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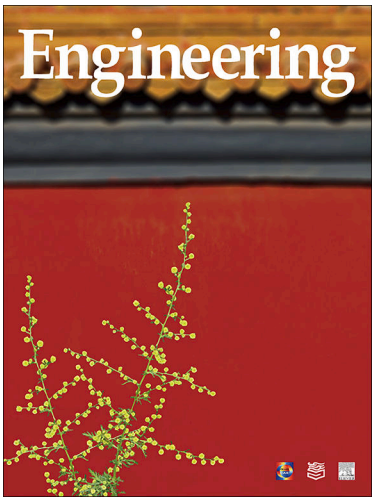

Review

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Research

Frontiers of Chemical Engineering—Review

Integrating Electrochemical CO_2 Reduction Technology for Smart, Sustainable, and Stable *In-Situ* Resource Utilization for Outer-Space Applications

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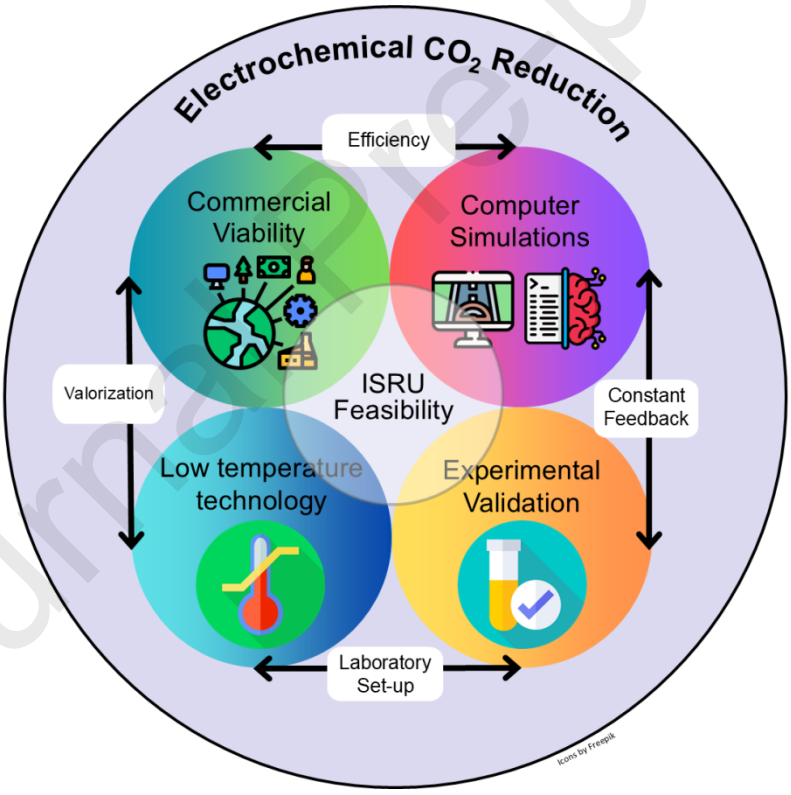

Abstract: Electrochemical carbon dioxide (CO_2) reduction (ECO2R) is an increasingly valuable technology that converts CO_2 into useful chemicals using various catalyst materials. This review underlines the advantages of ECO2R electrolyzers that use low-temperature electrolysis (25–80 °C) over other high-temperature electrolysis methods, particularly for applications in outer space. The potential of this technology for Mars missions is particularly intriguing, opening up new possibilities for *in-situ* resource utilization (ISRU) processes in upcoming space missions. This review also explores technology's commercial potential and the importance of utilizing gas diffusion electrodes (GDEs) to enhance the ECO2R process. ECO2R has the potential to transform outer-space activities and space exploration by significantly reducing the use of Earth's resources. It offers a sustainable alternative for continuous fuel and chemical production by utilizing gaseous CO_2, thereby reducing its carbon footprint on Earth, and presents a promising process for outer-space applications.

Keywords: Electrochemical CO_2 reduction; *In-situ* resource utilization; Computational fluid dynamics; Outer-space application

1. Introduction

Electrochemistry is emerging as a game-changing technology that addresses the problems climate change poses to civilization. The modern chemical industry, which firmly relies on fossil fuels, is under increasing pressure to adopt sustainable procedures that reduce carbon footprints. This aligns with the current worldwide focus on sustainability and climate change, established by the Intergovernmental Panel on Climate Change (IPCC)'s Working Group III, which emphasizes the significance of lowering carbon dioxide (CO_2) emissions in the chemical sector [1]. Electrolysis, particularly the electrochemical CO_2 reduction (ECO2R), is a potential technique for modifying industrial methods to minimize the resulting CO_2 emissions by converting CO_2 into relatively small carbon chains and valuable compounds that can be used for other processes [2–6]. By electrochemically reducing CO_2, the process becomes a key technology for decreasing carbon emissions in Earth's atmosphere. However, what if the products of CO_2-reduction can enable the sustainability of other processes from within an atmosphere almost entirely composed of CO_2? Mars's atmosphere is 96% CO_2, which introduces a new possibility for outer-space applications of CO_2 reduction. Adapting ECO2R for Mars-related scenarios, and thereby overcoming resource limitations in outer space, is vital for sustaining long-term human settlement and human-like activities away from Earth, by detaching from a reliance on Earth resources to sustain future missions. Such Earth-independent processes are generally referred to as *in-situ* resource utilization (ISRU) [7]. Proving the potential of a technology for such scenarios requires not only physical experiments but also computational modeling (e.g., computational fluid dynamics (CFD) and machine learning (ML)). This approach provides a robust framework for testing and improving the ECO2R process, ensuring its viability for industrial and outer-space applications. In fact, many of the technologies used in daily life today were initially developed as part of space-exploration research. Technologies such as medical imaging (e.g., magnetic resonance imaging (MRI) scans), satellite communications, and solar panels are just a few examples of innovations that emerged from space research and now benefit both Earth and future missions to Mars or other planets. The same perspective could apply to ECO2R, as advancements in this field for space exploration could lead to valuable solutions for sustainable resource utilization on Earth and beyond. Here, we start by examining other existing electrochemical technologies on Earth and comparing them with ECO2R.

1.1. Comparative insights into CO_2 electrolysis technologies

Electrochemical cells are categorized based on the type of electrolyte they use—alkaline or acidic—and the temperature at which they operate. An electrolyte is a substance that conducts ions and allows the cell's electric current to flow. Generally, fuel cells and electrolyzers can be made from proton-exchange (PE), anion-exchange (AE), solid-oxide (SO), and molten carbonate (MC) cells. The main difference is that electrolyzers use electricity to break apart molecules, such as water, into oxygen and hydrogen, while fuel cells use oxygen and hydrogen to produce both energy and water [8]. SO and MC cells operate at significantly higher temperatures, usually between 600 and 1000 °C, whereas PE and AE cells operate at comparatively moderate temperatures (20–250 °C) [9].

Solid-oxide electrolyzer cells (SOECs) form hydrogen (H^+) and oxygen ions (O_2^-) by gaining electrons through feeding water (H_2O) to the cathode. These O_2^- ions are transported through a solid electrolyte to the anode, becoming oxygen gas (O_2). High temperatures are required for the transport of these ions through the solid material. Such cells have demonstrated nearly 100% Faradaic efficiency (FE) at high current densities (up to 750 $mA \cdot cm^{-2}$) [5]. However, the disadvantage of SOECs lies in the long-term deterioration of their materials, especially the solid-ion-transport electrolyte. In proton-exchange membrane (PEM) and anion-exchange membrane (AEM) electrolyzers, which also use a solid, polymer-based electrolyte as a membrane, an ion separator is placed between two electrodes, permitting protons (H^+) or hydroxide ions (OH^-) to flow through, without electron conduction, respectively. Compared with SOECs, they operate at lower temperatures. This membrane-based setup simplifies the system design and can withstand acidity/basicity and high-voltage operations [10]. An electrolyzer setup with no separation of the components is known as a membrane electrode assembly (MEA)/zero-gap cell configuration.

Cells can also use aqueous electrolytes, although this introduces challenges such as potential leakage, high power loss due to the need for water splitting, and reduced efficiency at lower loads. These challenges must be addressed to achieve the full potential of low-temperature technology using alkaline or acidic aqueous electrolytes [10]. One approach involves using flow

cell electrolyzer configurations [11], especially by incorporating gas diffusion electrodes (GDEs). GDEs play a crucial role in enhancing the ECO2R process by facilitating the transport of gaseous CO_2 to the electrode surface and creating an active site with the electrons from the current and ions from the electrolyte. They overcome CO_2 mass transport limitations and enable the achievement of relevant current densities [12]. H-cells, which are commonly used in laboratory-scale CO_2 electrolysis, feature a separator between the cathode and anode to minimize product crossover. However, the relatively large inter-electrode distance increases the ionic path length, leading to high ohmic resistance and consequently low energy efficiency. Microfluidic reactors offer an alternative, using a very thin liquid channel (< 1 mm) between electrodes. They can operate with or without a membrane and allow product separation through the gas phase rather than relying on diffusion [13]. Molten-salt (MS) CO_2 electrolysis offers a promising route to produce value-added carbon materials or carbon monoxide (CO) with high selectivity without relying on costly catalysts or membranes. Typically, CO_2 is indirectly reduced via carbonate ions (CO_3^{2-}), which are reduced at the cathode to generate carbon or CO, while releasing oxide ions (O^{2-}) that react with CO_2 to regenerate CO_3^{2-}. Given the distinct CO_2 reduction and diffusion behavior in molten salts compared with that in aqueous systems, there is substantial research interest in studying the direct electrochemical reduction of CO_2 in these media [14]. As an alternative, zero-gap gas-phase configurations—that is, catholyte-free electrolyzers—have been gaining attention due to their compact architecture. These systems eliminate the need for a liquid catholyte and significantly reduce the distance between electrodes, thereby decreasing ohmic losses and simplifying the system by requiring fewer electrolyte pumps. They facilitate increased mass transport and can be integrated into stacked configurations to support scalable system design [13].

These systems are well-suited for the CO_2 reduction reaction (CO2RR), particularly ECO2R technology, which uses electricity to convert CO_2 into valuable chemicals and fuels [15]. Success in this area depends on optimizing the electrocatalysts, electrodes, and reactor design and their underlying mechanisms to overcome issues such as low selectivity, insufficient activity, and instability [11,16–18].

Recent efforts have made significant progress in increasing the FE of ECO2R technology, with researchers achieving FE values of over 90% toward CO by optimizing catalysts and cell configurations [19–21], compared with solid-oxide electrolysis (SOE). These improvements help mitigate issues such as carbonate formation and energy costs and demonstrate the potential of ECO2R technology in electrochemistry [6,22–24]. Although the evidence indicates that SOECs outperform their counterparts in energy efficiency and productivity, low-temperature electrolysis flow cells (25–80 °C) have matched SOECs in terms of FE, offering long-term stability (lower degradation) and the potential for directly producing a variety of value-added chemicals—not just oxygen or CO, which are the main products of the SOE process [5,25–31].

To fully grasp the experimental aspects of ECO2R cell design and the spectrum of products generated by reducing CO_2, it is first essential to comprehend an electrochemical cell's fundamental structure and operational principles. In a typical electrolysis flow cell, gaseous CO_2 is reduced at the cathode—one of two electrodes powered by an external voltage source—to produce either CO or methane (CH_4) (half-reactions (1) and (2)), among other possible products. Simultaneously, water is oxidized at the anode, yielding oxygen as a product (reaction (3)). The redox reactions occurring at the electrodes are usually separated by a barrier, such as a separator or a polymeric ion-exchange membrane (e.g., Nafion) that can allow the passage of ions, either positive or negative, depending on the nature of the membrane. This setup is crucial for facilitating the controlled movement of protons produced during the electrochemical process. These ions will be carried out by an aqueous solution, the electrolyte, which can be of different compositions for the cathode and anode—the catholyte and anolyte, respectively. These aqueous solutions are made of inorganic salts (e.g., $KHCO_3$, K_2SO_4, and Na_2SO_4), ionic liquids, or organic solvents [32–34].

The cathodic half-reactions are shown below:

$$CO_2 + H_2O + 2e^- \rightarrow CO + 2OH^- \quad (1)$$

$$CO_2 + 6H_2O + 8e^- \rightarrow CH_4 + 8OH^- \quad (2)$$

The anodic reaction in an ECO2R cell is as follows:

$$2OH^- \rightarrow H_2O + 0.5O_2 + 2e^- \quad (3)$$

The cell is designed to allow the simultaneous flow of liquids and gas, ensuring efficient interaction at the electrodes and the membrane section. On the cathodic side, multiple catalysts can take the CO_2 reduction further to produce other carbon byproducts [35]. The GDE cell configuration during electrolysis allows the CO2RR to be developed at a gas–liquid–solid

three-phase boundary: the active site [12]. This unique interface is effectively created by a gas diffusion layer, which is usually porous, pressed together with a catalyst layer, which is often both hydrophobic and porous. This configuration takes advantage of the electrode's porous structure to permit gas flow, allowing the gas to interact with the liquid electrolyte (i.e., its ions) at the catalyst, which is the conductive layer. The reaction occurs by creating active sites between these three components [36]. Fig. 1(a) illustrates the described setup's key elements and flow paths using a GDE configuration in a microfluidic cell. The anolyte (bottom blue lines) enters the cell from the bottom left, moves upward through the anode section, interacts with the anode and the membrane, and exits from the bottom right (Fig. 1(b)). Similarly, the catholyte (top blue lines) enters from the top right, moves downward through the cathode section, interacts with the cathode and the membrane from the other side, and exits from the top left. The gas (CO_2, shown in red lines) enters from the top left, saturates the chamber (Fig. 1(b)), and interacts with the GDE and the catalyst layer. This creates an active site where the gas, the catholyte, and electrons supplied by the electric current converge for efficient electrochemical reduction.

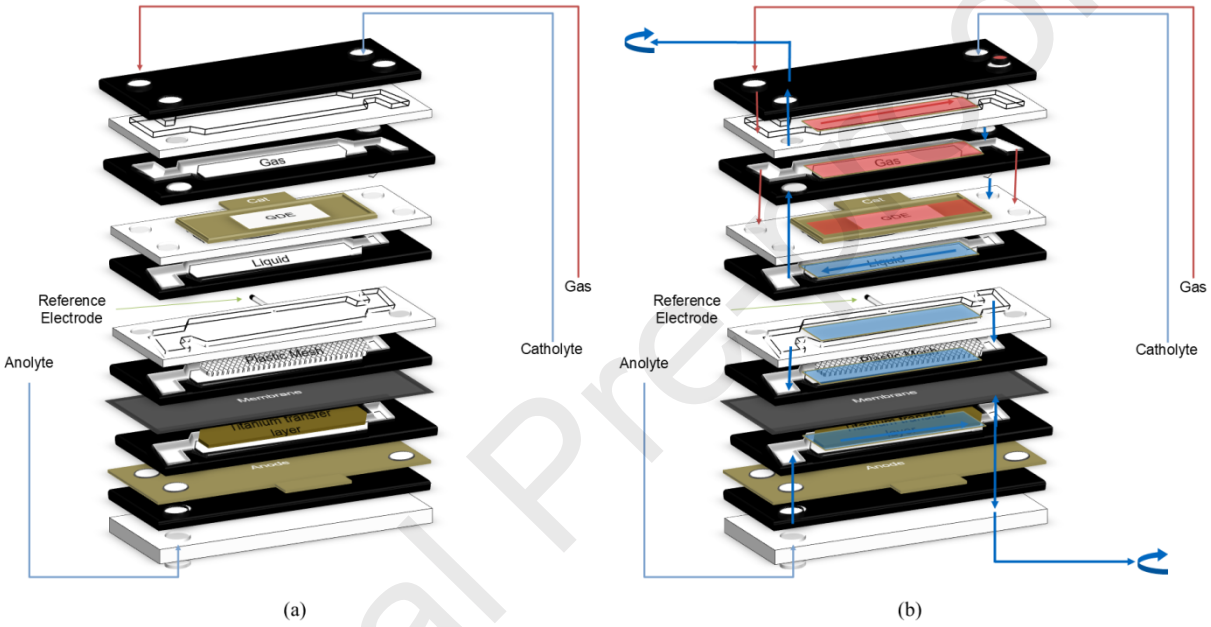

Fig. 1. Detailed configuration of (a) a microfluidic cell and (b) the same cell illustrating both liquid (anolyte and catholyte) and gas flow through the cell. Cat: catalyst.

The cell's key components include the anode at the bottom; the membrane that separates the liquid anolyte and catholyte; the GDE in the gas section, including the catalyst; the reference electrode positioned horizontally, which helps determine the efficiency of the working electrode—in this case, the cathode; and the top and bottom plates that encapsulate the cell structure, with inlet and outlet ports for the liquids and gases.

As the current densities increase, the need for a steady supply of the reacting gas to the catalyst's surface becomes even more crucial for sustaining high reaction rates and a stable active site at the catalyst layer, especially for commercial applications [37].

The choice of metal catalyst in the catalyst layer significantly influences the selectivity of the cathodic reaction toward different products [35]. These metals can be categorized based on their hydrogen and CO adsorption energies, forming four distinct groups that yield different CO_2 reduction products [38]. Evidence regarding the FE of the CO2RR related to the metal's hydrogen-adsorption energies suggests that the energy associated with hydrogen binding could be a theoretical bottleneck in increasing the FE of the CO_2 reduction process [38].

The generation of hydrocarbon products (e.g., with longer carbon chains) can be understood through a two-step mechanism. Initially, a two-electron reduction process converts CO_2 to either CO or formate (reactions (1) and (4), respectively).

Subsequently, further reduction occurs from the CO intermediate, leading to the formation of hydrocarbons such as CH_4 (reaction (5)) [39]. This mechanism illustrates the interconnection of processes for acquiring hydrocarbons, which are later utilized as fuels, through the capture and reduction of CO_2.

Formate formation from CO_2 reduction occurs as follows:

$$CO_2 + 2H^+ + 2e^- \rightarrow HCOO^- + H^+ \quad (4)$$

Further reduction from the CO intermediate absorbed on the catalyst (*CO) results in the formation of hydrocarbons (e.g., methane):

$$*CO + 6H^+ + 6e^- \rightarrow CH_4 + H_2O \quad (5)$$

The activation energy of the critical step—namely, CO_2 adsorption onto the catalyst—varies due to different adsorbed-CO_2 coordination modes influenced by the catalyst surface [39,40]. Electrodes with a high hydrogen overvoltage and minimal CO adsorption, such as mercury (Hg), cadmium (Cd), lead (Pb), thallium (Tl), indium (In), and tin (Sn), exhibit high current efficiencies in reducing CO_2 [40]. Nonetheless, these metals generally act as catalysts whose predominant product is formate. On the other hand, gold (Au) and silver (Ag) catalysts, especially in a GDE configuration, better absorb CO_2, achieving high FEs toward CO [39,41–44]. Copper (Cu) fits into this category but has stronger adsorbed-CO energy, enabling C–C coupling for various hydrocarbons and alcohols [18]. However, Cu is not very selective [45–49], although recent efforts have improved its selectivity [50,51].

Obtaining multi-carbon products through ECO2R presents a unique challenge. Such products typically require the CO_2 to be almost entirely depleted to achieve the highest FEs, in part because the creation of multi-carbon products involves chemical reactions starting with *CO molecules (adsorbed on the catalyst surface) and C–C coupling processes [52,53]. These reactions demand appropriate potentials and sufficiently high current densities to proceed effectively [54]. In other words, optimizing CO_2 reduction processes to produce multi-carbon products is more complex than obtaining single-carbon products. Achieving high FEs for multi-carbon products is intrinsically tied to operating conditions that push the limits of CO_2 depletion. This presents a significant challenge since new strategies and catalysts must be designed to be efficient, selective, stable, and fully operational under these conditions.

One strategy focuses on the vital role of electrochemical membrane reactor (ecMR) design, which extends beyond catalyst development, relying on achieving high performance in terms of current energetic efficiency by carefully selecting the membrane and the GDE composition, choosing accordingly the proportion of the binder, the metal, and its porosity ratio [55]. In terms of the membrane, cation-exchange membranes (CEMs) are limited by the significant hydrogen evolution reaction (HER) in acidic environments at the cathode side [24,55,56]. Bipolar membranes (BPMs), while effective, suffer from a considerable membrane potential, which requires a higher electrolysis voltage, reducing overall energy efficiency [24]. AEMs are emerging as a preferred choice, balancing advantages such as low HER and high selectivity/energy efficiency against disadvantages such as CO_2 crossover [57–60]. There is a current need for advanced membrane development, with ideal characteristics including low electrical resistance, high OH^- conductivity, controlled water uptake and swelling, minimal gas/liquid crossover, and stability in alkaline and alcoholic conditions [57]. However, this all depends on the nature of the experiment and its components (e.g., catalyst material, membrane, and catholyte).

In laboratory settings, ECO2R catalysts are typically evaluated at relatively low current densities, which do not accurately mirror the high current densities estimated in industrial operations. Such conditions can drastically change the local reaction environment, potentially altering catalyst performance significantly [61]. Therefore, a catalyst that exhibits promising results under laboratory conditions may underperform or behave unpredictably when scaled to commercial applications. Moreover, the stability of the electrocatalyst must be considered when designing electrochemical experiments over a significant period, and this can be a more substantial challenge to overcome than the high FE of the byproducts [62]. The transition from laboratory to commercial-scale ECO2R technology presents several challenges, yet recent progress in developing advanced electrocatalysts and optimizing electrolyzer designs has significantly improved productivity and energy efficiency [24,63]

In summary, while various CO_2 electrolysis technologies offer distinct advantages and limitations, their optimization often demands extensive experimental work, which can be both time- and resource-dependent. To streamline this process and enhance the quality of results, data obtained from preliminary experiments can be integrated into computational models and

simulations. This combined approach allows for more efficient exploration of operating parameters and accelerates the development of more effective CO_2 electrolysis systems.

1.2. Computer modeling

To further evaluate the viability of electrochemical reactions and various technologies such as ECO2R toward industrial applications on and outside Earth, computer simulations have been developed to complement experimental data, creating a reciprocal feedback loop that reduces error and increases the accuracy of both simulations and experimental data. This translates to fewer and more accurate experimental setups that provide quality results, consistently validated by experimental data. Computer modeling uses reaction–diffusion equations and mathematical models that can effectively approximate the similarities and differences in local reaction environments, which are the physics of the reaction [64,65], including low-gravity and low-pressure environments. These equations are particularly useful in analyzing various setups. For example, two standard configurations for ECO2R—namely, the H-cell and the flow cell with a GDE configuration—have been studied. The H-cell, comprising two half-cells separated by a membrane with electrodes immersed in an electrolyte, is ideal for liquid-phase reaction studies. However, the conventional H-cell setup with aqueous electrolytes has a limitation: The concentration of CO_2 near the electrode surface is restricted by its limited solubility, which results in a thicker diffusion layer, hampering the rate at which reactions occur [66]. This is also a difficult issue to tackle experimentally in low-gravity scenarios, where bubble formation hampers the electrochemical reaction. However, numerical simulations have helped to predict bubble formation under these conditions, showing that bubble fusion drives current increases as the bubbles detach, with greater effects when fusion is dominant [67,68]. An effective strategy to experimentally address the issue of increased diffusion-layer thickness due to bubble formation involves directly supplying gaseous CO_2 to the cathode by employing the GDE configuration [69]. As mentioned earlier, the GDE's key advantage lies in its efficient gas–liquid interaction and its ability to operate at higher current densities, making it more suitable for industrial applications and offering increased operational efficiency compared with the H-cell setup [70]. A thorough understanding of the electrochemical reduction of CO_2 to CO is crucial for optimizing this process, and this is where computer simulations come into play.

For instance, consider the electrochemical reduction of CO_2 to CO using an Ag-based GDE—a porous silver-coated electrode that enables the diffusion of CO_2 gas to catalytically active sites, where CO_2 is reduced to CO under an applied voltage [71,72]. Several factors influence this reaction, including the electrode surface properties, electrolyte nature, and operational conditions, such as current density and CO_2 gas volume per minute [44,73]. These numerous variables are a major challenge to control experimentally when designing a simulation of the electrochemical reduction of CO_2. Several CFD simulations based on different mathematical models provide a detailed and comprehensive analysis of the conditions within an electrochemical cell by accurately modeling fluid dynamics, gas diffusion, chemical reactions, and heat transfer, among other phenomena [74]. Moreover, design of experiment (DoE) is vital for developing efficient and scalable systems, by enabling accurate predictions of how variations in design and operational parameters impact performance before more experiments are undertaken. This predictive capability streamlines the design process, contributes to successful product outcomes, and collects critical feedback from physical experiments that can be used with computer modeling [67,75,76]. Such feedback is crucial for continuously improving a simulation, reducing errors, and refining the overall system. Fig. 2 illustrates four key models for simulating electrochemical processes, particularly in systems with a GDE configuration. Choosing the most accurate model depends on the simulation objectives and the desired outcomes to be predicted and/or simulated [76].

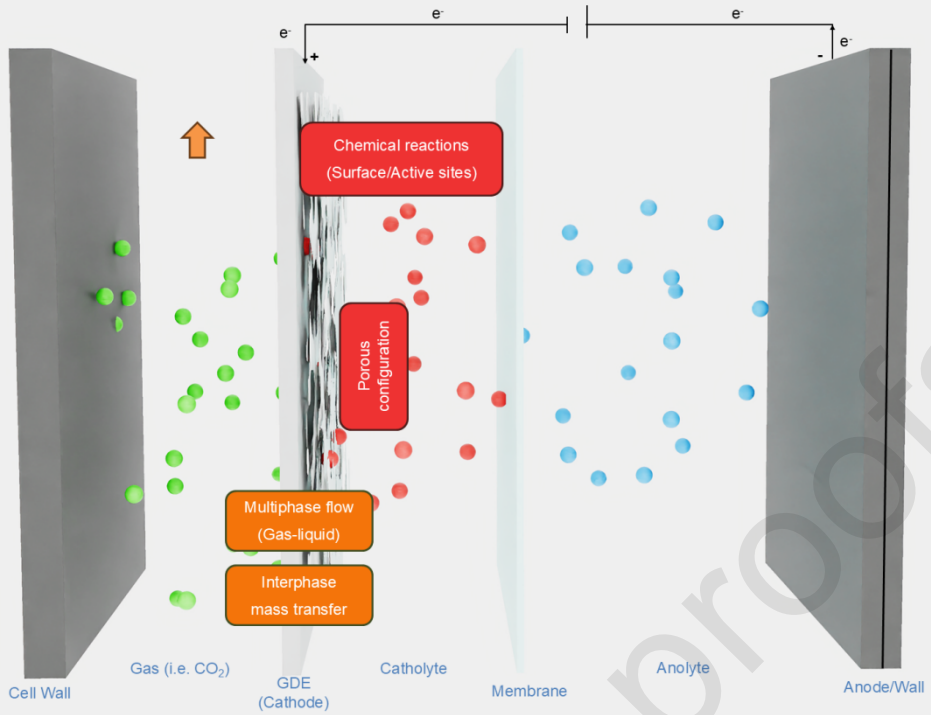

Fig. 2. Electrochemical flow cell with a GDE configuration for CO_2 reduction with four different simulation models. Gaseous CO_2 (green spheres) diffuses through the GDE (the porous-like configuration, exaggerated in the figure), generating an active site for the CO_2 gas (green spheres) involving the ions from the catholyte (red spheres) and the electrons at the catalyst. This leads to the electrochemical reduction of CO_2 into CO, CH_4, or other products. Simulations of this electrochemical cell using the working electrode as a cathode can be carried out using various models. Multiphase flow, interphase mass transfer, porous structure, and chemical reactions at the active sites (catalyst surface) are some of the main models used to describe phenomena at the cathode. The porous nature of the GDE facilitates gas–liquid interactions and offers a large surface area for the reaction. This process involves the catholyte (red spheres in the figure), where the electroactive species engage with CO_2 to generate the reduced species. The membrane in the middle separates the catholyte from the anolyte (red and blue spheres, respectively), and the anode where oxidation occurs. Walls on both ends enclose the cell.

The models shown in Fig. 2 (i.e., multiphase flow, interphase mass transfer, porous model, and chemical reactions at the active sites) focus on the working electrode, where the reduction process occurs—in this case, at the cathode. The porous model combines ideas from interphase mass transfer and multiphase flow, applying them to porous materials where gas, liquid, and solid phases interact. The multiphase flow and chemical reaction models are essential for simulating what happens near the electrode surface, where ions are absorbed—a critical area that dramatically affects how fast reactions occur and how efficiently the system works [8]. Moreover, the area near the catalyst surface is closely linked to the interphase mass transfer model, emphasizing its importance in mass transfer processes. The three-phase boundary where the GDE (catalyst), gas, and liquid converge plays a key role in efficiently transferring reactants and products, making it an essential focus when optimizing electrochemical processes and improving the active site where the reduction of CO_2 occurs and electrons are involved.

The analysis of each model fosters an integrated understanding, allowing for the optimization of specific aspects by transferring the insights derived from one model to another. For instance, analyzing how the porosity of the GDE can enhance the distribution of reactants and directly boost the efficiency of interphase mass transfer can lead to improvements in the availability of CO_2 at the active sites, thus optimizing the electrochemical reactions. However, it must be noted that porous electrodes frequently exhibit non-uniform structures and complex geometries, requiring characterization at more or less meso- and macroscopic scales [76]. Despite these complexities, this holistic approach not only deepens our understanding of each component's role but also significantly improves the design and operational efficiency of the overall system of ECO2R, as is supported by experimental evidence. This integrated approach represents the ultimate goal and the most effective strategy for advancing simulations of the ECO2R process or any electrochemical reaction. Studies have already modeled these interactions individually, underscoring their potential [77–81]. For example, Jung et al. [77] developed a three-dimensional CFD model incorporating interphase mass transfer and multiphase flow to evaluate how flow pattern design affects

performance in a 50 cm^2 electrolyzer. Their model, supported by experimental data, showed that optimizing convection through the GDE boosted CO production by 28%, offering scalable design guidelines. Similarly, Yang et al. [78] used a two-dimensional multiphysics model integrating chemical kinetics, interphase mass transfer, and electronic and ionic transport in order, to study gas–liquid transport, electrochemical reactions, and catalyst behavior. Their model accurately predicted current densities and selectivity under low-electrolyte (potassium hydroxide, KOH) concentrations and was used to analyze the influence of operational variables on product yield and energy efficiency. In contrast, models by Weng et al. [79] and Ehlinger et al. [80] focused more deeply on the catalyst layer microenvironment. Weng et al. [79] applied a porous electrode model with multiphase transport and chemical kinetics to simulate local distributions of CO_2, OH^-, and water in Ag-based GDEs under various operating conditions. Ehlinger et al. [80] designed a one-dimensional model of a zero-gap MEA that included porous transport, ionomer–catalyst interactions, and chemical kinetics. Their work emphasized how cathode flooding and ionomer distribution influence reaction kinetics and selectivity. Lastly, Chae et al. [81] used a porous flow model combined with experimental analysis to demonstrate how substrate structure (carbon paper versus glassy carbon) affects CO_2 delivery and CO diffusion, highlighting the critical role of substrate porosity in gas-phase transport and FE. All models discussed were validated with experimental data, ensuring their reliability and practical relevance for system operation and optimization.

Nevertheless, integrating several models remains challenging, given the complex and intricate nature of the processes to be modeled.

ML is the most recent tool for CO_2 reduction simulations, used as an additional resource, as traditional methods have been slow in identifying effective catalysts [82]. By utilizing ML algorithms, researchers are significantly accelerating the discovery and optimization of catalysts for ECO2R. Inputting an array of features related to a material—such as geometry, catalyst configuration, and electronic attributes, which can be obtained from experiments or online databases—into diverse ML models (e.g., random forest and neural networks) has been demonstrated to deepen insights into the underlying reaction mechanisms and the target of the simulation. It identifies potential improvements by focusing on predicted outcomes. ML marks a significant step in advancing ECO2R research by combining data-driven techniques with traditional electrochemical processes [82]. In addition, as mentioned earlier, it is beneficial—even highly recommended—to perform DoE to clarify the aspects that need to be modeled, especially when incorporating ML [83]. The integration of ML with DoE in chemical engineering achieves an “active ML” approach that can lead to more efficient and cost-effective research in terms of both budget and time expenditure. This combination increases the precision and relevance of the number of experiments needed to achieve the desired outcome and correlates it to modeling predictions, ultimately contributing to more robust and practical outcomes.

The continuous refinement of models is crucial in tackling the challenges of scaling up CO_2 electrolysis for industrial applications. With electrolyzer systems growing in size and complexity, issues such as thermal management, material/process stability, and system integration become more prominent. Models that can accurately predict these challenges and propose viable solutions are indispensable for the successful industrial implementation of CO_2 electrolysis. The two critical steps for industrial implementation are ① establishing a pilot plant for detailed performance data collection and ② developing robust chemical engineering process models [75], to ensure feasible implementation on outer space.

Recent advances in computational modeling, particularly CFD-based approaches, have provided valuable insights into the behavior of electrolysis systems under Earth-like conditions. However, the performance of these systems in non-Earth-like environments, such as those found on the Moon or Mars, remains less understood. A recent study by Burke et al. [84], building upon research presented at Accelerating Space Commerce, Exploration, and New Discovery (ASCEND) 2023, investigated the performance of electrolysis systems on the Moon and Mars. Their study used CFD models to simulate multiphase flow in water electrolysis, molten-salt electrolysis (MSE), and molten regolith electrolysis (MRE) across different gravity environments. In microgravity, compared with Earth conditions, surface tension plays a dominant role in fluid behavior. The study revealed that reduced gravity delays bubble detachment and decreases efficiency, particularly in water electrolysis, while MRE is less sensitive to gravity changes. Additionally, electrode surface roughness and orientation significantly affect bubble behavior, with rougher and vertically oriented electrodes increasing bubble retention. These results highlight the need for gravity-specific reactor designs in space applications, as well as computer simulation development (specifically CFD), to provide data-driven insights that can optimize systems further, especially when the environment cannot be entirely physically replicated on Earth.

Computer modeling plays a central role in modern research and development by enabling a deeper understanding of complex systems that can be validated by experimental data. Its effectiveness relies heavily on the quality of the input data and the robustness of the experimental design. Well-structured experiments generate reliable data that can be used to calibrate

and validate models, while accurate models can, in turn, guide experimental planning, optimize resource use, and highlight key variables. This feedback loop is essential not only for scaling up processes from the lab to pilot level but also for increasing model reliability and knowledge about a system. In the context of electrolysis systems on the Moon and Mars, CFD models have proven helpful in simulating multiphase flow under varying gravity environments. The insights gained from these simulations can significantly impact the design and performance optimization of these systems for space applications and can possibly offer a foundation for evaluating the potential commercial viability of these technologies both on Earth and in future space missions.

1.3. Commercial viability

Despite these challenges in scaling from laboratory conditions to commercial applications, the path to commercial success for CO_2 electrolysis technologies is intricately linked to economic and sustainability considerations of the technologies themselves. A critical economic challenge is the cost of the electrolysis process, which includes expenses for electricity, catalyst materials, and ongoing system maintenance. The efficiency of an electrolysis process is crucial because it affects how much electrical energy is needed, which influences the overall costs of running the system. High-temperature electrochemical technologies such as MC and SOE are efficient but rely heavily on elevated thermal conditions and suffer from slow start-up times [85]. On the other hand, low-temperature ECO2R (operating around 40 °C for an established pilot plant) stands out for its sustainability and financial viability [75,86,87].

As mentioned previously, sustainability is a critical aspect of CO_2 electrolysis technology. While the primary objective of this technology is to mitigate carbon emissions by transforming CO_2 into beneficial products, it is imperative to thoroughly evaluate the technology's environmental impact. This includes the lifecycle assessment of the electrolysis system, from the extraction and processing of raw material for catalysts and other components to the energy sources used to power the electrolysis process. High-temperature electrolysis using SOEC systems, particularly for producing CO and syngas [5], can be more efficient if integrated with thermochemical processes to reduce heating cycles [31]. However, the sustainability of SOECs is a concern due to their high energy requirements and their limited capability to convert CO_2 directly into a wide range of hydrocarbons and oxygenates—a feature more prevalent in low-temperature electrolysis systems [5,31,88,89]. This limitation in product diversity and the high energy demand of SOECs present notable challenges for their environmental impact and practical utility. Scaling CO_2 electrolysis technologies from the lab to industrial scale is critical for commercialization; it involves challenges such as maintaining efficiency and stability and optimizing design for mass production, which require advances in both science and engineering [75,78,90–92]. While integrating these systems into existing industries, such as power plants or cement factories, offers opportunities to reduce carbon footprints and secure CO_2 sources, it demands careful design consideration and economic feasibility assessment [31,75]. However, despite many companies globally operating in the field of CO_2 electroreduction, real commercial success has not yet been achieved. Applications for Earth have different technology readiness levels (TRLs) than those for Mars, with different priorities and development pathways. On Earth, CO_2 electroreduction technologies are relatively mature, primarily focusing on cost-efficient commercial deployment and system scalability. Currently, most technologies are at TRL 6, meaning that a prototype has been demonstrated in a relevant environment. However, they have not yet reached TRL 9, which indicates full commercial readiness [13]. Nevertheless, there is an aim to increase the TRL of the technology to 7, with the development of a pilot-scale plant designed to operate under industrially relevant conditions. This plant aims to convert CO_2 into e-fuels (C_1–C_4 alcohols) [93]. In contrast, for Mars, the emphasis shifts from scalability alone to include autonomous maintenance, reliability, and minimal interaction with the device (long durations). Looking ahead, the technology must be at least TRL 6 to be considered viable for space missions. Currently, most CO_2 electroreduction systems designed for or focused on Martian deployment remain at TRLs 2–4, with the notable exception of the Mars Oxygen *In-Situ* Resource Utilization Experiment (MOXIE), which successfully demonstrated a TRL 6 performance [94]. MOXIE will be discussed in detail in the following sections.

Considering all the previous factors, there is potential for CO_2 electrolysis technology to be both sustainable and economically feasible for industrial applications. Thinking beyond, it can even be presented as a viable option for deployment in off-planet scenarios, particularly in future space exploration missions and deep space research. However, a detailed evaluation of this strategic and industrial approach is essential for these technologies to be effectively adapted for extraterrestrial environments.

2. Outer-space applications—A perspective

Our prior discussions underscored ECO2R's role in reducing carbon footprints and CO_2 emissions, while requiring low energy and operating at lower temperatures [88,89]. However, there is a new challenge: the scarcity of minerals and elements

on Earth [95]. This scarcity is leading to a lack of the resources needed not only to produce technology and equipment but also to move away from fossil fuels (e.g., resources for solar panels, batteries, and electric cards). This situation indicates that there may come a point when depending on Earth's supplies for future industrial applications will no longer be feasible. ECO2R technology can be presented as a technology that can significantly assist in dealing with the lack of resources and increasing the feasibility of human exploration and long-term settlement on the Moon and Mars [96,97], potentially leading to the utilization of outer space resources. However, it is essential to recognize that other electrochemical technologies have already paved the way for space exploration. To fully grasp the scope of our interest in this field of application, we now revisit the underlying motivations for human space exploration.

The motivations for human space exploration encompass various factors, ranging from scientific objectives to engineering and technology development considerations, national security, prestige, and broader political motives [98]. Since the previous millennium, the space race has led to new methods to overcome obstacles and reinitiate lunar and space exploration in our current era. Various countries have launched lunar projects, and US National Aeronautics and Space Administration (NASA)'s International Space Exploration Coordination Group (ISECG) has been coordinating efforts with these interested agencies. Established in response to the 2007 "Global Exploration Strategy: The Framework for Coordination," the ISECG facilitated a study on human lunar exploration, resulting in the ISECG Reference Architecture for Human Lunar Exploration [99]. The newest update of the ISECG's 2018 Global Exploration Roadmap Supplement, released in October 2022, outlined missions starting with a near-Earth asteroid visit; this was followed by lunar missions as precursors to a Mars landing in the 2030s, and newly joined ISECG organizations, such as the Brazilian Space Agency, the Mexican Space Agency, and the Geo-Informatics and Space Technology Development Agency, all of which joined in 2020 [100–102]. Cost-effective strategies that require only a modest increase in the budget for operated space exploration can be devised. These strategies would involve gradually implementing versatile exploration technologies already developed by space agencies in Japan, India, China, the United States (i.e., NASA), and Europe (i.e., European Space Agency (ESA)). This involvement occurs both independently and through NASA's Artemis Accords. With 36 countries now participating, the Artemis Accords encourage global participation in future space exploration and establish guidelines for cooperative and peaceful exploration and use of the Moon, Mars, comets, and asteroids, including outer-space resources [103]. These approaches align with ESA's Moon and Mars exploration objectives, which have seen significant milestones with the launch of rovers on the Moon, the Mars Express in 2003, and the ExoMars Trace Gas Orbiter (TGO) in 2016. ESA also plans to launch the Rosalind Franklin rover by 2028 [104]. While all these efforts are currently aimed at reaching out to these outer-space bodies, human exploration cannot solely rely on the Earth's resources. ISRU is a crucial principle for these ambitious plans, underscoring the importance of using local resources, as the term ("*in-situ* resources") implies, to support processes that can enable human presence or human-like activities in our Solar System.

2.1. In-situ resource utilization

Depending entirely on Earth's resources is becoming impractical for sustaining human presence and activities in outer space, both in the near term (5 years) and long term (over 20 years). With challenges in meeting resource demands on Earth, securing a consistent supply of materials becomes vital. Developing an ISRU process in outer space was first envisioned in 1978, when the impracticality of depending exclusively on Earth for supplies was already emphasized [7]. To successfully develop an ISRU approach, researchers need to engage on various fronts of material sciences, ensuring that innovation efforts and research priorities are adjusted to commercial realities and thereby facilitating tangible impact in both the immediate and distant future [105]. The ISRU strategy of leveraging resources directly from extraterrestrial environments offers both efficiency and economic benefits. This concept is essential for the near- to long-term success of space missions; it represents a pivotal leap toward achieving autonomy beyond Earth's limitations, offering innovative solutions for human-like activities in space, such as mining, transportation, and construction [106]. This approach not only supports space activities but also offers the potential to benefit Earth by providing alternative sources of material extraction. Harvesting water and oxygen and utilizing local materials for habitat construction underscores the significant potential impact of ISRU processes [98,107].

Nevertheless, implementing ISRU technologies in space remains challenging. Since 1978, there has been a vision to produce rocket propellants on Mars using local resources, such as by extracting CO_2 from the atmosphere and tapping into subsurface water for electrolyzing oxygen and other valuable chemicals [7]. Such strategies are especially critical for missions to Mars, where logistical challenges are magnified. Mars has a CO_2-rich atmosphere, with CO_2 making up about 95% of its total composition, making Mars an ideal candidate for CO_2 reduction electrolysis technology to be implemented as an ISRU process [97]. However, adapting this technology for Mars involves modifying electrochemical reactors to perform well under the planet's low atmospheric pressure and varying temperatures. Achieving optimal performance requires careful design adjustments and rigorous testing through physical experiments and computer simulations.

2.2. Mars Oxygen ISRU Experiment

As part of NASA's Mars 2020 Perseverance mission, MOXIE represented a significant step forward in achieving IRSU goals under Martian conditions [94]. MOXIE successfully demonstrated the capability to produce oxygen from the CO_2 atmosphere, paving the way for future expeditions to depend on local resources for life support and fuel production. Placed in the 2020 Perseverance Mars rover, MOXIE collected Martian air, filtered out the CO_2 gas, and directed it into the compressor inlet. The CO_2 was then heated and sent into a stack of SOECs, where 30%–50% of the hot CO_2 was converted into CO and O_2 [94,108]. While MOXIE could efficiently obtain CO_2 byproducts using SOECs for a short time on Mars (< 100 h), the high energy demand and operation at temperatures up to 800 °C necessitate the use of ceramic materials such as zirconia (ZrO_2) for construction. Moreover, these high operational temperatures can impact the system's durability and maintenance [94]. MOXIE presented several issues after its performance in the Martian environment [109]. One major issue was thermal cycling, which led to material degradation and challenged MOXIE's goal of operating at least 10 times during a primary mission (> 1000 h) [108,109]. Mass, volume, and power constraints also compromised MOXIE's efficiency, potentially making a full-scale system impractical. Its use of nickel (Ni)—which acts as a catalyst for carbon formation at specific voltages—leads to cathode coating and structural damage with each cycle. This increases stack resistance over time due to oxidation, reducing the active electrode area [94]. Silver catalysts avoid CO_2 oxidation issues, with metallic Ag showing similar activity to state-of-the-art gold electrocatalysts [110]. Carbon-supported precious metal catalysts can reduce precious metal use while increasing durability. GDE-based cathodes in zero-gap electrolyzers improve ECO2R performance due to their better gas distribution and higher-pressure CO_2 delivery in comparison with bulk electrodes [110]. However, catalysts must be refined to achieve low overpotentials, adequate current density, and reduced CO_2 crossover [110]. These improvements are crucial for advancing ECO2R and enabling sustainable, durable resource utilization.

MOXIE also demonstrated the ability to reduce cathode pressure to approximately 0.22 bar (1 bar = 10^5 Pa), much lower than the local pressure on Mars, which is 0.7 bar. However, there is an absence of data for lower-pressure operations. Ongoing research is exploring the impact of pressure on aqueous-based ECO2R, offering promising avenues for optimization [111]. Looking ahead, a full-scale oxygen-producing ISRU system for human missions must be able to operate significantly longer than MOXIE. This extended operation may involve additional energy requirements and the potential degradation of filters, compressors, and electrolysis components. Preheating the SOEC to its 800 °C operating temperature alone consumes approximately half the total energy budget and requires at least 2 h. However, this cost is considered negligible for future continuous operating systems [94]. The power demand required to run the MOXIE compressor continues to pose a significant challenge, especially since thermal degradation over time is unsustainable for extended missions. In contrast, ECO2R is a low-temperature system compared with MOXIE, since it can operate at 25–80 °C, and it does not rely on temperature but electricity (i.e., electrons) to reduce CO_2 to value-added products. ECO2R provides several advantages over conventional methods by being based on a full understanding of how the catalyst's physical properties influence its electrocatalytic behavior and product selectivity, while operating without thermal management like SOEC systems. Notably, ECO2R improves carbon efficiency and enables effective integration with renewable energy systems [13]. As described, ECO2R operates under relatively moderate conditions, requiring lower temperatures and pressures.

In summary, the details of MOXIE in normal conditions are: It operates at a temperature of 800 °C and a pressure of 0.7 bar and requires a gas composition mirroring that of the Martian atmosphere [94,112]. Its Nernst potential, which represents the voltage at which a specific electrochemical reaction occurs, is calculated as E_{Nernst} = 0.9208 V, given the following reaction:

$$2CO_2 \rightarrow 2CO + O_2 \quad (6)$$

With technologies such as MOXIE, it is foreseen that future systems will be able to increase CO_2 utilization efficiency through techniques such as reducing the cathode pressure, carefully controlling the operating voltage to prevent carbon formation (for nickel catalysts), and employing alternative cathode materials that maintain catalyst stability without being damaged by carbon deposition or oxidation. Table 1 summarizes some chemical processes suitable for ISRU under Martian conditions, detailing the input and output resources and their primary applications. For more detailed information, please refer to Ref. [113], which aligns with the perspective presented in this review article.

Table 1

Processes for ISRU on Mars: Input products, output resources, and Martian applications.

Process name	Input products	Output resources	Primary applications	Chemical reactions involved
Sabatier reaction	CO_2, H_2	CH_4, H_2O	• Fuel • Life support	$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$
Oxygen production (MOXIE)	CO_2, H_2O	O_2, CO, H_2	• Life support	$CO_2 \rightarrow CO + 0.5O_2$ $H_2O \rightarrow 0.5O_2 + H_2$
Water electrolysis	H_2O	O_2, H_2	• Fuel • Life support	$H_2O \rightarrow 0.5O_2 + H_2$
RWGS	CO_2, H_2	CO, H_2O	• Fuel • Life support	$CO_2 + H_2 \rightarrow CO + H_2O$
ECO2R	CO_2, H_2O, electricity	Various (CH_4, CO, O_2, etc.)	• Fuel • Life support • Manufacturing	$CO_2 + H_2O + 2e^- \rightarrow CO + 2OH^-$ $CO_2 + 6H_2O + 8e^- \rightarrow CH_4 + 8OH^-$ …
Mineral processing	Martian regolith (soil)	Metals, O_2, silicon	• Construction • Manufacturing	—

RWGS: reverse water–gas shift.

2.3. Outlook on ECO2R

Looking ahead, the influence of electrochemical science and engineering on human space missions promises to be significant. Innovations in ECO2R and oxygen generation are set to transform life-support systems to enable sustained human exploration of Mars [96,100,114,115]. However, testing these phenomena experimentally on Earth poses significant challenges. While zero-gravity conditions can be simulated in various facilities or aircraft, simulation remains vital. Detailed models and certain physical properties presented in scenarios of reduced gravity, highlighting different electrochemical cell configurations, emphasize the importance of computational modeling in the context of space-simulated conditions [68,84]. NASA's commitment to employing SOEC technology for ISRU in upcoming missions to Mars and the Moon is evident [94,108,116]. The groundwork laid by MOXIE facilitates further advancement and fine-tuning of SOEC technology for extraterrestrial ISRU applications, and the ISRU chemical processes of ECO2R and reverse water–gas shift (RWGS), utilizing CO_2 and water, on Mars can be feasible for the upcoming years (Fig. 3) [109]. These processes are envisioned for future space missions to the "Red Planet" over the next 5–30 years and beyond, spanning near-term to far-term developments. In the first stages (near and later term), continuous support from space missions between Mars and Earth will be necessary to

maintain these processes. However, in the far term, reduced reliance on intermittent missions is anticipated, allowing these processes to be entirely self-sustained in Mars's extraterrestrial environment.

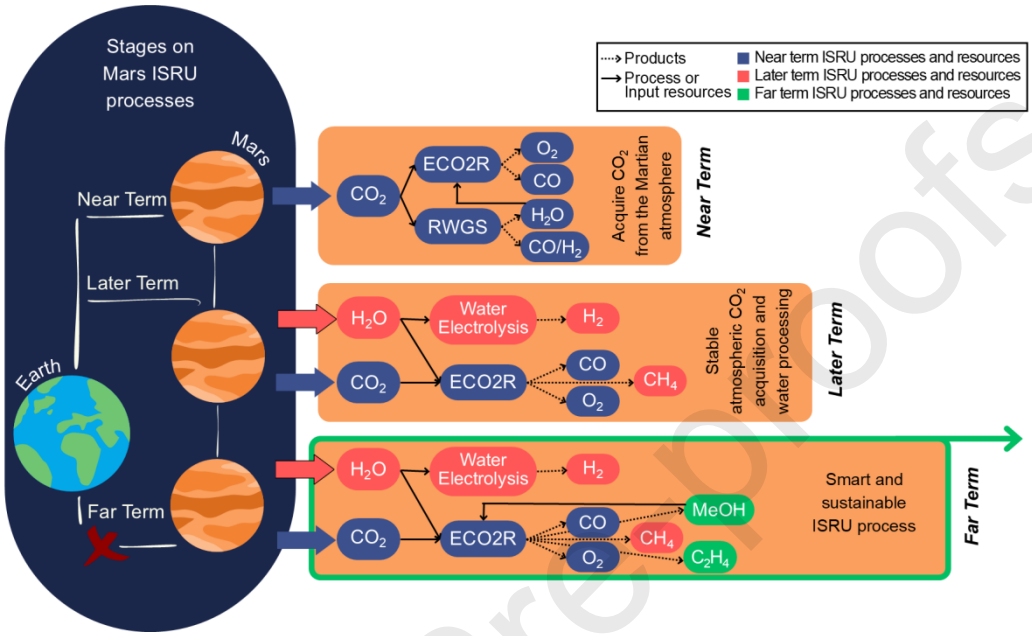

Fig. 3. Evolution of Mars ISRU chemical processes: Integrating ECO2R, RWGS, and water electrolysis in phased development stages—near, later, and far term—as projected in the analysis by Rapp and Inglezakis [109].

Building on the groundwork laid by MOXIE and the promising advancements in SOEC technology, ECO2R stands as an alternative approach that can increase the sustainability and viability of space exploration and habitation in extraterrestrial environments by providing a relatively resilient and energy-efficient alternative through the use of polymeric and metallic cell components, compared with the ceramic components used by MOXIE. This strategic vision involves leveraging the synergy between SOEC, ECO2R, and other technologies to create a robust ISRU framework. The aim is to optimize the utilization of local resources for mission-critical supplies such as oxygen and fuel, while demonstrating the versatility and adaptability of ECO2R in processing Martian resources.

ECO2R electrolyzers present challenges such as low temperatures (below –40 °C), which may affect the electrolyte conductivity (especially for aqueous systems, which can freeze). This necessitates the use of non-aqueous or low-freezing-point solvents (e.g., ionic liquids or deep eutectic solvents). ECO2R has been demonstrated using apolar solvents [117]. Radiation impacts polymeric and catalytic materials, requiring specialized design such as the use of radiation-resistant materials (e.g., perfluorinated membranes and ceramics) and microgravity may complicate mass transport and fluid handling, demanding innovative cell architectures.

Moreover, it is known that variation in CO_2 mass transport can significantly influence the kinetics of CO2RR, as local CO_2 concentration directly affects the surface coverage of key intermediates such as $*CO_2$, *H, and *CO. This, in turn, plays a critical role in determining the reaction pathways, particularly toward the formation of multi-carbon (C_2^+) products [118]. That being said, considering planetary ISRU systems utilizing ECO2R, the performance of the electrolyzer is closely tied to the concentration of CO_2 delivered to the reaction interface. While planets like Mars offer a CO_2-rich atmosphere, the absolute concentration of CO_2 is not determined by composition alone but is also influenced by pressure and temperature, as described by the ideal gas law:

$$C = \frac{n}{V} = \frac{P}{RT} \quad (7)$$

where C is the molar concentration of CO_2, n is the number of moles of gas, V is the volume of gas, P is the partial pressure, R is the universal gas constant, and T is the absolute temperature.

This relationship is critical when evaluating CO_2 availability for electrochemical conversion. Dilute CO_2 streams—that is, mixtures with CO_2 concentrations below 10%—are particularly challenging due to their inherently low CO_2 concentration. Despite the high CO_2 percentage on Mars (~95%), the very low atmospheric pressure (~6 mbar) results in a very low molar concentration of CO_2 [119], which limits mass transfer into the reactor and constrains electrochemical performance. However, recent efforts have proven that, even with dilute CO_2 streams, CO_2 can be effectively utilized through K_2CO_3-based reactive capture combined with a redox-active polymer, which facilitates *in-situ* electron transfer to the CO_2 released from the carbonate during electrolysis [120]. This work demonstrated a viable path forward for ISRU applications, especially on planets with diluted or variable CO_2 environments (e.g., the Moon's recycled air and Martian diurnal cycles), and eliminates the need for thermal desorption of CO_2 gas. Following this approach of focusing on how the catalyst itself can concentrate and activate CO_2 effectively, the choice of electrocatalyst and electrolyte composition can mitigate performance losses at low CO_2 levels [121]. CO-selective CO2RR catalysts, such as Ag- and Ni-based materials, combined with electrolytes that offer buffering capacity, help maintain high CO selectivity and FE even at low CO_2 concentrations.

As discussed above, ECO2R systems present distinct challenges. Depending on whether they are implemented on Earth or in outer space, the development of research around ECO2R can vary [97]:

- On Earth, reactor designs prioritize cost-effectiveness, scalability, and industrial robustness; in space, they must be compact, lightweight, and capable of autonomous operation under harsh and variable conditions.
- The choice of materials on Earth is guided by cost, durability, and atmospheric performance, while space applications demand materials that can withstand radiation, extreme temperature fluctuations, vacuum, low pressure, and microgravity.
- Catalysts in both environments require high selectivity and long-term stability; in space, however, they must also be resistant to radiation and capable of functioning with minimal maintenance.
- CO_2 feedstock on Earth typically originates from flue gases, direct air capture, or industrial emissions; in space, it may be sourced from crew exhalation, the CO_2-rich Martian atmosphere, or closed-loop ISRU systems.
- On Earth, product separation is relatively straightforward due to gravity-assisted gas–liquid separation; in microgravity, however, separation must rely on capillary forces, pumps, or specialized membrane systems.
- Energy supply on Earth can draw from grid or renewable sources; in space, systems must function using solar or nuclear energy with careful power management.
- Finally, while water is readily available and recyclable on Earth, in space it becomes a scarce and critical resource that must be conserved and fully recycled within closed-loop systems.

GDEs, which are integral to PEM electrolyzers and fuel cells, have proven effective in space missions, including on the International Space Station (ISS) and during the Gemini program [122]. While direct GDE testing in a vacuum remains somewhat limited in the publicly available literature, the success of broader electrochemical systems confirms their reliability in space. As missions targeting ISRU and long-duration exploration grow, GDE-based technologies will become increasingly crucial. Advancing ECO2R can enhance NASA's and ESA's sustainable, low-energy mission capabilities through global collaboration and innovation.

3. Conclusions and perspectives

ECO2R holds the potential to revolutionize future space missions, particularly those involving extended stays on planets such as Mars. This process, which aims to efficiently convert CO_2 into valuable compounds with minimal energy consumption, could be crucial for supporting human life on Mars by producing essential resources such as oxygen and fuel

directly from the Martian atmosphere. However, this capability remains theoretical and requires validation, making ECO2R a promising but yet-to-be-verified cornerstone in the hypothetical toolbox for advancing space exploration technology. While ECO2R is still under development and has not yet been deployed in space, its effectiveness and sustainability on Earth serve as a compelling proof of concept. ECO2R's potential to minimize dependence on Earth-supplied resources is a significant advantage in scenarios where frequent resupply missions are impractical.

Further exploration of Mars is an essential step in discovering new sources and improving electrolyzers for producing propellants and chemicals from local resources. Such exploration will be key to increasing the viability of ISRU, which is essential for enabling long-term, sustainable human colonization of Mars. Future research should optimize these electrolyzers, advance energy solutions, and deepen our understanding of Martian geology.

The future integration of ECO2R technology in space missions is gaining traction as agencies and research institutions increasingly prioritize closed-loop life-support systems, ISRU, and sustainable off-Earth habitats. ECO2R has the potential to convert abundant CO_2 into valuable products such as fuels (e.g., methane and ethylene), oxygen, and feedstock chemicals, playing a pivotal role in supporting long-duration missions and planetary colonization—especially on Mars, where the atmosphere is almost entirely composed of CO_2. By 2050, ECO2R is expected to become a technology for Martian ISRU, enabling the autonomous production of propellants and materials for life support, construction, and return missions. However, the path forward requires accelerated research and innovation across several integrated fronts. One major frontier is the development of catalysts and setups that can withstand Martian extremes (e.g., temperature swings, radiation, perchlorates, and abrasive dust) while maintaining their activity and selectivity for thousands of operational hours. Simultaneously, energy efficiency must be dramatically improved, as power is one of Mars's most limited and valuable resources. Achieving this will allow systems to downsize, reduce power infrastructure, and increase operational autonomy.

Beyond materials and energy, ECO2R must be imagined as part of a tightly interconnected ISRU ecosystem. Moreover, downstream processing is a critical component of a complete ISRU system. The product gas stream often contains a mixture of CO, unreacted CO_2, and water vapor, requiring gas-separation units to isolate high-purity CO and recover water for reuse. On the anode side, pure oxygen must be captured and purified. Depending on mission requirements, these outputs (CO, O_2, and water) must then be properly stored in pressurized or cryogenic systems. ECO2R systems should operate in parallel with oxygen-production, fuel-generation, and water-recycling units to build a self-sustaining closed-loop system, which could support long-term human missions on Mars and other planets. The ambition here is not only technical but also ecological. So, how can CO_2 reduction be integrated with O_2 generation, waste recycling, and resource-recovery loops for closed-loop life support? What are the best strategies to synchronize CO_2 electrolysis with the intermittent solar energy availability on Mars? How can we develop an ECO2R system that operates autonomously for over 5000 Martian sols (~14 Earth years), using only locally available inputs and powered entirely by renewable energy?

Crucially, the field must embrace collaboration—not competition—between diverse electrochemical platforms. Whether through SOECs, PEM cells, MC systems, or ECO2R, a cooperative strategy that leverages each technology's unique strengths will broaden the product spectrum and improve process reliability. This integrative spirit, bridging chemistry, systems design, and planetary science, will help build sustainable infrastructure not just for Mars but also for the Moon and other celestial bodies.

Declaration of competing interest

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT in order to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Declaration of Interest Statement

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