



## **AN INTEGRATED GREEN HYDROGEN–BIOSENSOR FRAMEWORK FOR ENVIRONMENTAL MONITORING AND CLIMATE SUSTAINABILITY.**

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### **Abstract**

Climate change, environmental pollution, energy insecurity, and ecosystem degradation require integrated technological solutions that simultaneously reduce greenhouse-gas emissions and improve environmental monitoring. Green hydrogen (GH<sub>2</sub>), produced primarily through water electrolysis powered by renewable energy, is increasingly considered an important energy carrier for decarbonizing difficult-to-electrify sectors. At the same time, biological sensors, including microbial, enzyme-based, immunological, and cell-based biosensors, provide opportunities for sensitive and real-time detection of pollutants and environmental changes. This research article proposes an integrated sustainability framework combining green hydrogen production and biological sensing technologies. The proposed system links renewable-energy-powered electrolysis with biological sensor networks for continuous monitoring of water quality, soil contamination, greenhouse gases, hydrogen-production inputs, and ecosystem health. Recent literature indicates that the environmental performance of green hydrogen depends strongly on electricity source, water consumption, electrolyser technology, infrastructure, and life-cycle boundaries. Similarly, recent advances in microbial bioelectronic sensors demonstrate their potential for rapid and cost-effective environmental monitoring.

The proposed integration can support data-driven optimization of hydrogen systems while simultaneously improving environmental protection. A literature-based methodological framework is developed using life-cycle assessment, techno-economic assessment, sensor performance analysis, and multi-objective optimization. The analysis suggests that combining clean energy generation with biological environmental intelligence could contribute to lower-carbon, resource-efficient, and adaptive climate infrastructure. However, challenges related to sensor stability, calibration, standardization, data integration, hydrogen cost, renewable-resource availability, and life-cycle impacts must be addressed before large-scale implementation.

**Keywords:** Climate Sustainability, Green Hydrogen, Biological Sensors, Biosensors, Renewable Energy, Environmental Monitoring, Life-Cycle Assessment, Sustainable Development, Decarbonization, Smart Sensing.

### **1. Introduction**

Climate sustainability requires simultaneous progress in clean energy generation, industrial decarbonization, resource conservation, and environmental protection. Hydrogen is receiving increasing attention because it can serve as an energy carrier and industrial feedstock in applications where direct electrification is difficult. Global hydrogen demand approached 100 million tonnes in 2024; however, low-emissions hydrogen still represented less than 1% of global production, demonstrating the considerable scale-up challenge ahead.

Green hydrogen is generally produced by water electrolysis using renewable electricity from sources such as solar and wind. Its potential applications include steel production, chemical manufacturing, long-distance transportation, energy storage, and renewable-energy balancing. Recent life-cycle studies emphasize that the environmental benefits of green hydrogen depend strongly on the electricity mix, electrolyser technology, water requirements, equipment manufacturing, and system boundaries used in assessment.

The International Energy Agency (IEA) reported in 2025 that more than 200 low-emissions hydrogen production projects had reached final investment decision since 2020, although high costs, infrastructure limitations, uncertain demand, and



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regulatory barriers continue to constrain deployment. The IEA also emphasizes that hydrogen can contribute particularly to sectors such as heavy industry and long-distance transport where alternative decarbonization pathways are more difficult.

Parallel to developments in clean energy, biological sensing technologies are emerging as important tools for environmental sustainability. Biological sensors use biological recognition elements—including microorganisms, enzymes, antibodies, nucleic acids, or living cells—to detect target substances or environmental changes. A 2025 review in *Nature Reviews Bioengineering* highlighted microbial bioelectronic sensors as an emerging approach for sensitive, rapid, and potentially cost-effective environmental monitoring.

The combination of green hydrogen infrastructure and biological sensing could therefore establish a more intelligent sustainability system. Biosensors could monitor water quality associated with electrolysis, detect biological or chemical contamination, assess surrounding ecosystems, and provide real-time information that can be incorporated into hydrogen-system management. Conversely, renewable hydrogen systems could provide clean electricity and energy-storage capabilities for distributed environmental monitoring networks.

Recent research has also emphasized the importance of integrating life-cycle assessment with multi-objective optimization. **Chavez et al. (2025)** identified shortcomings in existing green-hydrogen optimization studies, particularly the limited environmental detail and insufficient consideration of end-of-life impacts. This provides a strong rationale for developing an integrated framework in which energy, environmental, economic, and biological indicators are assessed together.

## 2. Objectives

The primary objective of this study is to develop a conceptual framework for integrating green hydrogen and biological sensor technologies to support climate sustainability.

The specific objectives are:

1. To examine the role of green hydrogen in reducing greenhouse-gas emissions and supporting renewable-energy integration.
2. To evaluate the potential contribution of biological sensors to real-time environmental monitoring.
3. To propose an integrated green-hydrogen–biosensor architecture for sustainable energy and environmental management.
4. To identify environmental, economic, technological, and operational parameters affecting the sustainability of the integrated system.
5. To develop a methodology combining life-cycle assessment (LCA), techno-economic assessment (TEA), sensor-performance evaluation, and multi-objective optimization.
6. To identify major research gaps and future opportunities for large-scale deployment.

## 3. Methodology

### 3.1 Research Design

This study adopts a literature-based conceptual research methodology. Recent peer-reviewed publications, international energy reports, and research on hydrogen life-cycle assessment and biological environmental sensors were examined. Emphasis was placed on literature published during 2024–2026.

The proposed system consists of four interconnected components:



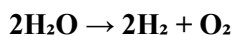
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## Renewable energy → Green hydrogen production → Biological/environmental sensing → Data-driven sustainability management

### 3.2 Green Hydrogen System

The proposed hydrogen subsystem uses renewable electricity to power an electrolyser:



Potential renewable sources include solar photovoltaic, wind, hydropower, and hybrid renewable systems. The produced hydrogen can be stored and subsequently used for industrial applications, fuel cells, transportation, or energy storage.

The sustainability of the hydrogen system should be evaluated using:

- Renewable electricity consumption.
- Hydrogen production efficiency.
- Water consumption.
- Greenhouse-gas emissions.
- Electrolyser lifetime.
- Hydrogen storage and transportation requirements.
- Infrastructure-related environmental impacts.
- End-of-life impacts.

Recent research demonstrates that the life-cycle carbon footprint of hydrogen can vary considerably according to production pathway and methodological assumption.

### 3.3 Biological Sensor System

The proposed biological sensing network consists of multiple sensor categories:

- **Microbial biosensors** for detecting organic pollutants and toxic compounds.
- **Enzyme-based biosensors** for specific chemical contaminants.
- **Immunosensors** for selective detection of biological or chemical targets.
- **Cell-based sensors** for evaluating environmental toxicity.
- **Microbial bioelectronic sensors** for monitoring complex environmental conditions.

The sensors could be deployed around hydrogen-production facilities, renewable-energy installations, wastewater-treatment units, agricultural areas, industrial sites, and natural ecosystems.

Parameters potentially monitored include:

- Water pH and dissolved oxygen.
- Organic pollutants.



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- Heavy-metal contamination.
- Nutrient concentrations.
- Microbial activity.
- Biological toxicity.
- Greenhouse-gas-related environmental indicators.
- Ecosystem stress.

Microbial bioelectronic sensing is particularly promising because biological activity can be translated into electrical signals suitable for continuous monitoring and digital data acquisition.

### 3.4 Integrated Data Architecture

Sensor data would be transmitted to a central digital platform using Internet-of-Things (IoT) communication. Artificial intelligence and machine-learning algorithms could then identify environmental changes and optimize hydrogen-system operation.

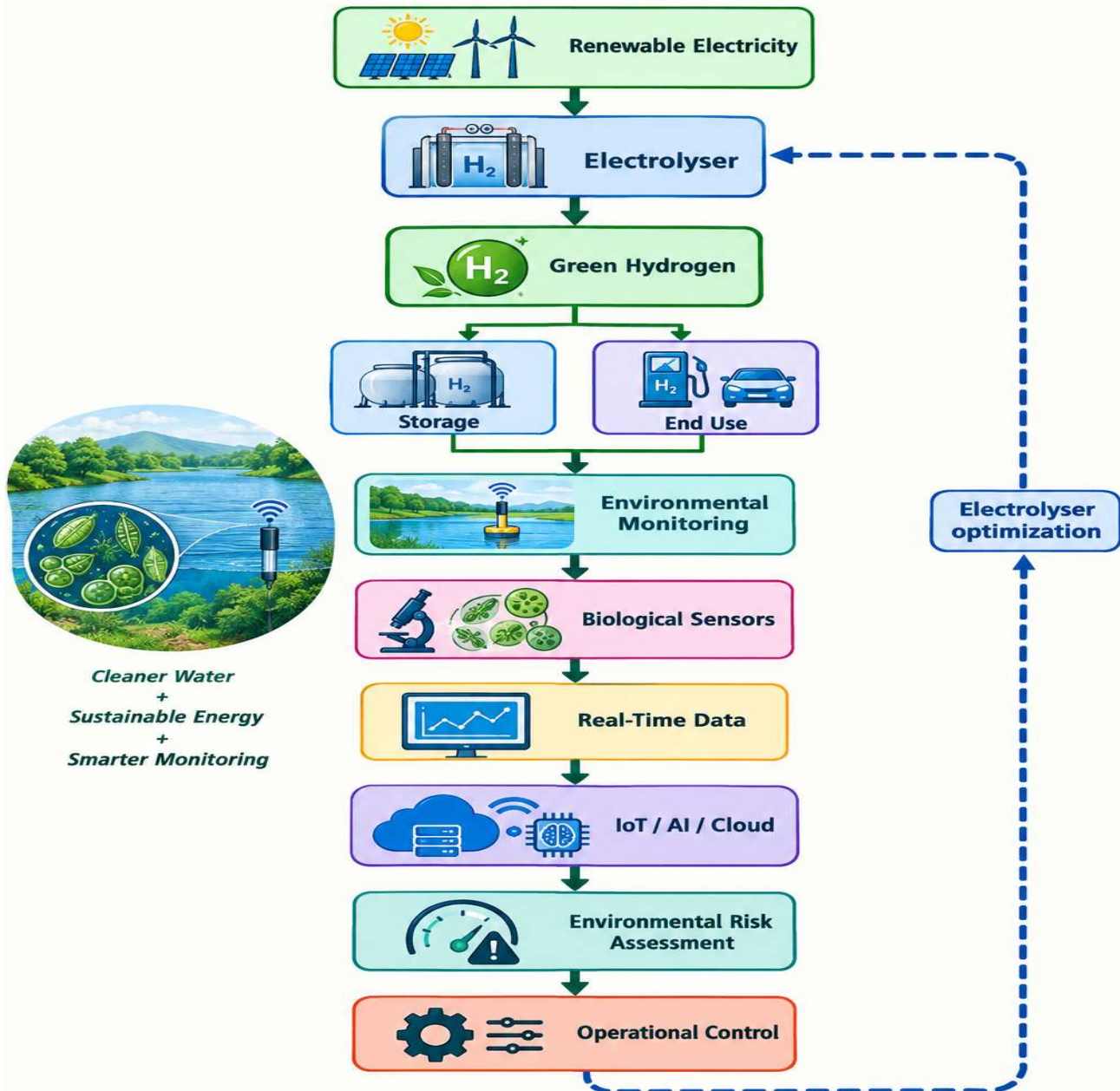
The proposed feedback loop is:

**Renewable generation → Electrolysis → Hydrogen storage/use → Biosensor monitoring → Data analytics → Environmental assessment → System optimization**

For example, abnormal changes in water quality could trigger an investigation of electrolysis-water treatment, while environmental conditions could be incorporated into decisions concerning hydrogen production intensity.



**Figure 3. Green Hydrogen–Biosensor Feedback Loop**



### 3.5 Sustainability Assessment

The proposed framework uses four major assessment categories.



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## Environmental assessment:

Greenhouse-gas emissions, water consumption, land use, resource depletion, toxicity, waste generation, and ecosystem impacts.

## Economic assessment:

Capital cost, operating cost, hydrogen production cost, sensor cost, maintenance, replacement frequency, and potential economic benefits.

## Technical assessment:

Electrolyser efficiency, hydrogen yield, sensor sensitivity, selectivity, response time, stability, reliability, and data transmission.

## Social and sustainability assessment:

Occupational safety, local environmental quality, resource availability, public acceptance, employment potential, and contribution to Sustainable Development Goals.

A multi-objective optimization model can be expressed conceptually as:

### Minimize:

GHG emissions + water consumption + cost + environmental risk

### Maximize:

Hydrogen efficiency + sensor accuracy + renewable-energy utilization + system reliability

Recent research recommends expanding hydrogen optimization beyond single environmental indicators toward broader cradle-to-grave sustainability assessments.

## 4. Results

Because this article presents a conceptual, literature-based framework rather than laboratory experimentation, the results represent synthesized findings from recent research.

### 4.1 Potential Climate Benefits

Green hydrogen can provide a pathway for reducing fossil-fuel dependence in sectors that are difficult to electrify directly. However, the climate benefit is highly dependent on the carbon intensity of the electricity used for electrolysis. Recent reviews conclude that renewable-powered hydrogen generally provides substantially better environmental performance than fossil-based hydrogen, although infrastructure and resource requirements must also be considered.

### 4.2 Environmental Monitoring Benefits

Biological sensors can complement conventional chemical and physical monitoring technologies by providing biological responses to pollutants and environmental stress. Recent research indicates that microbial bioelectronic sensors have potential for rapid and cost-efficient environmental monitoring.

### 4.3 Integration Benefits

The proposed integration could provide several advantages:

- Real-time environmental monitoring around hydrogen facilities.



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- Improved water-resource management.
- Early detection of contamination.
- Data-driven optimization of electrolysis operations.
- Integration of environmental indicators into hydrogen planning.
- Improved transparency of environmental performance.
- Support for circular and resource-efficient hydrogen production.

#### 4.4 Identified Limitations

The analysis also identifies important limitations. Green hydrogen remains comparatively expensive in many applications, while project development is constrained by infrastructure, regulation, and uncertain demand.

For biological sensors, long-term stability, calibration, biofouling, temperature sensitivity, biological variability, standardization, and field deployment remain important technical issues. Furthermore, sensor networks themselves have environmental footprints resulting from materials, electronics, batteries, communications, and eventual disposal.

#### 5. Discussion

The integration of green hydrogen and biological sensors represents a shift from treating clean energy and environmental monitoring as separate technological fields toward a connected sustainability ecosystem.

Green hydrogen alone does not automatically guarantee sustainability. Life-cycle studies show that renewable-energy source, electrolyser selection, infrastructure, water supply, and system boundaries strongly influence environmental performance. Consequently, hydrogen projects should be evaluated using comprehensive life-cycle indicators rather than only direct carbon emissions.

Biological sensors can strengthen this approach by providing continuous information about environmental conditions. Conventional environmental assessments are often based on periodic sampling and laboratory analysis. Distributed biosensor networks could potentially complement these approaches by providing higher-frequency measurements and early warning signals.

The integration is particularly relevant to water management. Electrolysis requires purified water, and large-scale hydrogen deployment may increase pressure on local water resources in water-stressed regions. Biological sensors could therefore be incorporated into water-reuse systems to monitor biological and chemical quality before and after treatment.

Another important opportunity is adaptive hydrogen production. Instead of operating electrolysers solely according to electricity availability or electricity price, future systems could incorporate environmental indicators into operational decisions. This could enable hydrogen facilities to reduce production during periods of water stress or abnormal environmental conditions.

However, the proposed system should not be viewed as a replacement for established environmental monitoring. Biological sensors should initially operate alongside conventional analytical methods to establish calibration, reliability, and regulatory confidence.

Future research should therefore focus on developing standardized biosensor protocols, durable field-deployable devices, low-energy communication systems, interoperable data platforms, and integrated LCA–TEA models. The literature on hydrogen sustainability increasingly supports multi-objective approaches that simultaneously consider economic and environmental performance.



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The current global hydrogen situation also demonstrates the importance of realistic deployment planning. Although low-emissions hydrogen projects are increasing, low-emissions production remains a very small proportion of total hydrogen production. A Therefore, technological innovation must be accompanied by supportive policies, renewable-energy expansion, infrastructure development, standards, and market creation.

## 6. Conclusion

The integration of green hydrogen and biological sensors offers a promising interdisciplinary pathway toward climate sustainability. Green hydrogen can support the decarbonization of hard-to-abate sectors and provide an energy-storage mechanism for renewable-energy systems, while biological sensors can provide continuous information about water, soil, pollutants, microbial activity, and ecosystem health.

This article proposes an integrated framework in which renewable electricity produces green hydrogen while distributed biological sensors monitor environmental performance. Data generated by the sensors can be integrated into life-cycle assessment, techno-economic analysis, and multi-objective optimization to create more adaptive and sustainable hydrogen systems.

The major potential benefits include reduced greenhouse-gas emissions, improved environmental monitoring, efficient water management, early detection of contamination, and data-driven operation of clean-energy infrastructure. Nevertheless, important challenges remain, including the cost and scalability of green hydrogen, renewable-resource requirements, water availability, biosensor stability, calibration, standardization, data security, and end-of-life impacts.

Future research should prioritize pilot-scale demonstration projects that combine renewable electrolysis, biological sensing, IoT-based monitoring, and life-cycle assessment. Such integrated systems could contribute to a transition from isolated clean-energy technologies toward intelligent, environmentally responsive infrastructure capable of supporting long-term climate sustainability.

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