Assessing the Feasibility of a Martian ISRU Propellant Plant

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In-situ resource utilization (ISRU) is the process of extracting local resources to provide consumables for propulsion and regenerate resources for life support systems rather than transporting consumables from Earth. Numerous multidisciplinary technologies are required to interact and synergize to develop efficient ISRU systems. Cost-effective techniques to extract consumables from the environment is a critical element of the supply chain that enables a sustained presence on the Martian surface. To assess the feasibility of a full-scale Martian ISRU architecture, the Systems Engineering and Integration (SE&I) ISRU Modeling and Analysis (SIMA) project developed the Mission Analysis and Integration Tool (MAIT), a modeling tool capable of calculating the mass, power, and volume requirements of an ISRU system based on location, production requirements, Concept of Operations (ConOps), and environmental conditions [1]. This tool follows digital engineering methodologies to create a standardized logical framework that integrates subsystem models created by government, industry, and/or academia into an ISRU end-to-end system architecture. This allows for the interactions between all subsystems (and related systems such as power and transportation) within an ISRU process to be parametrically assessed and optimized rather than each subsystem independently analyzed.

I. Nomenclature

API = Application Programming Interface
ConOps = Concept of Operations
ESM = Equivalent System Mass
EVA = Extravehicular Activities
FSP = Fission Surface Power
ISRU = In-Situ Resource Utilization
K = Reaction Quotient
LEO = Low Earth Orbit
LOx = Liquid Oxygen
M2M = Moon to Mars
MAIT = Mission Analysis and Integration Tool
MAV = Martian Ascent Vehicle
MBSE = Model Based System Engineering
MEMLI = Multi-Environment Multilayer Insulation
MOXIE = Mars Oxygen ISRU Experiment
MRO = Mars Reconnaissance Orbiter
PEM = Proton Exchange Membrane
RWGS = Reverse Water Gas Shift
RPM = Revolutions Per Minute
SE&I = Systems Engineering and Integration

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SIMA = SE&I ISRU Modeling & Analysis
SOA = State of the Art
SOE = Solid Oxide Electrolysis
SOXE = Mission-Scale Solid Oxide Electrolysis
TRL = Technology Readiness Level
t = Metric ton (1000 kg)
x = Molar concentration shift

II. Introduction and Background

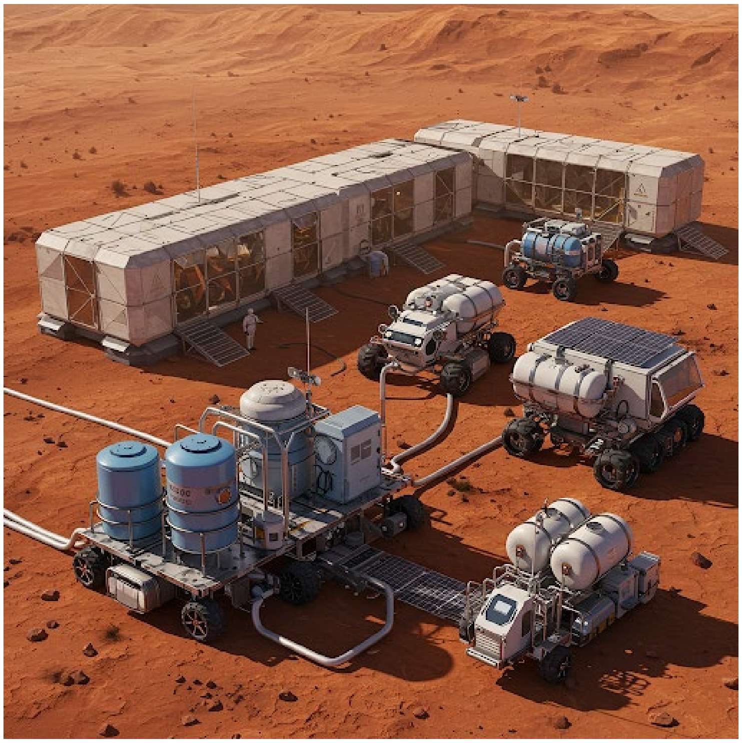

Figure 1 AI interpretation of a Martian ISRU production facility concept sustaining a temporary habitat

NASA's Mars mission logistics strategy was initially characterized within the Design Refence Architecture (DRA) 5.0 [1]. A major challenge identified in DRA 5.0 was focused on the difficulty of resupplying exploratory missions. The 26-month synodic window between Earth and Mars will not easily permit direct delivery methods, such as those employed for low Earth orbit (LEO), for longer missions, and will critically impact shorter sortie-class missions by limiting the system designs and amount of material that can be furnished enabling human exploration. In Situ Resource Utilization (ISRU)—the process of extracting resources from their natural state on Mars and converting them into a valuable commodity is the lynchpin to the DRA 5.0 surface operation success. Demonstrating cost-effective techniques is a critical first step to building a supply chain that enables sustained presence. Accordingly, a holistic ISRU system design intended to augment a Martian campaign will leverage both the planet's atmosphere and subsurface ice flows known to exist near mid-latitude locations [2]. Useful products include water (H_2O), oxygen (O_2), and methane (CH_4) for life support, extravehicular activities (EVAs), and ascent stage propellant. Similar ISRU case studies in Lunar environments estimated a substantial return on landed mass depending on production scale [3, 4].

System modeling is the ideal approach to address the Moon to Mars (M2M) capability gap CN-I-103M regarding operating exploration assets on the surface, where technologies are available at varying levels of readiness, and the full breadth of environmental conditions are not fully understood [5]. To assess the feasibility of a full-scale Martian ISRU architecture, the Systems Engineering and Integration (SE&I) ISRU Modeling and Analysis (SIMA) project developed the Mission Analysis and Integration Tool (MAIT), a modeling tool capable of calculating the mass, power, and volume requirements of an ISRU system based on location, production requirements, Concept of Operations (ConOps), and environmental conditions [3]. This tool follows digital engineering methodologies to create a standardized logical framework that integrates subsystem models created by government, industry, and/or academia into an ISRU end-to-end system architecture. This allows for the interactions between all subsystems (and related systems such as power and transportation) within an ISRU process to be parametrically assessed and optimized rather than each subsystem independently analyzed.

The SIMA team conducted analyses on a full-scale Martian ISRU production system for oxygen and methane cryopropellant, with the goal of recycling as much material as possible. The architecture considers chemical, physical, & thermal subsystem processes which were subjected to parametric iterations around key variables to better understand sensitivities to system mass, power, and volume. This design is broadly useful as it serves as a means of reexamining state-of-the-art (SOA) architecture upon which NASA and commercial sector teams are overseeing further research and design efforts.

III. Methodology – Architecture Definition

The origins of a Martian ISRU architecture can be traced back to the late 1970's, where the idea was conceived to react Carbon Dioxide (CO_2) from the Martian atmosphere, and Hydrogen (H_2) via electrolyzed H_2O from the soil, to produce a yield of CH_4 and O_2, respectively [6, 7]. Further iteration of the same fundamental architecture elements described by Ash (1978) led to the current trade space, whereby specific subsystems technologies (ranging from excavation to liquification) are selected to build a complete functional end-to-end system design to produce cryopropellant [8]. However, there remains a significant gap in the SOA between the demonstrated production scale and the processing rates required in the DRA 5.0, thus requiring continued pursuit of high-fidelity ISRU technology options [9]. The objective of this study was to expand on previous efforts to define a working Martian ISRU architecture utilizing new experimental subsystem models and MAIT to estimate system parameters and optimal design configuration within a parametric framework. The results bolster NASA's SOA and provide valuable information to commercial partners.

Table 1 Martian atmospheric composition (molecular weight = 0.0436 kg/mol).
***CO2 activity coefficient (γ) = 1.28**

Constituent Name	Wt%
Carbon Dioxide (CO_2)*	95.3
Nitrogen (N_2)	2.7
Argon (Ar)	1.6
Oxygen (O_2)	0.13
Carbon Monoxide (CO)	0.07
Water (H_2O)	0.03

Two cases at large scale are considered in this study: 30 & 300 metric tons (t) of liquified O_2 & CH_4 produced during the course of a Martian year (~687 Earth days), at a ratio of approximately 3.5:1, respectively. This is the correct blend of propellants to service a Martian Ascent Vehicle (MAV) [8]. The Martian ISRU process flow diagram is shown below in Figure 2. Carbon sourcing from atmospheric CO_2 was unchanged from previous SOA because of the ubiquity in the Martian environment and relative simplicity to collect (see Table 1). In contrast, traditional soil excavation and water extraction methods were foregone in favor of an alternative concept due to questions surrounding less than ideal soil composition and risks stemming from surface infrastructure complexity. Instead, an extraction method originally developed for polar field tests—a Rodriquez Well or Rodwell—was substituted into this phase to analyze its feasibility. It is possible that subsurface water resources could be located in remote regions outside the boundary of an ISRU plant, therefore transportation was modeled using a mobile tanker to estimate delivery fulfillment between peripheral surface and centralized processing locations. The accumulated liquid water store feeds a solid oxide electrolyzer (SOE) subsystem [OxEon Energy; Salt Lake City, UT], and subsequent O_2 gas from the anode is sent to a cryocooling/liquefaction storage stage. At the cathode, generated H_2 and unreacted water are sent to a downstream heat exchange and novel condensing radiator stage for liquid-gas separation. The high weight percent H_2 gas stream is mixed with CO_2 collected via filtered scroll pump [Air Squared; Thornton, CO] and used to feed several reactors in series to produce CH_4. Although many possible system configurations exist, the strategy employed in this study involved two Reverse Water Gas Shift (RWGS) reactors, in which CO_2 and H_2 are subjected to high-temperature equilibrium conditions to preferentially form CO and H_2O. Methanation of CO occurs following the gas shift. The reaction netted water streams from the condensing radiator are recycled back to the head of the plant for increased H_2 production efficiency. Produced CH_4 is finally further polished and prepared for 90 K cryostorage, similar to liquid oxygen (LO_2). Power generation for the entire system was assumed to be provided via fission surface power (FSP), a conceptual thermonuclear process capable of converting nuclear fuel into thermal power. The mass of the power infrastructure was equated using a power equivalency factor based on the mass of a 40 kW FSP unit estimated by subject matter experts.

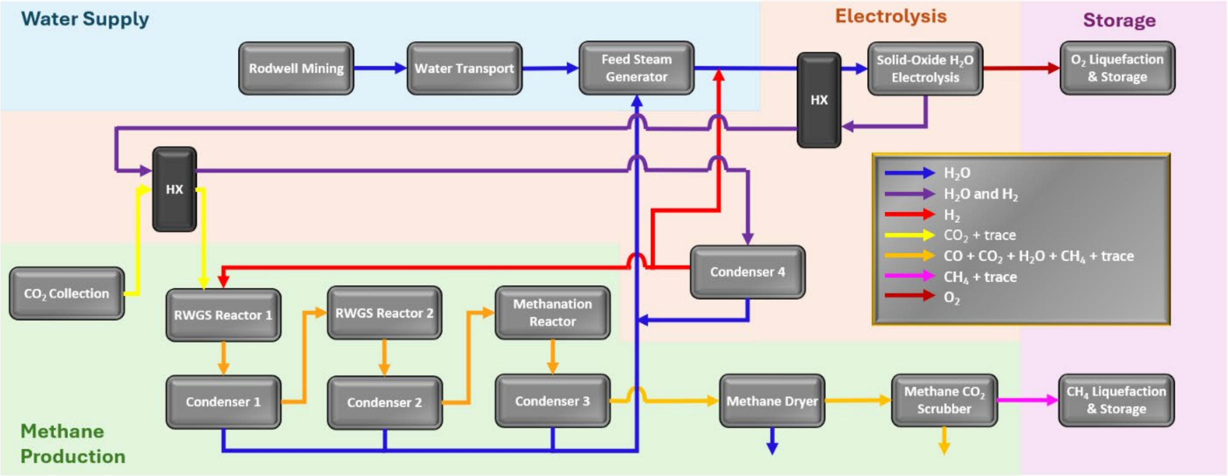

Figure 2 Martian ISRU broken into subsections. Background color breaks down ISRU plant sub-processes with multiple subsystems, arrow color indicates constituent streams. Water supply (blue), Electrolysis (orange), RWGS & methanation (green), liquefaction & storage (purple).

IV. Subsystem Model Details

A detailed description of the MAIT framework in MATLAB/Simulink can be found in previous published sources [3]. The principal feature of the tool includes a base layer of wrapper scripts, intentionally written with a standardized framework to interact with Application Programming Interfaces (API) in a variety of software packages (including Excel, COMSOL, and Thermal Desktop). The tool then integrates subsystem models to accurately pass information, such as mass flows, temperature, and pressure; estimate landed mass, power, and volume; and gauge system sensitivity to model variables. The subsystem portfolio includes a novel collection of custom-built, commercial, and government technology models. SIMA's ISRU model portfolio is one of the foremost accessible repositories spanning the breadth of known information on planetary commodity development within the recent SOA. The following section briefly summarizes the subsystem models implemented in the architecture described in the section above:

- **Rodwell Mine**

The design was first described in the U.S. Army Corps of Engineers design for Arctic base camp water resupply [10]. Subsequent to a layer of overburden removal, steam is pumped into subterranean ice creating cavity formation. A liquid reservoir is formed in the cavity body, which is assumed impermeable due to the characteristics of subsurface ice, and water is pumped to the surface at regular intervals. The subsystem model contains thermal-physical equations to determine mass and energy balance, including liquid, solid, and gaseous conductive and convective regimes, between ice walls, liquid reservoir, and cavern air. Most importantly, given a set of input conditions from the user, the model calculates if the well will collapse, i.e., a withdrawal rate greater than the reservoir volume. The input conditions were iterated upon until the withdrawal rate matched the requirements for water transport.

- **Water Transport**

The surface water transportation rover subsystem consists of a mobility chassis and water tanker [11]. The model uses as-built design specifications, such as average velocity, and rate-based calculations to align an operation of two tankers simultaneously filling and draining their payload between the Rodwell mine and the nearby plant. The chassis design grants a mass transfer limit of 5 m^3. The distance between locations is assumed to be 1.5 km. The model calculates the transportation commute time and sizes the battery accordingly. Future iterations of this system model will include Mars Reconnaissance Orbiter (MRO) data to build systems optimized for specific Mars locations (see Section VI Future Work).

- **Heat Exchange/Steam Generation**

Previous trade studies purposefully did not consider heat balance as a major factor in the system design [8]. The addition of thermal management is anticipated to be an advantageous part of a complete ISRU system design, as recycling heat results in substantial power demand reduction. Several models were created in-house among the SIMA team, such as the heat exchange process and steam generation stages dividing cold temperature inlet streams from hotter reactor systems. The logic for both subsystems consisted of a first principle enthalpy balance of inlet streams. The Feed Steam Generator determines the energy required to take two influent water streams at given temperatures and pressure to a single steam outlet flow. The conversion factors in both sensible and latent heat using the NIST REFPROP add-on tool [12]. The heat exchanger model was developed from crossflow design equations based on an assumed temperature difference and energy balance [13]. The heat exchanger size can then be determined.

Solid Oxide Electrolysis

The solid oxide water electrolyzer used in this case study is based on the mission-scale solid oxide electrolysis, or SOXE, developed by OxEon Energy for previous Lunar and Martian trade studies [14]. The model employs fundamental electrochemical equations, including the Nernst Equation to find non-standard reaction voltage, Ohm's Law to determine current, and Faraday's Law to finally determine anode O_2 production. Many of the sizing equations are determined using cell voltage, resistance, and dimensions from OxEon's early design experimentation.

Condensing Radiator

The condensing radiator subsystem provides heat rejection based on the radiative and convective environment that is anticipated to be experienced on Mars. The radiator face is assumed to be exposed to conservative surface temperatures, e.g., warmer conditions of the Martian mid-latitudes reported by the Viking II landing, and with a 50/50% view to the sky and ground. The radiator enthalpy balance was then estimated as a system of linear equations. The internal operation is expected to perform the following: hot gas enters the condensation chamber, the model calculates the temperature drop per length of line needed to decrease the temperature to the triple point of water (i.e., achieve a vapor quality of 0). With water now in the liquid state, it is envisioned a membrane or water wick would then draw the liquid away from the remaining gases.

CO_2 Collection

The system CO_2 collection step was derived from technical specifications and pump curve correlations from the Mars Oxygen ISRU Experiment (MOXIE) scroll pump [15]. The amount of CO_2 compression required stems from user-driven determination of system H_2:CO_2 ratio—a parametric variable, which is described in later sections. In other words, the H_2:CO_2 ratio is a system-wide tunable variable that connects two independently operating subsections, electrolysis and methanation, within the overall system. The scroll pump then determines the number of pump units required to reach the desired input flow rate to the first RWGS reactor. Other important design considerations that factor into the pump power demand include the revolutions per minute (RPM) necessary to achieve compression, which is interpolated using test data.

RWGS and Methanation

The RWGS and methanation module consists of three reactors-in-series separated by a condensing radiator for water removal. H_2 and CO_2 from upstream process form the inlet feed, where applied heat preferentially drives the reversible reaction towards a syngas product, chiefly CO and H_2. Both the RWGS and methanation processes occur under thermodynamic equilibrium conditions, which is governed by stoichiometry and Gibbs free energy equation that in turn affects the reaction quotient (K). The amount of concentration shift (x) that occurs to the reactants and products at the specified temperature was solved quadratically, all of which is in accordance with Le Châtelier's principle [16]. It is important to note that the gas composition of an upstream reactor were subsequently the inlet feed to any downstream reactors. Therefore, each reactor had to be modeled as separate subsystems to accurately capture dynamic initial concentrations of CO and H_2O, as well as potentially unreacted constituents H_2 and CO_2 from the overall module feed.

$$CO_2 + H_2 \Leftrightarrow CO + H_2O \tag{1}$$

$$K_{RWGS} = \frac{[CO_0 + x][H_2O_0 + x]}{[CO_{2_0} - x][H_{2_0} - x]} \tag{2}$$

Based on OxEon's methanation reactor test results [17, 18], the primary reactants dictating CH_4 production were CO and H_2. As validation that the reactor conditions have nearly 100% CO conversion efficiency to CH_4, the Gibbs free energy, and the reaction quotient with the extent of reaction were estimated under the appropriate temperature and flow conditions of the third reactor. Solving the cubic equation resulted in a root that was the exact same value as the inlet CO concentration, thus allowing the total module outlet gas molar concentrations to be accurately expressed. Any recalcitrant CO_2 remaining through two RWGS steps was assumed to have a modest conversion efficiency, as measured experimentally (not shown).

$$CO + 3H_2 \Leftrightarrow CH_4 + H_2O \tag{3}$$

$$K_{Methanation} = \frac{[CH_4+x][H_2O+x]}{[CO_0-x][H_{2_0}-3x]^3} \tag{4}$$

Methane Cleanup

A subsystem model was developed to include logic and sizing calculations for a CO_2 and humidity scrubber, as a way of simulating the gas cleanup steps necessary for removing undesirable constituents leftover from the RWGS and methanation module. It was conceivable that not all constituents would occur in every design iteration. For example, if the condensing radiator does not succeed in removing 100% of the humidity, a desiccant drying cannister is included to remove water. If there exists residual CO_2 from the upstream reactors, a CO_2 scrubbing cannister is added. Moreover, if excess H_2 occurs in any measurable amount (above 5 wt%), an additional Proton Exchange Membrane (PEM) electrolyzer is added to separate the methane from the H_2 gas. These devices are point solutions that are sized based on as-built specifications, either absorption capacity (kg absorbent/kg absorbate) or flow rate.

O_2/CH_4 Gas Liquefaction

The liquefaction and storage model determines the mass of a pre-cooling radiator and cryocooler to liquefy a relatively pure gas stream at 90K. The central equations within this subsystem estimate the number of tanks required to store the total propellant production volumes. The energy balance is resolved through an estimation of the heat leak from the tank wall and layers of Multi-Environment Multilayer Insulation (MEMLI) that are presumed for Mars missions.

V. Results

The complete Martian ISRU architecture—spanning water subsurface extraction and delivery, the thermochemical production stage, and finally cryostorage of the propellant commodity was assessed for feasibility under several distinguishing operating conditions. The parametric trade study encompassed 144 individual iterations around specific subsystem design variables, with major computational resources dedicated to converging mass balance on the five recycle streams from each condenser block (blue line in Figure 2). The overarching independent variables that govern the ISRU system included SOE stack configuration, H_2/CO_2 ratio in the carbon processing (discussed in previous sections), condenser water removal efficiency, and the cryostorage insulation. Although MAIT parametric analyses can comprise of any number of system variables, these were deemed the most critical based on subsystem model review.

The ISRU surface operation analysis indicate a substantial return on landed mass at full-scale plant sizes over the course of a Martian year (the nominal mass and power contributions are shown below in Figure 4 and Figure 5). For the 30t propellant production case, the system model estimated over 50% mass savings compared to baseline resupply-only strategy (23.3t O_2 & 6.7t CH_4). It was further observed that mass savings increased to nearly 75% at the larger 300t production target (233t O_2 & 67t CH_4), strongly implying that the subsystem operations become economical at higher production rates. This trend is also observed among previous Lunar ISRU case studies[3, 4]. It is important to note that the return on landed mass parameter compares infrastructure to raw resource values, and does not factor in the multitude of launch costs and infrastructure required to deploy packaged resource resupplies off-planet—this will be examined in future work. The methodology to find an optimal design condition at each production target was feasible on a first principles basis that compared favorably to similar Martian ISRU infrastructures [8].

The liquid methane and oxygen production strategy on the Martian surface constitutes a novel combination of government and commercial technology development. The utility in system modeling comes from the insight beyond a singular comparison of mass totals, i.e., deployed ISRU infrastructure vs open loop scenarios. In fact, detailed and high-fidelity modeling elucidates answers to key research questions and guides direct efforts to further advance the technology development space. This study identified several primary takeaways in this regard. Most critically, the model predicted that power generation systems account for a significant portion of the landed mass (34% of the total mass for 30 t plant and 59% of the total mass for the 300 t plant). Obvious identifiable sources of power demand (see Figure 4) clearly demonstrate that thermal power is at a premium, particularly for high temperature processes such as SOE and steam generation. Waste heat management was therefore a force multiplier when it came to hot and cold stream interfaces. A large portion of mass savings stemmed from the utilization of FSP, which traded better than solar arrays with batteries (see Figure 3) and would integrate well with thermal power-driven processes.

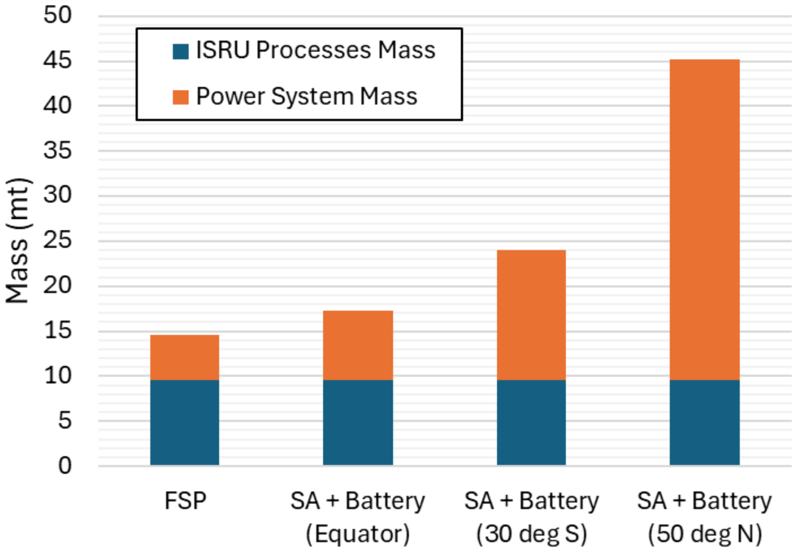

Figure 3 Power system mass equivalency (metric tons) for FSP vs Solar Array at various mid-latitudes

The SOE is the largest power draw of the system, accounting for 53% and 62% of the total plant power for the 30 t and 300 t plants, respectively. By contrast, the mass of the SOE is a small contributor to the system mass. For this reason, more optimization efforts should pursue as power efficient an SOE as possible, even at the cost of a higher mass subsystem. Continued research and development on advanced power generation systems, as well as establishing high-fidelity power generation subsystem models, has the potential to drastically reduce the overall system mass.

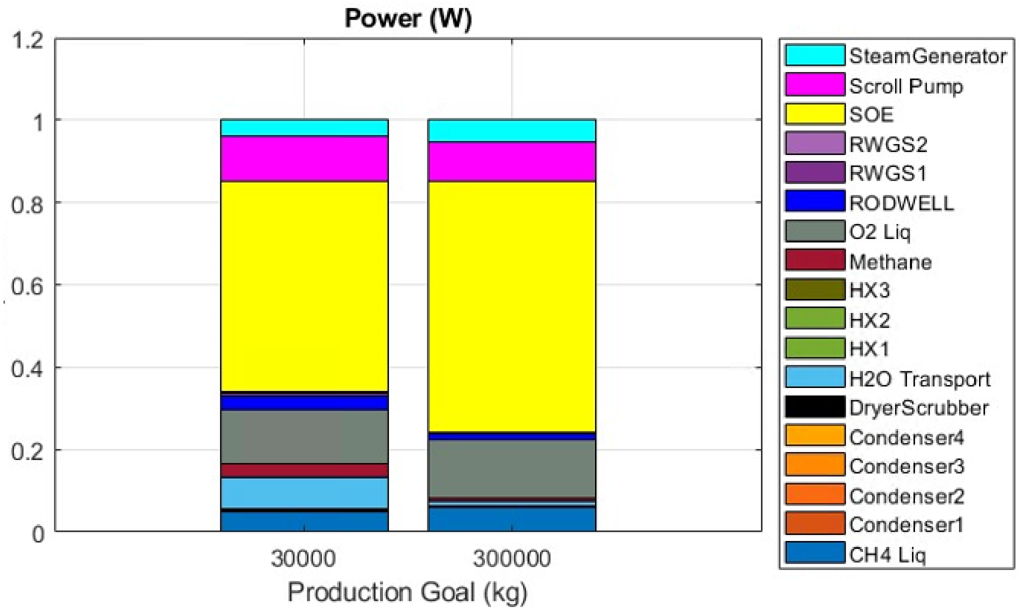

Figure 4 Martian ISRU subsystem power demand (W), normalized

Another takeaway was identifying the optimal ratio of H_2 to CO_2 in the RWGS and methanation processes. These ratios are vital to effectively manipulate equilibrium to achieve the desired reactor products. The objective was to create conditions in the first modules of the RWGS reactor to shift the syngas composition to majority CO, which Le Châtelier's principle would conclude is benefitted by increasing H_2 throughput in the reactor units and downstream methanation reactor. This means that there exists a threshold value of H_2:CO_2 necessary to meet production targets. It is further valid that higher concentrations of H_2 are needed to push the reactors to maximum equilibrium efficiency, particularly in the methanation reactions where unreacted H_2 from RWGS is necessary to form CH_4, and therefore decrease the mass of RWGS and methanation. However, the proposed ISRU configuration in Figure 2 is held together in a delicate balance, such that increasing H_2 mass flow rates to excess ignores the full breadth of system-level interactions upstream and downstream of methane production. Model sensitivity showed that increasing the H_2:CO_2 ratio by just 10% in an attempt to optimize methane production impacted the overall system mass by up to 2.5%. First of all, increasing H_2 requires modifications to the SOE and water collection systems, which in turn creates high power demand and/or unit scale. Moreover, if excess H_2 or CO_2 leaves the methanation outlet gas stream, this triggers additional infrastructure and power in order to reach necessary purity before CH_4 storage. Any inefficiencies in liquid condensate removal by the condensing radiators between subsystems similarly degrades performance because inlet water in the RWGS and methanation pushes equilibrium back to the reactants. The appropriate value for H_2:CO_2 ratio that achieves the objective production is a system-level variable that must incorporate significant engineering judgement.

On the other hand, system modeling within MAIT narrows the vast parametric space to inform technology developers of subsystem interface conditions that can be integrated together and provide the baseline values associated with the ground rules, assumptions, and constraints. The ratio between H_2 and CO_2 emphasizes the importance of system modeling. Optimizing an ISRU plant at a subsystem level may miss the effects of decisions on upstream or downstream processes. Water management throughout the delivery concept of operations (ConOps) from peripheral extraction sites and ISRU plant streams is critical to minimize the physical mass of deployed infrastructure. Results showed the water supply chain, i.e., the Rodwell Mine and Water Tank Transport chassis, constituted over 50% of the total system mass at the 30t production target. However, Martian transport technology is at a low Technology Readiness Level (TRL), and the technical specifications used for this subsystem model were originally correlated to the 300t production. Overall, this resulted in an oversized tanker with a trivial operating duty cycle versus downtime between filling and draining. In contrast, the water supply processes for the 300t production scale comprised only 11% of the system mass. The results made clear the need to appropriately size the water transport system between the Rodwell mine and the ISRU plant, especially at lower production scales (i.e. a scalable transportation subsystem model).

The ConOps of the transportation of water from the Rodwell mine can likely be further optimized to minimize the landed mass and power usage with further research (see Section VI Future Work). Reviewing results for water streams inside the ISRU plant, condensing radiator water removal efficiency also had some impact on the overall system mass. The condensing radiator subsystem model is a conceptual design in its current form, similar to water transport. In theory, according to the principles of vapor-liquid equilibrium, the unit should be able to fully remove water vapor in outlet gas streams. This judgement relies on many assumptions, however, and therefore the parametric space was designed to relax the 100% efficiency stringency. Reducing the water removal efficiency by a modest 10% (i.e., 10% water left in vapor phase), while holding all other variables in their most optimal state, will increase the overall system mass by hundreds of kilograms (nearly 2% of total system mass). For this reason, it is recommended to continue research and technology development on efficient condensing radiators capable of removing as much water as possible from a humid gas stream, as well as reviewing the concepts surrounding water delivery ConOps (see Section VI Future Work).

Finally, as production scales up to larger targets, the percentage mass contribution shifts heavily towards surface cryostorage infrastructure. Because of the vast volume of cryoliquid being made, more metal storage vessels are required, which results in a majority proportion to overall system mass. The liquefaction and storage processes make up nearly 25% of the total system mass for a 300 t plant. For this reason, alternative storage technologies (aside from metal), or a continuous use ConOps by a customer (i.e. directly refill launch vehicle and later transport vehicle to launch site), should be investigated in the future as a way of reducing the overall system mass.

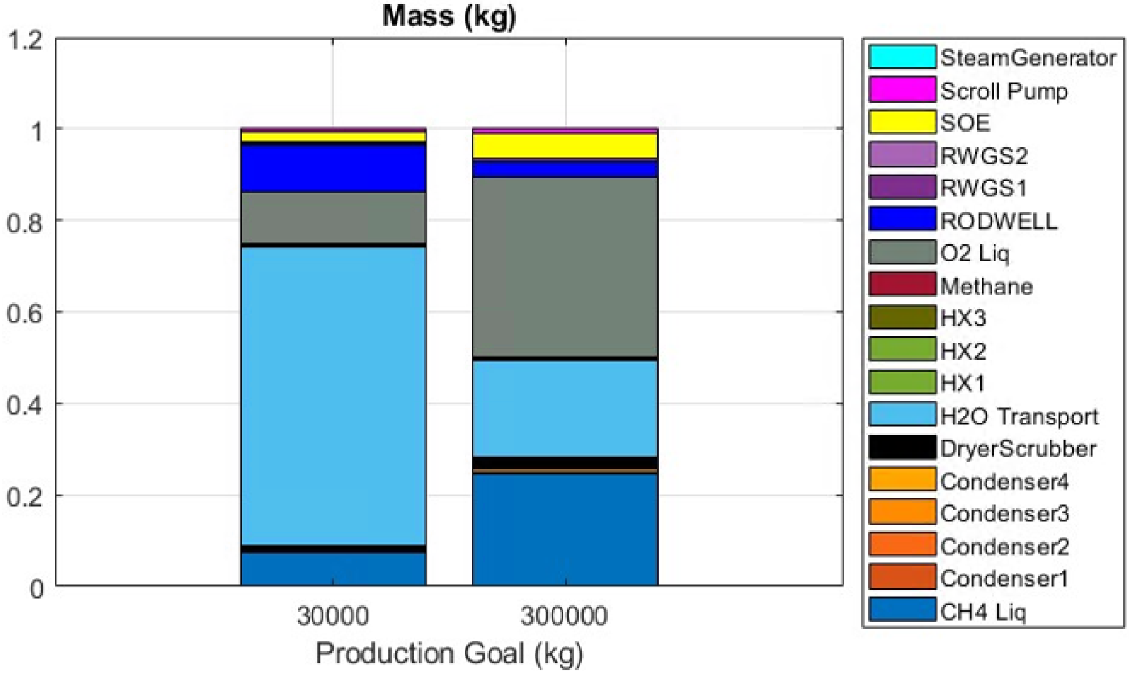

Figure 5 Martian ISRU subsystem infrastructure mass (kg), normalized

Subsystem Evaluation:

Two of the most common questions that arise from system-level ISRU modeling are: "What is the accuracy of your subsystem models?" and "How much confidence do you have in the results?". Ultimately, the answer is complicated due to the nature of system modeling, the availability and funding of physical subsystems, and the various degrees of fidelity to which models have been provided situated in an unknown environment. Model-based system engineering (MBSE) scoring framework organizes a qualitative evaluation of numerous subsystems of various type, range of activities, and level of development. With every case study, the SIMA team assesses each subsystem model within the ISRU architecture portfolio using a NASA Technical Standard 7009 [19]. The accepted set of criteria for modeling and simulation development (shown below) are ranked on a scale of 0-4 with 4 being the highest score and thus related to the highest level of model credibility:

- Data Pedigree: accuracy of input variables and traceability to real world system.
- Input Pedigree: accuracy of underlying equations used for model foundations.
- Verification: degree to which the model has been implemented correctly.
- Validation: accuracy of model in comparison to real world system.

- Result Robustness: knowledge on sensitivities of input parameters and comparison to real world system.
- Uncertainty Characterization: known analysis of the output uncertainty.
- Scalability: the degree to which the model is accurate over a given range of all inputs.

The Martian ISRU plant subsystem models demonstrated the highest credibility in its quality of subsystem variables and underlying equations (i.e., Input and Data Pedigree). For instance, the use of models from MOXIE, SOXE, and RWGS technologies is incredibly advantageous to teams replicating work in the digital domain, especially when the results hold up under first principles analyses. From the model results, the robustness of key variables also became evident, which positively correlated to a higher Equivalent System Mass (ESM) in the parametric analysis, like in the case of H_2:CO_2 ratio. Because the dynamics of a key system variable was examined, and not simply the physical structure, modeling results can now be used to broadly analyze interactions between processes. Conversely, some critical questions remain about how certain subsystem results would compare to test data. Therefore, the overall system retains a low score in Validation (as was the case for other architectures). In some cases, such as the heat exchanger and condensing radiator, detailed models were constructed with a high confidence in their proper implementation, but have not been followed by the construction of demonstration units. Other items, such as cleanup cannisters in the methanation chain, are commercial components, which may not require a detailed model, but require verification and some sense of scaling parameters in order for system modeling efforts to capture their effect in relation to other subsystems. Thus, the scoring in these areas reflect their deficiencies. In addition, the water supply subsystems could greatly benefit from an exploratory review of ConOps and input from knowledge geological subject matter experts.

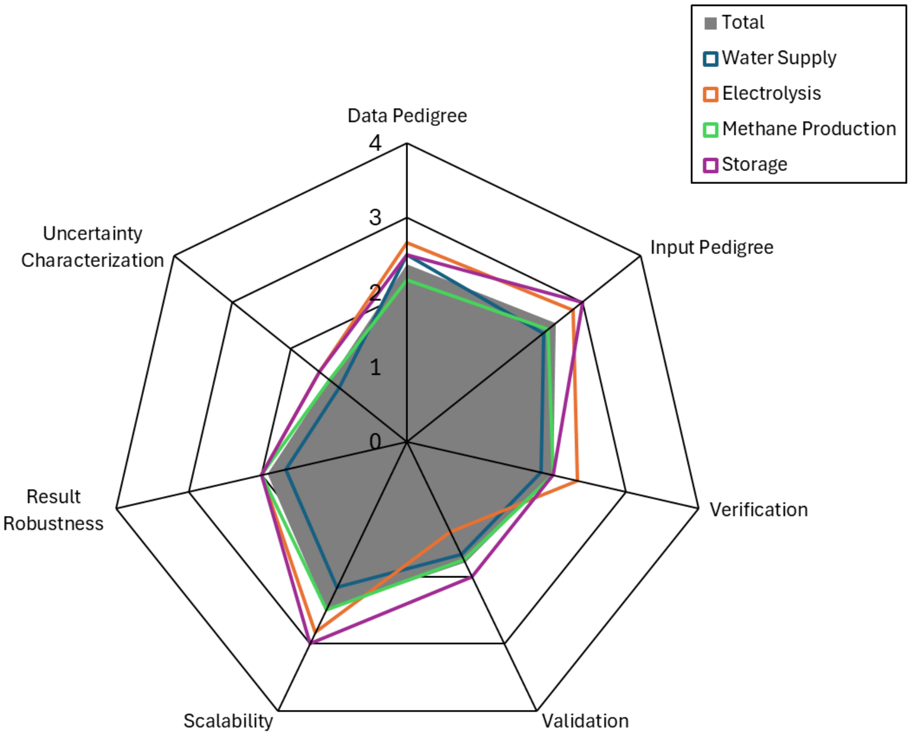

Figure 6 Spider Plot visual representation of NASA-STD-7009 model assessment rankings for the entire Martian ISRU plant (grey), and each of the individual system subsections. A rank of 4 indicates highest credibility, and 0 lowest credibility.

The Martian environment inherently contains a high level of uncertainty, and any forward-looking systems designs must account for a certain degree of unpredictability. The scores provided in Figure 6 fairly adjudicate this point. However, interdisciplinary and collaborative studies have effectuated a great deal of knowledge generation in this environment, and are ideal mode for reducing the effects of uncertainty. System modeling in MAIT has demonstrated with this Martian case study results that complement the current SOA. Further, MAIT provides a methodology to evaluate the completeness and credibility of involved subsystem models. Going forward with Martian ISRU, the

MBSE scoring highlights areas for improvement pertaining to technology development, continuity between subsystems, and clarifying uncertainty using knowledge from interdisciplinary subject matter experts.

VI.Future Work

FSP/Solar Array seasonal trade:

The SIMA team plans to obtain and implement a sizing model for the FSP so that the power generation mass can be calculated without having to use power equivalency factors. This will increase the level of detail at the component level and provide a better understanding of how FSP can integrate with surface operations. Further, the team intends to investigate the tradeoff of running with solar arrays and no batteries and only operating the plant during the daytime – accounting for variation in seasons rather than assuming only the worst-case scenario.

RWGS/Sabatier configuration:

The observed impact of H_2:CO_2 ratios on the methanation chain leads to further questions regarding how to best handle a complex set of gas streams in equilibrium. A couple pathways include identifying more modeling iterations and pilot-scale testing to refine the optimal H_2:CO_2 ratio to a RWGS inlet. Furthermore, alternative configurations could be considered, such as adding more RWGS reactors in a string, or step-feeding H_2 gas to certain points in the module. Another possibility would be the addition of a high efficiency Sabatier Reactor to supplement effluent CO_2 removal and improve the CH_4 conversion ratio.

Hydrated Minerals as alternative water supply:

The water supply ConOps is heavily reliant on site-specific conditions at the Martian mid-latitudes. Considering alternative water extraction options to the Martian ISRU concept could present new opportunities for mass reduction. One potential option worthing pursuit relies on evidence from the Martian planetary science community—the extraction of hydrated minerals detected widely on the Martian surface [20]. Various types of clay silicates have been detected on the surface using infrared spectrometry at 5-20 wt% concentration, and hydrated magnesium sulfates ($MgSO_4$*$7H_2O$) are predicted to exist in vast deposits at or near the surface [21]. Traditional robotic excavation would likely be able to handle the prerequisite soil excavation imagined in this method, while other challenges in water cleanup would need to be studied. With the addition of MRO location specific data, MAIT enables the comparison of commodity transport from a polar Rodwell mine to the ISRU system versus an equatorial ISRU plant excavating and extracting water near ideal habitat/launch sites.

VII. Conclusion

The Martian ISRU production system examined in this study demonstrates a feasible design solution for the production of 30 and 300t of propellant (O_2 and CH_4). The results sum each critical subsystem power demand and infrastructure mass, providing mission planners a return on landed mass for mission durations of one year or more (between 50-75% depending on production targets). Provision of Mars ISRU system architecture constitutes a major contribution to the SOA, and preliminarily addresses STMD and M2M goals. Sensitivity around key subsystem variables also led to several important observations:

- Despite the assumption that more efficient FSP would be available, power generation systems continue to account for a significant portion of landed mass.
- Efforts directed toward optimizing SOE power generation and heat recycling would result in the greatest power & thermal savings.
- Tight regulation of H_2:CO_2 in the inlet mass flow streams leads to better equilibrium outcomes. Efficient removal of reactant water further aids those system mass reductions.
- Water delivery and transport is an important step that must be appropriately sized to the production scale, or alternative strategies considered.
- Final storage of liquid cryopropellant is a considerable system mass contribution that could be reduced using alternative technologies, materials, or ConOps.

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