Quantitative Modeling of Water Demand to Support a Continuous Human Presence on Mars

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Quantitative Modeling of Water Demand to Support a Continuous Human Presence on Mars

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An important step toward establishing a continuous human presence on Mars is identifying landing sites that are suitable for human and scientific exploration. A key driver of landing site selection is the quantity of water needed to sustain human life. However, minimal work beyond first-order water demand estimates has been completed to date. To address this gap, this work quantitatively estimates how much water is needed to sustain a continuous human presence on Mars. Updates were made to a tool called HabNet, a MATLAB simulation tool that incorporates key mission parameters and outputs predictions of resource levels over time, to improve the accuracy and fidelity of water demand estimates. The updated HabNet tool was then used to simulate five discrete cases that collectively represent a Mars surface campaign crew profile that shows increasing and continuous human presence. Results from modeling water demand showed that the net total water demand for 4, 8, 12, 16, and 20 crew members on a 790-day mission are 38,669 kg, 76,545 kg, 118,069 kg, 151,617 kg, and 193,134 kg, respectively. For each crew size, 63-65 % of water is needed for generating MAV propellant, 22-23 % of the water is needed for crops, and 12-15 % is needed for life support. Additionally, the water demand per crew member per day was found to fluctuate between 12.00 kg to 12.50 kg across the five cases. Limitations associated with the water demand results were identified and areas for future work are discussed.

Nomenclature

BPC	=	Biomass Production Chamber
CCAA	=	Common Cabin Air Assembly
CDRA	=	Carbon Dioxide Removal Assembly
ECLS	=	Environmental Control and Life Support
ISRU	=	In-Situ Resource Utilization
ISS	=	International Space Station
LCH_4	=	Liquid Methane
LOX	=	Liquid Oxygen
MAV	=	Mars Ascent Vehicle
ORA	=	Oxygen Removal Assembly
PCA	=	Pressure Control Assembly
WHC	=	Waste and Hygiene Compartment
WPA/UPA	=	Water/Urine Processing Assembly

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I. Introduction

HOW much water is needed to sustain a continuous human presence on Mars? Water has always played a fundamental role in sustaining human life. On Earth, the availability of water for drinking, agriculture, and waste management made locations near bodies of water attractive and practical for early human settlements. Much like the crucial role that water plays for humans on Earth, the role of water for enabling a continuous human presence on Mars will be equally vital. On Mars, water will be essential for consumption, hygiene and health, science, and protecting crew and equipment from radiation. Water can also undergo electrolysis to produce hydrogen and oxygen: these byproducts can be processed to produce propellant for vehicles such as the Mars Ascent Vehicle (MAV) to enable the return of crew to Earth.[1] Given the potential benefits of harnessing In-Situ Resource Utilization (ISRU) capabilities to source water locally, quantifying water demand to support a human presence on Mars complements ongoing efforts to locate and quantify water availability. Water demand also serves as a key driver to identifying landing sites that are conducive to the exploration of Mars.

A Martian surface campaign crew profile that captures increasing and continuous human presence is shown in Figure 1 and is the baseline crew profile used for water demand investigation in this paper. This crew profile is an extension of the NASA DRA5.0 recommended conjunction-class sortie mission.[2] In the Figure 1 profile, each successive crew of four (each denoted by a unique color) spends progressively longer durations on the Martian surface until a predetermined steady state population is achieved. The length of stay for each group of crew follows the rule that the n^{th} group of crew remains on the surface for 790n+540 days until the $n+1^{th}$ crew group arrives. Subsequent crew groups after the $n+1^{th}$ remain on the Martian surface for 790(n+1) + 540 days in order to maintain the population.[2] These length-of-stay values are based on the assumption that a conjunction class mission trajectory is used to transport four crew members for each mission. This results in a minimum period between each resupply (i.e., when a new group of crew arrives) that is approximately equal to the synodic period of Earth and Mars around the Sun (~26 months or ~790 days).[2] The population ramp-up crew profile in Figure 1 was chosen because it facilitates the investigation of water demand requirements for space habitation capabilities that approach distant future “Earth Independence” capabilities (trajectory denoted by the blue arrow shown on Figure 2), which has yet to be explored.

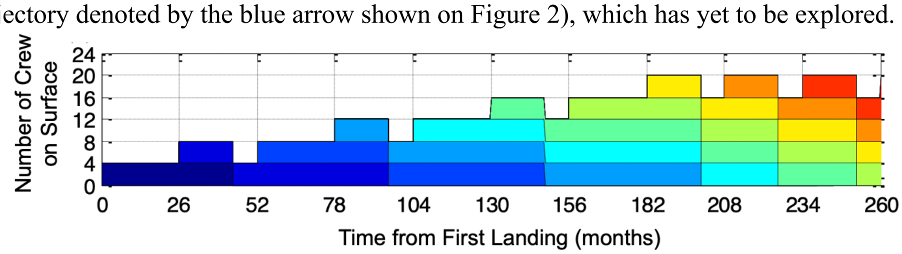


Figure 1. Mars surface campaign crew profile showing population ramp up over time.[2]

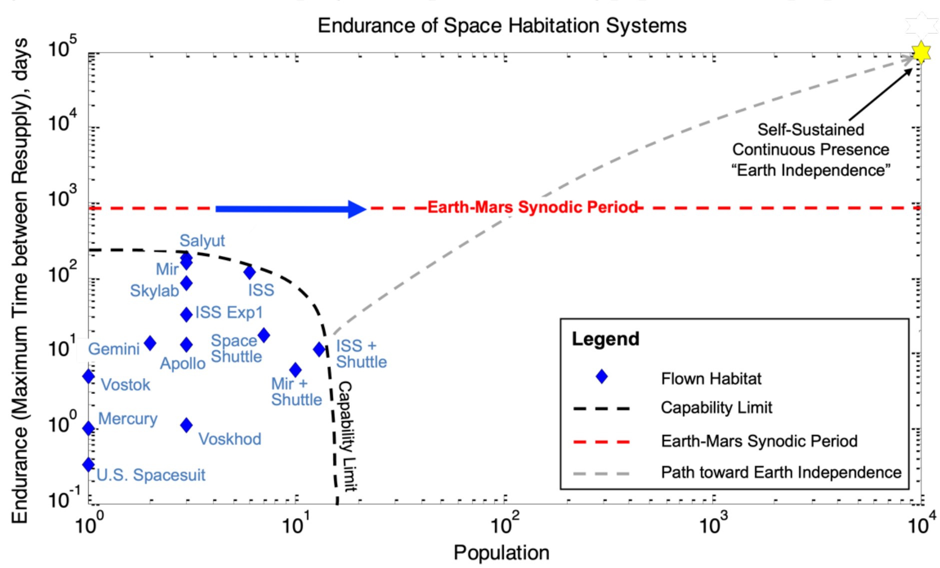


Figure 2. Evolution of Space Habitation Capabilities.[2] Note that the image is altered from the original image found in Ref.2 . The blue arrow represents space habitation capabilities within the scope of this paper that approach “Earth Independence” capabilities.

II. Methodology

A tool called HabNet was used to assess water requirements needed for sustaining a continuous human presence on Mars. HabNet is an integrated habitation and supportability architecting and analysis environment that was first developed at the MIT Strategic Engineering Research Group between 2013 and 2016. HabNet is capable of taking in key mission parameters, such as number of crew, mission duration, habitat layout, and Environmental Control and Life Support (ECLS) system architectures to predict the required consumables over the mission duration. Further information on how HabNet works, its past use cases on Mars mission architectures, and its associated assumptions can be found in Ref. 2 and Ref. 3.

A. Baseline ECLS Architecture

A baseline ECLS architecture for long duration missions shown in Figure 3 was derived from an internal presentation provided by NASA JPL.[4] This architecture was implemented into HabNet to help quantify net water demand to support a continuous human presence on Mars. Note that the Mars habitation module is surrounded by potable water storage as a method of shielding crew from deep space radiation.

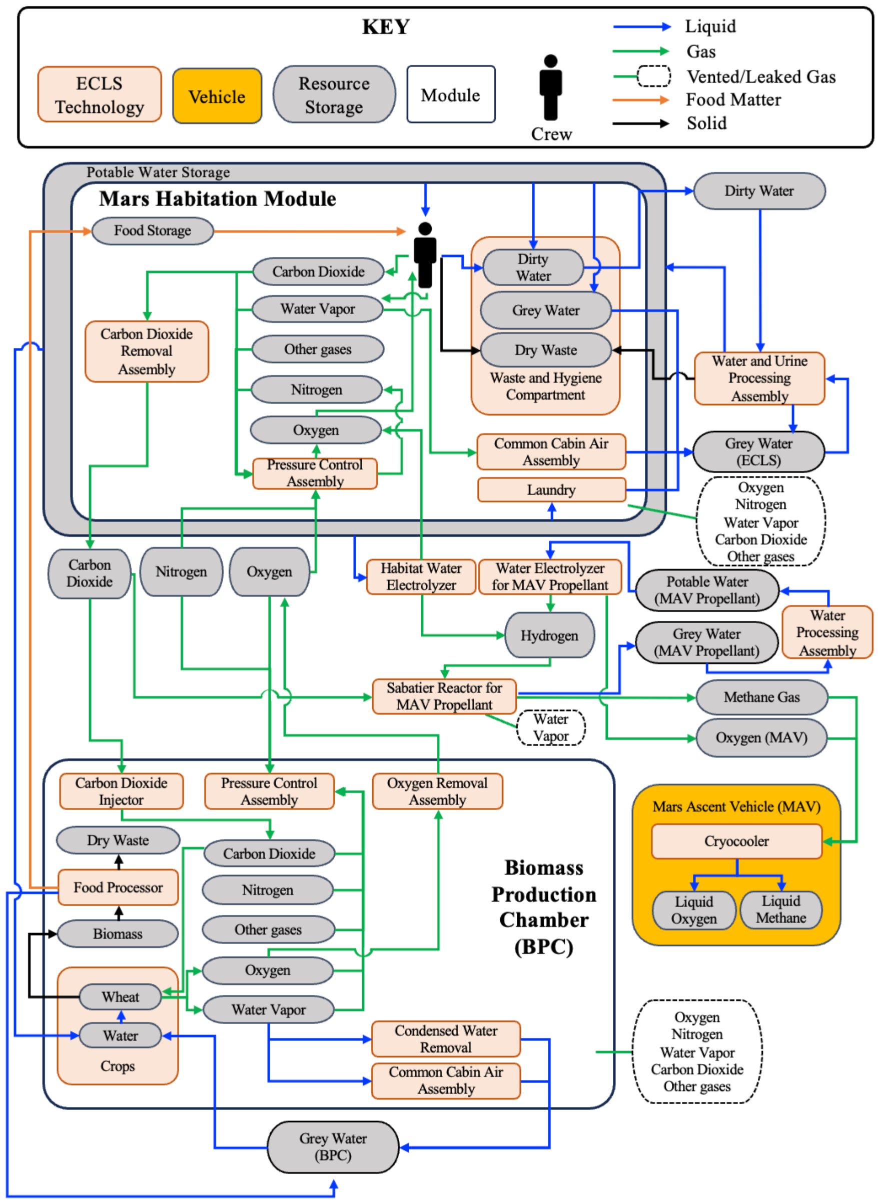


Figure 3. Baseline long-duration ECLS architecture.[4]

At a high level, the baseline long duration ECLS architecture presented in Figure 3 consists of three key water loops that are tracked: life support, biomass production chamber (BPC), and MAV propellant loop. In the three water loops, the water/urine processing assembly (WPA/UPA) and common cabin air assembly (CCAA) facilitate water recovery. Several of the key ECLS technology models, including the CCAA, WPA/UPA, carbon dioxide removal assembly (CDRA), and pressure control assembly (PCA) are ISS derived.[2] Other technologies modeled, such as the oxygen removal assembly and carbon-dioxide injector, are notional technologies.

1. Life Support Loop

Within the Mars habitation module where crew members live, life support equipment which includes the CDRA, habitat water electrolyzer, PCA, Waste and Hygiene Compartment (WHC), CCAA, and laundry machine work together to provide crew with food, water, hygiene facilities, and habitable environmental conditions. The WPA/UPA and CCAA function to reclaim water in the life support loop.

2. Biomass Production Chamber Loop

The BPC module supports crew food supply; it is where crops are grown and harvested to provide crew with food. It is important to note that the BPC and Mars habitation module are modeled as two separate entities that do not physically interface. Crew will not need to enter the BPC to harvest crops and it is assumed that food is directly transported from the BPC to the Mars habitation module for crew to consume. Within the BPC, the Oxygen Removal Assembly (ORA), PCA, carbon-dioxide injector, CCAA, and condensed water remover operate together to ensure that environmental conditions within the BPC can support crop growth. The crops and food processer work together to provide crew with food to consume during the mission. The "shelf stagger" feature is implemented in the BPC whereby a batch of crops are grown every day and harvested every day once the crops mature so that food production is continuous over the mission. Water reclamation in the BPC occurs primarily through the collection of water transpired by the plants that is then processed through the CCAA and used as a water source for the crops.

3. MAV Propellant Loop

The water electrolyzer and Sabatier reactor for MAV propellant, cryocooler, and MAV model work together to produce propellant (liquid oxygen and liquid methane) for the MAV. The water electrolyzer for MAV propellant transforms potable water into hydrogen and oxygen gases. Oxygen is then converted to LOX in the cryocooler, while hydrogen undergoes a reaction with carbon dioxide in the Sabatier reactor, resulting in the production of methane and grey water as byproducts. Methane is subsequently processed in the cryocooler to become LCH_4. The water processing assembly (WPA) reclaims water in the MAV propellant production loop, a notional capability that is introduced in this baseline long duration ECLS architecture.

B. Updates to HabNet

Recent work has been completed to update HabNet to better capture water demand elements. These updates included updating the crew model to reflect more recent data and constructing a waste and hygiene compartment (WHC) and laundry machine model.[3] Tests were completed to verify that the WHC, laundry and updated crew model work as intended.[3] The ECLS architecture shown in Figure 3 contains technologies that were not previously modeled in HabNet including the MAV, cryocooler, water electrolyzer for MAV propellant, and Sabatier reactor for MAV propellant. As such, they are created and verified as follows:

1. MAV and Cryocooler

The primary purpose of the MAV is to lift crew and cargo of the Martian surface and dock with a Mars-Earth transportation vehicle, facilitating the return of crew and cargo to Earth.[1] The MAV modeled uses cryogenic propellants (liquid oxygen (LOX) and liquid methane (LCH_4)) stored in cryogenic storage tanks that have an integrated cryocooler. As per the baseline long duration ECLS architecture, gaseous oxygen and methane are fed into the cryocooler to be converted into LOX and LCH_4, which are stored in cryogenic storage tanks as shown in Figure 4.

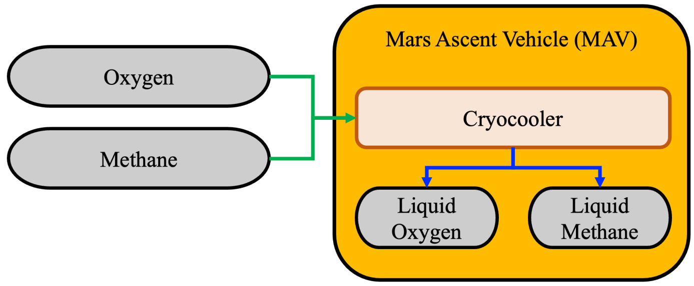


Figure 4. Resource flow diagram of the MAV and cryocooler model.

At a high level, the MAV model outputs the amount of LCH_4 and LOX that is required to be produced per crew mission day such that there is enough propellant to lift crew and cargo off the surface of Mars by the end of the mission duration. Data taken from an internal JPL spreadsheet contains estimates of the necessary quantities of LOX and LCH_4 for a specified number of crew members on the mission, as shown in Figure 5**Error! Reference source not found.**, and has been incorporated into the MAV model.

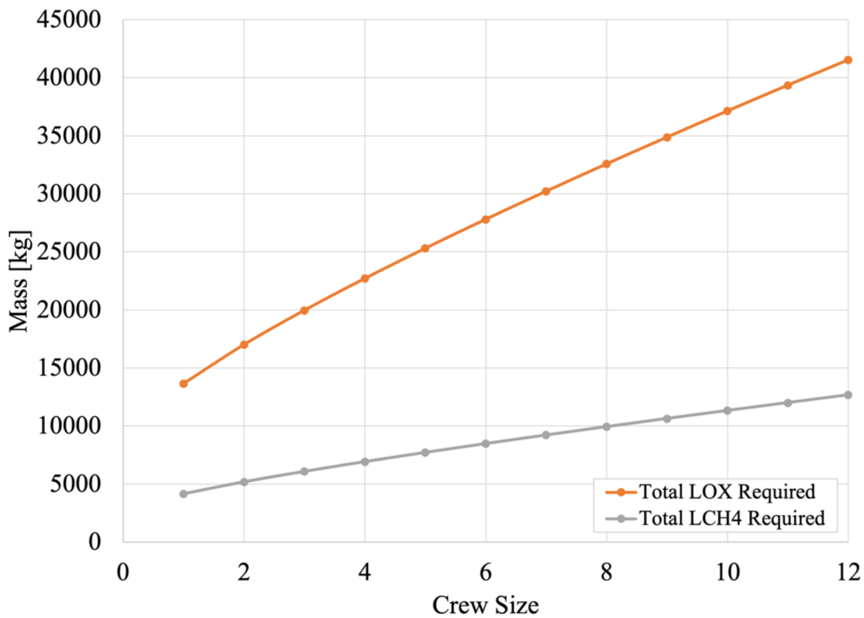


Figure 5. Plot of the LOX and LCH_4 mass required versus crew size. Note that the plot is altered from the original plot found in Ref. 5 to display relevant information and include formatting changes.

The cryocooler and cryogenic storage tanks for LCH_4 and LOX were captured within the MAV model by incorporating a user-inputted boil-off rate (BOR) parameter (%/day) for both the stored LOX and LCH_4. The MAV model uses the boil-off rates to calculate the amounts of LOX and LCH_4 that should be produced per day to ensure there is enough propellant at the end of the mission duration as per Figure 5. The amount of LCH_4 and LOX that needs to be produced per day is given by equations 1 and 2.

$$r_{LCH_4} = \left(\frac{\sum_{t=1}^{T} l_{LCH_4,t} \times BOR}{req_{LCH_4} - \sum_{t=1}^{T} l_{LCH_4,t} \times BOR} \right) \frac{req_{LCH_4}}{T} \tag{1}$$

$$r_{LOX} = \left(\frac{\sum_{t=1}^{T} l_{LOX,t} \times BOR}{req_{LOX} - \sum_{t=1}^{T} l_{LOX,t} \times BOR} \right) \frac{req_{LOX}}{T} \tag{2}$$

Where

r_{LCH_4}	=	rate of LCH4 production per day (factoring in the BOR) [kg/day]
r_{LOX}	=	rate of LOX production per day (factoring in the BOR) [kg/day]
t	=	time [days]
req_{LCH_4}	=	required amount of LCH4 (per Figure 5) [kg]
req_{LOX}	=	required amount of LOX (per Figure 5) [kg]
$l_{LCH_4,t}$	=	level of LCH4 at time t , $\frac{req_{LCH_4}}{T} + l_{LCH_4,t-1}\,(1 - BOR)$ [kg]
$l_{LOX,t}$	=	level of LOX at time t, $\frac{req_{LOX}}{T} + l_{LOX,t-1}\,(1 - BOR)$ [kg]
T	=	mission duration [days]
$l_{LCH_4,0}$	=	0
$l_{LOX,0}$	=	0

The integrated MAV and cryocooler model assumed that the BOR was the only efficiency loss in the cryocooling process that turns gaseous oxygen and methane into LOX and LCH4. Thermal efficiency, duty cycles, and power constraints were not factored into the MAV and cryocooler model. It was also assumed that the cryogenic propellant tanks could store any amount of LOX and LCH4.

2. Water Electrolyzer for MAV Propellant

The water electrolyzer for the MAV propellant electrolyzes potable water into gaseous hydrogen and oxygen. The oxygen gas is then processed into LOX in the cryocooler while the hydrogen gas gets fed into the Sabatier reactor to react with carbon dioxide gas and produce methane gas which is then sent to the cryocooler to be turned into LCH4. The block diagram in Figure 6 shows a resource flow diagram of the water electrolyzer for MAV propellant.

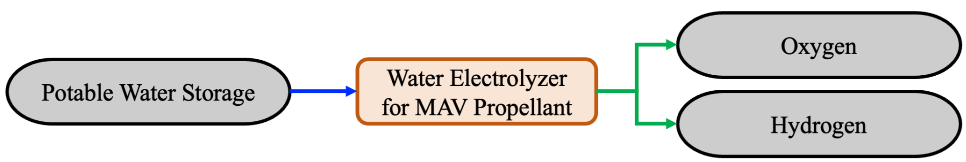


Figure 6. Block diagram showing the flow of inputs and outputs of the water electrolyzer for MAV propellant.

The water electrolyzer for MAV propellant model functions by taking in the amount of LOX and LCH4 production required per day from the MAV model output and converting that to moles of water needed per hour to produce the required amount of LOX and LCH4 based on the stoichiometric ratios shown in equations 3 and 4.

Water Electrolysis has the stoichiometric reaction shown in equation 3

$$2H_2O \rightarrow 2H_2 + O_2 \tag{3}$$

The Sabatier reaction has the stoichiometric reaction shown in equation 4

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{4}$$

Based on equations 3 and 4, it can be inferred that two water molecules can yield one O_2 molecule (2:1) while two water molecules can yield 0.5 CH_4 molecules (2:0.5). The molar oxidizer to fuel ratio (moles of LOX required to moles of LCH4 required) for 1-12 crew members is 1:1.64, meaning that hydrogen gas is the limiting reactant (i.e., the water required to be electrolyzed to produce enough MAV propellant is dependent on the amount of LCH4 needed, and will result in an excess of LOX).[5] The water electrolyzer then takes the amount of water from the potable water storage to produce the required amount of LCH4 indicated by the MAV model output.

It was assumed that the water electrolyzer for the MAV propellant could intake as much potable water as needed from the Mars habitation module and accommodate any oxygen production rate to ensure that enough LOX could be produced. A perfect stoichiometric reaction with no losses as shown in equation 3 was also assumed. It was assumed that there was no flow rate limit on any of the water/gas transfer processes.

3. Sabatier Reactor for MAV Propellant

The main function of the Sabatier reactor is to take in gaseous carbon dioxide and hydrogen to produce methane and water per the reaction shown in equation 4. The output methane is fed into the cryocooler to be turned into LCH_4 for the MAV propellant and the output water is fed into the grey water storage as depicted in the block diagram shown in Figure 7.

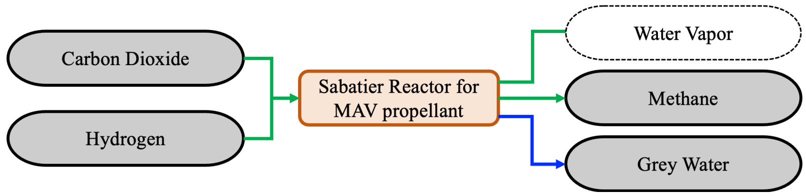


Figure 7. Block diagram showing the flow of inputs and outputs of the Sabatier reactor.

The Sabatier reactor was modeled such that it runs as soon as a 1:3.5 CO_2 to H_2 ratio is reached rather than a 1:4 CO_2 to H_2 ratio.[6] This is so that all the hydrogen in the storage tank is reacted as soon as possible since gaseous hydrogen is prone to leaking. In reality, some water product from the Sabatier reaction is lost as vapor. To account for this loss, the Sabatier reactor model includes a user input water conversion efficiency parameter that is currently approximated to be 0.9 (i.e., 0.9 of water produced gets reclaimed as grey water while 0.1 of water produced is vented away as water vapor).[7] It was also assumed that the Sabatier reactor for the MAV propellant could intake as much carbon dioxide and hydrogen as needed and accommodate any methane production rate to ensure that enough LCH_4 could be produced by the end of the mission duration.

4. Verification of the MAV and cryocooler, water electrolyzer for MAV propellant, and Sabatier reactor

To ensure that the MAV model, water electrolyzer for MAV propellant, and Sabatier reactor for MAV propellant all function as intended, a test was performed to see if the water electrolyzer for the MAV propellant and Sabatier reactor were both producing the expected amount of LOX and LCH_4 as output by the MAV model. This test ensured that the water electrolyzer for the MAV propellant was drawing the correct amount of water needed to produce sufficient MAV propellant and that the stoichiometric reactions in both the Sabatier reactor and water electrolyzer were implemented correctly. Plots showing the LOX and LCH_4 levels over a 500-day mission for one crew member at a 0.1%/day boil-off rate are shown in Figure 8 and Figure 9. Figure 8 shows that the amount of the LOX exceeded the required amount by the end of the mission (due to hydrogen being the limiting reactant) and Figure 9 shows that the LCH_4 level reached the required LCH_4 level by the end of the mission. A mass conservation check was also completed on the water electrolysis and Sabatier stoichiometric reaction (equations 3 and 4) assuming no boil-off. Per the water electrolysis stoichiometric reaction, 1.986 kg of potable water yielded 0.222 kg of hydrogen and 1.764 kg of oxygen during each hour of the mission (1.986 kg of reactants yielded 1.986 kg of products, indicating mass conservation). For the Sabatier reaction, 1.231 kg of carbon-dioxide and 0.222 kg of hydrogen yielded 0.442 kg of methane and 0.993 kg of water each hour (1.453 kg of reactants yielded 1.453 kg of products, which shows mass conservation).

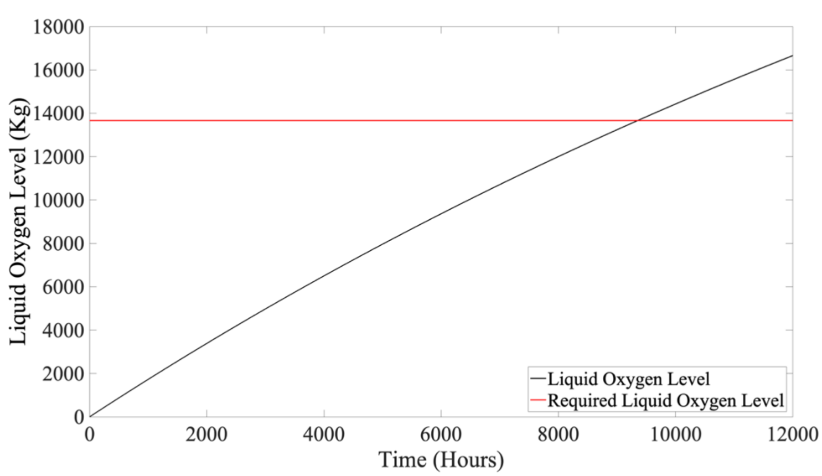


Figure 8. LOX level over time for a 500-day mission for one crew member at a 0.1%/day boil-off rate.

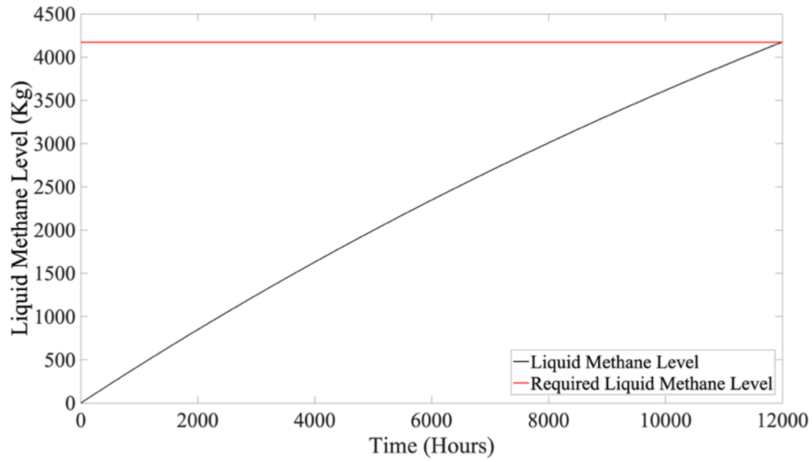


Figure 9. LCH_4 level over time for a 500-day mission for one crew member at a 0.1%/day boil-off rate.

At a 0.1%/day boil-off rate of LOX and LCH_4 over 500 days, 1128.94 kg of LCH_4 and 4503.51 kg of LOX are lost to boil-off. These outcomes were expected and indicate that the MAV model, water electrolyzer for MAV propellant and Sabatier reactor for MAV propellant all collectively function to ensure that sufficient MAV propellant is produced by the end of the mission duration.

C. Simulation Set-Up

1. Simulation Cases

To determine the water demand for the crew profile shown in Figure 1, five discrete cases that capture crew sizes of 4, 8, 12, 16 and 20 people were run as documented in Table 1.

Table 1. Simulation Cases

Case	Number of Crew	Duration
1	4	790 days
2	8	790 days
3	12	790 days
4	16	790 days
5	20	790 days

These five discrete cases represent the annotated cases shown in Figure 10 below. It was assumed that a steady state population of 20 people was desired and does not capture the dynamics of resource levels in between the discrete cases presented. Continuous simulation of the crew profile was left for future work. For consistency of the mission duration, Case 5 was run for 26 months (790 days) rather than 540 days.

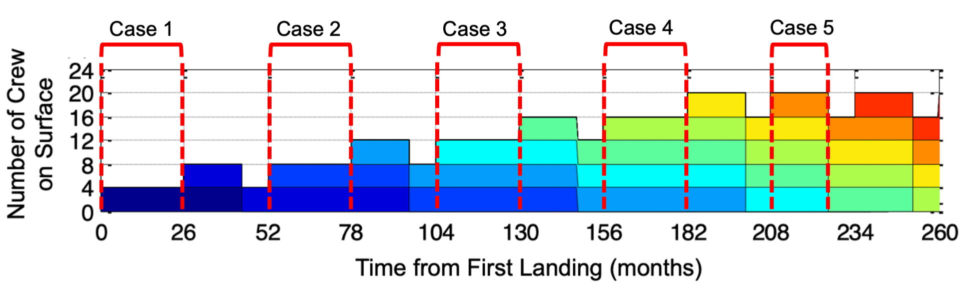


Figure 10. Simulation cases represented on the crew profile. Note that Case 5 will be run for 26 months (790 days) rather than 540 days for consistency of the mission duration. The figure was altered from the original figure found in Ref.2.

2. Input Parameters

The input parameters, which remained constant throughout all five cases, are presented in Tables 2 - 6. Based on Table 2, an unlimited initial supply of oxygen, nitrogen, carbon-dioxide, grey water, potable water, and power was assumed. The simulation started with an unlimited amount of potable water (for the Mars Habitation Module and MAV propellant) and grey water (for the BPC) to allow water depletion to be monitored over time and enable the calculation of net total water demand. For simplicity, only wheat was selected as the crop type for crew to consume because it is the most calorically dense per square meter of crop growth area per day.[2]

Table 2. Initial Storages (resources brought from Earth or assumed to be available on Mars)

Input Parameter	Units	Value
Crop type	N/A	Wheat
Food	N/A	Twice the amount needed to sustain crew members for the mission duration
Oxygen	Moles	Unlimited
Nitrogen	Moles	Unlimited
Carbon Dioxide	Moles	Unlimited
Grey Water (BPC)	kg	Unlimited
Potable water (Mars Habitation Module)	kg	Unlimited
Potable water (MAV propellant)	kg	Unlimited
Power Available	W	Unlimited

Tables 3 and 4 highlight air related parameters inside the BPC and Mars Habitation Module. In HabNet, air composition is abstracted into categories of oxygen, nitrogen, carbon dioxide, water vapor, and other gases. The initial target levels of each of these gases are presented in Tables 3 and 4. It is important to note that for the BPC, the target CO_2 molar fraction was set to 0.0012 (or 1200ppm) because it was found to the be the optimal concentration for maximizing photosynthesis rates in crops.[8] Oxygen fire risk molar fraction refers to the fraction of oxygen gas in the module that is considered a fire hazard. A key assumption made about the air tightness of the modules was a sustained leakage. For this work, it was assumed that there was a 0.05% air leakage rate per day.[9] The target relative humidity inside the Mars habitation module was also set to be 40%. This relative humidity level was selected because maintaining indoor relative humidity levels between 40-60% can minimize adverse health effects.[13] Last, the target relative humidity inside the BPC was set to be 55%. This selection was made to support the ideal relative humidity for wheat, which is between 50 and 60%.[10]

Table 3. Mars habitation module air parameters.

Input Parameter	Units	Value
Daily air leakage rate	%	0.05 [9]
Total atmospheric pressure targeted	kPa	55.2 [11]
Target O_2 molar fraction	-	0.32 [11]
Target N_2 molar fraction	-	0.6656
Target CO_2 molar fraction	-	0.0004 [12]
Target water molar vapor fraction	-	0.004 [12]
Target other gases molar fraction	-	0.01 [12]
O_2 fire risk molar fraction	-	0.5 [2]
Target relative humidity	%	40 [13]

Table 4. BPC module air parameters.

Input Parameter	Units	Value
Daily air leakage rate	%	0.05 [9]
Total atmospheric pressure targeted	kPa	55.2 [11]
Target O_2 molar fraction	-	0.32 [11]
Target N_2 molar fraction	-	0.6648
Target CO_2 molar fraction	-	0.0012[9]
Target water molar vapor fraction	-	0.004 [12]
Target other gases molar fraction	-	0.01 [12]
O_2 fire risk molar fraction	-	0.5 [2]
Target relative humidity	%	55 [10]

Each crew member followed the generic crew schedule shown in Table 5.[3] Every seventh day (once per week), each crew member spent an hour cleaning laundry during the "Intravehicular Activity" crew member activity. It was assumed that each crew member is a 35-year-old male who weighs 85kg. To prevent the simultaneous use of facilities (e.g., WHC, laundry, exercise equipment), each additional crew member followed the same sequence of activities shown in Table 5 but shifted by an activity from that of the previous crew member.

Table 5. Crew schedule.

Hour	Duration (Hr)	Crew Member Activity
1	0.5	Exercise - Aerobic
2	1	Exercise - Resistive
3	1	Recovery - Hour 1
4	1	Recovery - Hour 2
5	1	Recovery - Hour 3
6-15	10	Intravehicular Activity (laundry module triggered once every 7th day)
16	1	Intravehicular Activity (Toilet/Personal Hygiene)
17-24	8	Sleep

The BORs for LOX and LCH_4 are shown in Table 6 below.

Table 6. Boil Off Rates for LOX and LCH_4.

Fuel/Oxidizer	Boil Off Rate (%/day)
LCH_4	0.1
LOX	0.1

3. ECLS Architecture and Technology Running Order

The ECLS architecture presented in Figure 3 was incorporated into HabNet and the various ECLS technologies were triggered in the order documented in Table 7. It was essential that the ECLS technologies were triggered in the presented order because each have downstream impacts on other ECLS technologies. For example, the PCA located in the BPC and Mars habitation module needed to be triggered after all entities that move gases within the BPC and Mars habitation module (ORA, CDRA, Crops, CO_2 Injector, CCAA, Condensed Water Remover, Crew) have been triggered. This ensured that the modules were not under- or over-pressured and that the oxygen level inside the modules were sufficient but not in excess. The CO_2 injector (which adds CO_2 into the BPC), CCAA, and condensed water remover (all in the BPC) all ran after the crops have respired. This ensured that CO_2 levels and relative humidity values in the BPC reached target values by the end of each hour.

Table 7. Technology running order.

Technology	Location
1. Mars Habitation Module (air leakage)	N/A
2. BPC Module (air leakage)	N/A
3. Habitat Water Electrolyzer	Mars Habitation Module
4. Water Electrolyzer for MAV Propellant	MAV Propellant Water Loop
5. Sabatier Reactor for MAV Propellant	MAV Propellant Water Loop
6. WPA	MAV Propellant Water Loop
7. ORA	BPC
8. CDRA	Mars Habitation Module
9. Laundry	Mars Habitation Module
10. WPA/UPA	Mars Habitation Module
11. Crops	BPC
12. CO_2 Injector	BPC
13. CCAA	BPC
14. Condensed Water Remover	BPC
15. Food Processor	BPC
16. Crew	Mars Habitation Module
17. CCAA	Mars Habitation Module
18. WHC	Mars Habitation Module
19. PCA	Mars Habitation Module
20. PCA	BPC

Input Variables

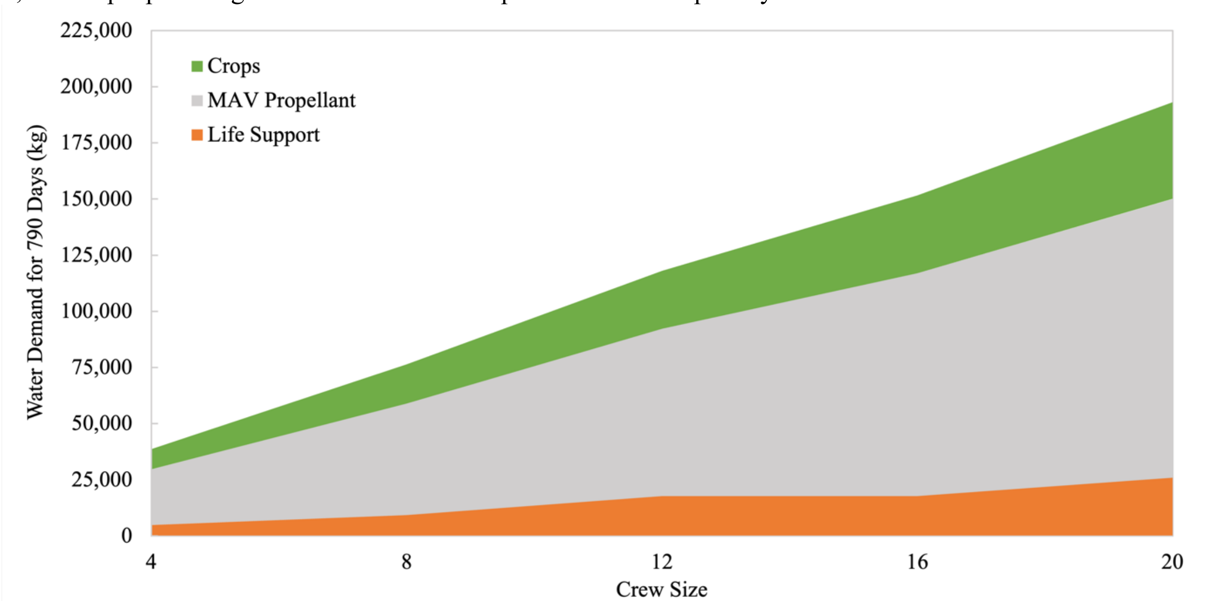
Table 8 below documents the input variables for each simulation case.

Table 8. Input Variables for the simulation cases.

Variable	Value				
	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Number of Crew	4	8	12	16	20
Mars Habitation Module volume [m^3]	60	120	180	240	300
	Estimates of the Mars habitation module volume used the Celentano curve parametric function found in Ref. 14 given by: $$Habitable\ Volume\ [m^3] = A\left(1 - e^{-\frac{duration}{B}}\right) \times Number\ of\ crew\ member$$ where the standard form uses $A = 5\ (tolerable), 10\ (performance), 20\ (optimum)$ and $B = 20\ days$; duration is in days A is assumed to be 15 for all simulation cases.				
BPC volume [m^3]	1000	1500	2000	2750	3250
	The BPC volume was sized to ensure that all crops stayed alive throughout the mission duration. For larger crew sizes, more crops were needed to provide enough food for crew and therefore more CO_2 was required for crops to respire and stay alive. Larger volumes were therefore needed to accommodate more crops as seen in the increasing BPC volume.				
Crop growth area[m^2]	156.685	313.370	470.056	626.741	783.426
	These were the crop growth areas required for different crew sizes to produce sufficient wheat crops to provide sufficient calories for crew members. Each crew member requires approximately ~3773.3 calories per day as calculated in the crew model of HabNet based on crew age, gender, weight, and crew activity intensity.[2] This crop growth area ensured that the rate of food production was greater than or equal to the rate of food consumption (supports 100% of crew caloric needs).				
Number of MAVs	1	2	3	4	5
	It was assumed that each MAV could carry four crew members (consistent with the MAV design in Ref.1) so that the number of MAV seats readily available was equal to the crew size.				
Number of CDRAs in the Mars habitation module	3	3	3	5	6
	The number of CDRA units was as many as required to ensure no crew members died of carbon dioxide poisoning. The current CDRA unit in HabNet was modeled after the ISS CDRA.[2]				
Number of WPA/UPA units for the life support loop	1	2	3	4	5
	An additional WPA/UPA system was brought and added to the Mars habitation module with each additional crew group of four. This ensured that the life support water loop water recovery rate (percentage of water output reclaimed) remained as close as possible to 93-94%, which is the water recovery rate on the ISS prior to the addition of the brine processing assembly (BPA).[15] Given that the ISS serves an analog for the life support loop of the Mars habitation module – where MAV propellant production and food crop growth are absent – each simulation case aimed to achieve a water recovery rate closely aligned to that of the ISS.				
Number of CCAAs in the BPC	10	10	10	15	17
	The number of CCAA units in the BPC was such that the relative humidity inside the BPC stays within ±10% of the target relative humidity of 55%.				
Number of CCAAs for the life support loop	1	1	1	2	2
	There were enough CCAA units to ensure that the relative humidity inside the Mars habitation module stayed within 30% to 60% (target relative humidity is 40%). 60% relative humidity was set to be the upper bound before another CCAA unit was added since 60% is stated to be the upper relative humidity bound to minimize adverse health effects.[13]				
Number of WPAs for the MAV propellant loop	There were as many WPAs as needed to ensure that the WPA did not need to run every hour as a result of reaching full capacity. One WPA was needed for the MAV propellant loop for all five cases to achieve a water recovery rate of approximately 45% in the MAV propellant loop.				

III. Results and Discussion

The five simulation cases were run using the input parameters and variables, ECLS architecture, and technology running order documented in Section II. Figure 11 presents the water demand for 790 days for crew sizes of 4, 8, 12, 16, and 20 people along with the water demand per crew member per day.



Crew Size	4	8	12	16	20
Total Water Demand [kg]	38,669	76,545	118,069	151,617	193,134
Water Demand per Crew Member per Day [kg/Crew Member/Day]	12.24	12.10	12.45	12.00	12.22

Figure 11. Water demand for 790 days for crew sizes of 4, 8, 12, 16 and 20 and the corresponding water demand per crew member per day.

Figure 11 shows that across all crew sizes, 63-65 % of water is needed for generating MAV propellant, 22-23 % of the water is needed for crops, and 12-15% is needed for life support. The water recovery rates across all the cases are documented in Table 9 for the life support and MAV propellant water loop. It should be noted that the water recovery rate of the life support loop across all five cases deviated no more than 2 % from that of the ISS prior to the installation of the BPA (93-94 %).[15] Note that the BPC water recovery rate was not quantified because the design of the water recovery system in the BPC water loop (i.e., the number of CCAAs in the BPC) was intended to let the BPC achieve the target relative humidity (55±10 %) rather than a predetermined and consistent water recovery rate.

Table 9. Water recovery rate for the life support water loop and MAV propellant water loop

Crew Size	Life Support Water Recovery Rate (%)	MAV Propellant Water Recovery Rate (%)
4	93.47	44.94
8	93.73	44.97
12	91.74	44.97
16	93.63	44.98
20	92.45	44.98

The water demand for each crew member per day fluctuates between 12.00 to 12.50 kg across the five cases. These results do not reflect the expected benefit of economies of scale, where the water demand per crew member per day decreases with a larger crew size. An intuitive explanation for this is that the crew schedule was not optimized for sharing resources as the crew size increases. For example, each crew member completes laundry once a week without sharing loads. In addition, the CCAA and WPA/UPA technologies in the Mars habitation and BPC modules are modeled based on systems that exist on the ISS that are not optimized for larger crew sizes.[2]

By comparing the average US household water consumption rates to those used by the Martian crew members, some key insights can be gained. Benchmarking the water demand estimates against the average American household water usage highlights the impact of incorporating water recovery capabilities in the ECLS architecture for long duration missions. According to the US Environmental Protection Agency, the average American family (between 3-4 people) uses over 300 gallons of water per day (~360 kg per person per day) for indoor and outdoor activities such as showering, laundry, and watering lawns.[16] This equates to ~900,000 kg over 790 days at an assumed 0 % water recovery rate. Comparatively, four crew members require 4.31% of that used by the average American family over 790 days. Even with a crew size of 20, the water demand is only 21.53 % of that used by the average American family in 790 days. These water demand estimates may seem unexpectedly low, but a key consideration that must be made is the use of water recovery methodologies. The average US household can be considered inefficient in their use of water whereas Martian use is more efficient through the implementation of water recovery technologies. The authors assert that this difference is a major source of disparity between Martian and Earth-based (average US household) water consumption rates. This difference is also highlighted as a critical factor in accurately modeling water demand and recovery needs for long term Martian missions.

While water reclamation technologies have the potential to reduce the amount of water that will need to be extracted from the Martian surface or brought to Mars, they can also introduce operational and integration complexities to the ECLS system. Implementing water reclamation technologies can also add to the launch mass needed for parts, spares, and maintenance capabilities. Determining water required to sustain continuous human presence on Mars can therefore be seen as a trade-off between many factors including but not limited to the ECLS system water recovery rate, launch mass, ECLS system complexity, and ISRU capabilities.

IV. Limitations and Future Work

The water demand estimates presented in this paper have associated limitations and areas for further work. Specifically, improvements to the simulation set-up, BPC module, Mars habitation module, and crew logistics are addressed.

A. Simulation Set-up

The five discrete case summarized in Table 1 were simulated to determine the water demand of the crew profile shown in Figure 1. However, these discrete cases do not capture the dynamics of resource levels in between the cases and thus necessitates continuous simulations of the crew profile. Performing continuous simulations in the future can help capture water demands at a higher fidelity. This includes modeling mission architectural elements such as changing crew sizes, the addition of ECLS technologies or modules throughout the mission, and resupply capabilities.

In addition, the simulation set-up incorporated simplifying assumptions, which included having access to an unlimited supply of power, oxygen, nitrogen, and carbon-dioxide. In reality, the gaseous resources can be locally generated from the Martian atmosphere using appropriate ISRU equipment, while power generation systems can produce the necessary power. These ISRU and power generating systems can be modeled in future iterations of HabNet to help accurately capture the quantities of resources available for use. Further literature review needs to be conducted to understand the availability and capabilities to extract these resources on Mars because having limited resources will pose constraints that impact water demand. For example, power constraints can impact the duty cycle of various ECLS technologies (e.g., CCCA, WPA/UPA, and water electrolyzer for the MAV propellant), which can impact the water recovery rate and water demand. Furthermore, water storage leakage and extravehicular activities were not modeled. Both may contribute to increased water demands to compensate for leaked water and for cooling spacesuits.

B. BPC Module

As seen in

Table 8, the BPC volume expanded as crew size increased to ensure that there was sufficient CO_2 to support more crops to feed more crew members. This suggests that the BPC volume can expand over time, which can pose logistical and operational challenges if implemented. An approach to fixing this issue could be to add smaller identical BPC modules to accommodate more crops. This strategy, rather than increasing the volume of a single BPC module, can also provide the crop growth system with redundancy.

Another limitation to the BPC module is that wheat was the only crop grown inside the BPC. While wheat provides sufficient calories for crew members to perform their activities, wheat does not have all the macronutrients necessary for a nutritious diet or to support critical bodily processes such as growth, development, and metabolic activities. Future simulations can incorporate other crop types already modeled in HabNet such tomatoes, beans, and rice.

In addition, the number of CCAAs currently installed in the BPC is aimed at ensuring the relative humidity remains within the desired bounds of 55 ± 10 %. An avenue for further exploration could be to size the number of CCAAs in the BPC to maximize the water recovery rate in the BPC, minimize power usage, and reduce system mass while still maintaining the desired relative humidity inside the BPC.

C. Mars Habitation Module

Estimates for the Mars habitation module volume for each crew size were based off the Celentano curve parametric function. However, there are known limitations with Celentano curves. The test conducted by Celentano et al., upon which the Celentano curves are predicated, had a maximum duration of seven days.[17] Data for habitable volume beyond the seven day time frame were extrapolated and may be inaccurate for durations as long as 790 days.[17] While the Celentano curve habitable volume estimate may initially suffice, future iterations of the simulation will need to implement a more robust habitable volume estimation scheme. Furthermore, updated information on hypoxia and hyperoxia conditions (i.e., target percent O_2 in the habitat) for crew, such as that found in Ref. 18, can be integrated into future iterations of HabNet to improve the accuracy of resource demand and crew survivability predictions.

D. Crew Logistics

In the current simulation cases, each additional crew member's schedule was shifted by an activity from the previous crew member's schedule. Although the shifted schedules aid in preventing the simultaneous use of equipment between crew members, the schedules may prove impractical for cohabiting crew members. For example, some crew members may be asleep while others are exercising, potentially causing disruption for those who are trying to sleep. To address this issue, optimal redesign of the crew schedule can help align sleep times for all crew members while ensuring that they can still avoid simultaneous use of facilities and equipment.

Furthermore, it was assumed that the number of MAV seats, with each MAV capable of transporting four crew members, matches the total number of crew in the mission. This provided the option for crew members to depart from the Martian surface at any time but is contingent upon the availability of 15 MAVs. With the current MAV model's capability of estimating LOX and LCH_4 requirements for a MAV that can hold up to 12 crew members, there is an opportunity of further investigate other crew return architectures. This exploration may prove beneficial in better understanding water demands for sustaining continuous human presence on Mars.

V. Conclusion

This paper focused on quantifying water demands for crops, life support, and MAV propellant production for a Mars surface campaign crew profile that captures increasing and continuous human presence. Using an updated version of HabNet, five discrete simulation cases were performed. It was found that the total water demand for 4, 8, 12, 16, and 20 crew members on a 790-day mission were 38,669 kg, 76,545 kg, 118,069 kg, 151,617 kg and 193,134 kg, respectively. For each crew size, 63-65% of water was needed for generating MAV propellant, 22-23 % of the water was needed for crops, and 12-15 % was needed for life support. These simulation cases implemented a long duration ECLS architecture with water recovering capabilities. Additionally, the water demand per crew member per day was found to fluctuate between 12.00 kg to 12.50 kg across the five cases.

The water demand estimates presented in this paper serve as a starting point for further water demand analysis and can be informative for making early-stage mission architectural decisions toward sustaining a continuous human presence on Mars. The methodology used to provide water demand estimates involved inherent assumptions and abstractions. Therefore, a valuable extension that is suggested as an item of future work is conducting a Monte Carlo analysis to capture uncertainties associated with the water demand estimates.

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