Equivalent System Mass Comparison of ECLSS CO_2 Removal Technologies

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This project employs equivalent system mass (ESM) analyses to evaluate and compare state-of-the-art spacecraft CO_2 removal systems. The ESM methodology converts sizing characteristics such as volume, power, and cooling requirements into a unified metric of mass, allowing for simple quantitative comparison of equipment impacts on a system level. Comparison of six high TRL technologies – the Carbon Dioxide Removal System (CDRS), Thermal Amine Scrubber (TAS), Carbon Dioxide Removal Assembly (CDRA), Four-Bed CO_2 Scrubber ($4BCO_2$), CO_2 and Humidity Control Swing Bed (CHC), and the Carbon Dioxide Removal by Ionic Liquid Sorbent (CDRILS) – was achieved using an existing ESM spreadsheet tool that formerly ranked such technologies for consideration on Gateway. Fidelity of the tool was increased through revision with the most up-to-date sizing and performance data for each technology. ESM values were then estimated using NASA-supplied Lunar, Martian, and low-Earth orbit habitat infrastructure costs. This paper details the ESM approach used, lists major performance variables for each CO_2 removal option, and summarizes conclusions of the technology comparison. The results are intended to act as a guide to assist programs in their selection of CO_2 technologies best suited for a specific vehicle or mission.

Acronyms and Nomenclature

$4BCO_2$	=	Four-Bed CO_2 Scrubber
CHC	=	CO_2 and Humidity Control Swing Bed
CDRA	=	Carbon Dioxide Removal Assembly
CDRILS	=	Carbon Dioxide Removal by Ionic Liquid Sorbent
CDRS	=	Carbon Dioxide Removal System
CM	=	crew member
CO_2	=	carbon dioxide
ECLSS	=	Environmental Control and Life Support System
ESM	=	equivalent system mass
I-HAB	=	International Habitation Module
JAXA	=	Japan Aerospace Exploration Agency
JETS	=	Johnson Space Center Engineering, Technology, and Science
LEO	=	low-Earth orbit habitat
LS	=	Lunar surface
LT	=	Lunar transit
M_c	=	gas consumables mass
M_s	=	system mass
MS	=	Mars surface
MT	=	Mars transit
P	=	power consumption
PCI	=	Precision Combustion, Inc.
Q	=	heat loss or gain
TAS	=	Thermal Amine Scrubber
TRL	=	technology readiness level
V	=	system volume
γ_P	=	power equivalency factor
γ_Q	=	thermal control equivalency factor
γ_V	=	volume equivalency factor

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I. Introduction

THIS CO_2 removal equivalent system mass (ESM) analysis task was conducted by Amentum JETS II in accordance with NASA to provide a comparison of competing Environmental Control and Life Support Systems (ECLSS) CO_2 removal technologies for manned space exploration. ECLSS CO_2 removal technologies typically work by either capturing CO_2 and venting it to space or capturing CO_2 and sending it to downstream processing to recover oxygen that can be recycled to the habitat [1]. For long-term human spaceflight, any CO_2 removal technology will need to integrate into existing vehicle systems and prove sufficient performance while maintaining a reasonable system-level impact. Evaluation and comparison of six technologies was achieved using an existing ESM excel tool that formerly ranked such technologies for consideration on Gateway. The following technology options have been assessed using metrics of mass, volume, power and cooling requirement, CO_2 removal performance, and gas consumables. The technology readiness level (TRL) of each system as evaluated for Lunar missions is listed.

- Carbon Dioxide Removal System (CDRS) – **TRL 7**
- Thermal Amine Scrubber (TAS) **– TRL 9**
- Carbon Dioxide Removal Assembly (CDRA) – **TRL 9**
- Four-Bed CO_2 Scrubber (4BCO_2) – **TRL 9**
- CO_2 and Humidity Control Swing Bed (CHC) – **TRL 9**
- Carbon Dioxide Removal by Ionic Liquid Sorbent (CDRILS) – **TRL 5**

Many of these candidates have been tested onboard the ISS, and some are still in development. Information on these technologies from the previous Gateway study has been revised with the most up-to-date data, where applicable, to increase the fidelity of the ESM model. Special consideration has also been taken in the ESM methodology for advanced technologies that have not yet been fully tested or characterized [2]. The following sections summarize the ESM approach used, the major performance variables for each CO_2 removal option being considered, and the results of the technology comparison. These results can be used to guide the mission-specific selection of CO_2 removal systems for future integration into ECLSS assemblies.

II. Equivalent System Mass Approach

The ESM method of analysis is typically used in life support applications to assess and compare system-level impacts of diverse equipment that may otherwise be very difficult to evaluate. This approach takes disparate sizing characteristics of technologies or subsystems and converts them into a unified, quantifiable metric that can be easily compared among multiple candidates [3]. Infrastructure costs are applied to convert sizing and performance parameters such as volume and cooling into units of mass. The converted values are then added to the actual system mass to yield a total ESM value, which can be directly compared against competing candidates [2]. For example, the impact of the heat load from a thermal control system on the habitat is accounted for by converting this heat load into an "equivalent" mass and adding it to the component mass. This enables a more apples-to-apples comparison of integrated system impacts across candidates rather than a simple direct comparison of component mass alone.

$$\mathbf{ESM} = \mathrm{M_S} + \mathrm{M_C} + \gamma_\mathrm{V}\mathrm{V} + \gamma_\mathrm{P}\mathrm{P} + \gamma_\mathrm{Q}\mathrm{Q} \quad (1)$$

Table 1. Description of ESM Variables.

Variable	Description	Units
M_S	System mass	kg
M_C	Gas consumables mass (O_2 and N_2)	kg
V	System volume	m^3
P	Power consumption	W
Q	Heat loss or gain (thermal control)	W
γ_V	Volume equivalency factor	kg/m^3
γ_P	Power equivalency factor	kg/W
γ_Q	Thermal control equivalency factor	kg/W

The ESM equation used in this study is given in Equation (1). The formula includes system mass, gas consumables mass, system volume, power consumption, and heat loss or gain, as shown in Table 1. All necessary equipment for each technology is considered when calculating system mass and volume, including blowers, air save pumps, heaters, coolants, controllers, etc. Heat loss or gain is determined based on system cooling requirements. For the purpose of consistency, all technologies in this study have been evaluated as pre-installed in the vehicle, as opposed to the option of being shipped separately (requiring an additional packaging mass).

The results of an ESM analysis depend on assumptions made about the operating environment, so it must be performed with a specific mission in mind [4]. Infrastructure costs depend strongly on mission architecture and are specific to mission location. While the previous Gateway ESM study was limited to the Lunar transit habitat, this ESM analysis has been updated to be more broadly applicable, looking beyond the scope of Lunar transit. The volume, power, and thermal control infrastructure costs used in this study are those listed under infrastructure costs in the 2022 Baseline Values and Assumptions Document [5], as shown in Table 2, which are evaluated by NASA according to current baselines for launch vehicles, spacecraft, and supporting equipment [2]. Otherwise known as "equivalency factors", these values represent the degree of impact, expressed in terms of mass, that system volume, power, and cooling requirements for technologies will have on the infrastructure of habitats for different missions.

Table 2. Infrastructure costs for Lunar, Mars, and LEO habitats.

Equivalency Factors	γ_V (kg/m^3)	γ_P (kg/W)	γ_Q (kg/W)	Pressure (psia)
Lunar transit (LT)	80.8	0.136	0.0554	10.2
Lunar surface (LS)	133.1	0.076	0.102	8.4
Mars transit (MT)	79.3	0.162	0.096	14.7
Mars surface (MS)	170	0.087	0.146	10.2
Low-Earth orbit (LEO)	79	0.162	0.18	14.7

Separate comparisons of ESM values for each CO_2 removal technology were performed for Lunar transit, Lunar surface, Mars transit, Mars surface, and low-Earth orbit mission habitats. Cabin pressures, which are used in the calculation of gas consumption for each technology, are also provided in Table 2. Note that pressures for Mars habitats have not yet been defined and are thus assumed based on ISS experience for transit and long-term visiting vehicle docking with Gateway for surface [6].

III. Technology Assessment

The following section summarizes operational details and metrics of each technology being evaluated in this study. A literature review was conducted to obtain accurate information on mass, power, volume, consumables, and CO_2 removal capacity for each technology option, and principal investigators were contacted for confirmation of the most up-to-date quantitative data. Calculated ESMs of the technologies in each mission habitat are presented in Table 3, along with available information on CO_2 removal performance at different CO_2 concentrations. Quantitative values that are not publicly available have been omitted (marked as "N/A"). Note that the CO_2 removal capability of hardware is not directly dependent on crew size, it is a function of CO_2 concentration. Whether the CO_2 concentration came from one crew member working hard or four crew members sleeping, the removal rate of the hardware does not change. The key parameter for direct comparison of these technologies is thus CO_2 concentration, which is a function of both crew size and crew activity.

The ESMs shown here include gas consumption calculated for 1 year of operation. This gas consumption is the O_2 and N_2 lost from the CO_2 removal process and does not include any recovery or regeneration from downstream processes. For all technologies except CDRILS, it is assumed that CO_2 is vented to space rather than recovered for downstream processing. Note that the ESMs do not consider reliability or sparing.

1. Carbon Dioxide Removal Assembly (CDRA)

The CDRA [7], [8], [9], [10] is a legacy four-bed molecular sieve assembly developed by Honeywell that uses a fully regenerative thermal/pressure swing sorption process to remove CO_2 from the ISS cabin air. It operates cyclically, using one desiccant and sorbent bed pair in adsorption mode, with another desiccant and sorbent bed pair in desorbing mode. Beds are cooled during adsorption, and electrical heaters and vacuum are used for temperature-pressure swing desorption. Outlet air is re-humidified by passage through the desiccant beds before it is directed back to the cabin. The CDRA has a long history of maintenance issues as well as obsolete core components; eventual retirement and redesign are intended to address mechanical failures due to issues such as zeolite dusting and thermal fatigue [1], [11]. Parameters for the CDRA ESM were obtained from the Honeywell CDRA handbook [12] and literature [9], [10].

2. Four-Bed Carbon Dioxide (4BCO$_2$) Scrubber

The 4BCO$_2$ scrubber [10], [11], is a potential redesign of the CDRA that was commissioned for flight demonstration onboard the ISS to prove its reliability for exploration missions with no resupply and light sparing capabilities, such as Mars transport. It was designed to operate in a partial closed-loop configuration removing 4 crew-equivalents of CO_2 with no unplanned maintenance for 3 years. While operating very similarly to the CDRA, this technology utilizes a new custom zeolite sorbent to improve CO_2 capacity and kinetics, decreased operational temperature and heater redesign to minimize dusting, and a cylindrical bed shape (as opposed to rectangular) to maintain compaction. The mass and volume of the 4BCO$_2$ scrubber are lower than those for the CDRA. One drawback to this technology compared to the CDRA is its increased power consumption; however, it does trade off with a reduced cooling requirement. The CO_2 removal capacity, power, and cooling requirements for the 4BCO$_2$ ESM were obtained from experimental data and literature [10], [11].

3. Thermal Amine Scrubber (TAS)

As a different alternative to CDRA, the TAS [13], [14], [15] is a solid amine-based system that utilizes thermal regeneration. Developed by Collins Aerospace, this system was launched as a flight experiment to the ISS to further develop solid amine CO_2 removal technology while also mitigating potentially increasing CO_2 levels with the arrival of additional crew members. Cabin air enters the TAS, where it is stripped of most humidity by a desiccant. The dry air is then delivered to a 4-bed system, where each bed adsorbs CO_2 and is simultaneously cooled to remove reaction heat and maintain a high CO_2 capacity. When one pair of beds is removing CO_2, the other pair of beds is being desorbed using synchronized elevated temperature and vacuum. The effluent air stream flows through the bulk water save bed, where previously captured water vapor desorbs from the desiccant back into the air stream, returning clean, humid air to the cabin [13]. Addition of components to the TAS that enable integration with a CO_2 reduction system have been considered for advancement towards missions requiring a fully closed loop ECLSS but are not included in this ESM evaluation. Compared to the other technologies in this study, the TAS is at the high end of mass and power and has by far the largest volume. Parameters for the TAS ESM were obtained from the 2019 TAS system performance report [16] and operations manual [17], as well as TAS model calculations.

4. Carbon Dioxide Removal System (CDRS)

Similar to the TAS, the CDRS [18] is another amine-based regenerative system that is currently being developed by JAXA for the International Habitation Module (I-HAB) of the Gateway Lunar space station. This technology uses one solid sorbent canister to adsorb CO_2 exhaled by the crew and a second canister to desorb CO_2 through heating and venting to space. Desiccant canisters are also implemented to capture humidity, which can be returned to the cabin air upon regeneration. This system has better CO_2 removal performance than the TAS and a much lower system volume, but a slightly larger mass and power consumption, and a larger cooling requirement. Current efforts aimed at addressing drawbacks of the CDRS include optimization of dew point control and associated power consumption, and evening out of the temperature distribution of the adsorbent heater to increase lifespan extension. Parameters for the CDRS ESM were obtained from ECLSS working group test reports from 2022 as well as CDRS breadboard modeling test updates.

5. Orion Carbon Dioxide & Humidity Control (CHC) System

The CHC technology [19], flown on Artemis I, is a regenerative amine dual bed system that simultaneously adsorbs CO_2 and humidity from the air in one bed while desorbing via vacuum in the second bed. This technology was developed by Lockheed Martin for use on Orion to support an extended integrated mission without the need for additional CO_2 removal-related consumables (such as lithium hydroxide canisters) or complicated humidity capture systems. Unlike the CDRA, 4BCO$_2$, and TAS, the CHC does not require any cooling. It is also more favorable than the other technology options in terms of mass, volume, and power requirements; however, the main drawback of the CHC is its large nitrogen and oxygen consumption via venting to space due to lack of an air save pump.

Parameters for the CHC ESM were obtained from the Orion CHC rotating algorithm document, test results, and Gateway Integrated ECLSS Model calculations. Total CO_2 removal capacity, gas consumables, power, and cooling requirements were taken as a sum of their respective quantities assuming separate periods of sleep (8 hours), awake

(14 hours), and aerobic exercise (30 minutes each for 4 crew members). CO_2 removal capacity was calculated using average values of removal efficiency output by the Gateway Integrated ECLSS Model with varying half-cycle times and flow rates for sleep, awake, and exercise periods. Mass and volume of the CHC system were calculated assuming three swing beds, given that exercise periods require three swing beds for sufficient CO_2 removal; however, only two swing beds are operational during sleep and awake periods. Gas consumption was calculated considering changes in the number of swing beds.

6. Carbon Dioxide Removal by Ionic Liquid Sorbent (CDRILS)

The CDRILS technology [20], [21], [22], [23], developed by Honeywell, is another system that was designed with the intent of avoiding the disadvantages of CDRA. This technology utilizes a regenerable ionic liquid sorbent that is continuously recirculated between a scrubber and stripper. The air stream enters the scrubber where CO_2 transfers through a hollow fiber membrane contactor into the ionic liquid. The loaded ionic liquid is then pumped to a separate contactor in which pure CO_2 is recovered via heating and vacuum for delivery to downstream processes. The CDRILS ground prototype also includes a membrane dehumidifier upstream of the scrubber to avoid condensation at the scrubber from the humid cabin air stream. De-humidified air that enters the scrubber is stripped of CO_2, then directed back through the dehumidifier where it is re-humidified before cycling back to the cabin.

Venting carbon dioxide overboard as a waste product results in the loss of oxygen molecules that could be supplied back to the cabin. Honeywell has investigated integration of the CDRILS flight demonstration unit with the Precision Combustion, Inc. (PCI) Sabatier reactor, which would enable oxygen recovery and reduce the need for resupply. Thermal integration of CDRILS with Sabatier would also allow for heat from the Sabatier reaction to be recovered and used to warm up the ionic liquid entering the stripper, thus saving power [22]. Table 3 shows the ESM evaluation of CDRILS with and without PCI Sabatier integration. Metrics for the calculation were based on a system integrated with a dehumidifier and a vacuum pump, which has also been shown to improve power savings. Values were obtained from Honeywell documentation or estimated from literature [21], [22], [23]. Both cases assume CO_2 is not vented, so there are no gas consumables.

Table 3. CO_2 Removal Technology Performance and ESM.

Technology	CO_2 removal capacity (kg/day)		ESM with gas consumables mass (kg)				
			Mission Habitat				
	@ 2 mmHg	*@ 3 mmHg*	*LT*	*LS*	*MT*	*MS*	*LEO*
CDRA	4.2	6.5	**429**	**483**	**508**	**576**	**636**
$4BCO_2$	4.5	6.9	**410**	**406**	**473**	**470**	**549**
TAS	3.8	4.7	**682**	**798**	**728**	**949**	**766**
CDRS	N/A	N/A	**573**	**568**	**636**	**641**	**699**
Orion CHC	3.9	5.3	**277**	**245**	**331**	**272**	**331**
CDRILS without Sabatier	5.0	N/A	**402**	**419**	**462**	**485**	**543**
CDRILS with Sabatier			**389**	**375**	**429**	**418**	**464**

The CO_2 removal rates included in Table 3 were all taken at a range of what is generally considered acceptable to human habitation, that is 65-85°F temperature, 25-75% relative humidity, 10.2-14.7 PSI pressure, and < 4 mmHg CO_2 partial pressure.

IV. Results

The ESM results for each CO_2 removal technology in each mission habitat are provided in Figures 1-5, with and without consideration of gas consumables mass. Gas consumables mass was evaluated based on cumulative gas consumption over a mission period of one year. ESM factors and tankage requirements were not applied to the gas consumables mass calculation, as those parameters become vehicle and Pressure Control System dependent and are outside the scope of this analysis. The figures also include a visual comparison of CO_2 removal performance at 3 mmHg partial pressure of CO_2 (indicated with black markers).

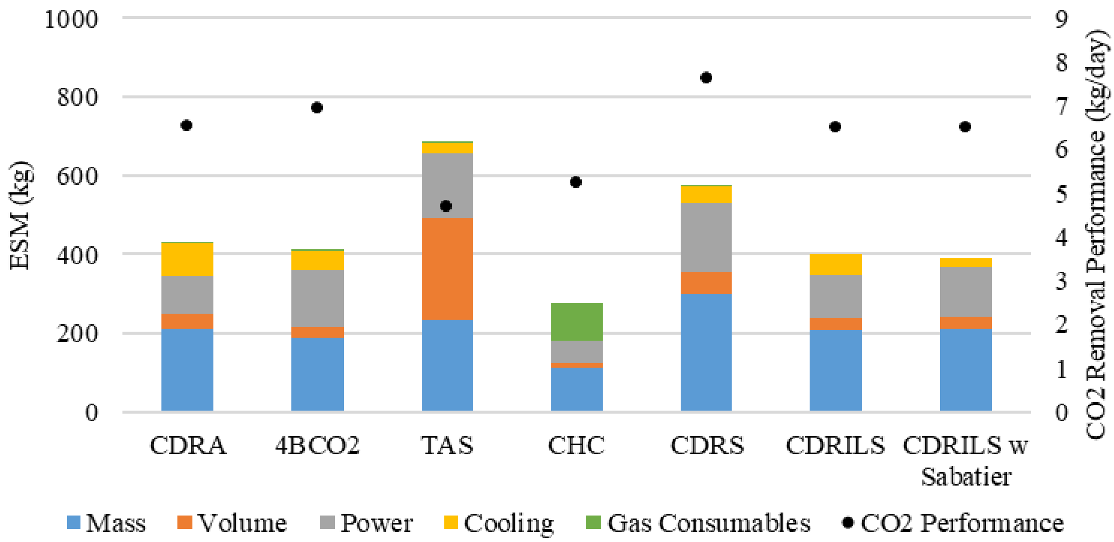

Figure 1. Comparison of ESMs for each CO_2 removal technology in Lunar transit mission habitat.

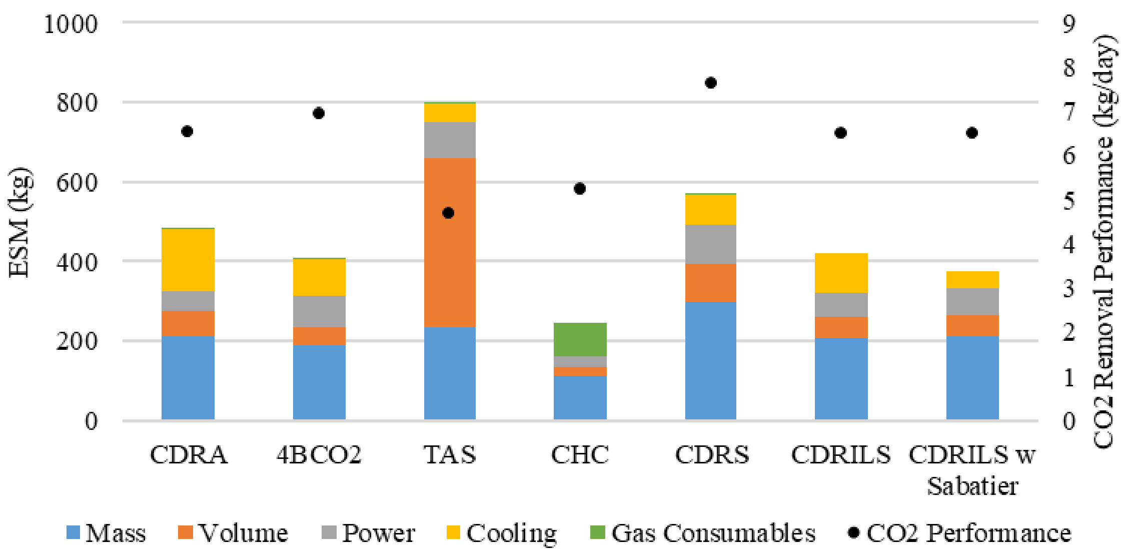

Figure 2. Comparison of ESMs for each CO_2 removal technology in Lunar surface mission habitat.

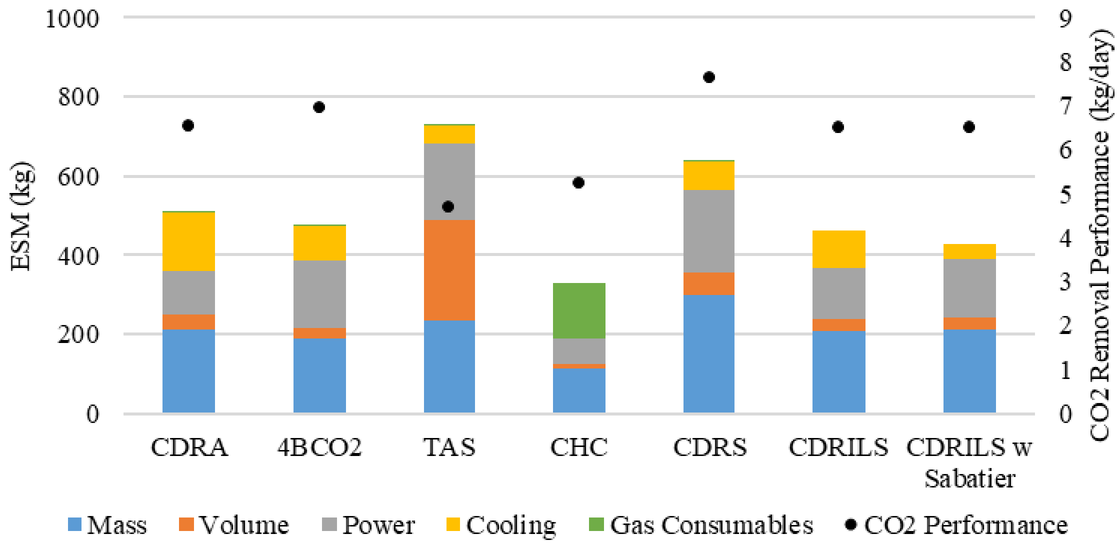

Figure 3. Comparison of ESMs for each CO_2 removal technology in Mars transit mission habitat.

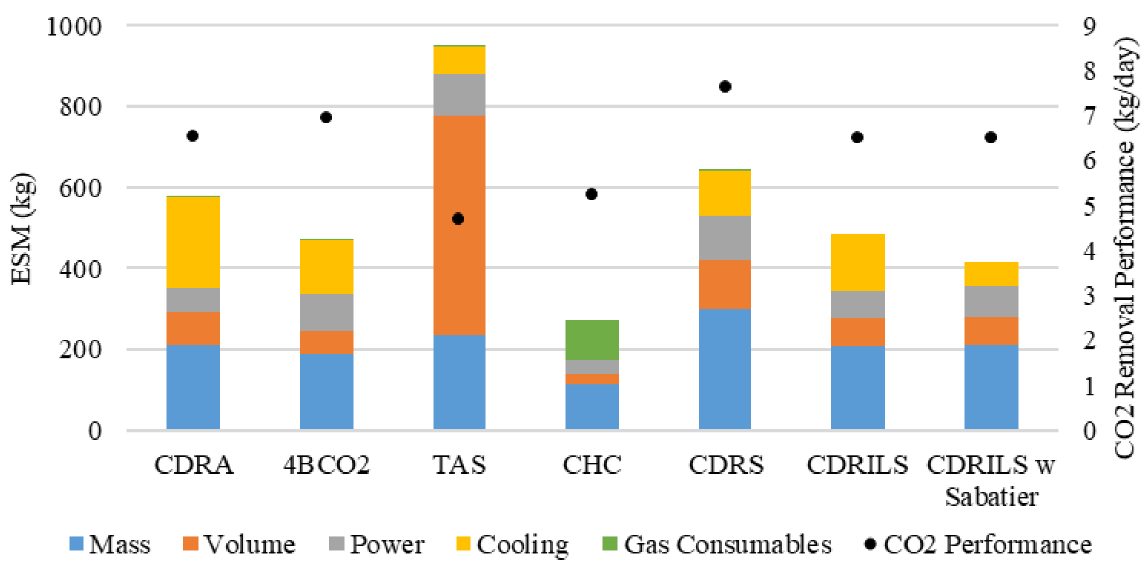

Figure 4. Comparison of ESMs for each CO_2 removal technology in Mars surface mission habitat.

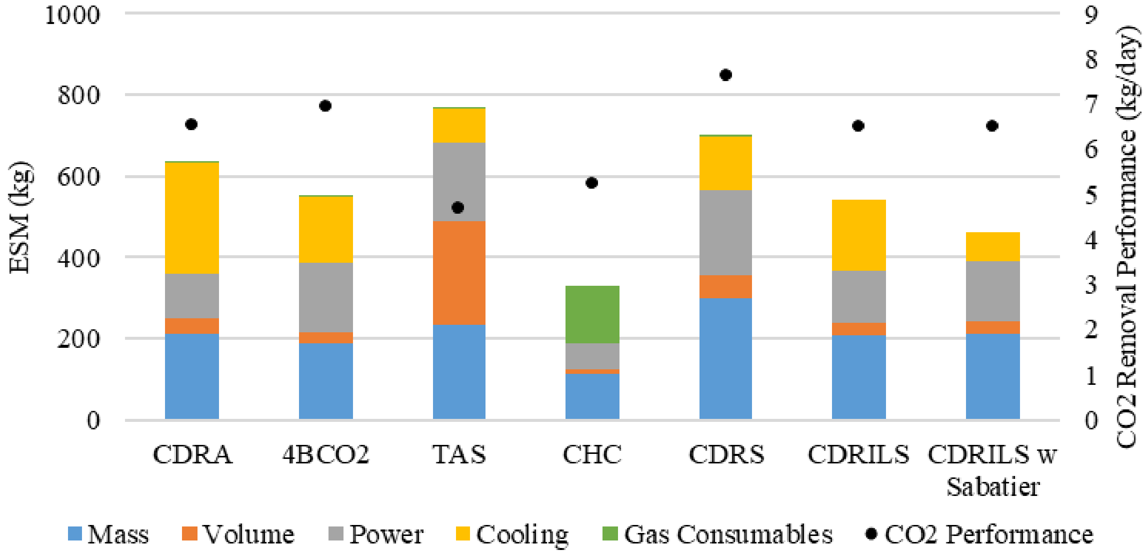

Figure 5. Comparison of ESMs for each CO_2 removal technology in low-Earth orbit (LEO) mission habitat.

The results demonstrate wide variations in the ESMs of the CO_2 removal technologies, with some having better return on mass than others. The CHC unit consistently has the lowest ESM across all the technologies, but has no air-save pump, leading to substantial gas consumables losses compared to the other systems. The lack of air save pump and active heating/cooling is the main driver for its decreased ESM. The CHC is also not compatible with a closed loop architecture. Despite having a larger mass and power draw than the CHC, CDRILS has no gas consumables losses, making it potentially more appropriate for a long duration mission where consumables are at a premium.

The TAS and CDRS solid amine options have the highest ESMs of all the CO_2 removal technologies. The TAS is shown to trade poorly, but this is in large part due to its volume, which is substantially out of family for the other technologies, and its overall CO_2 removal performance being below average. Comparatively, the CDRS has a tradeoff in that it has the best overall CO_2 removal performance, but at this stage is at a lower TRL than the ISS proven technologies.

Another comparison of note is the CDRA and the $4BCO_2$ scrubber. As discussed previously, the $4BCO_2$ scrubber is a version of CDRA that was redesigned based on lessons learned on board ISS, with a primary focus on reliability. The results show that with only a change in bed design, the $4BCO_2$ scrubber can achieve lower mass, volume, and cooling requirements than the CDRA while increasing CO_2 removal performance. The power requirement for the $4BCO_2$ scrubber is higher than for the CDRA, but it is still at a lower value than that for other similar technologies such as the CDRS and TAS. For most missions, the CDRILS ESM is comparable to that of the $4BCO_2$.

There is ultimately not a clear tradeoff between CO_2 removal performance and ESM, with some technologies having better CO_2 removal with a lower equivalent mass, and vice versa. Across the board, technologies that do not rely on heating and cooling of a swing bed seem to have lower total ESMs, but not always lower mass when considering consumables.

Figure 6 shows a comparison of the ESMs for each technology across all five mission habitats. The results give an indication of how changes in mission-dependent ESM coefficients affect the relative ranking of CO_2 removal technologies. Technologies that have high volume, power, or thermal control requirements will have more impact on habitats with higher corresponding equivalency factors. For instance, while CDRILS trades better than $4BCO_2$ in Lunar transit, Mars transit, and LEO, $4BCO_2$ trades better than CDRILS in Lunar and Mars surface habitats. This is because CDRILS has a higher volume and thermal control requirement, which is boosted by higher volume and thermal control equivalencies in surface habitats, while $4BCO_2$ has a higher power requirement, which is boosted by the higher power equivalencies in the transit and LEO habitats.

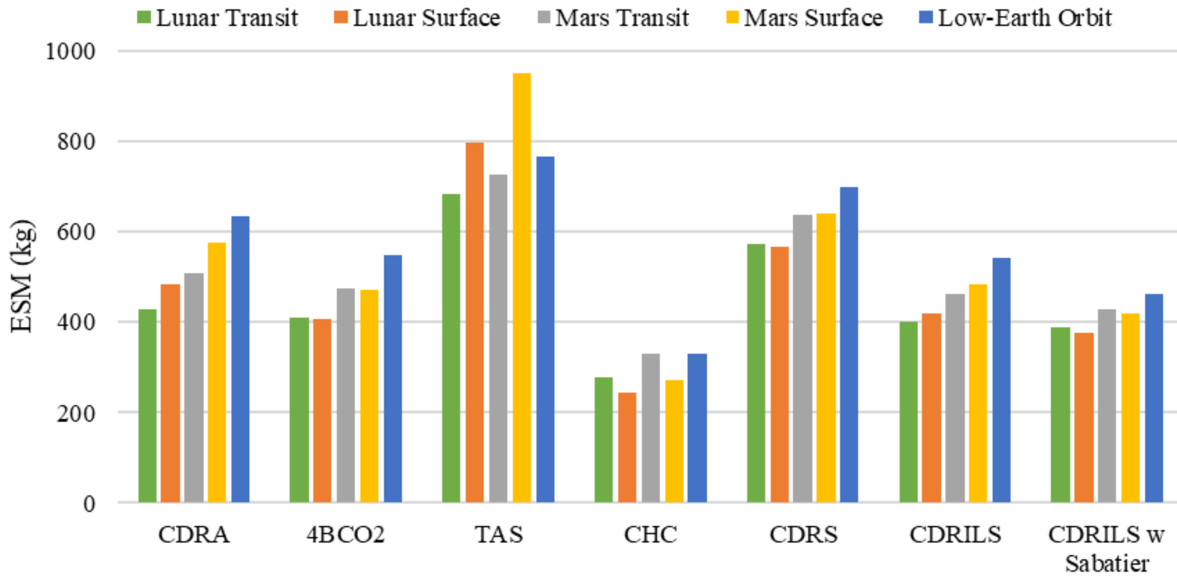

Figure 6. Comparison of ESMs including gas consumables mass for each CO_2 removal technology in each mission habitat.

Despite its low volume equivalency factor, the LEO habitat has high power and thermal control equivalency factors compared to the other habitats, leading to the highest ESMs among most of the CO_2 removal technologies. The Mars surface habitat has a high volume equivalency factor compared to the other habitats, yet it does not yield higher ESMs than the LEO habitat in any technology except for the TAS, which has a significantly larger volume than any of the other systems. In general, power and cooling requirements appear to be the more dominant contributors to the total ESM. Though technologies like TAS and CHC show consistent maximum and minimum ESMs compared to other technologies across all habitats, the overall trends suggest technologies well suited for one mission environment may not trade well in another.

V. Conclusion

The performance and ESM of current spacecraft CO_2 removal systems have been evaluated and compared for Lunar, Mars, and low-Earth orbit habitats. While this analysis does not capture the overall logistical impacts of technologies and is not sufficient for informing technology down-selection on its own, the data presented here can be used as a guide to assist programs in their selection of a CO_2 technology best suited for a specific vehicle and mission. Given the constant evolution of infrastructure costs and the ongoing testing and characterization of some of these candidates, the data presented here may shift over time and should be periodically revised to reflect the latest as technologies or operations advance.

Acknowledgments

This project acknowledges funding from the Mars Campaign Office. The authors also gratefully acknowledge Grace Belancik, Richard Koelsch, James Knox, Lyndsey Winslette, Jason Dake, and all other ECLSS principal investigators who provided useful input on the technologies evaluated.

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