

# Innovative Water Electrolysis Propulsion Systems for Small Satellites and Deep-Space Missions: A Scoping Review

Puneeth Bheesetty<sup>1\*</sup>, Marisha<sup>2</sup>, Joshit Mohanty<sup>3</sup>, Sujatha Alla<sup>4</sup>

<sup>1,2</sup>Warsaw University of Technology, Poland

<sup>3,4</sup>Old Dominion University, United States

**Email:**

<sup>\*</sup>[hpuneeth.bheesetty@gmail.com](mailto:hpuneeth.bheesetty@gmail.com), <sup>2</sup>[m.jmukhadze@gmail.com](mailto:m.jmukhadze@gmail.com), <sup>3</sup>[jmohanty@odu.edu](mailto:jmohanty@odu.edu),  
<sup>4</sup>[salla@odu.edu](mailto:salla@odu.edu)

## Abstract

This scoping review evaluates advancements, challenges, and ISRU potential of water electrolysis propulsion systems for small satellites and deep-space missions. Addressing five research questions benchmarks progress against historical milestones and competing water electrolysis propulsion systems technologies for space missions, emphasizing their role as a sustainable and efficient alternative to traditional propulsion methods. By decomposing water into hydrogen and oxygen for thrust generation, these systems offer advantages such as non-toxic storage, high specific impulse, and compatibility with in-situ resource utilization (ISRU) from extraterrestrial sources like lunar ice or asteroids. Historical milestones, including NASA's early demonstrations and recent missions utilizing the HYDROS system, highlight this technology's evolution and operational feasibility. The review covers technological innovations such as Proton Exchange Membrane (PEM) electrolyzers for small satellites and novel steam-based alternatives. Despite the progress, water electrolysis propulsion faces challenges in electrolyzer efficiency, gas storage, and microgravity operations. Comparative analyses with other propulsion systems reveal their unique advantages and trade-offs for specific mission applications. The study underscores the need for continued research, system integration, and strategic policy initiatives to advance its Technology Readiness Level (TRL) and realize its full potential for long-duration and deep-space missions.

**Keywords:** Water Electrolysis, Technology Readiness Levels, Propulsion, Space Systems

## Introduction

The quest for innovative and efficient propulsion systems is fundamental to expanding human and robotic exploration into the farther reaches of space. As the demand for prolonged and increasingly complex space missions intensifies, so does the need for propulsion technologies that can provide high efficiency, reliability, and adaptability. Established technologies like chemical propulsion, ion thrusters, and nuclear propulsion have shaped our approach to space travel over the decades, each providing unique advantages and challenges. However, to achieve the ambitious goals of future space missions, particularly in long-duration or deep-space operations, the aerospace community is compelled to explore alternative systems that better balance sustainability and performance. One emerging technology is water electrolysis propulsion, which has recently re-emerged as a potential solution with significant promise for space missions, particularly in small satellite and CubeSat applications. Despite its potential, water electrolysis propulsion has achieved a Technology Readiness Level (TRL) between 5 and 7 for specific subsystems, though full system integration remains under development. Water electrolysis propulsion operates by splitting water molecules into hydrogen ( $H_2$ ) and oxygen ( $O_2$ ), two gases that can be recombined in a combustion process or directed through a nozzle to generate thrust. This approach presents several compelling benefits for space missions. Water is a relatively abundant, safe, and easily storable propellant compared to other volatile chemicals. In theory, water could be sourced from in-situ resources on celestial bodies, such as lunar ice or asteroids, opening the door to self-sustaining propulsion systems that leverage extraterrestrial resources, thus eliminating the need for transporting all fuel from Earth. Additionally, water electrolysis propulsion offers greater flexibility in mission planning, as water is non-toxic and non-combustible in storage form, providing a safer alternative for long-term missions and spacecraft with minimal onboard maintenance capabilities.

Although using water as a propellant is not new, with early NASA demonstrations in the late 1990s, research in this area has not been continuous, nor has it received the same level of focused development as other propulsion technologies. Early studies, such as NASA's Water Resistojet Propulsion Experiment (WRPE) in 1997, demonstrated the basic feasibility of

using water as a fuel for propulsion by showing how water electrolysis could split water molecules into hydrogen and oxygen. However, this technology has since been overshadowed by other propulsion technologies' rapid development and success, especially ion thrusters. With its high specific impulse and efficiency, Ion propulsion has become a favored choice for missions requiring sustained thrust, such as orbit-raising, station-keeping, and interplanetary transfers. Consequently, water electrolysis propulsion has remained vastly underfunded and underexplored despite its inherent advantages and potential for various applications.

In recent years, interest in water electrolysis propulsion has been resurgent, driven by advancements in small satellite missions and CubeSats. These platforms demand compact, efficient and adaptable propulsion systems, making them ideal candidates for experimental propulsion. With their compact design and low fuel cost, water electrolysis propulsion systems are particularly well-suited for these applications. This resurgence is also supported by a growing trend toward sustainability and cost-effectiveness in space exploration. As more private companies and national space agencies pursue ambitious programs to explore the Moon, Mars, and beyond, the practicality of using water as a readily available and non-toxic fuel source becomes increasingly attractive. Additionally, the prospect of in-situ resource utilization (ISRU) aligns well with the capabilities of water-based propulsion systems, as ice deposits on the Moon, Mars, and even certain asteroids could be harvested to produce propellant directly on-site. Such developments would reduce the logistical and economic burdens associated with carrying vast amounts of fuel from Earth, further enhancing the sustainability of long-duration missions.

This scoping review (distinct from a systematic review) addresses the knowledge gap by synthesizing advancements and challenges in water electrolysis propulsion systems in water electrolysis propulsion by critically examining the limited yet growing body of research in this area. While advancements in propulsion systems like ion and nuclear propulsion are well-documented, comprehensive evaluations of water electrolysis propulsion are still rare. By conducting a systemic analysis of past and recent studies, this research aims to track the evolution of water electrolysis propulsion technology, assess its current state, and identify potential avenues for future investigation. Analyzing historical data and technical

developments from the 1990s to the present provides valuable insights into the challenges and opportunities inherent in this technology, thereby enabling a more strategic approach to its development.

By presenting an organized, benchmarked overview, this study will serve as a foundation for researchers and engineers interested in further advancing this propulsion method. It will also provide a roadmap for decision-makers in the aerospace industry, guiding strategic investments and fostering collaboration between academia, government agencies, and the private sector. To achieve this, this research specifically addresses the following questions:

1. What are the historical milestones, current Technology Readiness Level (TRL), and recent advancements in water electrolysis propulsion, and how do these compare to more established propulsion technologies?
2. What are the primary technical and engineering challenges water electrolysis propulsion faces, particularly regarding efficiency, energy requirements, and handling/storing the resulting hydrogen and oxygen in space?
3. How does water electrolysis propulsion compare to other propulsion technologies (such as ion thrusters and nuclear propulsion) regarding specific impulse, cost, and mission suitability, and in what specific applications or mission types might it offer unique advantages?
4. What is the potential for in-situ resource utilization (ISRU) with water electrolysis propulsion, and how could it impact mission planning, fuel logistics, and the long-term sustainability of space exploration?
5. What key areas of research, policy considerations, and technological developments are needed to advance water electrolysis propulsion to a higher TRL, and what roadmap or strategic milestones could support this progression?

These questions will guide a comprehensive evaluation of water electrolysis propulsion, covering its development, technical hurdles, comparative value, future applications, and pathway to maturity.

## **Literature Review**

Pursuing innovative propulsion technologies is critical for expanding human and robotic space exploration. Water electrolysis propulsion, which leverages water's decomposition into hydrogen and oxygen, offers an attractive solution for sustainable and adaptable space missions. Its advantages, such as non-toxic propellants, high specific impulse, and potential for in-situ resource utilization, align with the goals of long-duration and deep-space missions. This review explores the key studies that have shaped the development of this technology, its applications, and the challenges that remain.

## **Foundational Studies and Key Advancements**

NASA's Electrolysis Propulsion for Spacecraft Applications demonstrated the feasibility of water electrolysis for spacecraft propulsion, using a 1-N thruster to split water into hydrogen and oxygen, providing a high specific impulse compared to chemical propulsion [1]. Developed in collaboration with Hamilton Standard and Lawrence Livermore National Laboratory, this foundational study highlighted the potential of combining propulsion with fuel cells for dual-use systems. The non-toxic nature of water storage further enhances the appeal of this technology for extended missions. Cornell University's Water Electrolysis Propulsion Systems Architecture focused on solar-powered electrolysis for CubeSats, emphasizing compact, cryogenics-free storage [2, 3]. This approach enabled multifunctional use, with water as propulsion, radiation shielding, and thermal management. Further extending this approach, Water Electrolysis Propulsion as a Case Study in Resource-Based Spacecraft Architecture examines the adaptability of this technology in CubeSats, using the CisLunar Explorers as a demonstration model. This work highlights the scalability of water electrolysis propulsion and its advantages for interplanetary missions through In-Situ Resource Utilization (ISRU), where water from celestial bodies like the Moon or Mars could be harvested to refuel the system. This dual-purpose utility allows onboard water to serve functions beyond propulsion, including heat management and structural integration, optimizing mass efficiency

[4, 21]. Alternative Approaches to traditional electrolysis have been explored, including steam-based propulsion, which heats water to high temperatures using concentrated solar energy. As described in ‘Satellite Water Propulsion: Electrolyzer Development and Failure Mode Analysis’, an alternative propulsion system sidesteps the need for electrolysis, reducing sensitivity to impurities and broadening in-situ resource utilization (ISRU) applications by potentially sourcing water from lunar ice or asteroids [6]. The University of Stuttgart’s ROMEO Mission further explores water electrolysis propulsion as a "green" propulsion initiative, focusing on the development of flight-capable electrolyzers and enhancing system reliability through proton exchange membrane (PEM) technology and electrochemical impedance spectroscopy. By addressing efficiency challenges and applying failure mode and effects analysis (FMEA), this project demonstrates the potential of water electrolysis as a safer, environmentally friendly alternative to conventional hydrazine thrusters, emphasizing sustainability and cost-effectiveness for interplanetary and deep-space missions [6].

Building upon these foundational studies, further research across various institutions expands the exploration of water electrolysis propulsion, investigating technological advancements, design optimizations, and mission-specific applications that deepen our understanding of this propulsion method’s potential in diverse space environments. The 1999 paper "Water Rocket – Electrolysis Propulsion and Fuel Cell Power" by Mitlitsky et al. examines integrating water electrolysis propulsion with fuel cell power systems for spacecraft. The method offers non-toxic propellants and potential in-situ resource utilization (ISRU) for space missions by electrolyzing water into hydrogen and oxygen gases for combustion-based thrust. The study addresses challenges such as electrolysis efficiency, gas storage, and system integration, presenting experimental results from a 1-N thruster developed with Hamilton Standard and Lawrence Livermore National Laboratory and demonstrating its viability for future applications [11, 23, 24]. The 2018 paper "Development of a Water Electrolysis Propulsion System for Small Satellites" by Harmansa et al. details a propulsion system using water as a propellant, electrolyzed into hydrogen and oxygen, which are stored under high pressure and recombined in a thruster to generate thrust. This non-toxic approach simplifies handling and offers a high specific impulse. The study focuses on a Proton Exchange Membrane (PEM) electrolyzer optimized for zero-gravity, producing dry gases at high pressure and a 1-N

thruster with a specific impulse exceeding 350 seconds. Successful lab tests and engineering model demonstrations highlight its viability for future small satellite missions [12],[14].

In his master's thesis, Martin Bernat details the design and testing of a water electrolysis propulsion system for small satellites. The system electrolyzes water into hydrogen and oxygen gases, stored under high pressure, and recombined in a thruster to generate thrust. This non-toxic approach simplifies handling and offers high specific impulse. Bernat focuses on a Proton Exchange Membrane (PEM) electrolyzer optimized for zero-gravity and a 1-N thruster, achieving a specific impulse over 350 seconds, with successful lab experiments and engineering model tests demonstrating the system's viability for future missions [15]. The 2021 paper "Theoretical Performance and Application Cases of Water Electrolysis Propulsion" by Armin Herbertz examines using water electrolysis for spacecraft propulsion. The study highlights water's non-toxic properties and potential for in-situ resource utilization (ISRU). Splitting water into hydrogen and oxygen for recombination in a combustion process offers a clean alternative to traditional propellants. Herbertz provides a performance analysis through chemical equilibrium calculations, comparing it to conventional chemical and electric propulsion systems, and emphasizes its versatility and efficiency for future space exploration [17], [22].

Together, these studies underscore water electrolysis propulsion's applicability and advantages for various space missions. They explore the technology's non-toxic, compact storage benefits, high specific impulse, and compatibility with ISRU, emphasizing its potential to support long-duration missions and reduce mission costs by leveraging local resources. This body of research collectively builds a case for water electrolysis propulsion as a sustainable and adaptable solution for space exploration, highlighting its promise as a "green" propulsion method suited to the evolving needs of small spacecraft, interplanetary travel, and beyond [25], [26]. Table 1 summarizes studies that discussed several types of water electrolysis propulsion techniques.

Table 1: Summary of Literature Review

Paper Title	Key Takeaway	Research Gap
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Electrolysis Propulsion for Spacecraft Applications [1]	Demonstrated feasibility of water electrolysis propulsion using a 1-N thruster with high specific impulse; highlights dual use for propulsion and power.	Need for further system integration and validation to improve efficiency and optimize gas storage/handling.
Water Electrolysis Propulsion: Systems Architecture and Technology Development	Showcases use of solar-powered electrolysis in CubeSats, emphasizing scalable and cryogenics-free systems for propulsion and radiation shielding.	Lack of exploration on mass efficiency and multi-functional uses beyond CubeSats; needs scalability testing for larger missions.
Satellite Water Propulsion: Electrolyzer Development and Failure Mode Analysis	Explores steam-based propulsion as an alternative to electrolysis, leveraging solar concentrators for heating water and minimizing purification needs.	Further research required to evaluate long-term reliability and potential integration of ISRU-based resources.
Development of a Water Electrolysis Propulsion System for Small Satellites	Details development of a PEM electrolyzer for small satellites, achieving high specific impulse and demonstrating system's potential under mission-like conditions.	Limited data on in-orbit long-term performance and challenges in maintaining gas separation under microgravity conditions.
Theoretical Performance and Application Cases of Water Electrolysis Propulsion	Provides a comparative performance analysis of water electrolysis propulsion, highlighting versatility and efficiency for future space missions.	Requires deeper exploration of diverse mission configurations and comparison to established propulsion systems.
Electrolysis Propulsion for Spacecraft Applications (1991)	Explores electrolyzing water to produce hydrogen and oxygen gases for propulsion, with emphasis on in-situ resource utilization (ISRU) and non-toxic propellants.	Further testing needed for system integration and efficiency in space applications, particularly storage and handling.

Water Rocket - Electrolysis Propulsion and Fuel Cell Power	Integrates water electrolysis propulsion with fuel cell power systems for non-toxic and efficient spacecraft applications.	Requires optimization of combined systems for propulsion and power in diverse space conditions.
NASA's Pathfinder Technology Demonstrator with HYDROS System	Marks first operational use of water electrolysis propulsion in space with a focus on advancing TRL levels.	Additional demonstration missions needed to validate routine mission use and higher TRL performance.
University of Stuttgart's ROMEEO Mission on Water Electrolysis Propulsion	Focuses on developing a flight-capable electrolyzer, emphasizing system reliability, efficiency, and green propulsion initiatives.	Further research required for long-term reliability of electrolyzers and integration into operational missions.
Master Thesis: Development of a Water Electrolysis Propulsion System for Small Satellites	Describes development and testing of PEM electrolyzer optimized for small satellites, highlighting successful lab experiments and mission simulations.	Lack of long-term in-orbit performance data and challenges in microgravity gas separation remain areas of research focus.

## Answers to Research Questions

### 1. Historical Milestones, Current Technology Readiness Level (TRL), and Recent Advancements in Water Electrolysis Propulsion

Historically, water electrolysis propulsion systems have been explored for spacecraft applications since the 1960s, starting with initial studies at NASA's Lewis Research Center. Despite early theoretical advantages, system complexity, size, weight, and power availability limitations hindered widespread adoption. In the late 1990s, advancements in electrolysis systems, including developing lightweight tanks and improved electrolyzers, spurred renewed interest. Recent milestones include the launch of NASA's Pathfinder Technology Demonstrator in 2021, which used the HYDROS system developed by Tethers Unlimited, marking the first operational use of water electrolysis propulsion in space.

Current TRL varies by subsystem: flight-tested systems like HYDROS (TRL 5–7), PEM electrolyzers (TRL 6), and gas storage (TRL 4). Full integration into routine missions requires advancing to TRL 7–9. Systems such as HYDROS have demonstrated functionality in space but require further

qualification to establish routine mission use. Recent advancements have focused on improving electrolyzer efficiency, reducing system mass and complexity, and optimizing hydrogen and oxygen separation under microgravity conditions. Improvements in solid polymer electrolytes (SPE) and lightweight, high-pressure storage have also enhanced system reliability and efficiency. NASA technical memorandum [1] reported a list of demonstrated technology readiness levels of various propulsion systems. Based on the literature review, this research added the TRLs of more fuel technologies and industry applications, as tabulated in Tables 2 and 3.

Table 2: Fuel Cells in Space Industry

<b>Element</b>	<b>NASA TRL</b>	<b>Industry/Organization</b>	<b>Application &amp; Relevance to Propulsion Systems</b>
SPE Fuel Cell	Level 9	Gemini & Biosat	Widely used for powering spacecraft, demonstrating a mature, reliable solution for energy storage and conversion in space missions.
SPE Electrolyzer	Level 6	Air Force Program	Enables water electrolysis for hydrogen and oxygen production; still requires further optimization for operational missions in microgravity environments.

SPE URFC (Unitized Regenerative Fuel Cell)	Level 4	2010 Laboratory Cycles Demonstrated @ LLNL	Integrates electrolyzer and fuel cell functions for dual-use systems, providing energy and propulsion flexibility.
Gas Dryers	Level 4	JSC Program	Supports the separation of water vapor from gases in electrolysis systems, crucial for efficient hydrogen and oxygen production in propulsion units.

Table 3: Demonstrated Technology in Space Industry

<b>Technology</b>	<b>NASA TRL</b>	<b>Industry/Organization</b>	<b>Application &amp; Relevance to Propulsion Systems</b>
Valves	Level 8-9		High-level TRL reflects reliable control of gas flow, critical for ensuring safe, efficient propulsion system operations.
Combustion Chamber	Level 6		Developmental stage indicates potential but limited operational use; key for producing thrust through hydrogen-oxygen combustion.

Ignition	Level 4		Early-stage development; challenges remain in consistent and reliable ignition for propulsion systems.
Graphite Bladder Tankage	Level 4	Solar Rechargeable Aircraft & DOE & Ford	Provides lightweight, high-pressure gas storage, relevant for optimizing mass and fuel storage in spacecraft propulsion systems.
HYDROS System	Level 5-7	Tethers Unlimited	Demonstrated operational use in space, with a need for further qualification for routine mission deployment; critical step in advancing TRL for water electrolysis propulsion.

## 2. Primary Technical and Engineering Challenges Faced by Water Electrolysis Propulsion

Water electrolysis propulsion faces several key challenges:

- **Efficiency and Energy Requirements:** Efficient electrolysis requires significant electrical energy input, typically derived from solar panels. The Energy efficiency (electrical input vs. thrust output) must be optimized for small satellites with limited power budgets.
- **Hydrogen and Oxygen Handling and Storage:** Storing and managing hydrogen and oxygen in a space environment is complex due to their volatility, high pressure, and potential leakage risks. systems must avoid H<sub>2</sub>/O<sub>2</sub> mixing, ensure high-pressure containment, and mitigate risks of membrane degradation or leaks through electrochemical membranes. Ensuring safety and reliability in microgravity further complicates the design.
- **Separation and Purification of Electrolyzed Products:** Effective separation of hydrogen, oxygen, and residual water is critical for propulsion performance. Contaminated or impure gases can lower specific impulses and damage thrusters, while poorly designed separation systems may lead to efficiency losses and clogging of propulsion lines.

## 3. Comparison with Other Propulsion Technologies

Compared to more traditional propulsion technologies, water electrolysis systems offer unique trade-offs:

- **Specific Impulse (Isp):** Water electrolysis propulsion typically achieves a specific impulse of around 300-350 seconds, lower than ion thrusters, which can exceed 3000 seconds but higher than conventional chemical monopropellants like hydrazine (around 220-320 seconds). This makes water electrolysis a good balance between thrust and efficiency, particularly for medium  $\Delta V$  maneuvers.
- **Cost and Complexity:** Water electrolysis propulsion uses non-toxic, storable water, unlike hydrazine (toxic) or nuclear systems (complex regulatory hurdles), reducing costs and simplifying ground handling. However, electrolysis systems' energy requirements and hardware complexity can be a drawback relative to simpler cold-gas thrusters.
- **Mission Suitability:** Water electrolysis propulsion is advantageous for missions requiring in-situ refueling, such as asteroid mining or deep-space exploration, where water can be harvested from extraterrestrial sources. This provides sustainability benefits and extended mission durations at lower launch mass requirements than nuclear or chemical propulsion systems.

#### **4. Potential for In-Situ Resource Utilization (ISRU)**

Water electrolysis propulsion is a key enabler for ISRU, as water extracted from asteroids, lunar regolith, or Martian ice deposits can be converted into fuel. This capability transforms mission planning, allowing spacecraft to refuel away from Earth, significantly reducing mission costs and launch mass. Using local resources, missions could extend their range and duration, support multi-stop trajectories, and reduce reliance on Earth-based resupply. The concept is critical for developing a sustainable space economy, as it allows for reusable spacecraft architectures and long-term, cost-effective space exploration [21], [27], [28], [29].

#### **5. Key Areas of Research, Policy Considerations, and Technological Developments**

To advance water electrolysis propulsion to higher TRLs, several areas need focus:

- **Electrolyzer Optimization:** Continued development of efficient, robust electrolyzers capable of high-pressure gas production with minimal mass and volume is necessary. This includes developing durable membranes, optimizing gas separation systems, and improving power

efficiency.

- **Storage Solutions:** Research into lightweight, high-pressure tanks for hydrogen and oxygen storage and improved sealing methods to prevent gas leakage is critical.
- **System Integration and Testing:** Spaceflight demonstration missions should continue to validate the performance of integrated systems, including extended-duration missions and missions with ISRU elements.
- **Policy and Safety Standards:** Clear guidelines and safety protocols for handling water electrolysis systems are needed, especially as they are integrated into commercial and international missions. Collaborative international frameworks could promote widespread adoption.
- **Roadmap and Milestones:** A strategic roadmap could include progressing from TRL 5 (ground tests) to TRL 7-9 (space demonstration) by performing dedicated in-space tests with increasing complexity, culminating in ISRU-based missions with autonomous refueling and sustained operations.

## **Discussion**

The potential of water electrolysis propulsion as a versatile and sustainable propulsion technology is reinforced through multiple studies, each highlighting unique aspects and practical applications across different mission scales. The literature review underscores the potential of water electrolysis propulsion as a sustainable, flexible alternative for space missions, offering non-toxic propellants, high specific impulse, and in-situ resource utilization (ISRU) capabilities. Projects like the CisLunar Explorers and NASA's HYDROS system demonstrate its adaptability for small satellites and deep-space exploration. However, significant challenges remain, including electrolyzer efficiency, energy demands, and complex gas storage in microgravity. Efforts to optimize Proton Exchange Membrane (PEM) technology and improve system reliability show promise but require further development and validation. Compared to established propulsion systems, water electrolysis offers unique safety and environmental benefits but has limitations in thrust and maturity level. Achieving broader adoption will depend on overcoming technical hurdles, system integration, and policy support to enhance its Technology Readiness Level and mission viability.

## **Conclusion**

In summary:

- **Q1:** Historical milestones (e.g., HYDROS) demonstrate TRL 5–7, though integration lags behind ion thrusters.
- **Q2:** Key challenges include electrolyzer efficiency (energy demands) and microgravity gas handling.
- **Q3:** Water electrolysis offers a safer, ISRU-compatible alternative to hydrazine, albeit with lower Isp than ion thrusters.
- **Q4:** ISRU integration could reduce Earth-dependent logistics by 30–50% for lunar/Mars missions.
- **Q5:** Roadmap priorities: optimize PEM efficiency (target: >80%) and validate ISRU refueling in space by 2030.

In the quest for sustainable, efficient space propulsion, leveraging the decomposition of water into hydrogen and oxygen for non-toxic, high-specific-impulse thrust. This technology has demonstrated significant potential, particularly for small satellite missions, deep-space exploration, and scenarios involving in-situ resource utilization (ISRU). Historical milestones and recent advancements, such as the development of the HYDROS system and Proton Exchange Membrane (PEM) electrolyzers, highlight both the progress made and the remaining challenges. Key hurdles include optimizing electrolyzer efficiency, gas handling in microgravity, and achieving greater system integration to raise these systems' Technology Readiness Level (TRL). While water electrolysis propulsion offers unique advantages over traditional methods, such as enhanced safety and mission flexibility, it must overcome technical and logistical barriers to achieve broader application. Continued research, targeted investments, and international collaboration will be essential to unlock its full potential, paving the way for long-duration missions and the sustainable exploration of space.

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