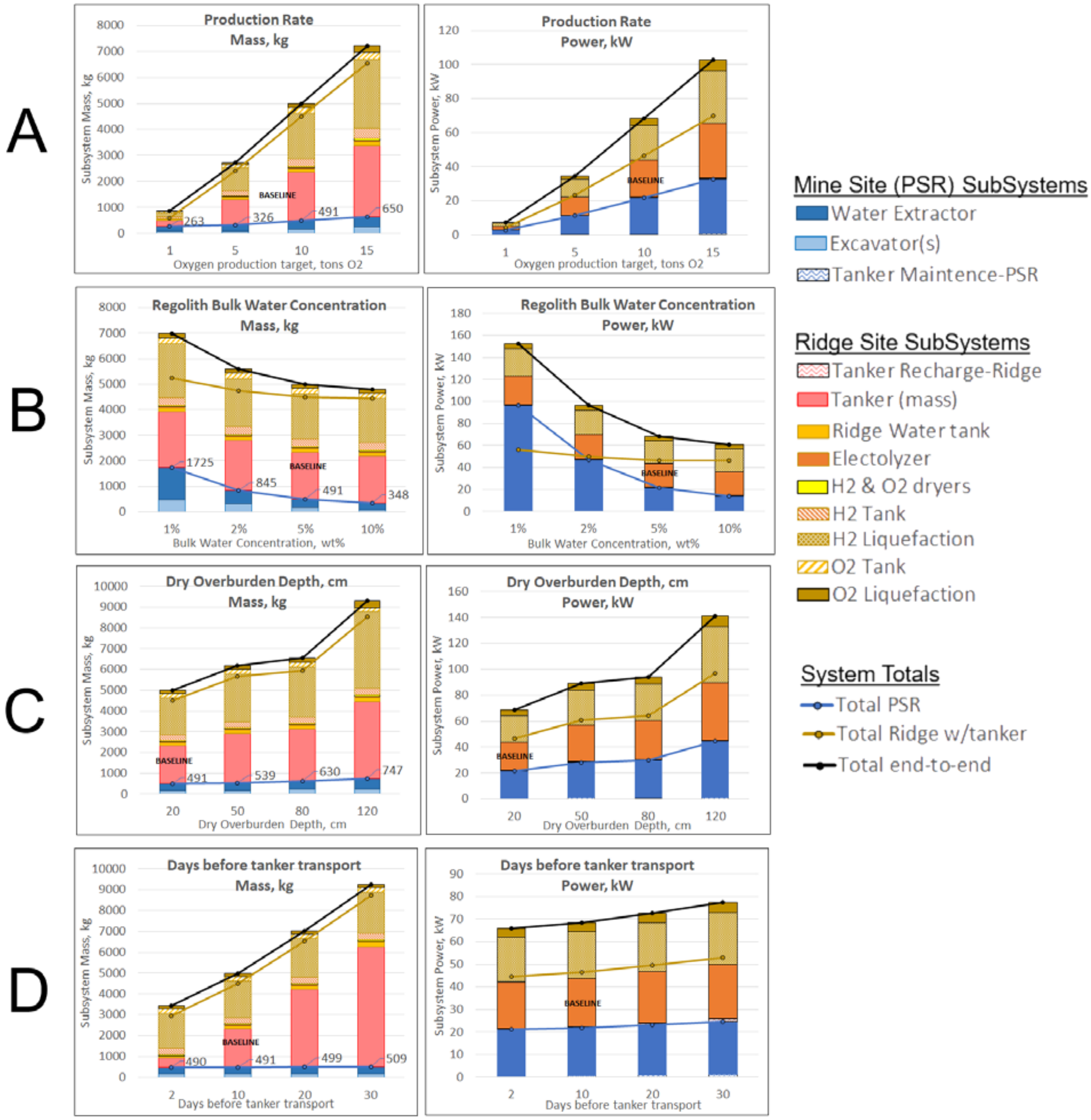

Figure 9. Results of the case studies for each of the key input parameters: A) oxygen production requirement, B) regolith bulk water concentration at the mine site, C) depth of the dry overburden which much be removed prior to production, D) number of days between water transport between the mine and ridge site. The baseline case is indicated on each of the sequences. Mass results are at left and power on the right. Colors indicate the subsystem contribution to each.

D. Water-Ice versus Oxygen from regolith

There are two primary lunar resources in consideration for ISRU. This study has focused on water-ice in cold traps at the lunar polar regions. However oxygen is available in silicate minerals within the polar regolith. Unlike the water, this oxygen is available anywhere on the lunar surface from the surface material. While the ease of access is much greater, the oxygen extraction process is high energy; the regolith must be melted. Also, only oxygen would be produced, so the fuel for propulsion must be transported from earth. A brief, preliminary comparison of the water ISRU system versus an oxygen ISRU system will be offered here.

A 10 mT oxygen extraction from regolith system was sized during a Compass study session in 2019[3]. This study baselined a carbothermal reduction reactor to extract the oxygen from silicate minerals. This is a three-step process, starting with the reduction of metallic oxides with a carbonaceous source at temperatures in the range of 1650 to 1800 degrees C. Methane is required to initiate the process, but is recycled. The study used the same total ISRU production time of 225 days. This was an end-to-end system including excavation hardware and liquefaction of the produced oxygen. However, it also included packaging on a lander for the complete system. An ISRU-only mass was provided (not including lander and bus) and will be used here for the comparison. A few differences in the assumptions are called out here, though others others may exist.

From a mass standpoint, the oxygen-only ISRU system is stated in Ref. 3 as 927 kg. However this does not include the oxygen tank (the study assumed that the lander tank is reused). The mass also does not include the hydrogen fuel (1.67 tons) which would need to be transported from earth, nor the tank to hold that. Using the water-ice model assumptions for tanks, the hydrogen from earth add 2.3 mT. However, it is very important to note that a solar array is included with the oxygen system to provide the electrical power. The mass of this solar array is 498 kg. The water case does not include mass for power systems. Taking this out of the oxygen system mass, the comparable masses are 2.7 mT for the oxygen from regolith system versus 4.9 mT for the water system.

For power, the oxygen from regolith ISRU system is 11.8 kW, versus the 68 kW for the full scale water system. However, the oxygen system uses direct solar heating to melt the soil via a solar concentrator. The estimated thermal power for the oxygen system is 33.3 kW. So the total system power is 45 kW, though only 11.8 kW is required of a surface power electrical source. The water system estimate of 68 kW includes 20 kW for the thermal power needed to extract the water with conservative conversion efficiencies.

While additional studies need to be conducted to ensure equivalent assumptions/assessment between the two options are being made, the comparison clearly reveals that an oxygen from regolith system is a lower mass and power option at this scale. Even with more optimized assumptions, it would be difficult for the water system to match the oxygen system, especially when you consider power systems and the higher complexity of emplacement of hardware and access of the resource. That being said, the value of producing fuel with the water system will increase over multiple missions; the hydrogen up mass of 2 mT per mission will accrue against the oxygen system.

V. Conclusion

A system model was generated to examine mass, power, and con-ops scenarios for an ISRU lunar water-ice system. For the sake of the case study, the location of a potential ISRU deposit was selected based on proximity to several Artemis Human Landing System site options. These locations were used to define system architecture assumptions and environmental conditions. The ISRU system architecture involves two sites; the mine site in a shadowed crater and the propellant production site at a ridge location where there are long periods of high illumination. Fixed hardware would be emplaced at each site. This also means that power would need to be supplied to each location. However, this case study does not include a power solution, but the power requirement is stated so that solutions can be traded. Additionally two mobility systems are needed. The excavators would stay at the mine site while two water tankers would transport water between the two locations. Technology solutions for each subsystem were selected based on those with the highest fidelity models or those that have empirical laboratory data to anchor to. Therefore, the result is not necessarily the most optimized solution.

The baseline case in this study assumed that 10 mT of oxygen, along with enough hydrogen to support a propulsion mixture ratio of 6 must be produced in 225 days. Therefore 15 mT of water would need to be collected and processed. The baseline solution resulted in a system mass of 5 mT; with the majority located at the ridge site (2.6 mT), 1.8 mT to support water transport using two tankers, and 0.5 mT for mine site hardware. The key variables that impact mass are production rate and time between water transports. While reducing the transport time would decrease mass, the increased number of trips would increase wear and risk, though this is not quantified. Total required power for the baseline case was 68 kW. Of that, 46 kW is needed at the ridge site, where solar power can be leveraged. The major drivers are the hydrogen liquefaction and electrolysis subsystems at 20 kW each. At the mine site 22 kW is needed with almost all (20 kW) dedicated to the water extractor subsystem. Note that both mass and power are most strongly impacted by production rate. A longer production time would reduce production rate without decreasing the amount of propellant produced.

The water based ISRU system was then traded against a system that would extract only oxygen from the surface regolith. Both systems targeted the same production requirement over the same time. Even considering the main assumption differences between the two models, and accounting for the mass of terrestrial hydrogen that would be needed for the oxygen from regolith case, the oxygen case clearly traded better in terms of both mass and power. The use of direct solar thermal energy to process the regolith and the ease of access of the resource resulted in significantly lower values for the oxygen from regolith case: 2.7 mT and 11.8 kW. However, the mass trade in particular would favor the water case over successive missions where the hydrogen up-mass of over 2 mT per mission will accrue against the oxygen system.

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