Assessing the Feasibility of a Martian ISRU Propellant Plant

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ASCEND, 24 July 2025

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How do we make rocket propellant on Mars?

Why do we want to make rocket propellant?

- To bring crew back home
  - Returning crew from Mars to the Earth will require hundreds of tons of rocket fuel
  - Transporting fuel to the Martian surface is expensive
- Mars has resources required to make valuable commodities
  - CO_2 in the atmosphere and frozen water under the surface can be used to produce liquid Oxygen and Methane
  - $CO_2 + 2H_2O \rightarrow 2O_2 + CH_4$

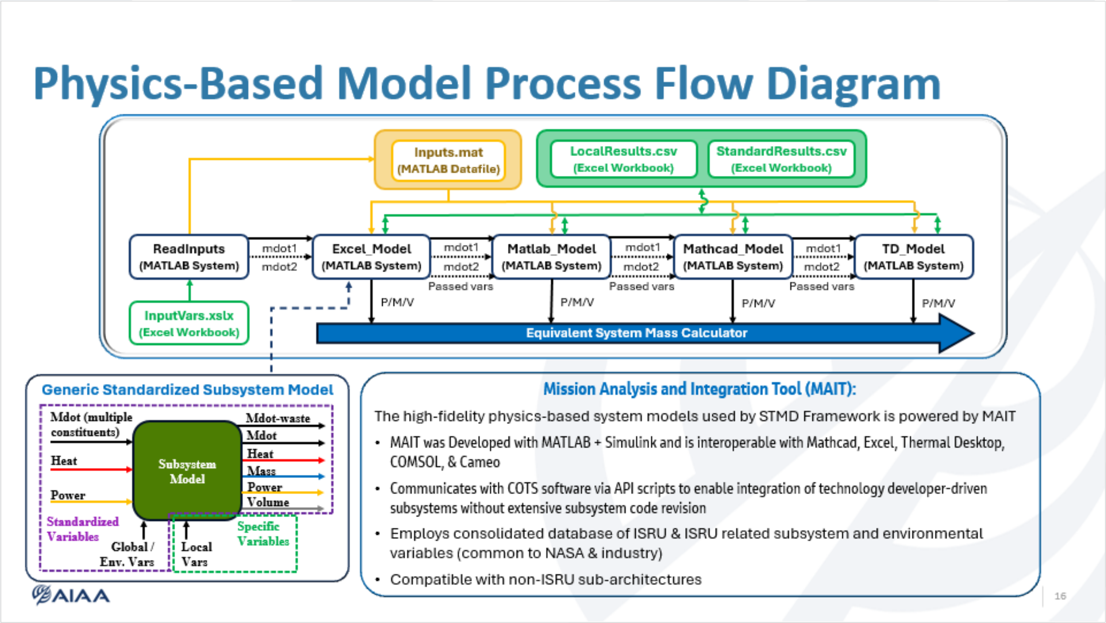
Challenges of Modeling

- ➢ Production of Methane and Oxygen requires understanding the full system from “end to end”
  - Understanding the feasibility of an ISRU propellant plant requires understanding of all infrastructure.
- ➢ Vast uncertainty in the critical inputs to development of a Martial ISRU plant
  - Technology selection – all technology is at different development levels
  - Concepts of Operation (ConOps) – numerous approaches to producing propellant
  - Resource availability – limited data on availability of water
  - Environmental conditions – environment conditions are not well defined

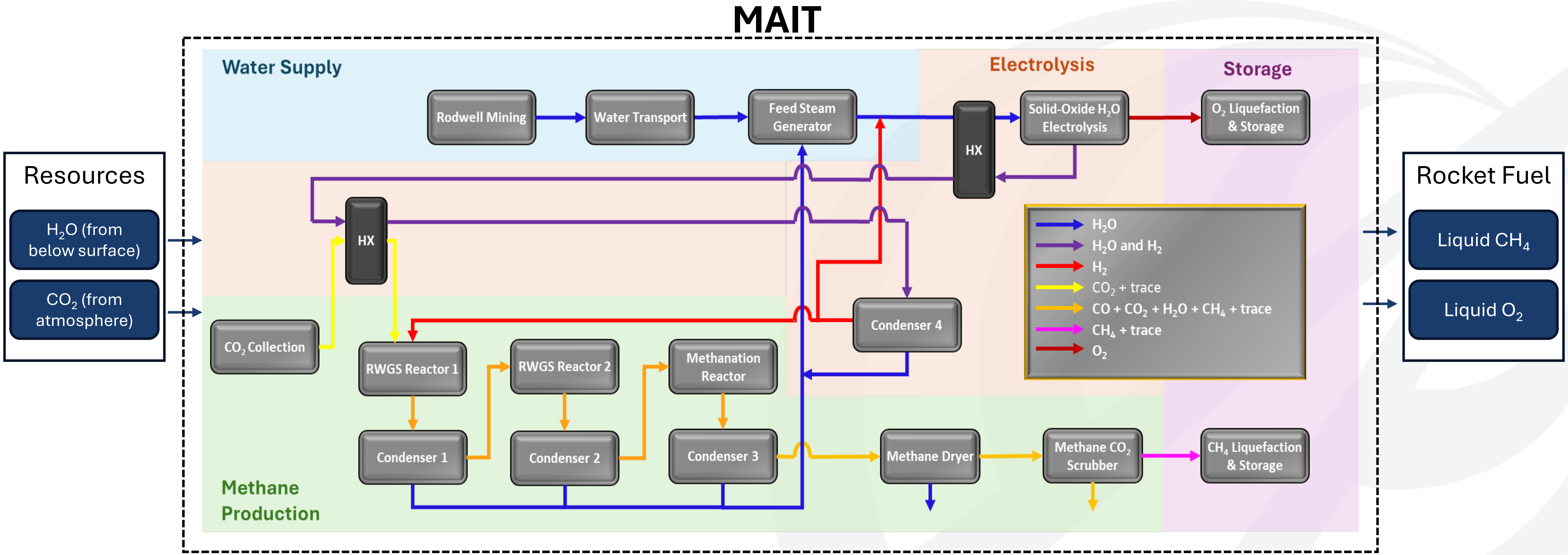
Mission Analysis & Integration Tool (MAIT)

Mars Study Partners:

- MAIT Model Framework was built in MATLAB/Simulink and directly addresses the challenges identified on previous slide
  - Flexible and modular tool for system sizing analysis
  - Designed to collaborate with technology developers
  - Robust framework for evaluating feasibility and optimizing the ISRU system design
  - Built in capabilities for conducting sensitivity studies on critical assumptions
- Call to action – we are looking for more technology partners



Approach


MAIT
Resources
H2O (from below surface)
CO2 (from atmosphere)
Water Supply
Rodwell Mining
Water Transport
Feed Steam Generator
Electrolysis
HX
Solid-Oxide H2O Electrolysis
Storage
O2 Liquefaction & Storage
HX
CO2 Collection
RWGS Reactor 1
RWGS Reactor 2
Methanation Reactor
Condenser 4
Condenser 1
Condenser 2
Condenser 3
Methane Dryer
Methane CO2 Scrubber
CH4 Liquefaction & Storage
Methane Production
H2O
H2O and H2
H2
CO2 + trace
CO + CO2 + H2O + CH4 + trace
CH4 + trace
O2
Rocket Fuel
Liquid CH4
Liquid O2

Approach

Modeling System Objectives:

Production Scenarios

- 30t Cryopropellant Plant (23.3t O_2 / 6.7t CH_4)
- 300t Propellant Plant (233t O_2 / 67t CH_4)

Parametric Trade Study

- 5 critical design variables were varied in understand the impact of inputs on results
  - Steam utilization, condensing radiator effectiveness, ratio of H_2:CO_2, number of electrolysis stacks, layers of insulation.
- 144 total iterations, including internal recycle

General Overview of Technology Subsystems

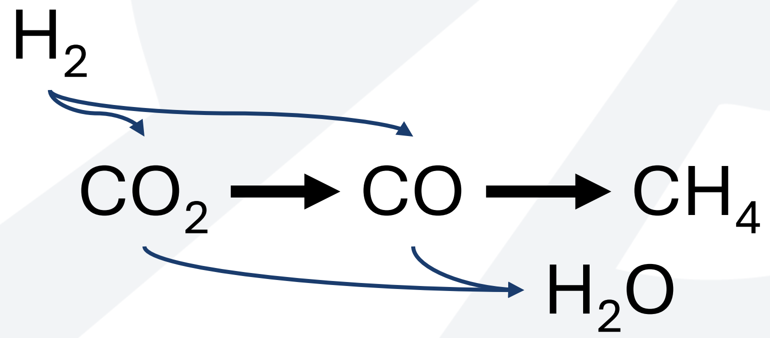
Water Extraction & Delivery

- Rodriguez Well (Rodwell)
- Mobility tanker

Solid Oxide Electrolysis → O_2 direct production
→ H_2 directed to methane

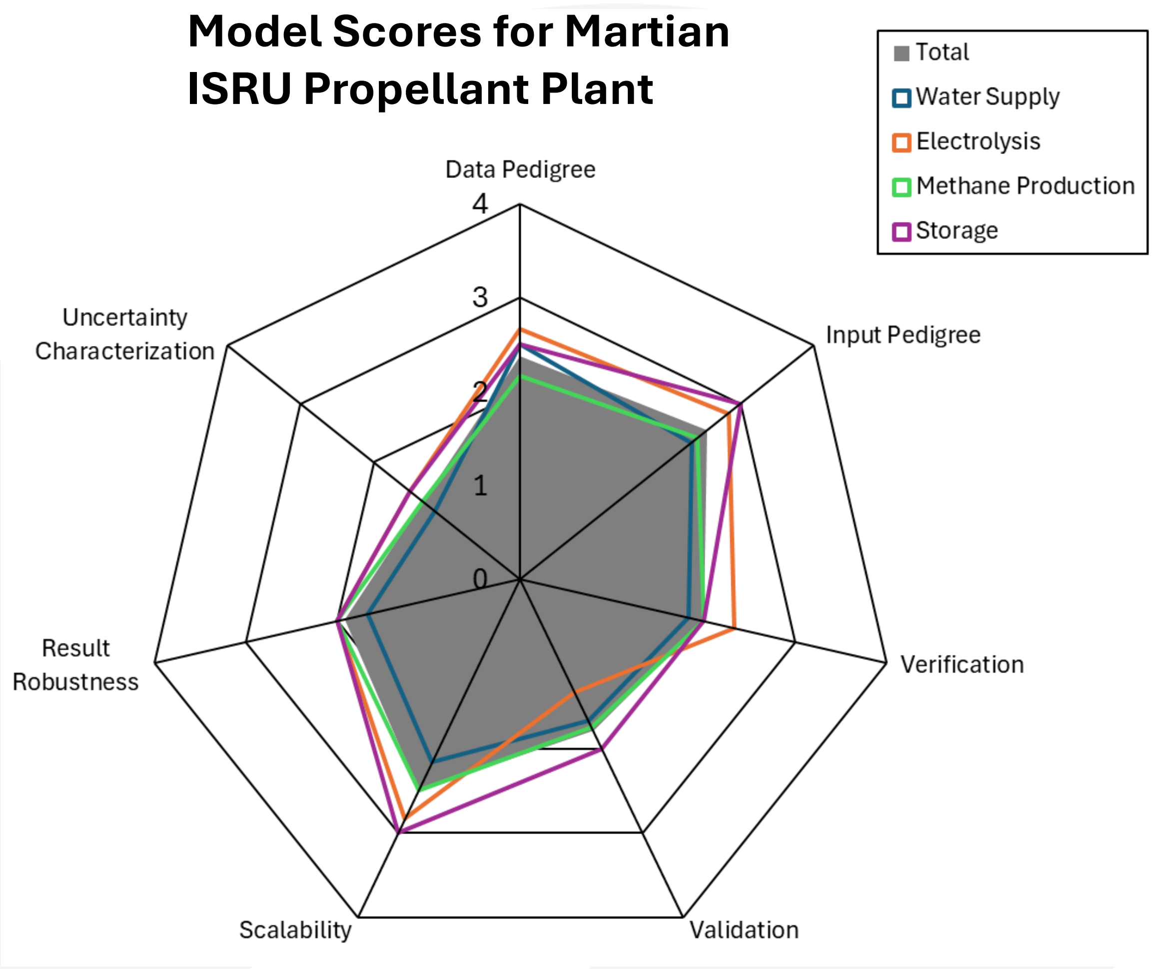
Methane Production

- Reverse Water Gas Shift (RWGS) + Methanation



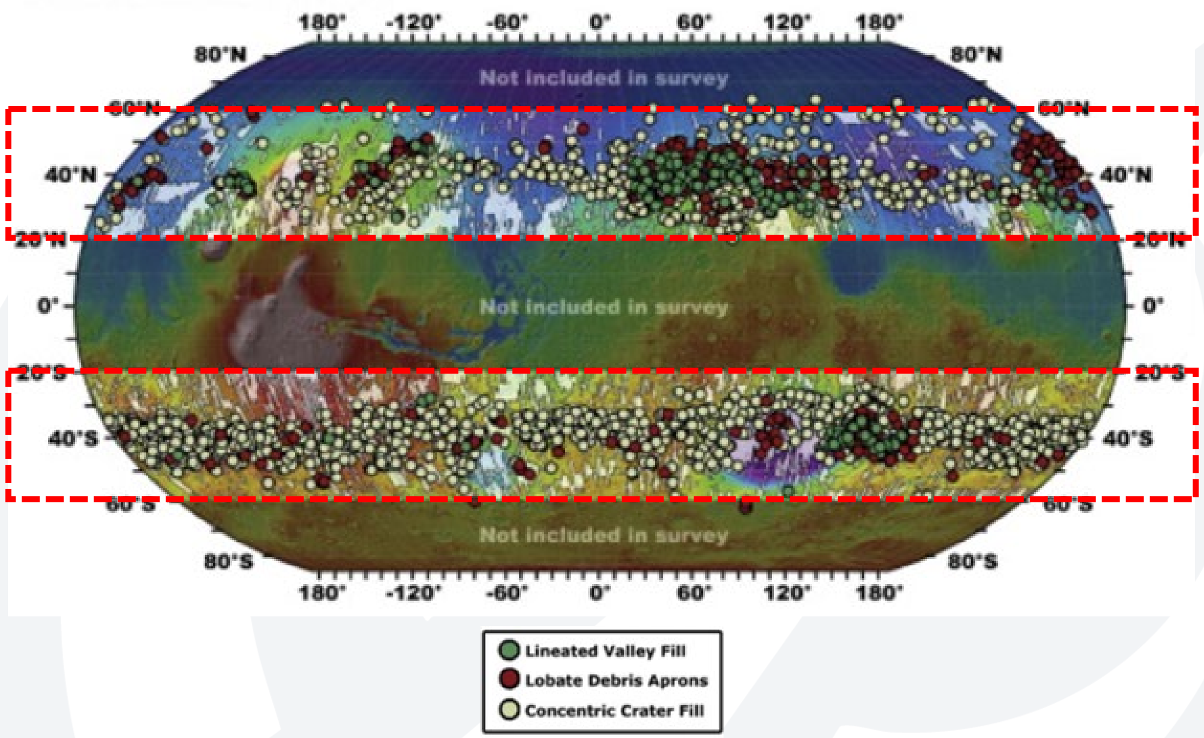
Documentation of Model

- ISRU System Modeling Team maintains a database of all models used in ISRU investigations
- Each model is independently assessed to quantify performance of model in categories identified in the NASA Standard for Models and Simulations (NASA-STD-7009)
  - Most models have low scores in uncertainty characterization, verification, and validation
- Future collaborations with industry and academia can increase accuracy of subsystem models



Critical Assumptions

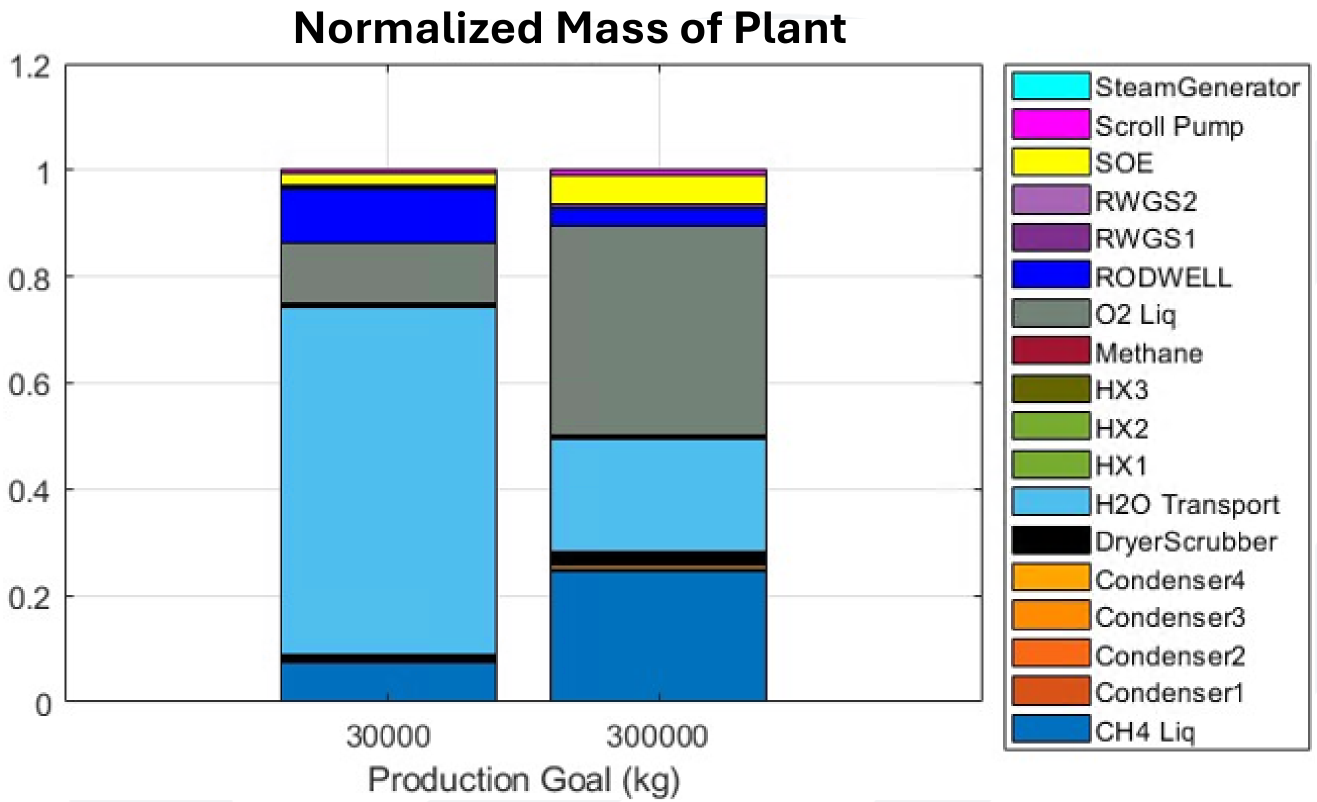
- ISRU plant is in the mid-latitude, providing access to large sub-surface ice
- 600-day production time (Martian year is 687 days, leaving time for setup/maintenance)
- 1.5 km is assumed between the Rodwell water mine and remainder of ISRU plant
- RWGS and Methanation reactors operate at a pressure of 14.7 psia
- Environmental temperature conditions are based on conservative (hot) conditions for condensing radiators



Source: [1] "A Water-Rich Mars Surface Mission Scenario". Hoffman, et al. (2017).

ISRU System Mass

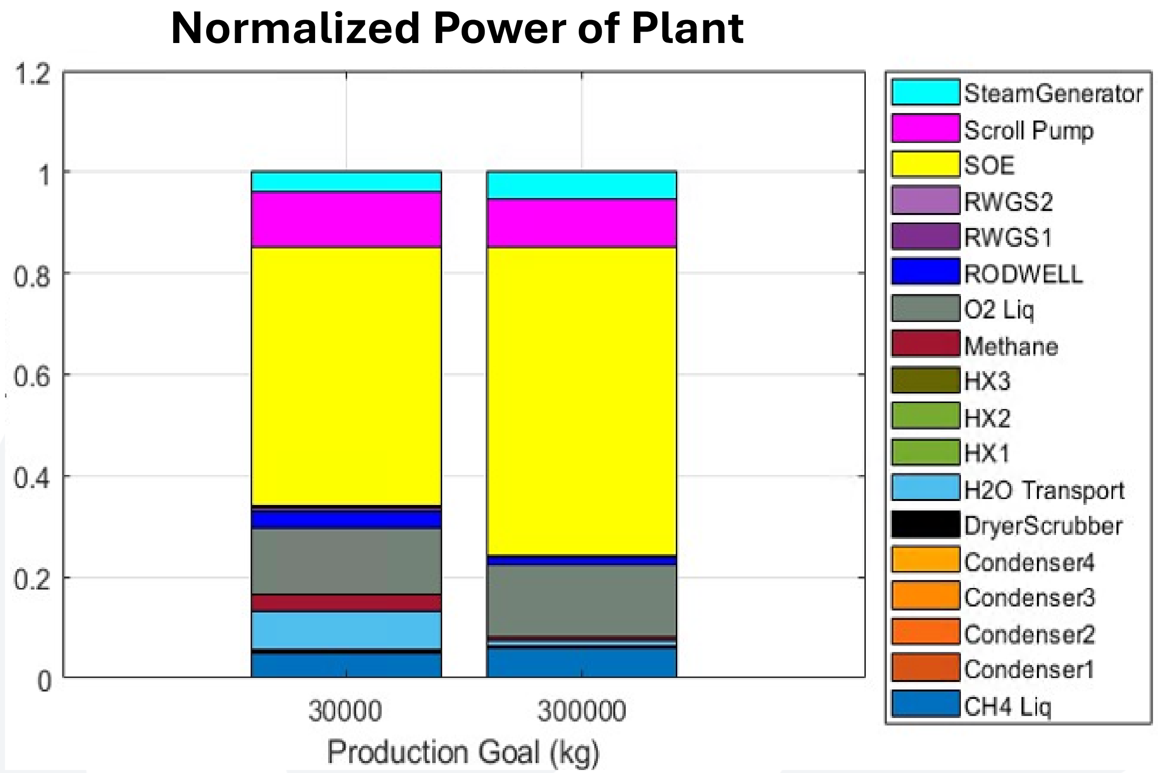
- For 30 t production goal:
  - The water transport platform is the most mass intensive process
    - This is due to poor scaling model which can be addressed in future efforts
  - The liquefaction and storage of the products (O_2 and CH_4) are the next biggest contributors
- For 300 t production goal:
  - The liquefaction and storage of products are the greatest mass contributors
  - The water transport platform is a much smaller proportion of mass at higher production targets



AIAA

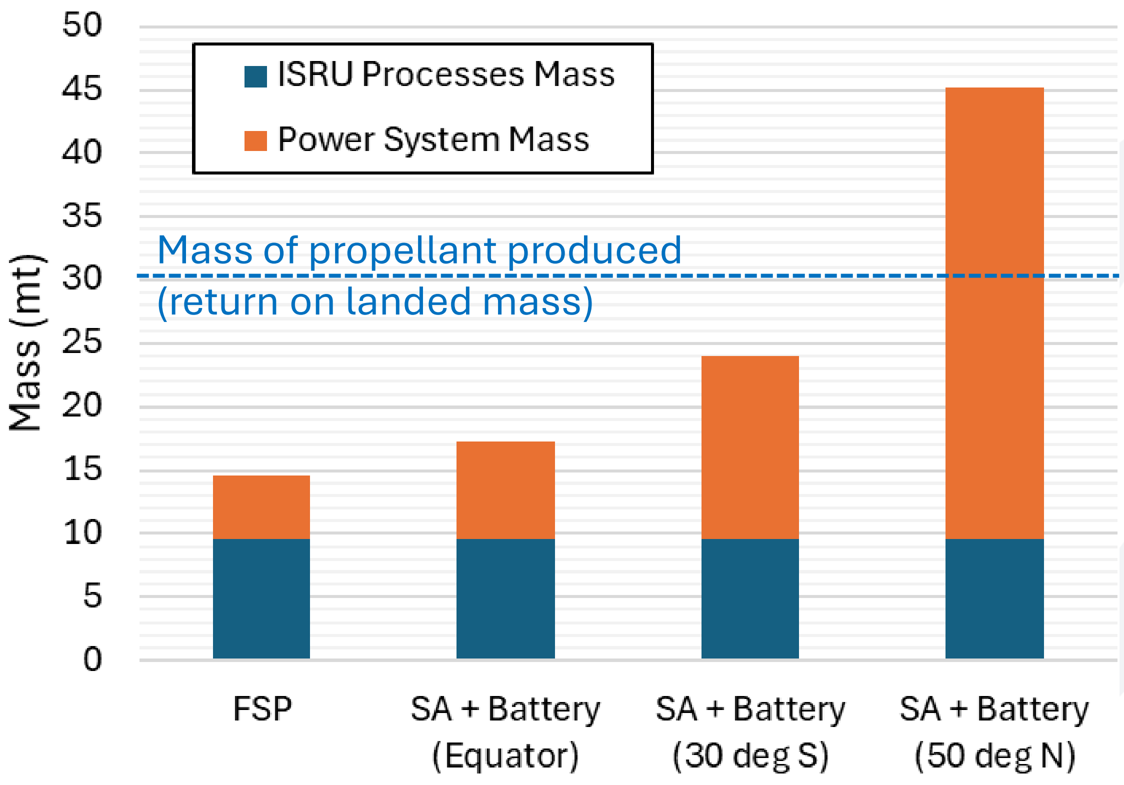
ISRU System Power

- ➢ Electrolysis process (SOE) is the most power intensive portion of the ISRU plant
  - 53-62% of total power
  - SOE model is based on scalable version of OxEon Energy design of MOXIE
- ➢ There are only minor difference in normalized power between the two production goals
  - Most power intensive systems scale well with production target



ISRU System Power

- ➢ Power demands are converted into landed mass based on the type of power generation
  - Fission Surface Power (FSP)
  - Solar Array (SA) with batteries for producing through the night
- ➢ FSP results in a lower system mass than using solar arrays and batteries



Results of Simple Sensitivity Study

- Of the five model inputs that were considered in the sensitivity study, the inputs with the greatest impact on system mass were the **ratio of H_2:CO_2** and **efficiency of condensing radiators.**
  - A 10% adjustment in the optimal ratio of H_2:CO_2 will increase the total ISRU plant by over 2.5%
    - Too high of a ratio results in excessive power for electrolysis
    - Too low of a ratio results in inefficient methanation reaction
  - A 10% degradation in the efficiency of the condensing radiators will result in a nearly 2% drop in the overall system mass
  - Steam utilization factor (in SOE), layers of insulation on storage tanks, and number of SOE stacks only had small impacts on the overall plant design.
- Sensitivity to the environment condition was not assessed in this study (conservative assumptions were used) but is a potential future effort.
  - Site specific data could be used to improve analysis.

Conclusions & Future Work

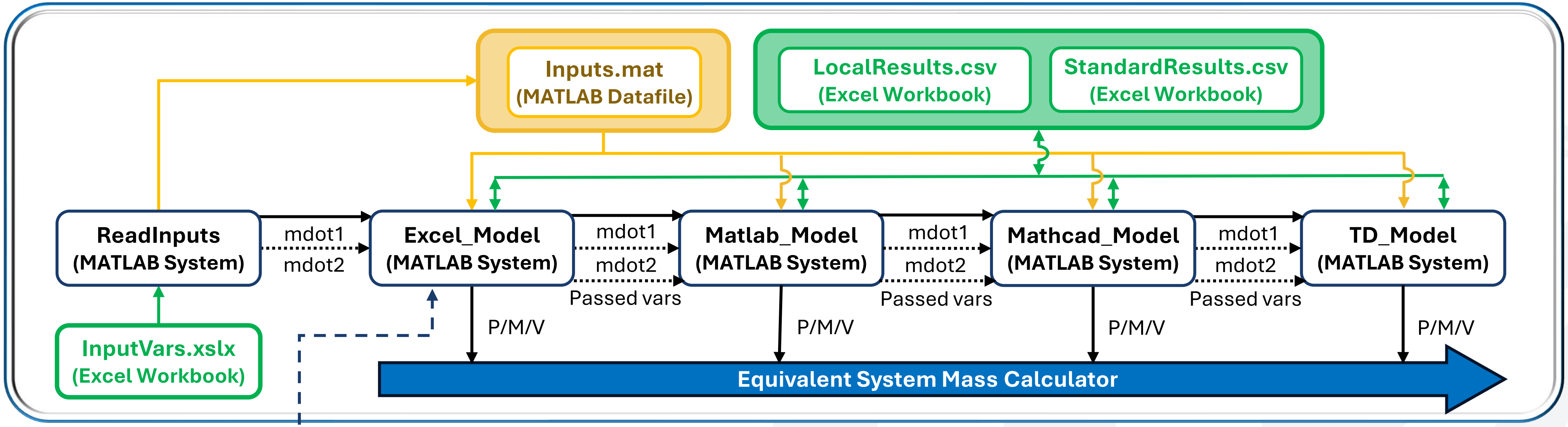
- Producing propellant on the Martian surface using a reverse water gas shift and methanation reactor is a viable option
  - The largest masses of the plant are the liquefaction and storage of propellant, transportation of water, and power generation subsystems
    - The SOE is the largest power draw for this system, using between 53% and 62% of the total plant power
  - Fission surface power is a more viable power generation technology than solar arrays
  - Efficiency of the condensing radiators has a significant impact on the overall system mass
  - Optimizing the ratio of H_2:CO_2 in the methanation reactor is critical to minimizing the mass of the plant
- MAIT can be used to address alternative propellant plant designs and expand modeling capabilities
  - Investigation of an alternative system that compresses atmosphere and flows thru high-efficiency Sabatier reactor
  - Small scale ISRU systems that provide make-up commodities for ECLSS using alternate water collection methods
  - Accounting for seasonal operation
  - Add Mars Reconnaissance Orbiter (MRO) data to include distances for transportation models
  - Improving the fidelity of subsystem models with lowest scores on model assessment.
  - Working with new collaborators in government/academia/industry to investigate alternative technologies

Thank You

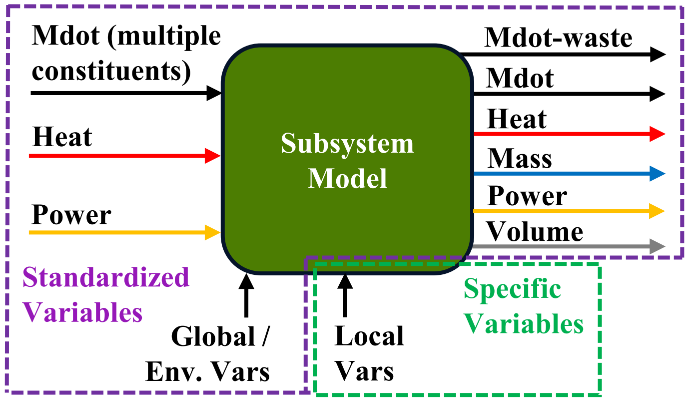
The authors would like to thank:

- Michele Hollist from OxEon Energy for providing valuable data for modeling of the RWGS and Methanation Reactors.
- Tony Colozza and Wesley Johnson from Glenn Research Center (GRC) for providing value models for modeling condensing radiators and liquefaction models, respectively.

Physics-Based Model Process Flow Diagram



Generic Standardized Subsystem Model



Mission Analysis and Integration Tool (MAIT):

The high-fidelity physics-based system models used by STMD Framework is powered by MAIT

- MAIT was Developed with MATLAB + Simulink and is interoperable with Mathcad, Excel, Thermal Desktop, COMSOL, & Cameo
- Communicates with COTS software via API scripts to enable integration of technology developer-driven subsystems without extensive subsystem code revision
- Employs consolidated database of ISRU & ISRU related subsystem and environmental variables (common to NASA & industry)
- Compatible with non-ISRU sub-architectures