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Electrolysis and Co-Electrolysis: Reducing CO₂ Emissions and Advancing Sustainable Energy

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**Abstract:** This paper aims to provide a comprehensive overview of electrolysis and co-electrolysis technologies, with a focus on their contribution to reducing carbon dioxide (CO₂) emissions into the atmosphere. The exacerbation of climate change due to rising CO₂ concentrations has intensified the search for effective technological solutions. In this context, electrochemical processes such as electrolysis and co-electrolysis have emerged as promising alternatives for the capture and conversion of CO₂ into value-added products and sustainable fuels. Electrolysis, traditionally used for water splitting, and co-electrolysis, where carbon dioxide and water vapor are simultaneously converted into synthesis gas (syngas), are being investigated in terms of their efficiency, scalability and economic feasibility. The main technical challenges and innovations to improve these technologies will also be discussed. The central aim is to highlight the benefits and specific advantages of electrolysis and co-electrolysis in reducing CO₂ emissions and to emphasize their potential for integrating renewable energy sources and contributing to a low-carbon, environmentally sustainable economy.

* 1. Introduction

The continuing rise in carbon dioxide (CO₂) emissions has intensified the drive for advanced technologies to reduce environmental damage and promote sustainability. The increase in greenhouse gasses in the atmosphere, largely due to industrial activities and the overuse of fossil fuels, is one of the main causes of climate change. In response to this global problem, international agreements such as the Kyoto Protocol and the Paris Agreement have set clear targets for the reduction of CO₂ emissions and promoted the development of technologies that can efficiently capture, store and reuse this gas (Urbano & Pahon, 2024).

Electrolysis and co-electrolysis stand out among the new technologies as promising approaches for converting CO₂ into valuable compounds that support the energy transition and reduce dependence on fossil fuels. Electrolysis is already well established for the production of hydrogen from water and plays an important role in clean energy production, especially when powered by renewable sources. In contrast, co-electrolysis enables the joint conversion of CO₂ and water vapor into syngas, an important intermediate for the synthesis of fuels and chemicals, while contributing to a more sustainable carbon cycle (Cardoso et al., 2021; Tu et al., 2024).

In addition to CO₂ conversion, integrating electrolysis and co-electrolysis with fuel cells offers a strategic pathway for clean and efficient energy generation. Hydrogen obtained from electrolysis can be directly used in fuel cells to produce electricity without harmful emissions, supporting the decarbonization of the energy system. This synergy promotes low-carbon solutions capable of reducing industrial emissions and meeting future energy demands. Advancing and refining these technologies is essential for large-scale deployment and improving both energy efficiency and economic viability. This study explores the fundamentals of electrolysis and co-electrolysis, their integration with fuel cells, current challenges, and their role in a sustainable energy future (Cardoso et al., 2023; Dash et al., 2024; Tu et al., 2024).

* 1. Hydrogen

Global agreements have prompted many countries to adopt strategies to decarbonize their economies. The Paris Agreement, signed by 195 nations under the UNFCCC, sets targets to reduce greenhouse gas emissions and limit global warming to no more than 2°C above pre-industrial levels. These targets were reaffirmed at COP26 in 2021 by the Glasgow Agreement. However, achieving these targets depends on stronger efforts in all sectors that contribute to anthropogenic emissions (Cardoso et al., 2023; Scopel et al., 2023).

Carbon dioxide (CO₂) is the main greenhouse gas released into the atmosphere. While some CO₂ emissions occur naturally through biological respiration and the decomposition of biomass, human activities are responsible for the release of millions of tons per year, mainly through the burning of fossil fuels. The main sectors contributing to these emissions include energy production (mainly thermal power plants), transportation (through the combustion of diesel and gasoline) and industrial processes. In addition, agriculture, waste management and changes in land use also play a role in CO₂ emissions. Although industry is only part of the overall emissions scenario, hydrogen production stands out as the main source of industrial CO₂ emissions.

Hydrogen is used in many industries such as oil refining, fertilizer production and metallurgy. However, most of the current supply comes from fossil fuels, particularly from methane steam reforming (SMR). In 2021, this method caused over 900 million tons of CO₂ emissions associated with the production of around 94 million tons of hydrogen. In contrast, low-emission methods such as water electrolysis contributed to less than 1 million tons of CO₂, with only 35 kilotons attributable to electrolysis. These figures underline the urgent need to switch to cleaner hydrogen production technologies (Cardoso et al., 2023; Dash et al., 2024; Sezer et al., 2025).

Water electrolysis offers a viable route for producing low-emission hydrogen by splitting water into hydrogen and oxygen using electricity. When powered by renewable energy, this process yields what is commonly referred to as "green hydrogen." Despite its environmental benefits, green hydrogen faces significant cost barriers, it is currently about three times more expensive than blue hydrogen, which is produced via methane reforming with carbon capture. These high costs are primarily driven by the price of electrolysis equipment and renewable electricity, along with other technical and economic challenges (Cardoso et al., 2023; Antunes et al., 2025).

Several countries are establishing strategic collaborations to enhance hydrogen production and storage, with a focus on exporting from regions with high production potential to those with limited capacity. By 2030, for example, exporting hydrogen from Colombia is expected to cost around 3.1 dollars per kilogram to Europe and 3.47 dollars per kilogram to Asia. Besides economic factors, the widespread adoption of green hydrogen also depends on addressing challenges such as access to freshwater and the development of infrastructure for its storage and distribution. Hydrogen combustion is represented by the following chemical reaction (1):

2H2 (𝑔) + O2 (𝑔) → 2H2O (𝑔) | Δ𝐻° = −286 𝑘𝐽.𝑚𝑜𝑙-1 (1)

This reaction highlights a key advantage of hydrogen as an energy carrier: its combustion produces only water, in contrast to fossil fuels that emit carbon dioxide. Hydrogen also stands out for its extremely low density, approximately 0.09 kilograms per cubic meter under standard conditions (Xi et al., 2022; Cardoso et al., 2023; Sebbahi et al., 2024; Tu et al., 2025). When converted from gas to liquid, its volume is reduced by a factor of about 840, making storage more efficient. Furthermore, hydrogen is the lightest element in the periodic table and offers one of the highest energy densities among known fuels, as shown in Table 1.

Table 1: Comparison of the calorific value of fuels

|  |  |
| --- | --- |
| Fuel | Calorific values (MJ/kg) |
| Gaseous hydrogen | 120-142 |
| Liquid hydrogen | 120-142 |
| Coal (wet basis) | 15-30 |
| Diesel | 42-46 |
| Ethanol | 42-44 |
| Gasoline | 43-46 |
| Liquefied petroleum gas (LPG) | 46-50 |
| Methanol | 20-23 |

* 1. Electrolysis and co-electrolysis

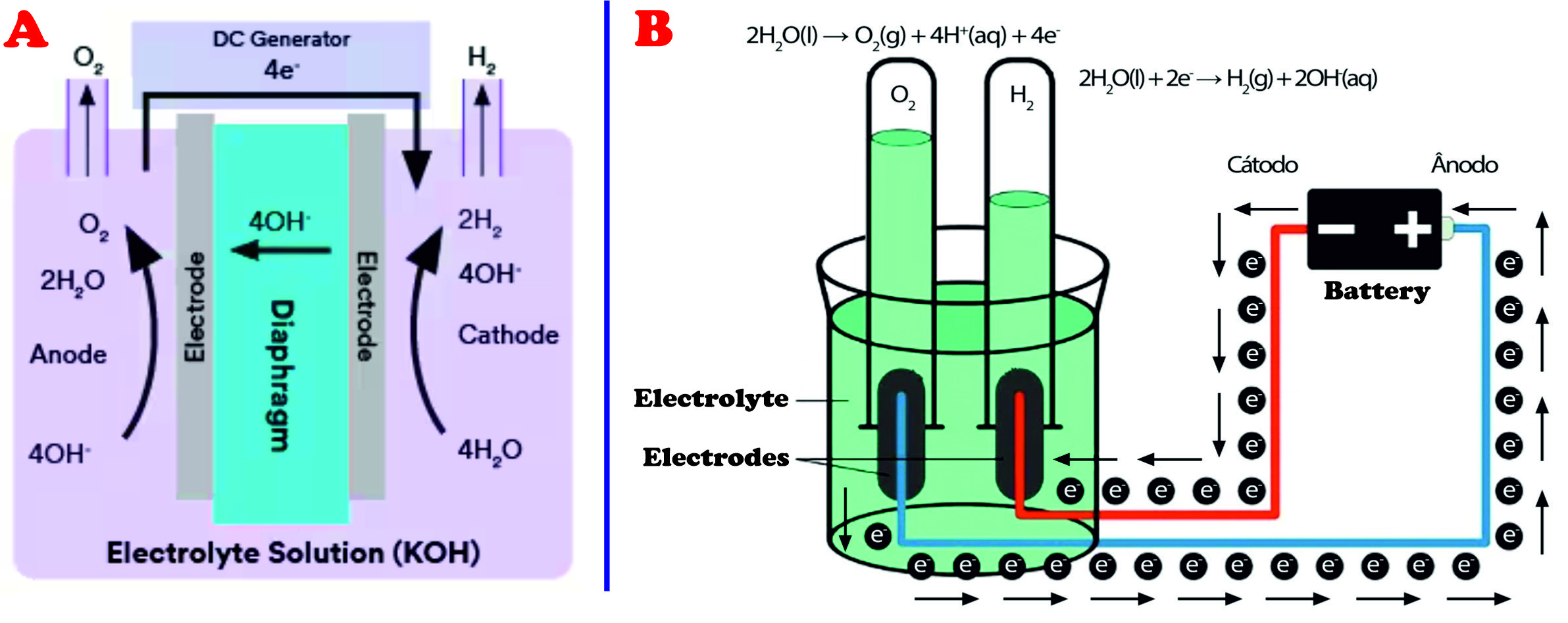
Electrolysis is a key electrochemical process that separates substances by applying an electric current. Its most widely recognized application is the decomposition of water into hydrogen and oxygen, a reaction that plays an increasingly important role in the pursuit of sustainable energy. The hydrogen generated can serve as a clean fuel, reducing reliance on fossil sources and supporting decarbonization in both the energy and industrial sectors. An electrolysis cell consists of two electrodes, the anode and the cathode, which are immersed in an ion-conducting electrolyte. When voltage is applied, oxidation occurs at the anode and oxygen is released, while hydrogen forms at the cathode through a reduction reaction. The efficiency and industrial relevance of the process depend on specific operating conditions, including temperature, pressure, and the type of electrolyte used (Cardoso et al., 2023; Sebbahi et al., 2024).

Electrolysis can be classified into different types, each presenting distinct characteristics in terms of efficiency, applicability, and cost. Conventional electrolysis is widely applied in industrial settings and operates with liquid electrolytes, requiring a continuous supply of electrical energy to sustain the process. High-temperature electrolysis functions at temperatures above 700 degrees Celsius, enhancing energy efficiency by reducing dependence on external electricity sources, which makes it particularly suitable for integration with heat recovery systems. Low-temperature electrolysis, in contrast, employs ion-conducting polymer membranes to generate high-purity hydrogen, making it especially appropriate for domestic and mobile applications.

The efficiency of electrolysis depends on the materials used in electrodes and electrolytes, as well as on operating conditions. While advanced catalysts like platinum and iridium improve performance, their high-cost limits large-scale use. Research is focused on developing more affordable alternatives such as metal alloys and carbon-based materials. Beyond hydrogen production, electrolysis is essential in industries for generating chemicals like chlorine and caustic soda and for extracting metals such as aluminium. It also serves as a method for storing renewable electricity, supporting grid stability. When powered by clean energy, electrolysis becomes a key tool for producing green hydrogen and reducing greenhouse gas emissions (Liang et al., 2024).

This feature makes electrolysis essential for meeting international climate targets such as those outlined in the Paris Agreement and for advancing circular economy models. Its integration with fuel cells is crucial for developing a sustainable energy system. Fuel cells convert hydrogen into electricity through efficient electrochemical reactions without releasing pollutants. When powered by renewable energy, this combination creates a closed energy loop where water is split into hydrogen, which is later used to generate electricity. This approach is especially promising for transportation, energy storage, and decentralized power generation, enhancing both the flexibility and reliability of energy networks (Patcharavorachot et al., 2023).

Electrolysis will continue to evolve through technological innovations that lower costs and enhance efficiency. Research on nanomaterials, process optimization, and integration with fuel cells and hybrid storage systems is key to establishing electrolysis as a core technology in the global energy transition (Liang and Han, 2022; Cardoso et al., 2023). With sustained investment, electrolysis is set to play a vital role in building a resilient and sustainable energy infrastructure. Figure 1 presents the basic mechanism of water electrolysis.



*Figure 1: (A) Alkaline water electrolysis, (B) Water electrolysis*

Co-electrolysis is an advanced electrochemical process that converts water vapor and carbon dioxide into synthesis gas, a mixture of hydrogen and carbon monoxide. This gas can be used to produce synthetic fuels and chemical intermediates. Unlike conventional electrolysis, which only splits water, co-electrolysis also reduces CO₂, expanding its potential to mitigate carbon emissions. The process occurs in solid oxide electrolysis cells at high temperatures, improving energy efficiency by reducing electricity demand. Among its key advantages are the direct reuse of CO₂, the generation of clean fuels compatible with existing infrastructure, and the possibility of integration with renewable energy. Co-electrolysis stands out as a promising solution for decarbonizing carbon-intensive industries and advancing the energy transition (Sezer et al., 2025).

Co-electrolysis plays a key role in the chemical industry, as the syngas it produces can serve as a feedstock for methanol, ammonia, and other essential compounds used in plastics, fertilizers, and aviation fuels. This contributes to a gradual shift toward more sustainable industrial practices. Syngas can also be transformed into liquid hydrocarbons through the Fischer-Tropsch process, allowing for the production of synthetic fuels that are compatible with existing fossil fuel infrastructure (Meharban et al., 2025).

Co-electrolysis can be applied in power plants to convert captured carbon dioxide into low-carbon fuels, reducing emissions and enabling efficient energy storage during periods of low demand. The hydrogen and carbon monoxide generated can later be used in fuel cells to produce electricity, increasing grid flexibility and resilience. This capacity to store and reuse renewable energy positions co-electrolysis as a strategic tool in the shift toward an energy system based on variable sources like solar and wind (Cardoso et al., 2022a; Li et al., 2024).

The transportation sector stands to gain considerably from co-electrolysis, as synthetic fuels derived from syngas can be used in existing combustion engines, allowing for a progressive shift to cleaner energy without major infrastructure changes. This is especially relevant for aviation and maritime sectors, where full electrification remains technically challenging. In aviation, sustainable fuels can be blended with kerosene or used directly, significantly lowering CO₂ emissions. In shipping, synthetic fuels help reduce fossil fuel dependence and improve efficiency. When combined with carbon capture technologies, co-electrolysis enables the production of carbon-neutral fuels with long-term environmental benefits (Nnabuife et al., 2024).

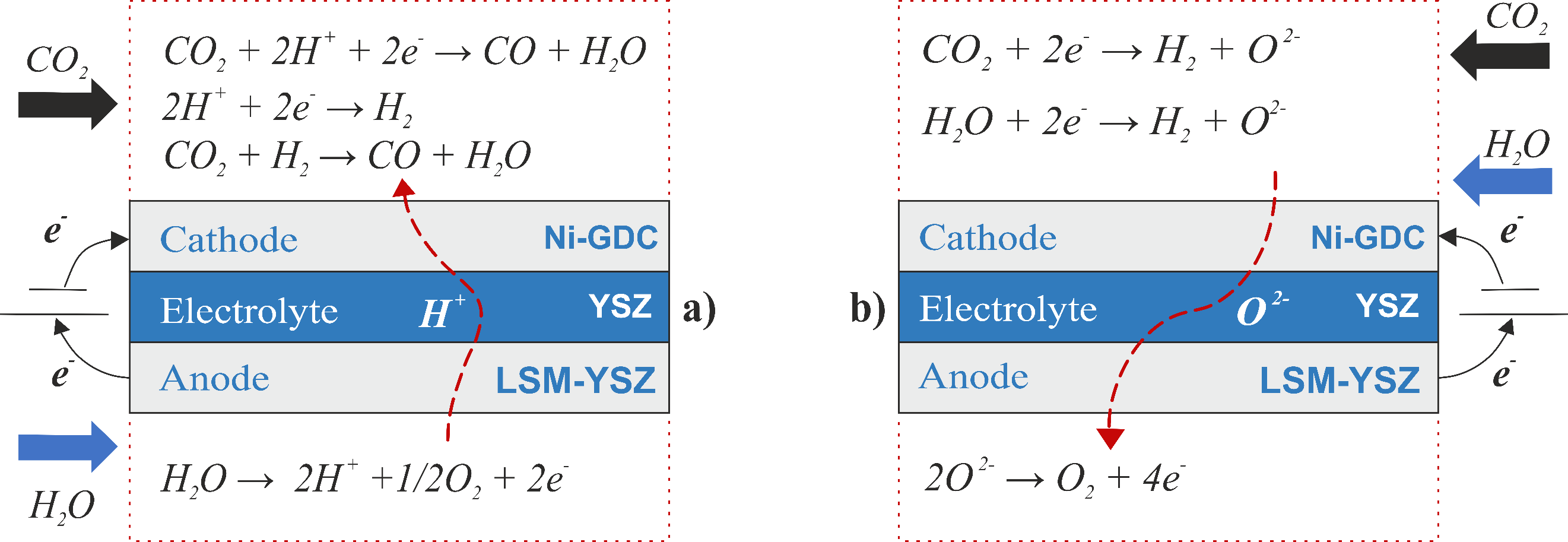
Although co-electrolysis shows strong potential, its large-scale adoption depends on technological improvements and cost reductions. Research efforts are focused on enhancing the durability and efficiency of solid oxide electrolysis cells and optimizing CO₂ capture and reuse. A major challenge is the degradation of electrodes and electrolytes at high operating temperatures, which reduces device lifespan and raises maintenance demands. To address this, studies are exploring advanced metal alloys and high-performance ceramics to improve component stability and overall process efficiency (Xi et al., 2022; Cardoso et al., 2022b).

In addition to the technological improvements, the economic viability of co-electrolysis also depends directly on the cost of the electricity used in the process. The success of this technology depends on access to low-cost electricity from renewable sources to make the production of synthetic fuels competitive with conventional fossil fuels. Government incentives and carbon pricing policies also play an important role in making this technology economically viable. Regulations that favour the capture and reuse of CO₂, as well as investment in hydrogen production and distribution infrastructure, can accelerate the adoption of co-electrolysis at scale (Li et al., 2024).

Co-electrolysis can be combined with a range of other new technologies to maximize its benefits. For example, it can be combined with bioenergy systems with carbon capture and storage (BECCS) to produce carbon-negative fuels that actively remove CO₂ from the atmosphere. Similarly, integration with solar thermal reactors can provide heat to increase the efficiency of electrochemical processes and reduce reliance on external electricity (Cardoso et al., 2022b; Ajeeb, 2024; Ince et al., 2023; Fei et al., 2024).

There are two main types of co-electrolysis: proton-conducting and oxygen-ion-conducting, as illustrated in Figure 2. In the case of co-electrolysis based on proton-conducting electrolytes, the perovskite material BaCe₀.₅Zr₀.₃Y₀.₁₆Zn₀.₀₄O₃−δ is used as the electrolyte, enabling efficient proton transport (Ince et al., 2023). In this system, nickel facilitates the oxidation of H₂O/H₂ at the anode, while CO₂ reduction occurs at the cathode, assisted by nickel or iron. This type of cell operates at temperatures up to 600°C, offering thermodynamic advantages (Liang & Han, 2022; Ince et al., 2023; Li et al., 2024).

On the other hand, in a typical solid oxide electrolytic cell using an oxygen-ion-conducting electrolyte, as illustrated in Figure 2, a dense Yttria-Stabilized Zirconia (YSZ) electrolyte separates the electrodes. The cathode consists of a cermet made of Nickel-Gadolinium-Doped Ceria (Ni-GDC), while the anode is composed of Strontium-Lanthanum Manganite with Yttria-Stabilized Zirconia (LSM-YSZ).



*Figure 2: The scheme of the design of a co-electrolysers* ***a)*** *proton conductive* ***b)*** *oxygen-ion conductive.*

In the future, co-electrolysis could play a key role in the global hydrogen economy as an efficient method of producing hydrogen and synthetic fuels from captured CO₂. As the cost of renewable energy continues to fall and technologies evolve, co-electrolysis is expected to become a viable and widespread solution for reducing carbon emissions and creating a more sustainable and circular economy (Li et al., 2024). With continued investment in innovation and infrastructure, co-electrolysis can play a key role in the transition to a low-carbon economy by promoting the efficient integration of carbon capture, renewable energy generation and sustainable fuel production (Cardoso et al., 2022b; Ajeeb, 2024). Co-electrolysis is expected to develop into a viable solution for the hydrogen economy in the coming decades, offering a sustainable alternative for electricity generation and synthetic fuel production with low environmental impact.

In addition to cells that use proton-conducting electrolytes, co-electrolysis can also be carried out with ceramic electrolytes that can transport oxygen ions. In this configuration, the electrolyte typically consists of yttrium-stabilized zirconia, a dense and durable material that operates effectively at high temperatures above 800 degrees Celsius. The electrochemical reaction involves the simultaneous reduction of carbon dioxide and water vapor at the cathode, resulting in the production of carbon monoxide and hydrogen. The oxygen ions produced in this process migrate through the electrolyte to the opposite electrode, where they are oxidized and release molecular oxygen (Li et al., 2024).

While proton-conducting cells rely on the transport of ionic hydrogen to the cathode for the reduction of CO₂, oxygen ion-conducting cells carry out the reduction directly at the cathode and transport O² ions to the anode, creating a separate electrochemical conversion pathway. This difference in ion transport mechanisms influences the choice of catalytic materials and defines the optimum operating conditions for each cell type.

The advantages of oxygen ion conducting systems include their high thermal stability and strong ionic conductivity in different atmospheres, making them suitable for long-term industrial applications. These systems are also compatible with widely used catalytic materials such as nickel and lanthanum manganite. However, the high operating temperatures can accelerate the degradation of the components, requiring the use of more robust materials and preventive strategies (Cardoso et al., 2022b; Ajeeb, 2024).

On the other hand, proton-conducting cells operate at lower temperatures, typically between 500 and 600 degrees Celsius. This favours a longer component lifetime and can reduce the costs associated with continuous operation. However, further research is needed to develop more stable electrolyte materials for these systems. The decision between using proton or oxygen ion conducting cells depends on several factors, including the energy integration strategy, the availability of heat supply, the desired product gas and the downstream infrastructure. Understanding these differences is crucial for optimizing the co-electrolysis process and its large-scale implementation (Cardoso et al., 2022b; Ajeeb, 2024; Ince et al., 2023; Fei et al., 2024).

* 1. Storage and Logistics Perspectives

A comprehensive understanding of the hydrogen supply chain requires careful evaluation of the renewable energy sources available for its production. The development of advanced materials is essential to lowering the cost of electrolysers and improving the overall feasibility of green hydrogen technologies (Cardoso et al., 2023). Storage methods, including liquefaction, compression, and conversion into liquid organic carriers, are key elements that impact efficiency and scalability. Advancements in these areas are necessary to overcome current limitations and to ensure more effective distribution systems (Urbano and Pahon, 2024; Meharban et al., 2025).

Transport and distribution strategies also play a critical role. While studies have explored the use of existing natural gas pipelines and the potential for decentralized hydrogen production, further research is needed to address long-distance transport challenges. This is particularly relevant for countries positioned as potential hubs for green hydrogen exports. The structure of the supply chain should be tailored to specific demands, as different factors determine the most suitable methods for production, storage, and distribution (Cardoso et al., 2021; Cardoso et al., 2022b; Ince et al., 2023).

* 1. Final considerations

Electrolysis and co-electrolysis are emerging as key technologies for reducing CO₂ emissions and advancing a sustainable energy system. Electrolysis allows the production of clean hydrogen from water, especially when powered by renewable sources, and plays a significant role in decarbonizing industry and the energy sector. Co-electrolysis builds on this by enabling the simultaneous conversion of carbon dioxide and water vapor into syngas, a crucial feedstock for synthetic fuels and high-value chemicals (Ince et al., 2023).

These technologies offer notable advantages in energy efficiency, compatibility with variable renewable energy, and chemical energy storage. However, their scalability depends on the development of more cost-effective and durable materials, as well as supportive public policies for carbon capture and utilization. Their integration with fuel cells, CO₂ capture systems, and hydrogen infrastructure creates an opportunity to establish circular, low-carbon energy systems. With sustained research and innovation, electrolysis and co-electrolysis are poised to become central components of the global response to climate challenges in the coming decades.

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**LETTER RESPONSE**

1) The plagiarism assessment report (attached) has identified potential instances of plagiarism. Please review and address these concerns.

The plagiarism assessment conducted through the University of Genoa's official service, Compilatio (<https://www.compilatio.net/it>), indicated less than 5% similarity. Nonetheless, several sections of the manuscript have already been rewritten and adapted to ensure originality and alignment with academic standards.

2) Avoid using bold text in the manuscript, such as in the following cases: page 2 (“Table 1 shows”); page 3 (“Conventional electrolysis,” “High-temperature electrolysis,” “Low-temperature electrolysis,” “Figure 1”). Other instances of bold text are present throughout the document—please ensure consistency.

All instances of bold text in the manuscript have been reviewed and removed, including those on page 2 (“Table 1 shows”) and page 3 (“Conventional electrolysis,” “High-temperature electrolysis,” “Low-temperature electrolysis,” and “Figure 1”). We have ensured consistency throughout the document.

3) The methodology section lacks detail. Clearly specify the criteria used for selecting studies, including the date range and databases consulted. 4) The references contain formatting inconsistencies, including variations in journal title capitalization, incomplete entries, and missing DOIs or URLs. Please correct these issues to

ensure uniformity.

The citation and formatting style were verified and are consistent with the guidelines of the CET Journal. Regarding the inclusion of DOIs, I reviewed the latest issue of the journal and noted that none of the first five published articles include DOI information. Therefore, I followed the same formatting standard adopted by the journal.

4) Chapter 3: The functioning of co-electrolysis using proton-conducting electrolytes is well explained. However, the operation of co-electrolysis with oxygen-ion-conducting electrolytes is less detailed. I suggest expanding this section by providing more information on its working principles and possibly highlighting the differences and respective advantages of the two technologies.

The requested revision has been completed. The section on co-electrolysis with oxygen-ion-conducting electrolytes has been expanded with additional details on its working principles, and the differences and respective advantages between the two technologies are now clearly presented.

5) Chapter 4: As currently presented, this chapter appears to serve as a conclusion, but in reality, it introduces new aspects related to hydrogen storage, transport, and logistics. I recommend separating these concepts from the final reflections.

The requested adjustment has been made. The content related to hydrogen storage, transport, and logistics has been separated from the final considerations to ensure clarity and proper structural organization of the chapter.

6) You could, for instance, rename Chapter 4 to something like “Storage and Logistical Perspectives”, and then add a new concluding chapter to summarize the key points and provide a broader outlook. Thank you for your attention, and I wish you all the best with your work.

The suggested changes have been implemented. Chapter 4 has been renamed to “Storage and Logistical Perspectives,” and a new concluding chapter has been added to summarize the main findings and provide a broader outlook.