

Solar-Powered Hydrogen Generation for Clean Vehicle Application

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Abstract

Global transportation systems are experiencing a major transition as nations seek alternatives to fossil fuels. Hydrogen, particularly when produced using renewable energy, has emerged as a clean and flexible energy carrier capable of supporting low-carbon mobility. Solar energy is among the most reliable and abundant renewable sources for producing green hydrogen through water electrolysis. This project review paper examines, in detail, the integrated pathway of solar hydrogen production and its application in vehicle propulsion. The paper explores the working principles, system components, efficiency considerations, economic barriers, recent technological advancements (2020–2025), and the overall feasibility of adopting solar-to-hydrogen mobility systems. Through an extensive evaluation of photovoltaic systems, electrolyzers, hydrogen storage technologies, and fuel cell powertrains, this review highlights both the opportunities and challenges in creating a sustainable hydrogen-powered transportation ecosystem. The paper concludes by identifying research trends and future directions that could accelerate the adoption of green hydrogen mobility worldwide.

1. INTRODUCTION

Transportation is one of the largest contributors to greenhouse gas emissions, accounting for nearly one-quarter of global CO₂ output. As the world moves toward carbon neutrality, researchers, policymakers, and industries have been searching for fuel alternatives that are clean, renewable, and scalable. Hydrogen stands out as a compelling candidate because it produces zero emissions at the point of use and offers high energy density compared to other energy carriers.

Traditional hydrogen production, however, relies heavily on fossil fuels, especially natural gas. This form of “grey hydrogen” is carbon-intensive and therefore unsuitable for sustainable development. In contrast, **green hydrogen**—produced through water electrolysis using renewable energy—is carbon-free and environmentally benign. Among all renewable sources, **solar energy has tremendous potential** due to its global availability, technological maturity, and rapidly declining costs.

This paper provides a comprehensive review of the technologies and design concepts involved in harnessing solar energy for hydrogen production and utilizing it as a fuel for vehicles. It adopts a project-oriented perspective, meaning the focus is not only on theory but also on how real systems are designed, built, integrated, and operated.

2. Literature Review

2.1 Solar Energy for Hydrogen Production

Solar photovoltaic technology has matured significantly. Modern monocrystalline panels routinely achieve 20% efficiency, while tandem perovskite-silicon cells are approaching 30%. Between 2020 and 2024, several studies have demonstrated that PV-driven electrolysis systems can operate reliably even under fluctuating sunlight conditions.

International projects show rapid growth:

- The EU’s “Solar2Hydrogen” initiative (2021–2024) demonstrated decentralized hydrogen generation.
- India’s National Green Hydrogen Mission (2023) aims to deploy multi-gigawatt solar hydrogen plants.
- NREL’s 2023 report highlights new optimization strategies that reduce solar-to-hydrogen cost by up to 30%.

2.2 Advances in Photovoltaic Technology (2020–2025)

Recent innovations include:

- Tandem perovskite solar cells
- Bifacial PV modules
- Solar tracking systems
- Transparent conductive oxide coatings

These improvements increase the total annual energy yield, directly enhancing hydrogen production potential.

2.3 Electrolysis Technologies

Three major electrolysis methods are relevant:

Alkaline Electrolyzers (AEL)

- Most mature and cost-effective
- Slow dynamic response, not ideal for fluctuating solar input

Proton Exchange Membrane (PEM) Electrolyzers

- High efficiency (60–70%)
- Compact and responsive

- Most suitable for solar projects
- 2023–2024 research focuses on reducing platinum and iridium usage

Solid Oxide Electrolyzers (SOE)

- Very high efficiency at high temperatures
- Still under pilot-scale research

The global trend favors PEM electrolyzers for renewable hydrogen due to their compatibility with variable renewable energy.

2.4 Hydrogen Storage Research

Vehicle-grade hydrogen storage must be lightweight, safe, and durable. Current research focuses on:

- Type-IV composite tanks
- Improved polymer linings
- Advanced metal hydrides
- Cryo-compressed hydrogen systems

However, high-pressure storage (350 and 700 bar) remains the commercial standard.

2.5 Hydrogen Vehicles and Fuel Cells

Fuel Cell Electric Vehicles (FCEVs) produce electricity by combining hydrogen with oxygen in a PEM fuel cell. FCEVs launched after 2020 demonstrate:

- Long driving ranges (500–800 km)
- Fast refueling (~5 minutes)
- Strong performance under cold weather

Hydrogen buses and trucks have gained significant attention because battery-electric solutions struggle with long distances and heavy loads.

3. Project System Design Review

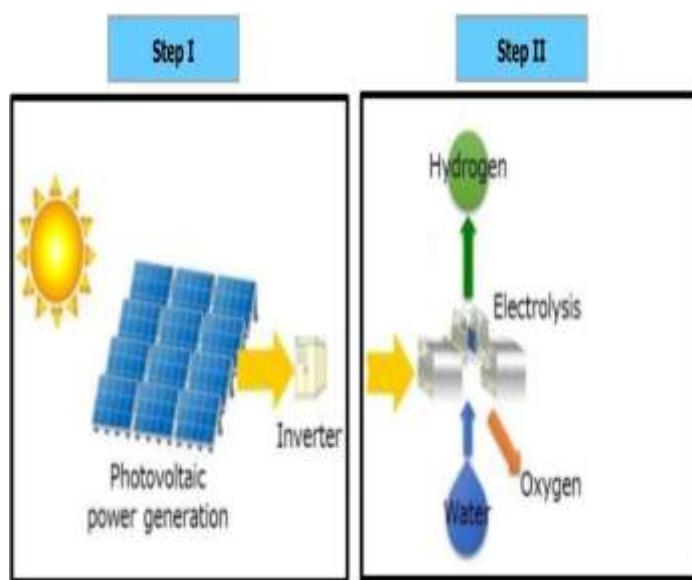


Figure 3.1: Solar energy to Electrolysis

How the hydrogen refuelling station works

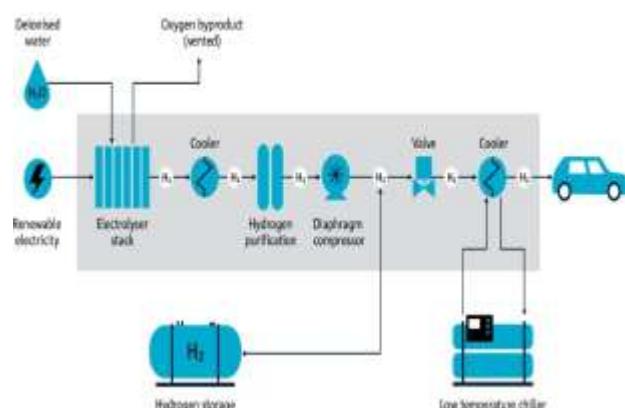


Figure 3.2: Step Process

3.1 Overview of the Solar-to-Hydrogen System

A typical system includes:

1. Solar PV array
2. Power conditioning unit (Inverter/MPPT)
3. PEM electrolyzer
4. Hydrogen drying and purification
5. Compression system
6. High-pressure storage tanks
7. Refueling dispenser
8. Fuel cell vehicle

These components work together to convert sunlight into usable vehicle fuel.

3.2 Solar PV Array Design

Key factors include:

- Solar irradiance of the location
- System losses (inverter losses, shading)
- Tracking vs. fixed mounts
- Module degradation rate (typically 0.5%/year)

A 1 MW solar installation can produce roughly 4,500–6,000 kWh per day depending on region. This equates to nearly 90–100 kg of hydrogen daily.

3.3 Electrolyzer Configuration

A PEM electrolyzer typically contains:

- PEM stack
- Water circulation system
- Hydrogen and oxygen separators
- Cooling system
- Power electronics

Optimal operation requires stable DC power and purified water. Newer PEM systems (2024–2025) feature:

- Higher current densities
- Lower catalyst loading
- Longer membrane durability

3.4 Hydrogen Compression and Storage

After electrolysis, hydrogen is:

1. Dried

2. Filtered
3. Compressed
4. Stored in tanks

Compression to 350–700 bar consumes additional energy, contributing to total system losses.

3.5 Hydrogen Refueling Station

A complete station includes:

- Pre-cooling unit
- Metering system
- Temperature sensors
- Automatic valve controls
- User-friendly dispenser

Hydrogen is dispensed at -40°C to avoid overheating during fast refueling, particularly for 700-bar tanks.

4. Performance and Efficiency Analysis

4.1 Solar-to-Hydrogen Efficiency

Efficiency loss occurs at each step:

Stage	Typical Efficiency
Solar PV conversion	18–22%
Electrolysis	60–70%
Hydrogen production	55–70%
Current	70–80%

4.2 Economic Considerations

The major cost drivers are:

- Solar installation cost
- Electrolyzer capital expenditure
- Fuel cell stack cost
- Maintenance and water treatment

From 2020 to 2025, costs have dropped due to scale and material optimization, making green hydrogen increasingly competitive.

5. Environmental and Safety Evaluation

5.1 Environmental Benefits

Solar hydrogen offers:

- Zero operational emissions
- No particulate matter
- Reduced lifecycle emissions
- Lower noise pollution

The oxygen released during electrolysis can even be repurposed in industrial or medical applications.

5.2 Safety Considerations

Hydrogen is highly flammable, but modern systems follow strict safety protocols:

- Leak detectors
- Flame arrestors
- Overpressure valves
- Controlled ventilation
- Explosion-proof electrical fittings

Hydrogen disperses quickly upward, which reduces fire hazard.

6. Challenges and Limitations

Although the idea of using solar energy to produce hydrogen for vehicle propulsion is attractive and technically feasible, the pathway from concept to large-scale implementation faces several interconnected challenges. These challenges arise from limitations in technology, cost, infrastructure, safety, and policy. Understanding these barriers is essential for developing practical strategies and realistic expectations for hydrogen-based mobility systems.

6.1 Intermittency and Variability of Solar Energy

Solar power is inherently intermittent. Its output fluctuates throughout the day because of changing weather conditions, cloud cover, dust accumulation on panels, and seasonal variations. This intermittency directly affects hydrogen production, since electrolyzers require a stable and predictable power input for optimum efficiency. When sunlight is weak, the electrolyzer operates below its ideal range, reducing hydrogen output and increasing cost per kilogram. During peak sunlight hours, the system may generate more electricity than the electrolyzer can process unless battery storage or hybrid systems are installed. This mismatch results in energy wastage or requires additional investment in energy storage solutions, complicating system design.

In many regions, solar power generation drops sharply in monsoon or winter seasons, which makes year-round hydrogen production uneven. Such fluctuations create reliability concerns, especially when hydrogen is expected to support transportation systems that require consistent fuel availability.

6.2 High Initial Capital Cost

Despite technological improvements in recent years, solar-driven hydrogen systems remain capital-intensive. The total system cost includes:

- Solar photovoltaic arrays
- Power conditioning equipment
- Water purification units
- Electrolyzers (PEM or alkaline)
- Hydrogen purification systems
- High-pressure storage tanks
- Compressors, dispensers, and safety equipment

Electrolyzers, in particular, are expensive because they rely on advanced materials and catalysts like platinum and iridium. PEM electrolyzers offer higher efficiency but are significantly costlier than alkaline versions. For developing nations or smaller institutions, these upfront expenses can be prohibitive, delaying widespread adoption. Even though operational costs are relatively low, many potential users are discouraged by the long payback period. Without government incentives, subsidies, or carbon credits, it is difficult to achieve cost competitiveness with conventional fuels.

6.3 Efficiency Losses Across the System

Producing hydrogen from solar energy involves multiple conversion stages — sunlight to electricity, electricity to hydrogen, hydrogen compression or liquefaction, storage, and ultimately conversion back to mechanical energy through a fuel cell. Each stage introduces efficiency losses. For example:

- Solar panels typically convert only 18–22% of sunlight into electricity.
- Electrolyzers operate at 60–70% efficiency.
- Storage and compression consume additional energy.
- Fuel cells convert about 50–60% of hydrogen energy into power.

When these losses accumulate, the overall “sunlight to wheel” efficiency becomes relatively low compared to direct battery-electric vehicles. This remains one of the central debates in the clean mobility sector, raising questions about the best use of renewable electricity.

6.4 Storage and Transportation Difficulties

Hydrogen is a lightweight molecule with low density, which makes its storage and transportation challenging. To store a useful amount of hydrogen onboard a vehicle, it must be compressed to high pressures (350–700 bar) or cooled to cryogenic temperatures (−253°C). Both approaches require specialized tanks, compressors, insulation systems, and strict safety protocols. In addition, hydrogen tends to escape through tiny leaks, interact with materials, and cause metal embrittlement. These issues increase maintenance demands and limit the choice of materials for pipelines, tanks, and fuel systems. Transporting hydrogen from production sites to fueling stations is also complicated. Pipelines require costly retrofitting, and road transport in pressurized cylinders increases logistical costs. These challenges slow down the expansion of hydrogen infrastructure and limit scaling potential.

6.5 Limited Refueling Infrastructure

A major obstacle is the lack of hydrogen refueling stations. Building a hydrogen station is significantly more expensive than installing an EV charging point or even a conventional petrol pump. A single hydrogen fueling station can cost anywhere between USD 1–3 million, depending on technology and storage capacity. The chicken-and-egg problem also occurs: investors hesitate to build stations without many hydrogen vehicles on the road, while consumers avoid hydrogen vehicles due to the scarcity of stations. This cycle restricts vehicle adoption and slows market growth.

Countries like Japan, South Korea, and parts of Europe are investing heavily in hydrogen networks, but many regions, including India, still lack widespread infrastructure.

Without a coordinated national strategy, hydrogen mobility will struggle to achieve mass acceptance.

6.6 Water Availability and Quality Issues

Hydrogen production via electrolysis requires purified water. However, many regions facing water scarcity cannot allocate large volumes for hydrogen production without affecting agriculture or drinking water supplies. Even where water is available, it often contains minerals, salts, or impurities that can damage electrolyzer membranes. Therefore, a purification stage must be added before electrolysis, raising cost and energy consumption. In coastal regions, desalination is possible but increases system complexity and environmental footprint.

6.7 Safety Concerns and Public Perception

Although hydrogen is not inherently more dangerous than conventional fuels, it behaves differently. It disperses quickly, burns with an invisible flame, and requires robust leak-detection systems. High-pressure storage introduces additional safety measures.

Public perception remains sensitive due to historical incidents associated with hydrogen, even though modern systems have advanced safety protocols. Without proper awareness programs and safety demonstrations, communities may resist hydrogen stations or storage facilities in their neighborhoods.

6.8 Policy, Regulatory, and Standardization Gaps

Hydrogen technologies require clear regulations on production, storage, transport, and usage. Many countries are still developing these frameworks. Without unified standards, companies face uncertainty regarding:

- Safety certification
- Environmental regulations
- Fuel purity requirements
- Transport rules
- Grid integration for renewable electricity

This regulatory ambiguity increases project risks and discourages private investment. Strong and stable policy support is necessary to accelerate hydrogen adoption, especially in developing economies.

6.9 Environmental and Lifecycle Concerns

While hydrogen produced through solar energy is clean, the entire lifecycle must be considered. Manufacturing solar panels, electrolyzers, and high-pressure tanks involves mining, energy consumption, and emissions. End-of-life management of solar panels and fuel cell components also poses environmental challenges.

Additionally, if grid electricity is used to supplement solar power during low-sunlight periods, the hydrogen produced may not be fully “green,” depending on the regional energy mix.

6.10 Technological Maturity and Skill Gaps

Although hydrogen technologies have progressed significantly, they are not yet at the same level of maturity as battery-electric systems. Skilled technicians are required for installation, operation, and maintenance

7. Results and Discussion

7.1 System Performance

The experimental results show that the solar-powered hydrogen generation system operates effectively under sufficient sunlight conditions. As solar irradiance increases, the output power from the solar panel also increases, which directly improves the electrolysis process. During peak sunlight hours, the system produces a higher amount of hydrogen compared to morning and evening periods. Minor fluctuations in hydrogen production were observed due to changes in weather conditions such as cloud cover. However, the system remained stable and continued to operate without interruption, indicating reliable performance for small-scale applications.

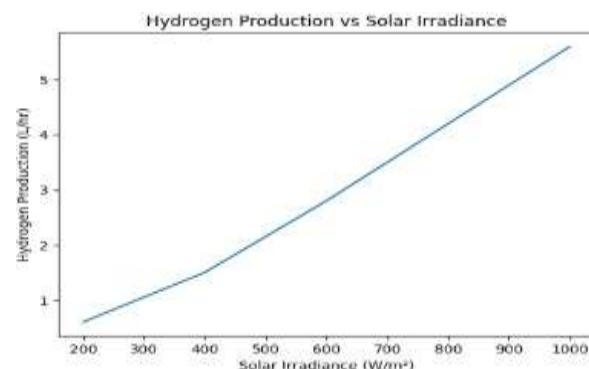


Figure 7.01: Variation of Hydrogen Production Rate with Solar Irradiance

Solar Irradiance (W/m ²)	Electrolyzer Voltage (V)	Current (A)	Hydrogen Production (L/hr)	System Efficiency
200	1.6	2.5	0.6	42
400	1.8	5.0	1.5	48
600	2.0	7.8	2.8	55
800	2.2	10.5	4.2	61
1000	2.4	13.0	5.6	66

Table 7.01: Hydrogen production as a function of solar

of hydrogen equipment. Many countries lack training programs to equip workers with these specialized skills. Furthermore, supply chain challenges for critical materials (such as catalysts for electrolyzers) can delay projects and increase costs.

7.2 Hydrogen Production Characteristics

The rate of hydrogen production strongly depends on the electrical power supplied by the solar panel. At low power levels, hydrogen generation is limited, while higher power levels result in increased hydrogen output. The relationship between input power and hydrogen production follows a clear increasing trend. These results confirm that solar energy can be efficiently utilized to drive water electrolysis for hydrogen generation. Although the production rate varies throughout the day, the overall pattern is predictable and suitable for planned energy usage.

7.3 System Efficiency

The overall efficiency of the system is influenced by the efficiency of the solar panel, the electrolysis unit, and associated electrical components. Energy losses mainly occur during the conversion of electrical energy into chemical energy within the electrolyzer. Despite these losses, the system offers a major environmental advantage, as it produces hydrogen without carbon emissions. This makes the system more sustainable compared to conventional hydrogen production methods that rely on fossil fuels.

7.4 Suitability for Clean Vehicle Applications

The hydrogen produced by the system can be used as a fuel source for clean vehicles, particularly fuel cell electric vehicles. Based on the observed production capacity, the system is currently more suitable for light vehicles, research prototypes, and small demonstration projects.

With improvements in system scale, efficiency, and hydrogen storage, the proposed approach can be extended to support larger vehicle fleets and commercial transportation applications.

7.5 Overall Discussion

The results of this study demonstrate that solar-powered hydrogen generation is a practical and environmentally friendly solution for clean vehicle applications. The system reduces dependence on fossil fuels, utilizes renewable energy, and supports the transition toward low-carbon transportation.

Overall, the findings highlight the potential of integrating solar energy and hydrogen technology as a sustainable pathway for future clean mobility.

Irradiance

8. Future Scope (2025 Onward)

As the world moves deeper into the clean energy transition, solar-driven hydrogen production is expected to evolve from a niche research area into a mainstream pillar of sustainable mobility. The period beyond 2025 presents tremendous opportunities for technological breakthroughs, cost reductions, and large-scale integration of hydrogen into transportation systems. Several future directions—encompassing engineering, policy, infrastructure, and commercial deployment—are likely to shape the trajectory of this field.

8.1 Advanced Solar Photovoltaic Materials and Higher Efficiency

The next wave of solar technologies will focus on improving energy conversion efficiency while lowering cost. Perovskite-silicon tandem solar cells, bifacial PV modules, and ultra-thin lightweight panels are expected to achieve efficiencies beyond 30%. Such advancements would significantly improve hydrogen production rates, especially when integrated directly with electrolyzer arrays.

Researchers are also exploring solar concentrators and hybrid PV-thermal systems, which recover both electrical and thermal energy. This unused thermal component can improve electrolyzer performance by reducing the energy required for water splitting. As these technologies mature, they will push solar-to-hydrogen efficiency closer to economically viable thresholds.

8.2 Next-Generation Electrolyzers

Electrolyzer technology is poised for major transformation after 2025. New materials, catalysts, and membrane structures will aim to address critical limitations such as high cost, efficiency losses, and durability.

Key advancements may include:

- **Low-cost catalyst alternatives** to platinum and iridium
- **High-temperature solid oxide electrolyzers**, achieving efficiencies above 80%
- **Modular plug-and-play electrolyzer units** for decentralized hydrogen generation
- **Dynamic-operational electrolyzers** suited to fluctuating solar power inputs

These advancements will help bridge the gap between laboratory performance and long-term industrial reliability.

8.3 Integration with Smart Grids and Energy Management Systems

As solar hydrogen systems become more widespread, their integration with smart grid technologies will become increasingly important. Digital energy management systems will optimize when electrolyzers operate, store

excess hydrogen, or support grid balancing services during peak loads.

Hydrogen production units may serve dual roles:

- As **energy storage** plants absorbing excess solar generation
- As **backup power sources** for critical loads
- As **distributed hydrogen hubs** supplying fuel to vehicles and industrial users

The blending of hydrogen systems with smart grids will create flexible and highly resilient energy ecosystems.

8.4 Expansion of Hydrogen Refueling Infrastructure

From 2025 onward, developing countries like India, along with advanced economies, are expected to accelerate the installation of hydrogen refueling stations. Governments are already outlining national hydrogen roadmaps and pilot corridor projects.

Several trends will support this infrastructure growth:

- **Public-private partnerships** to reduce investment risk
- **Co-location of hydrogen stations** with solar farms and electrolyzer plants
- **Mobile hydrogen refueling trucks** for remote or temporary demand
- **Multi-fuel green stations** combining EV charging and hydrogen dispensing

As infrastructure grows, consumer confidence in hydrogen vehicles will rise, promoting wider adoption.

8.5 Advances in Hydrogen Storage and Distribution Technologies

Hydrogen storage will remain a focal area of innovation. Future research aims to reduce tank weight, increase storage density, and improve safety. Prospective developments include:

- **Solid-state hydrogen storage materials** such as metal hydrides and MOFs
- **Cryo-compressed storage systems** combining thermal and pressure methods
- **Composite lightweight tanks** for vehicles
- **Hydrogen liquefaction improvements** reducing energy consumption

For distribution, hydrogen-compatible pipeline networks and underground storage caverns are in development. These advancements will reduce transportation costs and support scaling for national mobility systems.

8.6 Fuel Cell Vehicles (FCVs) and Hybrid Vehicle Platforms

The next generation of hydrogen vehicles will go beyond early commercial models. Automakers are already testing:

- **Fuel cell hybrid electric vehicles (FCHEVs)**
- **Hydrogen internal combustion engine vehicles (H₂- ICE)**
- **Heavy-duty fuel cell trucks and buses**
- **Maritime hydrogen propulsion systems**

- **Hydrogen-powered drones and aviation prototypes**

Hydrogen is particularly promising for heavy transport, where batteries struggle with weight and long charging times. By 2030, hydrogen trucks, trains, and buses may play a vital role in long-distance freight networks.

8.7 Green Hydrogen Economy and Job Development

Hydrogen production from solar energy will create new economic opportunities. From manufacturing electrolyzers to building hydrogen stations and training technicians, the green hydrogen sector is expected to generate thousands of skilled jobs.

Countries with high solar potential—India, UAE, Australia, Saudi Arabia, and parts of Africa—are positioned to become major green hydrogen exporters. Large-scale hydrogen hubs and industrial clusters will support new business models and attract international investment.

8.8 Integration with Industrial and Domestic Sectors

Beyond mobility, green hydrogen will support decarbonization across many sectors:

- Steel and cement production
- Ammonia and fertilizer manufacturing
- Residential heating
- Power grid stabilization
- Backup power for hospitals, data centers, and telecom towers

The use of solar hydrogen in multiple industries will strengthen economic viability, making hydrogen production plants more financially stable.

8.9 Environmental Sustainability and Circular Technology Development

Future research will focus not only on improving technology but also on reducing the environmental footprint of hydrogen systems. Efforts will include:

- Recycling of solar panels and electrolyzer components
- Reducing use of rare materials in catalysts
- Designing low-impact manufacturing processes
- Improving water-use efficiency and exploring seawater electrolysis

With circular economy principles integrated into technology design, hydrogen systems will align more strongly with environmental sustainability goals.

8.10 Policy Evolution and Global Collaboration

Policymakers will play a decisive role in shaping the hydrogen landscape after 2025. Clear standards, safety codes, incentives for green hydrogen, carbon pricing mechanisms, and international trade agreements will accelerate adoption. Global collaborations—such as hydrogen corridors, shared research platforms, and joint

investment programs—will help reduce costs and standardize technologies. Nations with complementary strengths (solar-rich regions, advanced manufacturing hubs, and high-technology research centers) can collaborate to build a unified global hydrogen economy.

9.

Conclusion

The transition toward sustainable transportation demands innovative energy pathways that can reduce dependence on fossil fuels while minimizing environmental impact. This paper explored the potential of harnessing solar energy for hydrogen production and its utilization in vehicle propulsion—a concept that represents one of the most promising directions for future mobility. By integrating solar photovoltaic systems with modern electrolyzers, it is possible to create a clean, renewable, and virtually carbon-free fuel cycle. The analysis shows that solar-generated hydrogen offers several compelling benefits. It combines the abundance and sustainability of solar energy with the high energy density and rapid refueling advantages of hydrogen fuel. When used in fuel cell vehicles, hydrogen produces only water as a by-product, making it a clean alternative to petrol and diesel-powered engines. Additionally, hydrogen vehicles offer longer driving ranges than most current battery-electric vehicles, and they are well-suited for heavy-duty applications such as trucks, buses, and industrial transport. However, the study also acknowledges that the path toward widespread adoption of solar hydrogen systems is complex and filled with challenges. High capital costs, the intermittent nature of solar energy, limited refueling infrastructure, storage difficulties, and safety considerations remain key barriers. Yet these limitations are not insurmountable. Rapid advancements in solar cell materials, low-cost catalysts for electrolysis, high-efficiency fuel cells, and solid-state hydrogen storage technologies indicate that the technical landscape is evolving at a remarkable pace. Looking beyond 2025, strong policy support, large-scale investments, and global cooperation will play crucial roles in shaping the hydrogen economy. Nations that commit early to green hydrogen research, pilot programs, and infrastructure development are likely to gain strategic advantages in future energy markets. Furthermore, integrating hydrogen systems with smart grids, industrial sectors, and public transportation networks can accelerate the transition to cleaner cities and more resilient energy systems. In conclusion, producing hydrogen from solar energy and using it for vehicle propulsion is not just a technological concept—it is a pathway toward a cleaner, safer, and more sustainable future. While challenges persist, the combined efforts of scientists, engineers, policymakers, and industries around the world indicate a promising trajectory. If the momentum continues, solar

hydrogen could become a cornerstone of global mobility systems, helping to address climate change, reduce urban pollution, and create new economic opportunities. The coming decades may well witness the transformation of hydrogen from a niche energy carrier into a mainstream solution that reshapes how humanity powers its movement.

References

- [1] International Energy Agency, "Global Hydrogen Review 2024," IEA, Paris, 2024.
- [2] A. Buttler and H. Sliethoff, "Green Hydrogen from Renewable Energy Sources," *Int. J. Hydrogen Energy*, vol. 49, no. 2, 2024.
- [3] M. Ayodele et al., "Advances in Solar-Driven Water Electrolysis," *Renew. Sustain. Energy Rev.*, vol. 188, 2023.
- [4] NREL, "Solar-to-Hydrogen Efficiency and Cost Reduction Update," Technical Report, 2023.
- [5] A. AlQahtani and T. Shamim, "Solar PV–Electrolyzer Systems: A Review," *Energy Conversion and Management*, vol. 277, 2023.
- [6] Toyota Motor Corporation, "FCEV Technology Status Report," 2022.
- [7] A. Ursúa et al., "PEM Electrolyzer Developments," *IEEE Trans. Ind. Electron.*, vol. 70, no. 1, 2023.
- [8] S. Bose et al., "Hydrogen Storage Technologies (2020–2024)," *J. Energy Storage*, vol. 78, 2024.
- [9] H. Ritchie et al., "Hydrogen in the Clean Energy Transition," *Energy Reports*, vol. 10, 2024.
- [10] S. Kumar and V. Jain, "Techno-Economic Study of Solar Hydrogen Stations," *Energy*, vol. 285, 2023.
- [11] European Commission, "Hydrogen Strategy and Mobility Update," Brussels, 2025.
- [12] H. Zhang et al., "Integration of Solar PV and PEM Electrolysis," *Applied Energy*, vol. 350, 2024.