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System-of-Systems Evaluation of Oxygen Recovery Technologies for Extended Space Missions

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As NASA and international partners advanced the Moon to Mars (M2M) exploration strategy, long-duration space missions and planetary habitats demand increasingly closed-loop life support systems. While the current International Space Station (ISS) Environmental Control and Life Support System (ECLSS) achieves near-complete water recovery, oxygen recovery remains a key performance gap. Technologies such as the Sabatier and Bosch processes offer pathways to higher oxygen loop closure, but their evaluation has often been limited to isolated or component-level analyses. This study proposes a system-of-systems evaluation of oxygen recovery technologies using an integrated simulation framework that models their interactions within a full ECLSS architecture. The work focuses on assessing the prospective impacts of Sabatier, Reverse Water Gas Shift (RWGS) and Bosch on resource recovery performance, system complexity, and mission-level sustainability metrics such as total system mass demand. By embedding these technologies into mission-representative simulations, this research aims to provide a more holistic understanding of how oxygen recovery solutions influence the overall life support ecosystem.

Acronyms and Nomenclature

ATCS = Active Thermal Control System
BPA = Brine Processing Assembly
CDEA = Carbon Dioxide Extraction Assembly
CFR = Carbon Forming Reaction
CHX = Cabin Heat Exchanger
CDRA = Carbon Dioxide Removal Assembly
ECLSS = Environmental Control and Life Support System
ECRS = ElectroChemical Reduction Systems
ESM = Equivalent System Mass
EVA = Extravehicular Activity
HEA = Hydrogen Extraction Assembly
HELIOS = Habitable Environmental Life Support Integrated Operations System
OGA = Oxygen Generation Assembly
ISS = International Space Station
IWP = Ionomer-membrane Water Processor
ISRU = In-Situ Resource Utilization
LEO = Low Earth Orbit
LSMAC = Life Support Multi-Dimensional Assessment Criteria
M2M = Moon to Mars
MSFC = Marshall Space Flight Center
PPA = Plasma Pyrolysis Assembly
TCCS = Trace Contaminant Control System
TRL = Technology Readiness Level
TT&E = Test, Teardown and Evaluation
RTIL = Room-Temperature Ionic Liquid
RWGS = Reverse Water Gas Shift
UPA = Urine Processing Assembly
WPA = Water Processing Assembly
WRS = Water Recovery System

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I. Introduction

LOOKING back on more than 25 years of continuous human presence aboard the International Space Station (ISS), the Environmental Control and Life Support System (ECLSS) community has worked relentlessly to advance the state of the art in life support system with the overarching goal of reducing logistics dependence and the long-term cost of human space habitation. Over this period, incremental yet effective upgrades to regenerative ECLSS hardware, including the Carbon Dioxide Removal Assembly (CDRA), Oxygen Generation Assembly (OGA), Water Processing Assembly (WPA), Urine Processing Assembly (UPA), and Brine Processing Assembly (BPA), have steadily increased system loop closure capability.

These evolutionary improvements have significantly enhanced overall resource recovery performance, particularly on the water side, where the Water Recovery System (WRS) now achieves approximately 96–98% closure. This high level of water loop closure has substantially reduced potable water resupply requirements and demonstrated the viability of long-duration regenerative life support operations in low Earth orbit [1].

Despite these successes, the ISS ECLSS architecture remains not fully self-sustaining. On the atmospheric side, oxygen loop closure is limited to approximately 50% through the integrated operation of the OGA and CDRA, with the remainder dependent on resupply and supplemental oxygen sources. As a result, logistics and sustaining engineering costs remain substantial, with total ISS operations and resupply expenditures averaging approximately $1.1 billion per year between FY 2016 and FY 2020 [2]. This persistent reliance on Earth-based resupply underscores both the achievements and limitations of the current ECLSS architecture and highlights the need for more fully closed-loop, robust, and maintainable life support systems to enable future deep-space and planetary surface missions.

It has been an ongoing effort in NASA to seek various ways to advance the current state-of-the-art ECLSS technologies to either help improve overall technology efficiency and sustainability, solve issues identified from on-orbit operations, and prepare ECLSS for the future human exploration missions beyond Low Earth Orbit (LEO), such as NASA's Artemis Program [3]. The exploration technologies is demonstrated in two ways. One way is to enhance the system's overall performance with a higher loop closure rate by incorporating higher-performing technologies, while the other is to utilize new advancements to address existing gaps.

One successful demonstration is the employment of BPA. The BPA was developed to demonstrate water recovery rates of up to 98% aboard the ISS as noted, directly supporting the requirements of long-duration human exploration missions beyond low Earth orbit. The BPA is based on Paragon's patented Ionomer-membrane Water Processor (IWP) technology, a membrane-distillation–based Water Recovery System (WRS). It operates in an open-loop configuration with the spacecraft cabin air and leverages existing ISS subsystems, including the Cabin Heat Exchanger (CHX) and Trace Contaminant Control System (TCCS), to minimize additional mass, volume, and system complexity. Flight hardware was launched to the ISS in February 2021, and installed on orbit in March 2021. Since activation, on-orbit operations have continued with ongoing performance assessments to optimize system utilization in the spacecraft environment. To date, the BPA has accumulated 612 days of operation, recovered approximately 741 kg of water and yielded an estimated $80 million in launch and waste disposal cost savings. Exceeding its one-year design life, the BPA has substantially surpassed its water recovery requirements and has played a critical role in achieving NASA's 98% water recovery objective on the ISS [3-6].

As the water subsystem has accomplished a very high recovery rate, the next is to improve the resource recovery in the air side to improve the ECLSS loop closure rate. And the key capability missing is the CO_2 reduction. This aspect of ECLSS is critical for long duration missions aiming to minimize resupply needs and maximize onboard resource utilization. However, the ISS has limited operational experience in this area. One notable CO2 reduction technology employed on the ISS was the Sabatier process, designed to support the station's goal of achieving a closed-loop ECLSS.

The Sabatier assembly used excess H_2 from the OGS and CO_2 removed from the cabin atmosphere to produce H_2O and CH_4. The process had the potential to generate up to 907.2 kg of additional water per year, significantly reducing the need for water resupply and enhancing onboard water recovery to close the regenerative ECLSS loop [3,7]. The Sabatier 1.0 system was launched aboard STS-131 and installed on the ISS in October 2010. However, external hardware issues rendered the system inoperable between October 2010 and June 2011. When operations resumed, the system was operating with an off-nominal configuration and interface, generating approximately 1,081 kg of water by October 2017. Only about 2.5 years of operation were utilized. By 2018, the Sabatier assembly was returned to Collins Aerospace due to performance degradation, with Test, Teardown, and Evaluation (TT&E) revealing contamination as the cause of catalyst poisoning [7-9]. Efforts to improve the system led to the development of Sabatier 2.0, which began in 2021. Despite initial progress, the project was eventually canceled in 2024, leaving the ISS without a future operational CO_2 reduction system. This underscores the challenges associated with implementing robust CO_2 reduction technologies and the need for continued innovation to support future exploration missions [3].

Beyond the Sabatier reaction, efforts are underway to develop technologies that either enhance oxygen recovery or serve as alternatives. One such technology is the Plasma Pyrolysis Assembly (PPA), developed by Umpqua Research Company, which enables further closure of the oxygen loop by recovering hydrogen from methane produced by the Sabatier process. A crucial aspect of this approach is the purification of hydrogen from the PPA output stream, which contains acetylene, unreacted methane, as well as byproducts such as water and carbon monoxide [10,11]. The effectiveness of PPA has been validated through extensive ground-based testing. In 2019, zero-gravity tests using the PPA flight fixture demonstrated key microwave plasma capabilities, including ignition and sustainment of H_2 and CO_2 plasmas at zero g, transition between H_2 and H_2/CH_4 plasmas, and operation through varying gravity cycles, including Martian and Lunar gravities. Optimal methane pyrolysis conditions are with a 4:1 H_2/CH_4 ratio and pressures of 110 torr, while CO_2 plasmas were used to remove carbon buildup at 80 torr. Although an incorrect gas mixture (0.36:1 H_2/CH_4) was used in one test, methane pyrolysis still occurred, producing acetylene, but with significant carbon formation [12,13]. Similarly, in the field of methane post-processing to support enhanced oxygen recovery, Honeywell Aerospace's proposal for the Phase II Methane Pyrolysis System for High-Yield Soot-Free Recovery of Oxygen from Carbon Dioxide was selected in 2017 as one of two proposals for the development of oxygen recovery technologies under the Phase II Spacecraft Oxygen Recovery Development program [14,15].

Compared to Sabatier process, the Bosch process catalyzes CO_2 and H_2 to produce solid carbon and water, involving the Reverse Water-Gas-Shift (RWGS) reaction and hydrogen reduction. Initially understood as a two-step process, the Boudouard reaction, where CO is converted into CO_2 and solid carbon, was later identified as a critical contributor. Although the Bosch process itself was first studied in the 1960s during NASA's investigations, the RWGS reaction had been explored earlier. Researchers reported that RWGS could be completed over iron, iron oxide, or copper oxide catalysts at high temperatures (811K–922K). Studies on iron carbides in the mid-20th century revealed that cementite (Fe_3C) deactivated catalysts and produced unwanted byproducts such as methane, while Fe_5C_2 and Fe_7C_3 were more thermally stable under specific conditions [16]. In 1966, General Dynamics Corporation evaluated Bosch systems for use in spacecraft and developed a reactor capable of dual-functioning as a Sabatier reactor. Integration challenges included material limitations, system leaks, and sustainability concerns for subsystems like CO_2 concentrators and electrolysis units. Later, researchers optimized feed compositions and temperatures to improve reactor efficiency, with steel wool catalysts yielding better carbon deposition when pre-activated. During the 1970s, work at Massachusetts Institute of Technology identified the Boudouard reaction as the primary carbon source at 873K and explored how feed gas ratios and catalyst surface areas influenced reaction outcomes. Key findings included the inhibition of carbon deposition by wustite (FeO) and the significant role of catalyst pre-conditioning in increasing effective surface area [16]. Subsequent studies in the 1980s and 1990s focused on alternative catalysts, including nickel, cobalt, and alloys, to improve performance and reduce recycle ratios. These studies demonstrated that nickel and cobalt wire catalysts outperformed traditional iron catalysts in reducing the required recycle ratio while maintaining high carbon deposition rates. Research also indicated that alloy catalysts with distinct contributions to different reactions could optimize the overall Bosch process. The development of kinetic models in later studies highlighted 773K as the optimal temperature for carbon deposition and suggested using pre-conditioned iron-supported catalysts to enhance carbon yield while preventing fibrous carbon formation. These advancements laid the groundwork for modern Bosch systems, emphasizing tailored catalysts and reactor designs for improved efficiency [16]. There are various efforts in developing Bosch technologies. Starting with Series-Bosch (S-Bosch) technology which has a theoretical maximum oxygen recovery of 100% and is one approach to achieve the goal of >90% recovery. It involves a two-step mechanism to convert CO_2 and hydrogen into water and solid carbon. In the first step, CO_2 reacts with hydrogen in the RWGS reaction to produce CO and water. In the second step, the CO is further reduced to solid elemental carbon, either through hydrogen reduction or self-disproportionation via the Boudouard reaction. This combination of reactions forms the basis for efficient carbon and water recovery in the Bosch process. The system involves two reactors, the RWGS reactor and the Carbon Forming Reaction (CFR) and two membranes, the Carbon Dioxide Extraction Assembly (CDEA) membrane (Polaris) and the Hydrogen Extraction Assembly (HEA) membrane (Proteus). In 2016, integrated testing of the Series-Bosch system demonstrated significant potential, leading to design modifications of the CFR to enhance its performance further. Various demonstrations and tests are currently underway at Marshall Space Flight Center (MSFC) as part of the ongoing development process [16-20]. In addition, the Continuous Bosch Reactor, proposed by UMPQUA Research Co. was selected in 2017 as one of two proposal for the development of oxygen recovery technologies as part of Phase II Spacecraft Oxygen Recovery Development [14,15].

Within the Bosch process, ongoing efforts focus on advancing catalyst recycling, improving the conversion of CO_2 to methane, and optimizing the conversion of CO_2 to carbon monoxide. These advancements increasingly utilize IL, liquid organic salts with unique properties particularly advantageous for space applications. IL are of interest due to their low flammability, negligible vapor pressure, and the ability to be tailored for specific tasks, making them well-suited for the demanding requirements of space environments [21]. To address the challenge of frequent catalyst resupply caused by carbon fouling in the Bosch process, NASA MSFC has been advancing the development of a fully regenerable oxygen recovery system leveraging IL. In 2015 and 2016, feasibility studies demonstrated the potential of ILs to significantly reduce catalyst resupply requirements in a closed-loop ECLSS Atmosphere Revitalization system, achieving a Technology Readiness Level (TRL) of 2.5. Building on this success, efforts to scale the proposed technology commenced in 2017, aiming to enhance its applicability for long-duration space missions [21]. In the area of utilizing IL to improve the conversion of CO_2 to carbon monoxide and oxygen, the University of Colorado Boulder, in collaboration with MSFC, has been actively working on this technology, particularly focusing on Room-Temperature Ionic Liquid (RTIL), which offer promising advantages. RTILs, known for their high CO_2 solubility, non-volatility, and stability, can function as electrolytes and catalyst promoters in electrochemical systems, enabling selective product formation with lower energy costs. Despite their potential, these technologies are not yet at a sufficient TRL for spacecraft applications. Current research focuses on advancing the maturity of RTILs-assisted ElectroChemical Reduction Systems (ECRS), with conceptual designs and system-level assessments (mass, volume, power) being developed. These efforts aim to evaluate ECRS feasibility within ECLSS and In-Situ Resource Utilization (ISRU) systems [22]. Similarly, the concept of a self-cleaning Boudouard reactor was introduced to extend catalyst lifetime and address the primary challenge of the Bosch process as mentioned: catalyst fouling due to carbon buildup. This reactor incorporates mechanisms to continuously remove accumulated carbon during operation, maintaining catalyst activity and ensuring efficient CO_2 conversion. Initial testing of the self-cleaning Boudouard reactor showed promising results. The yield of CO_2 conversion increased consistently throughout the test duration for both 1-inch and 2-inch diameter reactors. Notably, the 2-inch reactor achieved a maximum carbon collection efficiency of 74%, which improved over the course of the test. However, for the self-cleaning concept to operate indefinitely, the system must recover 100% of the carbon. During testing, traces of iron were detected in the collected carbon, possibly originating from the catalyst or reactor body. It is unclear whether this indicates gradual catalyst degradation or an initial reaction phase where iron is released until carbon forms a protective coating on the catalyst and reactor surfaces. Further testing of the 2-inch reactor will continue to gather data and better understand these dynamics, with the ultimate goal of achieving a fully sustainable self-cleaning mechanism [23]. All oxygen recovery technologies are important to long term human presence in the space. They represent transformative strides toward achieving sustainable life support systems for long-duration space missions, enabling greater efficiency, reduced resupply needs, and enhanced feasibility for human exploration beyond LEO.

There is still one problem to be addressed in regarding the trade studies in comparing the most promising oxygen recovery techniques. Abney et al. present a comparative assessment of exploration oxygen recovery technologies using Equivalent System Mass (ESM) and the Life Support Multi-Dimensional Assessment Criteria (LSMAC) framework. The study revisits the historical Bosch–Sabatier trade and extends the analysis to multiple developmental oxygen recovery concepts across lunar and Mars mission scenarios. By incorporating additional criteria such as maintainability, risk, technology readiness, reliability, and uncrewed operations, the work demonstrates that technology rankings are highly sensitive to evaluation weighting and mission context, reinforcing the value of multidimensional trade approaches beyond mass-based metrics alone [24]. However, the study does not explicitly evaluate system performance nor assess oxygen recovery technologies within a fully integrated system-of-systems framework. Performance and operational coupling with other ECLSS subsystems are not modeled. Consequently, emergent interactions, lifecycle effects, and architecture-level tradeoffs critical to long-duration missions remain unaddressed, motivating the need for integrated, performance-driven system-of-systems analyses to complement ESM and LSMAC-based screening studies.

II. System of Systems Integration and Evaluation

To evaluate these oxygen recovery technologies, Habitable Environmental Life Support Integrated Operations System (HELIOS) was utilized for evaluation. HELIOS is a modular, physics-based simulation framework developed to evaluate the performance, mass, power, and operational characteristics of ECLSS for long-duration lunar surface missions. The framework integrates subsystem-level models, including air revitalization, water recovery, oxygen generation, and CO_2 reduction, with mission timelines, logistics, and technology maturity assumptions to enable end-to-end architecture assessments. Unlike single-technology or component-level studies, HELIOS is designed to capture system-level interactions, loop-closure effects, and sustaining operations over extended mission durations. This capability allows consistent trade studies across alternative ECLSS architectures, technology selections, and levels of loop closure, supporting data-driven decisions for self-sustaining lunar habitat design [28].

A. Sabatier

First technology was evaluated is the Sabatier. The system combines two CO_2 molecules recovered from cabin air by the CDRA and H_2 from the OGS to generate water and methane via the Sabatier reaction [29]. The fundamental chemical reaction is:

$$CO_2 + 4H_2 \rightarrow 2H_2O + CH_4$$

For the Sabatier system performance, the operational ISS Sabatier Assembly produced over 1000 liters of water over 20,000 hours prior its degradation due to poison issue in the reactor [9]. By utilizing the stoichiometric conversion, the amount of water produced is equivalent to demonstrating a sustained CO_2 processing rate of 66.1 g/hr over 20,000 hours. The performance was 25% lower than the laboratory capabilities. Under controlled condition, the same ISS design reactor achieved 88 g CO_2/hr [26]. This 33% performance increase over flight hardware highlights the impact of real-world operational factors on catalytic efficiency. Next-generation Microlith-based systems demonstrated 134.8 g CO_2/hr - 204% of flight hardware performance through advanced engineering [27]. However, the Microlith prototype for Sabatier application is still TRL 6 [25]. To utilize the baseline, the ISS Sabatier without degradation issue is modeled. The Sabatier processor interfaces with key resource streams. Carbon dioxide is received from the CO_2 store, typically sourced from the CDRA, while hydrogen is supplied from the H_2 store, derived from the OGS. Electrical power is required to support heaters, pumps, and control electronics. On the output side, water is produced and directed to the wastewater store for processing by the WPA, while methane may be stored or vented, depending on mission architecture. Thermal energy is also released as a byproduct of the exothermic reaction (not modeled since it is part of thermal system). The modeled Sabatier system supports multiple operating modes to optimize performance across different mission needs. In Nominal mode, the system operates under standard conditions, consuming approximately 500W of power and processing CO_2 at a rate of 1.0 mole per hour, which corresponds to 50% of its maximum capacity. The reactor is maintained at a temperature setpoint of 350°C. Under High mode, the system maximizes throughput, operating at full capacity with a CO_2 processing rate of 2.0 moles per hour, consuming 800W of power, and reaching a peak temperature of 400 °C. In Low mode, throughput is reduced to 0.5 moles per hour (25% of capacity), with power consumption lowered to 300W and the reactor temperature set to 300 ◦C. The Standby mode maintains the system in a heated but non-reactive state, drawing 100W of power and stabilizing the reactor at 200 ◦C with no CO_2 processing occurring. In terms of performance, the system achieves a default assumed reaction efficiency of 100%. At maximum capacity, the CO_2 processing rate reaches 2.0

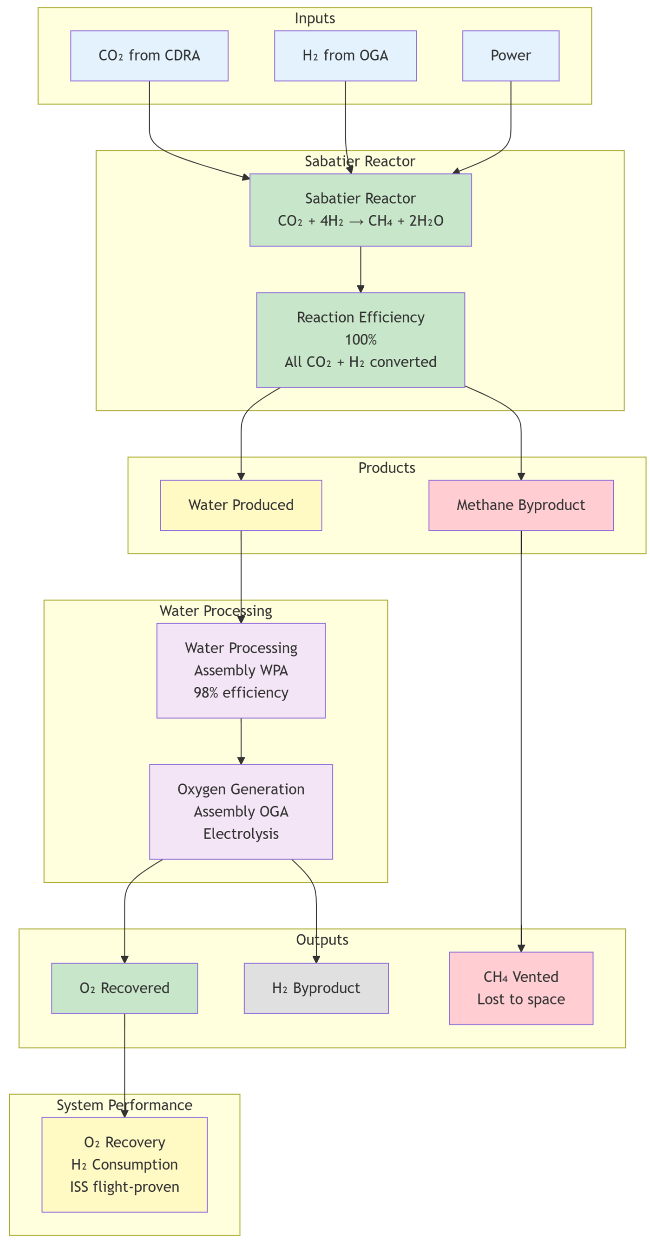

Figure 1: Sabatier Integration

moles per hour (equivalent to 88.0 g/hr). Hydrogen is consumed at a stoichiometric ratio of 4 moles per mole of CO_2, resulting in the production of 2 moles of water and 1 mole of methane per mole of CO_2 processed.

As shown in Figure 1, the Sabatier subsystem is integrated within the ECLSS as a regenerative carbon dioxide reduction pathway that couples air revitalization, water recovery, and oxygen generation into a closed-loop architecture. Carbon dioxide removed from the cabin atmosphere by the CDRA is supplied to the Sabatier reactor, while hydrogen is provided by the OGA as a byproduct of water electrolysis. Electrical power supports reactor operation and thermal control. Within the reactor, CO_2 and H_2 react according to the Sabatier process, which in this architecture is assumed to operate at 100% reaction efficiency, converting all supplied reactants into water and methane. The produced water is routed to the WPA for processing and subsequently returned to the OGA, where electrolysis regenerates oxygen for cabin use while producing hydrogen as a byproduct. This excess hydrogen may be vented depending on system balance. Methane generated by the reaction is treated as a waste byproduct and vented overboard, resulting in a net loss of hydrogen from the system. At the system level, this integrated Sabatier–WPA–OGA loop enables approximately 50% oxygen recovery from metabolic CO_2, consistent with demonstrated ISS flight performance, while introducing a hydrogen consumption penalty that must be offset by resupply or additional recovery technologies in long-duration missions.

B. Reverse Water Gas Shift (RWGS)

The Reverse Water-Gas Shift reaction represents a promising alternative for oxygen recovery in high loop closure ECLSS for long-duration space missions. As space agencies prepare for exploration-class missions to the Moon, Mars, and beyond, improving the closure of oxygen recovery loops becomes critical for reducing consumable resupply mass and enabling sustainable crewed operations.

Current state-of-the-art oxygen recovery relies on the Sabatier process, which reacts carbon dioxide with hydrogen to produce water and methane. While this system has achieved high TRL and has been flight-proven, its inherent limitations constrain mission scalability. Specifically, the Sabatier reaction requires a high hydrogen-to-carbon dioxide stoichiometric ratio (4:1), and discards half the hydrogen in the form of methane, leading to a theoretical maximum of ~50% oxygen recovery from CO_2. To reclaim the remaining oxygen, either additional hydrogen must be supplied (via electrolysis or resupply), or supplemental processing such as methane pyrolysis must be added, which introduces further complexity and power demands.

In contrast, the RWGS reaction offers a more hydrogen-efficient pathway. It converts CO_2 and H_2 into carbon monoxide and water ($CO_2 + H_2 \rightarrow CO + H_2O$), requiring only a 1:1 stoichiometric ratio. Importantly, the unreacted hydrogen can be partially recovered and recycled. Recent studies suggest ~50% of input H_2 may be recycled depending on reactor design and operating conditions. For a notional 4-person crew configuration, RWGS would consume just 0.18 kg of

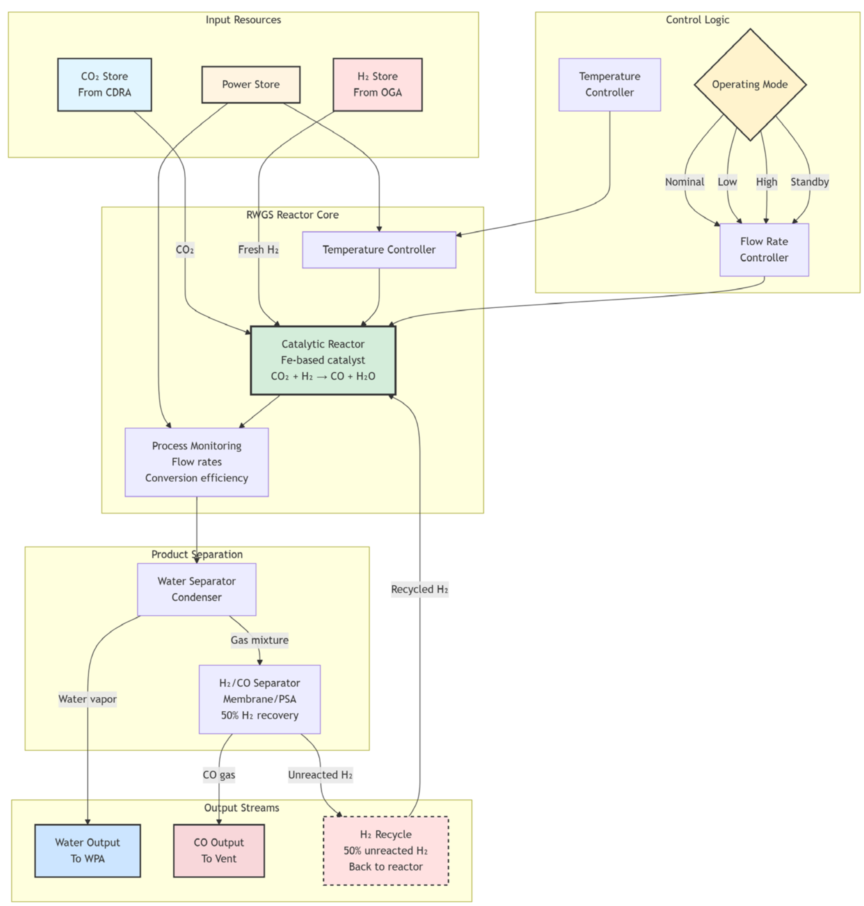

Figure 2: RWGS Integration

H_2 per day based on stoichiometry. With 50% hydrogen recycle efficiency, the net hydrogen demand drops further to ~0.17 kg/day, representing a 72% reduction compared to the ~0.62 kg/day required by Sabatier. This equates to 0.45 kg/day of hydrogen saved, which could be redirected to other uses such as propulsion or stored for contingencies. In scenarios where water electrolysis is used to supply hydrogen, the reduced net demand also lessens the load on the OGA, lowering overall power and water consumption.

Beyond improved hydrogen economy, RWGS systems also offer favorable thermal integration potential. Operating temperatures of 500–750°C match well with upstream or downstream high-temperature subsystems, and unlike Sabatier, RWGS avoids hydrocarbon production and methane venting. While the output product, carbon monoxide, cannot be vented in a closed cabin, it serves as a feedstock for further reactions (e.g., methanation, carbon deposition, or oxidation), enabling its integration into multistage or hybrid life support architectures. Notably, the RWGS reaction is also a core front-end in the Series Bosch concept, where it is paired with a downstream carbon formation reactor to yield solid carbon and water, effectively closing the oxygen loop at 100% efficiency.

Overall, the RWGS process offers a high-potential alternative to Sabatier by reducing hydrogen consumption, increasing oxygen recovery efficiency, and improving system adaptability for deep-space mission architectures. These advantages motivate ongoing development and system-level trade studies to mature RWGS-based technologies for future crewed exploration missions.

The RWGS processor is modeled with four distinct operating modes to provide flexibility across different mission phases, crew loads, and power availability. In Nominal mode, the system processes approximately 2.0 kg of CO_2 per day, matching the daily metabolic output of four crew members. This serves as the baseline for steady-state operation. During periods of reduced occupancy or constrained power, the unit can shift to Low mode, processing 1.0 kg/day of CO_2. For periods requiring increased throughput, such as after system downtime or crew reentry, the High mode provides accelerated CO_2 removal at a processing rate of 4.0 kg/day. Finally, in Standby mode, the system enters a low-power state maintaining a stable reactor temperature with no CO_2 throughput. This operational mode is intended for periods of crew absence, maintenance, or when life support functions are offloaded to redundant systems. These flexible modes allow the RWGS processor to adapt dynamically to mission needs while optimizing power use and thermal load.

Similarly, as shown in the Figure 2, the RWGS subsystem is integrated within the ECLSS as a controllable carbon dioxide reduction process with partial hydrogen recovery. Carbon dioxide stored from the CDRA, hydrogen supplied from the OGA, and electrical power are provided as input resources to the RWGS reactor core. Reactor operation is governed by an operating mode control logic that modulates reactant flow rate across multiple discrete throughput settings, including standby, low, nominal, and high processing modes. Within the catalytic reactor, carbon dioxide reacts with hydrogen according to the RWGS reaction, with temperature actively regulated to maintain desired conversion efficiency. Process monitoring tracks flow rates and reaction performance in real time. The reactor effluent is routed to a product separation stage, where water is condensed and separated for delivery to the WPA. The remaining gas mixture is processed through a hydrogen–carbon monoxide separation system, represented here by a membrane or pressure swing adsorption unit, achieving 50% recovery of unreacted hydrogen. Recovered hydrogen is recycled back to the reactor inlet, while carbon monoxide is vented as a waste product. At the system level, this RWGS configuration enables partial hydrogen recovery and flexible operational throughput, reducing net hydrogen consumption relative to Sabatier-based architectures while maintaining integration with existing ECLSS water and oxygen recovery loops.

C. Bosch Process

The Bosch reaction represents the most oxygen-efficient method for recovering breathable oxygen from metabolic carbon dioxide in the ECLSS. As future missions move beyond low Earth orbit toward lunar bases and Mars surface operations, maximizing resource recovery and minimizing resupply requirements become critical. Unlike the Sabatier process, which discards half of the input hydrogen as methane, or the RWGS reaction, which produces toxic carbon monoxide, the Bosch reaction converts carbon dioxide and hydrogen into water and solid carbon ($CO_2 + 2H_2 \rightarrow C + 2H_2O$), allowing for complete oxygen recovery when paired with water electrolysis. Its stoichiometry enables the production of two moles of water per mole of CO_2, facilitating the recovery of all oxygen atoms as O_2, while the solid carbon byproduct can be stored or potentially repurposed for in-situ manufacturing. In terms of hydrogen efficiency, the Bosch reaction requires only 0.36 kg of H_2 per 4.0 kg of CO_2 processed daily, and with 97% hydrogen recycling, the net hydrogen consumption can be reduced to approximately 0.062 kg/day, yielding a 92% savings compared to Sabatier and 65% compared to RWGS. Additionally, the doubled water production significantly reduces the load on the OGA, which typically electrolyzes water to supply breathing oxygen and hydrogen for CO_2 reduction.

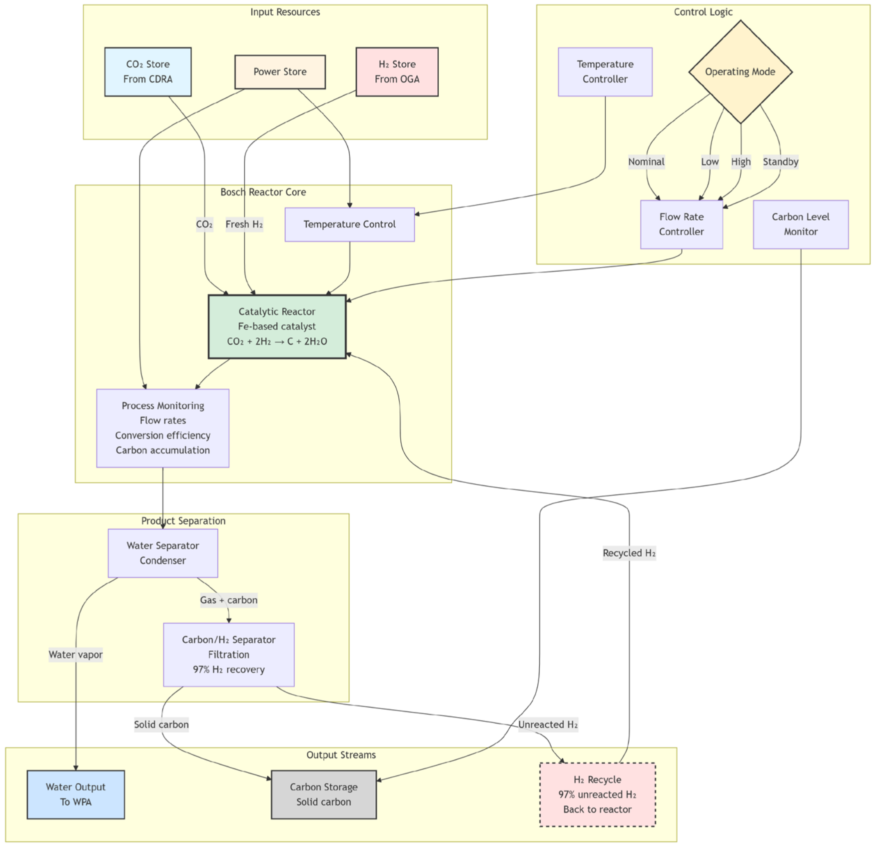

Figure 3: Bosch Integration

RWGS	$CO_2 + H_2 \leftrightarrow H_2O + CO$
CO Hydrogenation	$CO + H_2 \leftrightarrow H_2O + C(s)$
Boudouard	$2CO \leftrightarrow CO_2 + C(s)$
Bosch Process	$CO_2 + 2H_2 \leftrightarrow 2H_2O + C(s)$

Figure 4: Bosch Process [16]

Despite these compelling advantages, Bosch technology faces notable challenges that have limited its deployment to date. Chief among them is carbon fouling: as solid carbon accumulates on catalyst surfaces, it can impede gas flow and degrade system performance, necessitating regular maintenance or advanced carbon separation mechanisms. The Bosch reaction also requires higher operating temperatures (typically 550–750°C), has slower reaction kinetics than Sabatier or RWGS, and exhibits the highest power demand among the three systems. Furthermore, while the Sabatier system is flight-proven and RWGS has undergone recent prototyping, Bosch remains at a lower TRL with no flight heritage. However, advances in system architecture, such as modular series-Bosch configurations with decoupled carbon formation stages, are addressing these limitations and enabling more robust, continuous operation. In light of its superior oxygen recovery efficiency and dramatically reduced hydrogen demand, the Bosch process remains a highly attractive candidate for deep-space life support applications where long-duration sustainability is paramount.

As shown in Figure 3, the Bosch subsystem is integrated within the ECLSS as a high-closure carbon dioxide reduction process with near-complete hydrogen recovery. Carbon dioxide stored from the CDRA, hydrogen supplied from the OGA, and electrical power are provided as input resources to the Bosch reactor core. Reactor operation is governed by an operating mode control logic that modulates reactant flow rate across discrete throughput settings, including standby, low, nominal, and high processing modes, while a dedicated temperature controller maintains conditions suitable for sustained catalytic operation. Within the reactor, carbon dioxide reacts with hydrogen over an iron-based catalyst according to the Bosch reaction. Process monitoring tracks flow rates, conversion efficiency, and carbon accumulation to support stable long-duration operation. The reactor effluent is routed to a product separation stage, where water is separated and delivered to the WPA, and solid carbon is removed via filtration and directed to dedicated carbon storage. Unreacted hydrogen is separated from the gas stream with an assumed recovery efficiency of 97% and recycled back to the reactor inlet. At the system level, this Bosch configuration enables near-complete oxygen recovery from metabolic CO_2 while minimizing hydrogen losses through aggressive hydrogen recycle, at the expense of increased system complexity and solid carbon handling requirements.

III. Simulation Environment

The Habitable Environmental Life Support Integrated Operations System (HELIOS) was utilized for testing which is a Python-based discrete-event simulation framework developed at the Georgia Institute of Technology to evaluate high loop-closure ECLSS architectures. HELIOS provides a physicochemically validated, system-of-systems modeling environment capable of simulating coupled air revitalization, water recovery, and oxygen generation processes under long-duration mission conditions. The framework is specifically designed to assess integrated performance, resource flows, and operational interactions among ECLSS subsystems rather than isolated component behavior.

HELIOS employs a modular, layered architecture to support flexible configuration and technology trade studies. The core layer manages global simulation time advancement at an hourly resolution, resource storage accounting, and habitat environmental state tracking. The systems layer implements first-principles and semi-empirical physicochemical models of individual ECLSS subsystems, including carbon dioxide removal, oxygen generation, water processing, waste processing, and thermal and humidity control. The crew layer models crew metabolic loads, consumable usage, and crew movement between habitat modules, including the effects of Extravehicular Activity (EVA). The features layer enables reliability modeling, failure injection, and maintenance scheduling, while the configuration layer supports scenario definition, parameter management, and technology selection for comparative analyses.

Key HELIOS capabilities include conservation-based tracking of mass and energy flows at each simulation time step, multi-module habitat representation with inter-module ventilation and crew mobility, configurable subsystem activation logic, and integrated modeling of oxygen recovery processors including Sabatier, RWGS, and Bosch reactors. All system states and resource inventories are logged at hourly resolution, enabling post-processing of transient and steady-state performance metrics. The framework has been validated against ISS operational trends to ensure physically realistic behavior.

The test habitat modeled in HELIOS consists of a five-module configuration arranged in a hub-and-spoke layout representative of lunar Gateway or Mars transit vehicle architecture. Each module has an internal volume of 100 m^3, resulting in a total habitable volume of 500 m^3. The central core module functions as the primary ECLSS equipment hub, housing the oxygen generation system, oxygen recovery processor, and associated power interfaces. Four peripheral modules support crew quarters, science operations, EVA preparation, and utility functions, respectively.

Active inter-module ventilation is modeled with a minimum balanced airflow rate of 200 m^3/hr to ensure uniform atmospheric mixing across the habitat. Crew movement between modules is explicitly simulated, with an average of three module transitions per crew member per day. This movement influences localized metabolic loading and transient atmospheric conditions, particularly in high-occupancy or EVA-adjacent modules.

Nominal atmospheric setpoints are maintained at Earth-sea-level conditions, with a total pressure of 101.3 kPa and an oxygen partial pressure of 21.3 kPa. Carbon dioxide partial pressure is actively controlled below 0.5 kPa through CDRA activation logic. Thermal and humidity control targets are set to 40% ± 10% relative humidity, respectively. A time-dependent leakage model is enabled to represent realistic habitat losses and continuous make-up gas demand over long-duration operations.

To compare the performance of these technologies, only one oxygen recovery processor is active during each simulation run. Three configurations are evaluated. The baseline configuration employs a Sabatier reactor, which converts CO_2 and hydrogen into methane and water. While the Sabatier process provides flight-proven reliability, no hydrogen recycling is assumed, and methane is vented.

The alternative configuration uses an RWGS reactor operating at 500°C with iron-based or copper-zinc oxide catalysts. CO_2 is processed at a rate equivalent to 2.0 kg/day, converted to an hourly basis. Partial hydrogen recycling is implemented at 50% efficiency with a 1.0 mol buffer capacity. Carbon monoxide byproduct is treated as a toxic waste stream and vented.

The last configuration employs a Bosch reactor operating at 650°C with iron- or nickel-based catalysts. The Bosch system processes CO_2 at the same nominal rate as the RWGS configuration while achieving 97% hydrogen recycling efficiency with a 0.5 mol buffer. Solid carbon byproduct is accumulated in a dedicated storage unit and removed when the total mass exceeds 5 kg.

IV. Results

All three oxygen recovery system configurations, Sabatier, RWGS, and Bosch, were successfully operated within the HELIOS simulation framework for the full 730-day mission duration with a four-crew complement. Throughout the simulation, the crew remained viable and all ECLSS subsystems functioned nominally. No system-level constraint violations were observed, and supporting subsystems, including the WRS, demonstrated sufficient capacity to accommodate the additional loads imposed by the different oxygen recovery processes. These results establish a consistent baseline from which technology-specific performance differences can be evaluated.

To enable a direct comparison, all three configurations were modeled with the same carbon dioxide processing rate, equivalent to a two-crew CO_2 reduction capability based on ISS Sabatier performance. This constraint was selected to isolate differences in hydrogen utilization, water recovery, and waste production rather than absolute CO_2 throughput, particularly given the hydrogen-intensive nature of the Sabatier reaction.

A. Potable Water Performance

Potable water storage levels were compared over the 730-day mission as shown in Figure 5. All three configurations started with 3495 kg of water. Lower end-of-mission potable water inventory corresponds to greater net water consumption and reduced recovery efficiency, while higher remaining inventory indicates more effective water regeneration.

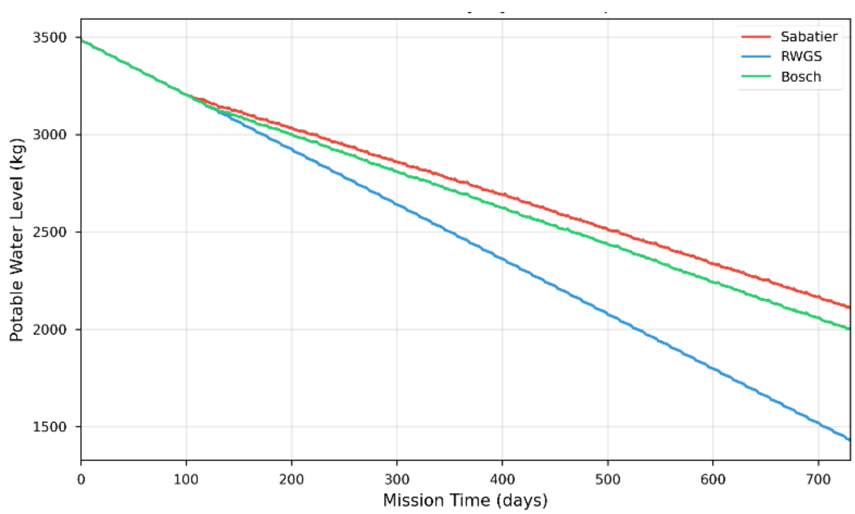

Figure 5: Potable Water Recovery: System Comparison

The Sabatier configuration maintained the highest potable water level at the end of the mission (2110.09 kg), reflecting strong water production through the conversion of CO_2 and hydrogen into water. The Bosch configuration followed closely, with a final potable water inventory of 2000.13 kg, demonstrating comparable water recovery performance despite its more complex reaction pathway. In contrast, the RWGS configuration exhibited a significantly lower potable water level (1430.68 kg), indicating substantially reduced water recovery relative to both Sabatier and Bosch.

These results highlight a key architectural distinction: while RWGS enables partial hydrogen recycling, its limited water production efficiency leads to greater reliance on stored and recovered water from other ECLSS subsystems. Over long-duration missions, this characteristic directly increases pressure on the water recovery architecture and logistics chain.

B. Hydrogen Storage and Utilization

Hydrogen storage level is a critical performance indicator given that all three systems were modeled with identical CO_2 processing rates. Differences in hydrogen inventory therefore directly reflect hydrogen consumption and recycling efficiency within each oxygen recovery process.

As shown in Figure 6, the Sabatier system accumulated the lowest hydrogen inventory by the end of the mission (93.75 kg), consistent with its stoichiometric requirement of four moles of hydrogen per mole of CO_2 and the absence of hydrogen recycling. In contrast, the RWGS configuration accumulated the largest hydrogen inventory (309.73 kg), reflecting partial hydrogen recycling and comparatively low hydrogen demand per unit CO_2 processed. The Bosch system demonstrated intermediate behavior, with a final hydrogen inventory of 244.32 kg, consistent with its high hydrogen recycling efficiency (~97%) but nonzero net consumption.

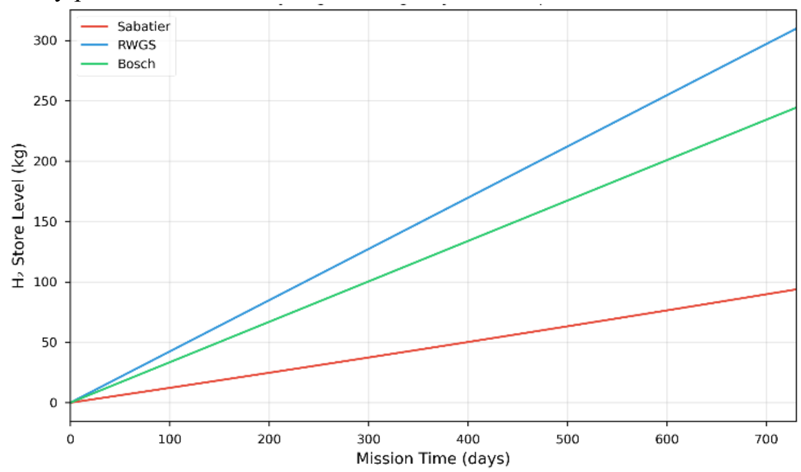

Figure 6: Hydrogen Storage: System Comparison

From an air-loop resource recovery perspective, these results indicate that RWGS and Bosch significantly reduce hydrogen demand compared to Sabatier, with Bosch offering a balanced trade between hydrogen efficiency and water production. Hydrogen availability emerges as a key architectural driver for long-duration missions where hydrogen resupply is constrained or tightly coupled to water electrolysis capacity.

C. Carbon Dioxide Storage and Reduction Consistency

Carbon dioxide storage trends (Fig. 7) indicate that all three oxygen recovery configurations were modeled with the same nominal CO_2 processing setpoint, corresponding to a two-crew-equivalent reduction capacity consistent with ISS Sabatier-class performance. While the commanded CO_2 throughput is identical across cases, small but systematic differences in CO_2 inventory growth are observed over the mission duration, with the RWGS configuration exhibiting the highest accumulated CO_2 by end of mission.

These differences arise from technology-specific reaction efficiency assumptions rather than from fundamental disparities in system sizing or operating mode. In the current exploratory model, RWGS is assumed to operate at an effective hydrogen reaction efficiency of approximately 85%, resulting in a realized CO_2 conversion rate of ~1.70 kg/day relative to the 2.0 kg/day target. In contrast, both Sabatier and Bosch systems are modeled with higher effective conversion efficiencies (~95%-100%), yielding realized CO_2 reduction rates of ~1.90 kg/day. Over the 730-day mission, this efficiency-driven shortfall leads to a modest but cumulative increase in stored CO_2 for RWGS, consistent with the trends shown in Fig. 7. This modeling approach is particularly important for Sabatier, which is inherently hydrogen intensive; by constraining the nominal CO_2 processing setpoint while allowing realized conversion to reflect efficiency, the comparison isolates downstream impacts on hydrogen utilization, water recovery, and waste handling without conflating results with differences in reactor sizing.

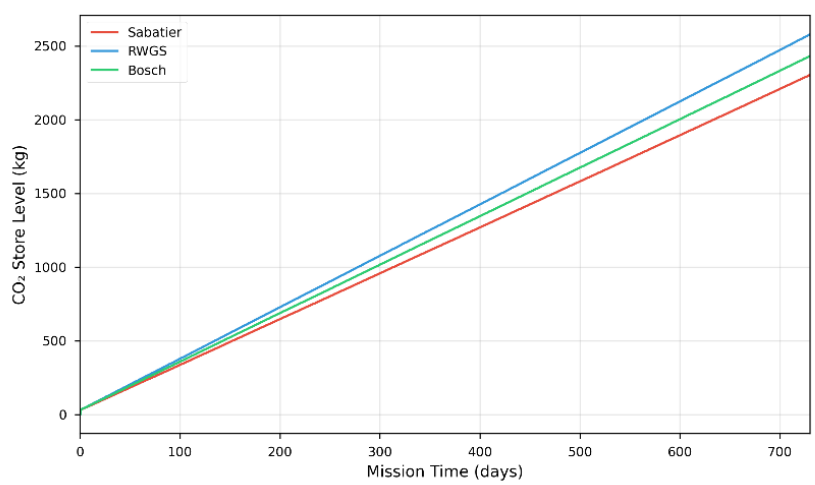

Figure 7: Carbon Dioxide Storage: System Comparison

The reaction efficiencies applied in this study represent reasonable values selected for an early-phase, architecture-level trade analysis. As additional test, demonstration, or flight data become available, particularly for RWGS and Bosch systems, the assumed efficiencies can be readily updated within the HELIOS framework. This flexibility enables future studies to refine CO_2 reduction performance and reassess system-level impacts using higher-fidelity, technology-specific performance data as the technologies mature.

D. Waste Production and Planetary Protection Implications

Waste production represents a growing design concern for future exploration missions, particularly in the context of planetary protection, contamination control, and spacecraft logistics. Waste products may be vented to the external environment or returned to Earth, both of which impose operational, regulatory, and mass-volume penalties.

Figure 8 and 9 compares cumulative waste product accumulation for the three oxygen recovery systems, assuming no downstream waste processing. Over the 730-day mission, the RWGS configuration produced the largest waste mass (789.69 kg of carbon monoxide), followed by the Sabatier system (552.61 kg of methane). The Bosch configuration produced the least waste, accumulating 378.48 kg of solid carbon

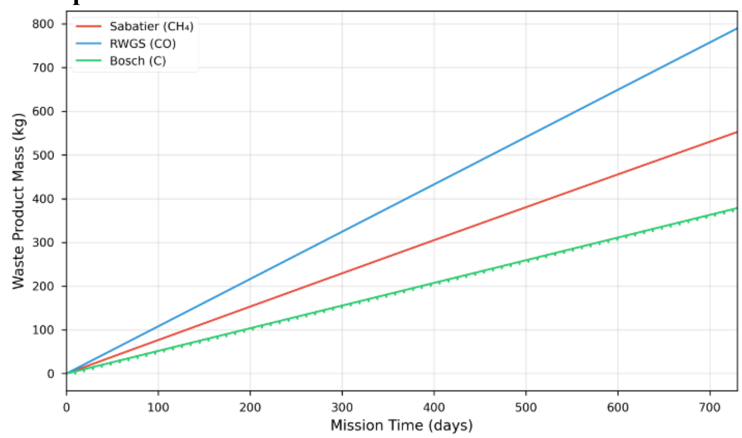

Figure 8: Waste Product Accumulation

In addition to mass, waste volume requirements further differentiate the systems. As shown in Figure 9, solid carbon storage for Bosch requires approximately 1.23 m³, whereas gaseous methane and carbon monoxide storage for Sabatier and RWGS require 4.84 m³ and 3.96 m³, respectively. This corresponds to volume increases of approximately 293% for Sabatier and 222% for RWGS relative to Bosch.

From a planetary protection perspective, these differences are significant. Gaseous waste products are more likely to be vented or require return to Earth, increasing contamination risk and competing with high-value logistics cargo. In contrast, solid carbon produced by the Bosch reaction is inherently easier to contain, store, and potentially repurpose, making it more compatible with long-duration surface missions and closed-loop architectures.

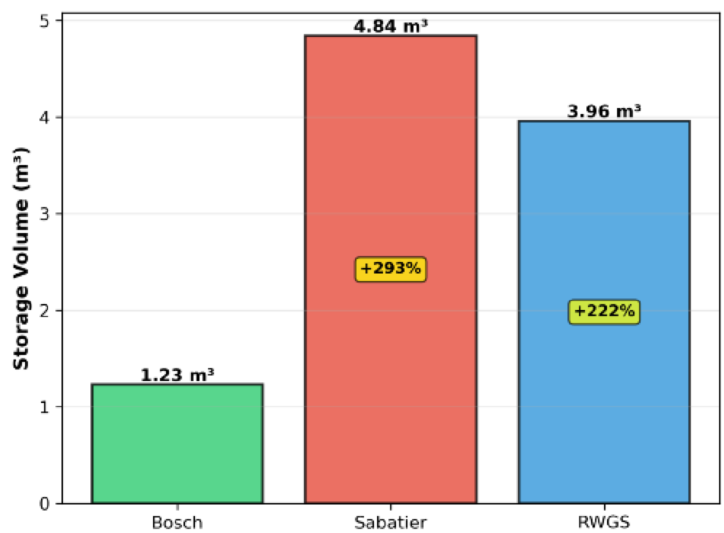

Figure 9: Waste Store Volume

E. Summary of Trade Implications

Taken together, the HELIOS results demonstrate that all three oxygen recovery technologies are capable of supporting long-duration crewed missions when operated nominally. However, their system-level impacts differ substantially. Sabatier provides strong water recovery but at the cost of high hydrogen consumption and large gaseous waste volumes. RWGS offers reduced hydrogen demand but suffers from poor water recovery and the highest waste production. Bosch presents a balanced solution, achieving high water recovery efficiency, strong hydrogen recycling, and the lowest waste mass and volume, albeit with increased system complexity and power demand.

These findings underscore the importance of evaluating oxygen recovery technologies within an integrated ECLSS framework rather than as standalone reactors. When viewed through the combined lenses of resource recovery efficiency, waste management, and planetary protection, Bosch-based architecture offers compelling advantages for future long-duration lunar and Mars missions.

V. Conclusion

This study applied the HELIOS simulation framework to explore and compare Sabatier, RWGS, and Bosch oxygen recovery technologies within an integrated ECLSS architecture. All three configurations were shown to support a four-person crew for a continuous 730-day mission while maintaining nominal operation across all ECLSS subsystems. The results demonstrate that the supporting air revitalization, water recovery, and pressure control systems were capable of accommodating the additional loads imposed by each oxygen recovery process under the modeled conditions.

It is emphasized that the intent of this work is exploratory rather than deterministic. The analysis is designed to investigate system-level trends, sensitivities, and trade relationships rather than to predict absolute flight performance or to establish final design margins. By constraining the nominal CO_2 processing rate to an equivalent two-crew reduction capacity, the study isolates technology-specific impacts on downstream resource flows, such as hydrogen utilization, water recovery, and waste production, without conflating results with reactor sizing or detailed control optimization.

Within this exploratory framework, the results indicate that Sabatier provides strong potable water recovery but at the cost of high hydrogen consumption and substantial gaseous waste production. RWGS reduces hydrogen demand relative to Sabatier but exhibits significantly lower water recovery efficiency and the highest accumulation of waste products. The Bosch configuration demonstrates a more balanced performance, combining high hydrogen recycling efficiency, competitive water recovery, and the lowest waste mass and volume among the three technologies.

Waste handling emerges as a key discriminator when viewed through the lenses of logistics efficiency and planetary protection. Gaseous byproducts associated with Sabatier and RWGS impose significant storage volume penalties and increase reliance on venting or Earth return, while solid carbon produced by the Bosch process is inherently easier to contain and manage. These differences become increasingly consequential for long-duration missions, particularly in lunar and Mars architectures where mass, volume, and environmental impact are tightly constrained.

Overall, this work demonstrates the value of integrated, architecture-level ECLSS modeling for early-stage technology trade studies. The HELIOS framework enables rapid exploration of coupled system behavior and provides a flexible platform for updating performance assumptions as additional experimental, test, and flight data become available. Future efforts will transition from exploratory to increasingly deterministic analyses by incorporating higher-fidelity test data, reliability and failure effects, power and thermal coupling, and potential integration with ISRU systems to support informed design decisions for sustained human exploration beyond low Earth orbit.

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