Effects of Space Biomanufacturing on Fuel Production Alternatives for Mars Exploration

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Space biomanufacturing garners substantial attention for its potential to save launch mass and power, but biological processes are inherently slower than analogous abiotic manufacturing routes. Their delays motivate studying the trade-offs between space biomanufacturing and traditional *in situ* resource utilization (ISRU) technologies to meet mission needs. An important need that deserves further scrutiny is fuel production for spacecraft propulsion, because recent comparative studies between space biomanufacturing and abiotic ISRU concentrate on a single fuel, methane, and evaluate only the launch mass cost. However, there exists a rich palette of fuels attainable by both biological and chemical techniques, namely, hydrogen, C2 and C3 alkanes and alkenes, biodiesel, nitrous oxide, and hydrazine, as well as different combustion scenarios (e.g., monopropellant, or bipropellant with oxygen). Accordingly, this paper performs a comprehensive analysis of the production of fuel alternatives to capture a trade-off between propulsion efficiency, quantified by the specific impulse, and required production resources and infrastructure. The study assesses biological techniques that generate different fuels against abiotic technologies for Martian ascent. The Equivalent System Mass (ESM) metric, which augments traditional shipped mass costs with pressurized volume, demanded power and thermal control, and needed crew time, forms the comparative basis for evaluating the fuel production alternatives. A key finding is that methane bioproduction is competitive with abiotic manufacturing techniques, even under more detailed scrutiny than past analyses of methane biomanufacturing. The study also incorporates a parametric sensitivity analysis to highlight the high impact of bioproduction yield changes on non-carbon-based fuels. This work adds insight into future mission optimization through appropriate fuel production technology selection.

Nomenclature

ALSSAT	=	Advanced Life Support Sizing Analysis Tool
BIOMEX	=	BIOlogy and Mars EXperiment
BIO-Plex	=	Bioregenerative Life Support System Complex
C	=	thermal control demand
C_{eq}	=	mass-equivalence factor for thermal control
CT	=	daily time of crew operation

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CT_{eq}	=	mass-equivalence factor for crewtime
CUBES	=	Center for the Utilization of Biological Engineering in Space
D	=	days of crew operation
Δv	=	change in velocity
ESA	=	European Space Agency
ESM	=	Equivalent System Mass
g_0	=	acceleration due to Earth gravity
I_{sp}	=	fuel specific impulse in combustion
ISRU	=	*In Situ* Resource Utilization
ISS	=	International Space Station
M	=	mass of shipment
MAV	=	Mars Ascent Vehicle
MELiSSA	=	Micro-Ecological Life Support System Alternative
m_f	=	fuel mass
m_s	=	spacecraft mass excluding fuel
NASA	=	National Aeronautics and Space Administration
P	=	power demand
P_{eq}	=	mass-equivalence factor for power
S	=	startup energy demand for bioprocesses
S_{eq}	=	mass-equivalence factor for startup energy for bioprocesses
V	=	pressurized volume of shipment
V_{eq}	=	mass-equivalence factor for volume

I. Introduction

SPACE biomanufacturing is the use of biology to manufacture desirable products in space. The field is of immense interest because of its capacity to reduce launch mass[1-5]. An important manufacturing output in space is propellant[6,7], which microbial synthetic biology[8,9] can generate[3,4] from on-site resources. A recent analysis of one popular fuel found that the dimensions of a processing plant that leveraged existing biology were substantially smaller than those of an abiotic processing plant[3]. Thus, biological approaches to *in situ* resource utilization (ISRU)[10,11] for fuel production constitute an exciting and promising technology[12] to support long-duration space exploration.

However, biomanufacturing fuel in space has multiple challenges[4]. Biochemical processes are inherently slower than abiotic ones, and therefore require a larger time horizon to meet a specific demand. This implies that biomanufacturing is better for missions that permit a longer processing time. An open question then is the trade-off between space biomanufacturing suitability, mission length, and fuel demand. Further, multi-step biochemical processes complicate biomanufacturing, because initial or intermediate feedstocks for each step may not be readily available. For instance, the Moon does not have an atmosphere, so shipping or excavating carbon or nitrogen is necessary[3]. Similarly, Mars' atmosphere, while 95.5% carbon dioxide, is lean in elemental nitrogen and oxygen[10]. Hence, space biomanufacturing analyses must include the complete costs of producing and shipping resources and infrastructure. Additionally, ascertaining the relative merit of both biochemical and physicochemical fuel production methods necessitates performance comparison at scale. Here, we perform a preliminary suitability trade-off analysis between biological and abiotic production protocols for multiple candidate propellant fuels on the Martian surface.

We assess the suitability of producing fuel alternatives to propel a Mars Ascent Vehicle (MAV) from the surface of Mars to high Mars orbit. Our assessment is preliminary because we do not quantitatively incorporate such factors as technology readiness levels, Mars environment effects, and premature combustion risk. Instead, we focus solely on Equivalent System Mass (ESM)[13], a metric that augments traditional shipped mass costs with those of pressurized volume, demanded power, thermal control, and needed crew time. While studies compare avenues of *in situ* production of methane and oxygen for space propulsion[3,10,14,15], a comprehensive evaluation of different fuels and their production strategies based on ESM, as in this paper, is lacking. Our intellectual contributions in this work are as follows:

1) We consider a diverse suite of fuel-oxidizer candidates: methane-oxygen, hydrogen-oxygen, hydrazine-oxygen, nitrous oxide monopropellant, and nitrous oxide-ethane fuel blend. These candidates capture trade-offs between using carbon-based or nitrogen-based fuels, as per the resource availability at a Mars location.
2) We contrast the cases of biochemical and physicochemical fuel production on the Martian surface. This analysis determines the transition threshold between the relative merits of biotic and abiotic manufacturing.
3) We use ESM to account for all supporting infrastructure like power supply and thermal control. Prior studies[3] focused only on launch mass.

4) We include a sensitivity analysis of constituent processes and their parameters on manufacturing performance, as characterized by ESM.
5) We identify the performance rationale and bottlenecks in fuel production protocols for further research.

The remainder of this paper is as follows. Section II presents background, summarizes relevant literature, and describes investigated scenarios. Section III details the ESM cost of various fuel production alternatives, and includes a parameter sensitivity analysis. Section IV contextualizes our Section III results.

II. Background

A. Related Literature Studies

Synthetic biology is a frontier ISRU technology[16] that pushes the boundary on biological applications in life support systems. Recent applications include the Bioregenerative Life Support System Complex (BIO-Plex),[17] a NASA endeavor. Although the BIO-Plex emphasized crop cultivation, microbial communities recovered resources to attain closed loop functionality[17,18]. Micro-Ecological Life Support System Alternative (MELiSSA), an ongoing ESA initiative, also focuses on crop cultivation for life support in space missions, and on microorganisms for both food supplements and waste treatment to recycle essential nutrients[19,20]. Biology and Mars Experiment (BIOMEX) from ESA/Roscosmos engaged in International Space Station (ISS) experiments with simulated Mars-like conditions to study the long-term habitability of archaea and bacteria on Mars[21]. Recently, NASA instituted the Center for the Utilization of Biological Engineering in Space (CUBES)[22] to advance biomanufacturing of various mission items such as polymeric tools and chemicals from *in situ* resources, alongside crop cultivation on a Mars mission. Thus, our work comparing biofuel production processes, while aligned with space systems biology research, is a novel addition.

There are many choices for spacecraft fuel and oxidizer. Ref. 23 presents various liquid fuel candidates for propelling rockets. These include methane, hydrogen, and hydrazine as well as its derivatives (such as monomethyl hydrazine) as fuel options with oxygen, fluorine, and nitrogen tetroxide as potential oxidizers. However, most ISRU studies of the MAV propulsion system[6,7,10,14,15] focus on methane as the fuel, with oxygen as the oxidizer. Although the literature reports hydrogen and monomethyl hydrazine as candidate fuels with oxygen as oxidizer[7], their ISRU-production lacks substantial study. Similarly, studies of ISRU-production of nitrous oxide as a candidate monopropellant in the presence of a catalyst[24], or as a fuel blend (NOFBX™)[25], are also incomplete. With the advent of advanced abiotic and biotic technologies, ISRU of fuel alternatives can offer feasible production options, depending on available resources. Prior comparative analyses[3] of traditional physicochemical and novel biochemical methods of ISRU, primarily for methane as propellant, only consider shipped mass rather than ESM.

ESM is a comprehensive and inclusive metric to evaluate the relative performance of different ISRU technologies[13]:

$$ESM = M + V_{eq} \times V + P_{eq} \times P + C_{eq} \times C + CT_{eq} \times D \times CT, \quad (1)$$

where pressurized volume (V), power (P) and thermal control (C) that is consumed by utilities, and crew time requirement (at a daily rate of CT) over a mission horizon (D) augment physical shipped mass (M). The equivalence factors V_{eq}, P_{eq}, C_{eq}, and CT_{eq} in (1) that convert inputs of V, P, C, and $D \times CT$ to mass units are functions of deployed technologies, such as solar or nuclear power, and the specifications for a lunar or Martian, transit or surface mission.

ESM equivalence factors are not generic, and many prior ISRU studies on fuel production[10,14,15], crop cultivation[26], and microalgae cultivation[27] separately report the mass, volume, and power demand for different scenarios. There are studies[28-30] that use ESM to analyze life support system provisions of air, water, biomass, and waste, for several missions. Our study focuses on MAV propulsion, drawing appropriate equivalence factors from Ref. 31. We also include the impact of technology change in power generation and thermal control on ESM in a sensitivity analysis.

B. Scenario Descriptions

We investigate the fuel options and production protocols of Figure 1. We focus on four liquid fuel candidates, methane (CH_4), hydrogen (H_2), hydrazine (N_2H_4), and nitrous oxide (N_2O). One candidate, CH_4, is primarily carbon-based, and N_2H_4 and N_2O are primarily nitrogen-based. Liquid oxygen is the oxidizer for all candidates except N_2O, which has oxygen in its molecule. We analyze N_2O as a monopropellant with a catalyst[24], and as a NOFBX™ fuel blend[25] that mixes nitrous oxide and ethane. We source the fuel candidates with different scenarios, considering shipment from Earth or production on Mars. For the latter, our ISRU production protocols are either abiotic (i.e., physicochemical) or biotic (i.e., biochemical), using Martian carbon dioxide and/or water.

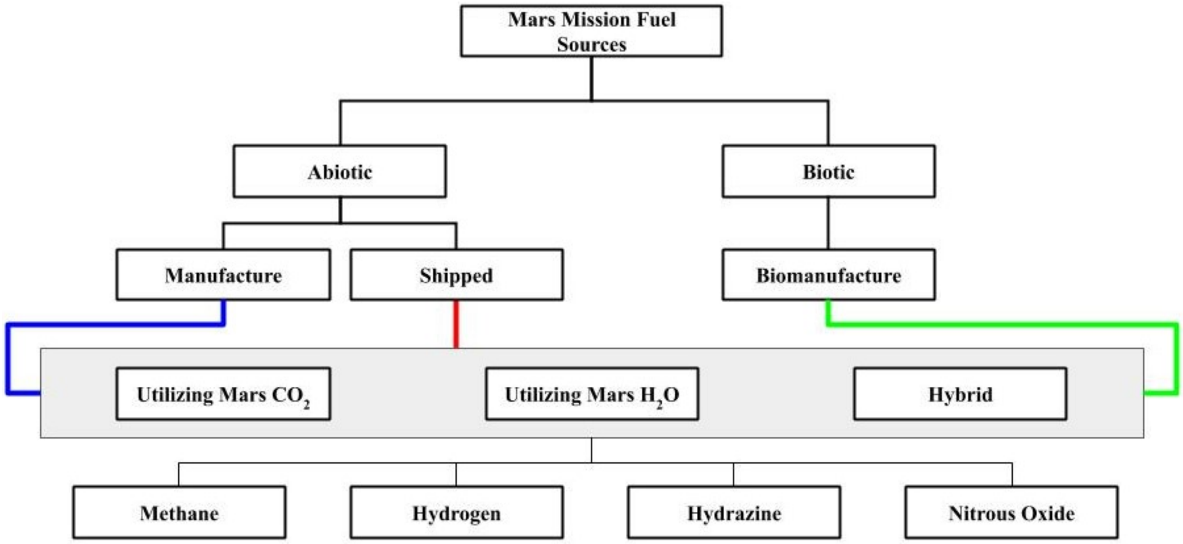

Figure 1. Fuel options and production alternatives in this paper.

The performance of the MAV propulsion system is a function of fuel and oxidizer selection, since the thrust that the MAV engine generates varies with combustion efficiency. The delivered specific impulse characterizes engine performance for a given fuel-oxidizer combination. Specific impulse, I_{sp}, is a fuel-oxidizer characteristic parameter and is an input into the ideal rocket equation[23]

$$\Delta v = I_{sp} \times g_0 \times \ln\left(\frac{m_s+m_f}{m_s}\right), \tag{2}$$

which defines a change in spacecraft velocity, Δv. In this equation, m_f is the combined mass of fuel and oxidizer to propel a spacecraft of mass m_s (that excludes fuel and oxidizer), and g_0 is the acceleration due to Earth's gravity, 9.80665 m/s^2. Accordingly, a velocity change Δv yields the requisite amount of fuel for the MAV to propel itself to a desired orbit. The Δv to propel the MAV to high Mars orbit[10] is 5.625 km/s, and the m_s is 8,518 tons[3]. The necessary amount of fuel and other relevant fuel-specific parameters are in Table 1, as are physicochemical and biochemical ISRU avenues for fuel production. We consider a production horizon of 540 days for ISRU processes on Mars[32].

Table 1 shows that methane-oxygen possesses a very high I_{sp}. Methane production on Mars is very promising due to the high concentration of carbon dioxide in the atmosphere. The oxidizer oxygen is obtainable from electrolyzing water, which we can either ship from Earth or excavate from Martian regolith. Hydrogen-oxygen has an even higher I_{sp}, but its storage and handling is challenging[23]. Hydrazine-oxygen has a moderately high I_{sp}. However, hydrazine is toxic, and its production on Mars is difficult due to low atmospheric nitrogen concentration. This production challenge is also true for nitrous oxide monopropellant and NOFBX™ blends even though they are safe for handling[24,25]. Table 1 includes abiotic and biotic methods of production for these fuel alternatives. Additionally, Table 1 reports the computed demand of fuel for different options of fuel and oxidizer based on typical ratios in the literature.

III. Results

Fuel production protocols stipulate the infrastructure to ship from Earth, such as chemical reactors, bioreactors for bioprocesses, excavators, and liquefaction systems, all of which contribute to ESM. The Advanced Life Support Sizing Analysis Tool (ALSSAT)[33] provides the necessary values for mass, volume, power, and thermal control demand for a Sabatier reactor and a solid polymer electrolyzer. The corresponding values for the excavator and liquefaction system are in Ref. 10, while those for bioreactors are in Ref. 3. We provide sample ESM calculations in the Appendix. We assume that the necessary physicochemical or biochemical reaction ingredients for nitrogen-based fuels like hydrazine, nitrous oxide, and NOFBX™ will be shipped from Earth due to a nitrogen-lean atmosphere on Mars. We defer other methods of sourcing these ingredients to future work. However, for carbon-based fuels like methane, we do not mandate shipping all needed reactants due to plentiful carbon dioxide in the Martian atmosphere.

For power generation, we consider a nuclear power source with thermal control attained from vertical flow-through radiators made of aluminum with silver Teflon coating[31]. For bioprocesses, alkaline fuel cells provide initial startup energy to attain an operational temperature that may exceed the outside Martian temperature. We modify (1) for bioprocesses to account for this startup energy as follows:

Table 1
Demand and Production Protocols for Fuels

Fuel *	Oxidizer	I_{sp} [s^{-1}] *	Requisite amount of fuel and oxidizer [kg]	Production Protocols *
Methane	Oxygen (3 times the fuel amount)[15]	371[4]	Methane: 7,864 Oxygen: 23,592	Abiotic: Sabatier reaction[33] Biotic: Methanogenesis with bacteria[34]
Hydrogen	Oxygen (3.4 times the fuel amount)[23]	440[7]	Hydrogen: 5,193 Oxygen: 17,657	Abiotic: Electrolysis of water Biotic: Biohydrogen from algal bacterial culture[35]
Hydrazine	Oxygen (0.75 times the fuel amount)[23]	300[23]	Hydrazine: 28,067 Oxygen: 21,051	Abiotic: Raschig synthesis[36] Biotic: Anammox bacteria[37]
Nitrous Oxide	-	206[24]	Nitrous Oxide: 129,392	Denitrification of nitrite to nitrous oxide Abiotic: By carbonate green rust and siderite[38] Biotic: By bacterial culture[38,39]
Nitrous Oxide -Ethane as NOFBX™ (8:10 ratio)[4]	-	325[25]	NOFBX™: 41,235 (Nitrous Oxide: 18,326 and Ethane: 22,909)	

* References listed as superscript

$$ESM = M + V_{eq} \times V + P_{eq} \times P + C_{eq} \times C + S_{eq} \times S, \quad (3)$$

where S and S_{eq} are the startup energy demand and the corresponding equivalence factor, respectively. For abiotic processes, the startup energy is not considered because power and thermal control already account for it. We also do not account for crewtime in ISRU production processes since we assume that these processes are automated. Moreover, the human intervention CT for such exploration mission operations is not yet precisely quantified.

A. Computed ESM for Different Fuel Candidates

We consider 3% water content in Martian regolith from the possible range in the literature[10]. Figure 2 presents ESM values for different scenarios when methane is the propellant and oxygen is the oxidizer. Shipping the entire requisite fuel and oxidizer from the Earth results in the highest ESM (32,480 kg) compared to ISRU methods, confirming their merit and corroborating existing studies[10,14,15].

ISRU schemes harness carbon dioxide's reaction with hydrogen to produce methane and water. Electrolysis turns water into oxygen, with the byproduct, hydrogen, recycled as input feed. The reaction scheme is:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O, \quad \text{and} \quad 2H_2O \rightarrow 2H_2 + O_2.$$

Because the hydrogen from this scheme alone is inadequate (two mol H_2 obtained from recycling on the right vs. four mol H_2 needed per mol CO_2), we require an additional source. Further, the amount of oxygen needed for the oxidizer is three times the amount of methane (Table 1). However, from the above stoichiometry, oxygen production is only two times the amount of methane. As a result, additional water must be readily available for conversion into oxygen.

In this study, we consider two sources of water: shipped water and water excavated from Martian regolith. Compared to the case of shipping all materials, ESM drops by around 25% when shipping only water, and by around 70% when using Martian water (Figure 2). For these two water sources, we analyze bioproduction of methane via *Methanobacterium thermaggregans*. This wild-type microbe is considered a promising methane bioproducer as it can already produce 97% of the maximum methane hourly rate of the model and well-engineered microbe *Methanothermobacter marburgensis*[34], and has room for future bioengineered advancement. *M. thermaggregans* requires[34] a bioreactor that operates at 60°C, adding startup energy in ESM (Figure 2). Shipped mass is the major contributor to total ESM for all production routes except the ones that use Martian water, for which power demand has almost equal impact as shipped mass. For the case of shipped water, fuel bioproduction with *M. thermaggregans* performs marginally better (1.2% ESM) than abiotic Sabatier production, while for the case of excavated water, fuel bioproduction with *M. thermaggregans* is similarly marginally improved (2.8% ESM, calculation in the Appendix). Thus, methane bioproduction is competitive with abiotic techniques.

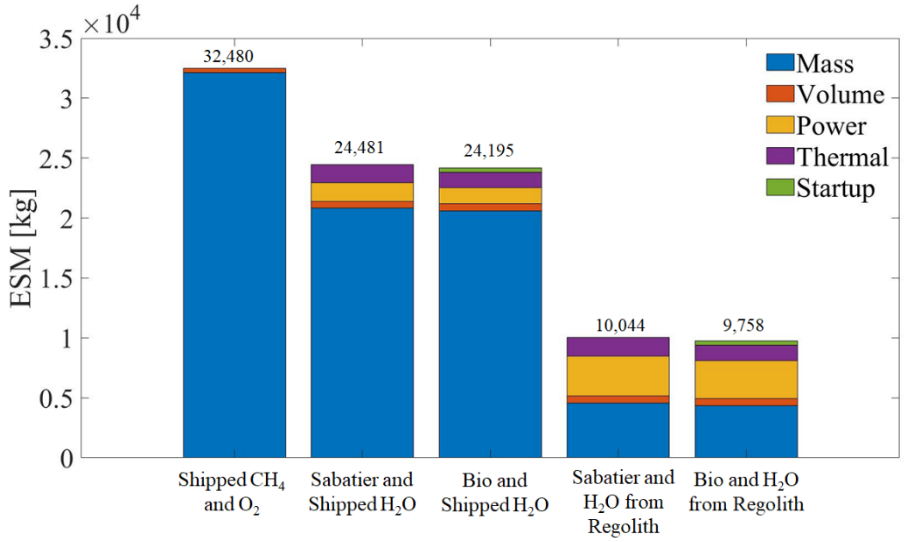

Figure 2. ESM for the scenarios where methane is the propellant fuel. ISRU fuel bioproduction is competitive with a traditional abiotic Sabatier approach regardless of water source.

However, biologically producing fuels may not always be competitive with abiotic techniques. Consider hydrogen, which has the highest specific impulse of the fuels we study, thereby requiring the least fuel mass (Table 1). The total ESM for shipping hydrogen fuel and oxidizer is 25,401 kg (this includes cryotank storage and necessary power, calculation in the Appendix). The resultant ESM is less than shipping methane and oxygen by 22% (Figure 3). Hydrogen and oxygen produced through electrolysis has an ESM that is less than shipping them, at 16,476 kg (Figure 3). However, this case is more expensive than the equivalent methane production process, which has an ESM of 10,044 kg (Figure 2), because we must excavate more regolith before electrolysis. A potential route for biohydrogen production involves algal-bacterial co-culture[35] of *Chlamydomonas reinhardtii* algae and a variant of *Pseudomonas sp.* BS4 bacteria, with oxygen from water electrolysis that also supplements hydrogen stocks. This case performs poorly in terms of ESM, at more than seven times the ESM of shipped fuel and oxidizer from Earth. In general, launch mass is the most significant contributor to ESM.

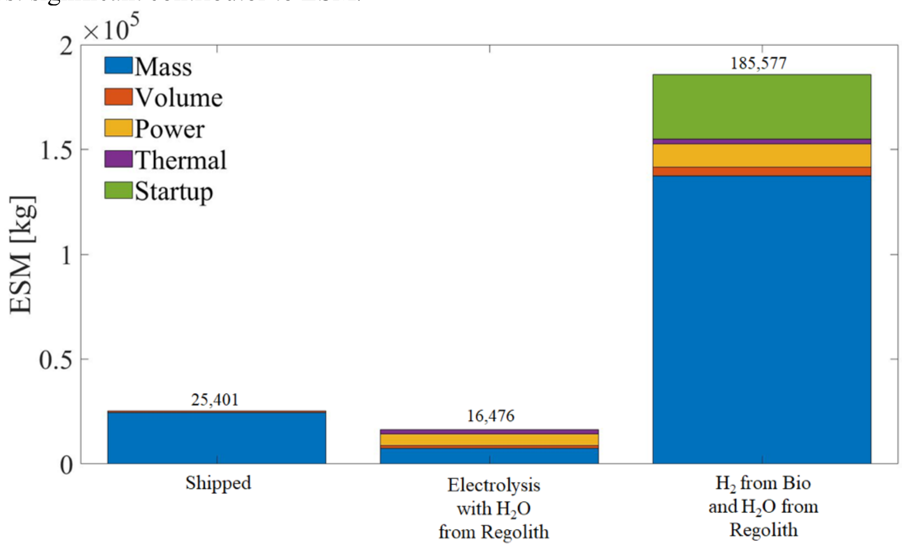

Figure 3. ESM for the scenarios where hydrogen is the propellant fuel. Water electrolysis is best for the studied scenarios.

Resource availability can substantially bias the benefit of space biomanufacturing, and ISRU more broadly. For hydrazine, ESM values (Figure 4) are much higher, with launch mass as the major contributor. When shipping hydrazine and oxygen from Earth, the 50,293 kg ESM exceeds previous fuel options, since hydrazine's I_{sp} is low

(Table 1). The necessary reactants for abiotic hydrazine generation[36], ammonia and sodium hypochlorite, must come from Earth owing to their unavailability on Mars. Oxygen comes from water (3%) in Martian regolith. The associated ESM rises by 2.38 times that of shipped hydrazine and oxygen. Biologically, anammox bacteria can produce hydrazine with shipped ammonium sulphate, sodium nitrite and Fe(II)-EDTA-NO chelate[37], while oxygen comes from 3%-Mars-regolith-water, but this process causes an extremely high ESM (20.75 times that of abiotic production). A low reaction yield also contributes to this high ESM value.

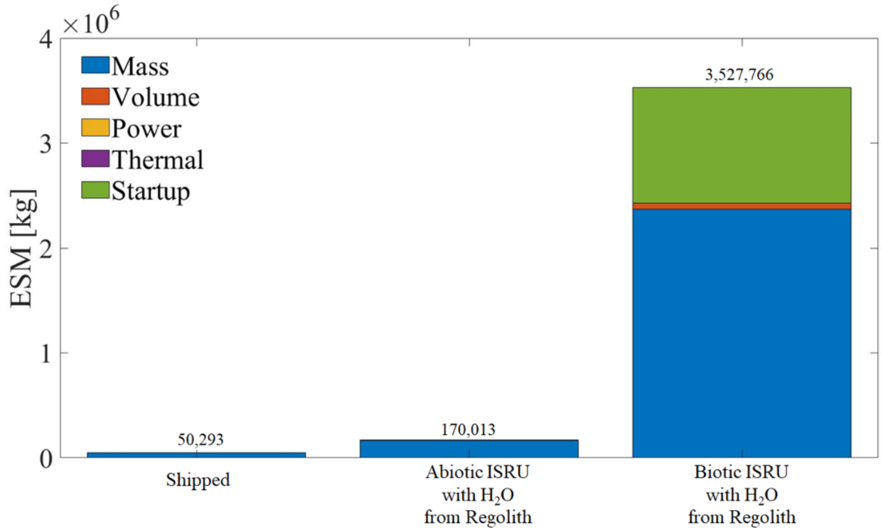

Figure 4. ESM for the scenarios where hydrazine is the propellant fuel. Resource unavailability renders ISRU very costly.

Resource scarcity similarly impacts nitrous oxide fuel production, both as monopropellant and as NOFBX™ fuel blend (Figure 5). Nitrous oxide I_{sp} as a monopropellant is the lowest among the considered fuel options (Table 1), and so the ESM for shipping this fuel is the most among all fuels, at 134,006 kg. The ESM for the NOFBX™ shipment is around 32.6% of the ESM for monopropellant shipment, owing to its comparatively higher I_{sp}. For physicochemical manufacturing of nitrous oxide on the Martian surface with ethane shipped from Earth, carbonate facilitates sodium nitrite conversion to nitrous oxide, while for biomanufacturing, denitrifiers like *Pseudoxanthomonas sp.* accomplish this conversion[38,39]. We assume that it is necessary to ship the requisite nitrite from Earth since the Mars atmosphere is nitrogen-lean, which results in a large shipement. Further, we assume that we ship siderite ($FeCO_3$), a necessary reactant for the abiotic route, or sodium acetate (CH_3COONa), which is necessary for bioproduction. We defer analyzing ISRU for these ingredients to future work. The conversion efficiency of N in nitrite to N_2O is 82% for the abiotic reaction and 70% for the biotic method. Thus, the entire amount of N in nitrite does not convert to N_2O, as nitrogen gas is a side-product. Because we ship siderite for abiotic conversion and sodium acetate for the biotic route, for all four cases in Figure 5 (abiotic ISRU calculation in the Appendix), launch mass has an oversized impact on total ESM.

B. Sensitivity Analysis

Parameters like equivalence factors, demand, and process efficiency all affect ESM, necessitating a sensitivity analysis for these parameters. First, we analyze the impact on ESM of possible changes in power generation and thermal control technologies, which affect the ESM equivalence factors. Nuclear power generation and thermal control by vertical flow-through radiators with silver Teflon coating have equivalence factors P_{eq} and C_{eq} of 54 kg/kW and 145 kg/kW, respectively[31]. To study their sensitivity on ESM, we substitute solar photovoltaic (PV) power generation[31] for an updated P_{eq} of 178 kg/kW. We also include a fuel cell storage[31] equivalence factor of 10 kg/kWh, and change the radiator for thermal control to a light-weight one of composite materials, thereby imparting[31] a C_{eq} of 121 kg/kW.

With PV power, the ESM is much higher than nuclear power, and thus, the total ESM for all scenarios increases substantially. Methane production through biology with oxygen from Martian regolith water is still the best, in terms of least ESM at a value of 24,088 kg, which is 2.46 times the ESM with nuclear power. As compared to Sabatier production of methane, the ESM for methane bioproduction is now 4.3% less (it previously was 2.8% less). These new abiotic and biotic ESM values are very similar to that of shipped hydrogen fuel and oxygen from Earth. In general, the change to solar power hardly impacts the ESM to ship any fuel and oxidizer. For nitrogen-based fuels, the ESM is barely changed for both shipping and ISRU approaches, since shipped mass is prominent in all options.

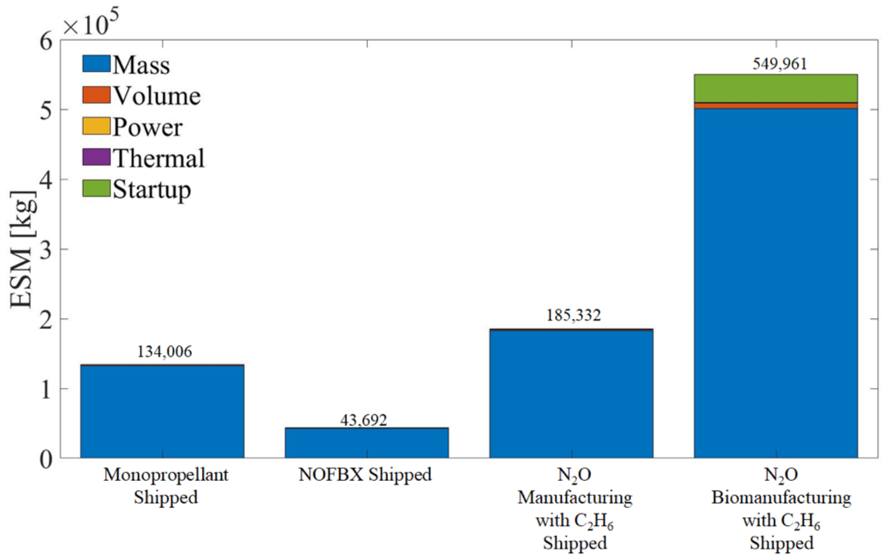

Figure 5. ESM for the scenarios where nitrous oxide is the propellant fuel. Like hydrazine, resource scarcity makes ISRU challenging.

Unlike the change to PV, a change in thermal control radiator material does not affect any ESM (new ESM values are only 0-3% different from prior Section A values across the different fuel production strategies). This is due to a smaller role for thermal control in the total ESM in our considered scenarios.

Second, we analyze the impact of water content in Martian regolith, which affects excavation demand. Instead of 3% water content in regolith, an 8% water content value reinforces bioproduction as the best alternative to generate methane. The ESM is 8,136 kg, a drop of 17% from the ESM with 3% water content. (A similar percentage drop exists for the Sabatier route, but both ESM values exceed the respective bioproduction method). In the case of hydrogen as fuel, an increase to 8% water content drops ESM by 20% for both abiotic and biotic production methods on Mars.

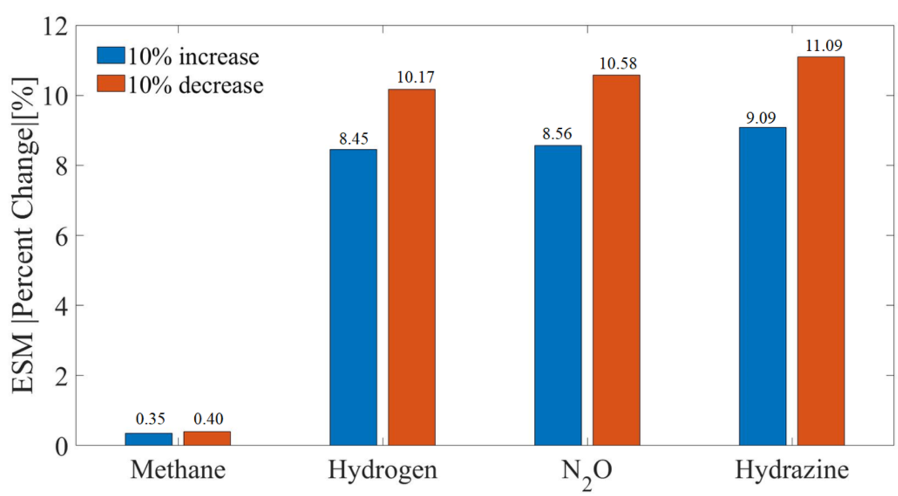

Figure 6. Changing fuel bioproduction yield ±10% has little impact on the ESM of the support structure and requisite energy that generate methane. However, yield changes can greatly affect the ESM of the support structure and requisite energy to make non-carbon-based fuels. All these fuels see similar impacts.

Third, we quantify the impact of ISRU bioproduction yields on the ESM, and thus, the process performance (Figure 6), using cases with 10% increase or decrease in fuel yield. As expected, ESM is inversely proportional to yield. However, two trends are apparent: (1) The ESM for methane bioproduction remains almost constant because the necessary shipment infrastructure is the same, even as yield[34] is varied from 16 gm/L/day. Moreover, water electrolysis, which had a major contribution in the base case ESM (Figure 2), still has the same efficiency for this sensitivity analysis. (2) ESM is almost similarly affected for all other fuels when yield varies. Base case daily yield (section A) was 12.6 mg/L for hydrogen[35], 8.8 mg/L for hydrazine[37], and 47 mg/L for nitrous oxide[39]. The change in ESM values for 10% yield increase and decrease are not identical due to discrete design variables, such as the number of reactors. Nevertheless, ESM changes by 8-11% for non-carbon-based fuel bioproduction.

IV. Discussion

There is much fervor about space biomanufacturing, but its true merit lacks quantification. Past *in situ* resource utilization (ISRU) studies deeply examined how best to produce fuel on the Mars surface, emphasizing methane due to plentiful atmospheric carbon dioxide. However, comprehensive analyses of non-carbon-based fuel generation utility are not widespread, and are needed despite Mars' skewed atmospheric composition toward organic carbon dioxide. We take this opportunity to analyze non-carbon-based fuel production methods together with methane as a use-case of space biomanufacturing impact. We include non-carbon-based fuels because of the possibility that bioproduction methods can make these fuels (from an organic feedstock) in a less costly way than non-biological means. We employ the common space systems engineering cost metric of "equivalent system mass" (ESM) to compare the viability of biological technologies against physicochemical ones. ESM augments traditional shipped mass costs with pressurized volume, demanded power, thermal control, and needed crew time. Our work is unique given the scope and fuel production methods that we consider.

This work is significant because we find that methane bioproduction is competitive with abiotic manufacturing techniques, even under more detailed scrutiny than past analyses of methane biomanufacturing. This result remains surprising given how well-studied methane ISRU production is; its physicochemical Sabatier reaction process is well-established. But unsurprisingly, biomanufacturing non-carbon-based fuels is uncompetitive with traditional physicochemical means. In fact, should we desire a non-carbon-based fuel for Mars use, we determine that it is best to ship that fuel. Resource inavailability plays a critical role in this decision. The results would differ if Mars had a nitrogen-rich atmosphere or if Mars regolith contained nitrogen-based salts like ammonium and nitrates. It is plausible that such salts exist in the regolith[40].

The chosen non-carbon-based fuels are also highly sensitive to bioproduction yield changes. Of course, bioprocesses are relatively novel and, thus, have a great scope for future improvement. However, maintaining process efficiency at a desired level by nullifying disturbances from Mars climate conditions is challenging for bioprocesses. Our initial analysis here did not include Mars environment (e.g., radiation, pressure, temperature) effects. We also omitted bioreactor life span analyses and associated risk impacts on ESM. Thus, a more advanced analysis that incorporates these factors is necessary in future work, as is scoping out a robust control architecture to maintain desired operation. Bioproduction yield changes will also affect the length of the operation horizon, and associated process scaling determines the requisite demand for support structure and energy that will then impact ESM.

Caveats exist, as current technologies continue to develop. When humans finally travel to Mars, the technologies they use may advance beyond the technologies that we consider in this study. Differences may exist in efficiency, power consumption, and even necessary shipped mass. Engineering of the microbes that we selected for bioproduction is likely to increase yield and tolerance of the Martian environment. In our analysis, we also excluded smaller components like reactor connectors and piping, and additionally neglected multi-purpose subsystems that may have secondary downstream benefits. We anticipate that these smaller components will contribute minimally to ESM, and affect both biotic and abiotic fuel production methods equally. Further, the neglected multi-purpose subsystems may even reduce ESM. Thus, the conclusions from our analysis remain unchanged.

Future work includes increasing the number of fuel alternatives, and the number of production routes for each fuel.

Appendix: Spreadsheet of Sample Calculations from Available Data

Methane: 3% Martian Water + Sabatier				
	Mass (kg)	Volume (m^3)	Power (kW)	Thermal (kW)
Sabatier Reactor	737.90	1.44	3.80	2.00
Soil Excavators (x2)	1,183.00	11.48	1.53	
Soil/Water Extraction Plant	615.00	7.05	31.90	
Liquefaction System	30.00	0.18	4.38	
Electrolyzer	1,336.58	4.62	16.50	8.70
Total Tank Values	655.20	39.40		
CO_2 Pressurization			3.87	
ESM Factor	1.00	9.16	54.00	145.00
Total	3,820.78	574.61	3,141.72	1,261.50

Methane: 3% Martian Water + Biomanufacturing					
	Mass (kg)	Volume (m^3)	Power (kW)	Thermal (kW)	Startup Energy (MJ)
Bioreactor	535.20	1.20	0.55	0.08	168.00
Soil Excavators (x2)	1,183.00	11.48	1.53		
Soil/Water Extraction Plant	615.00	7.05	31.90		
Liquefaction	30.00	0.18	4.38		
Electrolyzer	1,336.58	4.62	16.50	8.70	
Total Tank Values	655.20	39.40			
CO_2 Pressurization			3.87		
ESM Factor	1.00	9.16	54.00	145.00	2.22
Total	4,354.98	585.60	3,171.53	1,273.10	373.33

Shipped Hydrogen				
	Mass (kg)	Volume (m^3)	Power (kW)	Thermal (kW)
Hydrogen	5,193.24	73.35		
Oxygen	17,657.01	15.48		
Cryocooler for Hydrogen	7.56	0.03	0.06	
Cryocooler for Oxygen	8.25	0.02	2.18	
Combined Tank Mass	1,600.00			
ESM Factor	1.00	9.16	54.00	145.00
Total	24,466.06	814.18	120.85	

Abiotic Production of N_2O with Shipped Ethane				
	Mass [kg]	Volume [m^3]	Power [kW]	Thermal [kW]
Shipped Ethane	22,908.45			
Ethane Tank	1,184.00	68.00		
Cooling	8.40	0.04	0.07	
Total Reactor Mass	400.00	26.00		
Sodium Nitrite	106,483.55			
Sodium Nitrite Storage Vessel	856.61	49.00		
Reactors	3,176.00	8.00		
Liquefaction System	33.00	0.90	8.70	
Ferrous Carbonate	48,314.00	12.40		
ESM Factor	1.00	9.16	54.00	145
Total	183,365.01	1,505.31	473.58	

Abiotic Production of Hydrazine with 3% Martian Water				
	Mass [kg]	Volume [m^3]	Power [kW]	Thermal [kW]
Soil Excavators (x2)	1,183.00	11.48	1.53	
Soil/Water Extraction Plant	615.00	7.05	31.90	
Liquefaction System	30.00	0.18	4.38	
Ammonia Tank Mass	700.00	42.62		
Ammonia	29,833.96			
Cooling System	6.91	0.03	0.06	
NaOCl Storage	2,055.87	117.50		
NaOCl	130,399.84			
Fuel Tank	750.00	55.59		
Pressurization			0.02	1.69
ESM Factors	1.00	9.16	54.00	145.00
Total	165,574.58	2,147.51	2,045.82	244.76

Acknowledgments

We are grateful for feedback from M.K. Ewert and P.E. Hintze on preliminary results. **Funding:** This study was supported by NASA (NNX17AJ31G) Center for the Utilization of Biological Engineering in Space (CUBES). **Author contributions:** S.S.G. and A.A.M. conceived the study; S.R.D. and S.S.G. developed the model; and S.R.D., S.S.G., A.J.B., and A.A.M wrote the paper. **Competing interests:** The authors declare that they have no competing interests.

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