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Powering Purity and Fuel: Solar Energy for Clean Water and Green Hydrogen

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Abstract

The escalating demand for sustainable energy and clean water has positioned solar energy as a transformative solution to address these global challenges. This review explores the dual role of solar energy in advancing water purification and large-scale hydrogen production. It presents an in-depth analysis of recent technological breakthroughs in solar-driven processes such as desalination, photocatalysis, and solar-assisted filtration, all of which offer environmentally sustainable and cost-effective alternatives to conventional water treatment methods. Simultaneously, solar-enabled hydrogen generation techniques—including photovoltaic electrolysis, photoelectrochemical (PEC) water splitting, and thermochemical cycles—are gaining momentum as viable pathways for clean fuel production. The paper evaluates the current status of these emerging technologies, discusses key technical and economic barriers, and outlines prospective directions for future research and innovation. By leveraging solar energy, significant strides can be made toward achieving global water and energy security, while also facilitating the transition to a hydrogen-based economy and sustainable resource management.

Keywords: Renewable Energy, Solar-Driven Technologies, Hydrogen Production, Clean Energy Solutions, Desalination.

1. Introduction

The world's population is still expanding at a rate never seen before, which is increasing demand for two vital resources: sustainable energy and clean water. The world's population is predicted to approach 10 billion people by 2050, and energy and water consumption are predicted to rise significantly at the same time. The UN estimates that 2.2 billion people do not have access to clean drinking water, and that during the same period, there will be a roughly 50% increase in the need for energy. These patterns highlight how critical it is to create novel, environmentally friendly approaches to energy production and water treatment. One potential solution to these interconnected problems is solar energy, a clean, practically limitless resource

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[1]. Solar energy has the potential to revolutionize two important fields: water purification and hydrogen manufacturing. Conventional water treatment techniques, like chemical coagulation, filtration, and disinfection, mainly depend on fossil fuel-derived electrical power, which increases greenhouse gas emissions and degrades the environment. Similar to this, the majority of fossil fuel-based processes, such as steam methane reforming, are required for the creation of hydrogen, which has the potential to play a significant role in the energy landscape of the future. The objectives of environmental sustainability and carbon neutrality are at odds with this method's high carbon intensity. A route toward more ecologically friendly and sustainable solutions is provided by the incorporation of solar energy into the production of hydrogen and water treatment processes [2].

1.1. Water Treatment: The Need for Innovation

A serious challenge to both wealthy and developing countries is water scarcity, which is made worse by climate change and excessive freshwater resource extraction. The contamination of freshwater sources by industrial pollutants, agricultural runoff, and untreated sewage is on the rise. This calls for the use of cutting-edge treatment systems that are sustainable and efficient. Despite their effectiveness, conventional water treatment methods can involve high chemical and energy use. For example, reverse osmosis desalination, a popular process for making freshwater from saltwater, has high running costs and demands a significant energy input [3–4].

Because solar energy is low-carbon and renewable, it offers a way to overcome the energy-intensive characteristics of traditional water treatment methods. To clean water while lowering dependency on fossil fuels, a number of solar-driven water purification technologies, including solar desalination, photocatalysis, and solar-powered filtration, are being explored. For instance, solar desalination uses the sun's heat energy to evaporate water, removing pollutants and salts in the process. In a similar vein, photocatalysis uses solar light to activate substances that degrade pathogens and organic contaminants in water. Particularly in isolated and off-grid locations, these techniques have the potential to drastically lower the energy requirement for water treatment, increasing access to clean water [5-7].

1.2. Hydrogen Production: The Path to a Clean Energy Economy

As a clean, adaptable energy source that can power everything from cars to power plants with zero emissions at the point of use, hydrogen has attracted attention on a global scale. Hydrogen is viewed as a crucial element in decarbonizing industries that are challenging to electrify, such as heavy industry, aviation, and shipping, as nations strive to reach their climate targets under the Paris Agreement. But the objectives of a low-carbon future are not compatible with the ways that hydrogen is now produced. Significant volumes of CO_2 are released during carbon-

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intensive processes such steam methane reforming, which generates around 96% of the hydrogen used worldwide [8–9].

A viable substitute is hydrogen generation fueled by solar energy. Solar-driven techniques, such as photovoltaic (PV) electrolysis, photoelectrochemical (PEC) water splitting, and thermochemical water splitting, can produce hydrogen with no negative environmental impact by using the sun's energy to break water molecules into hydrogen and oxygen. By using solar energy, which is abundant and renewable, these methods enable the electrolysis of water without emitting carbon dioxide, which is a byproduct of traditional hydrogen synthesis. Within this framework, solar hydrogen is a viable means of decarbonizing several industries while bolstering global energy security [10–12].

1.3. Objectives of the Review

The goal of this review is to give a thorough overview of how solar energy is being incorporated into technology for producing hydrogen and treating water. It examines the most recent developments in solar-powered water purification techniques, including photocatalysis, solar-powered filtration devices, and solar desalination. It also looks at the main solar-powered hydrogen generation methods, such as thermochemical water splitting, photoelectrochemical water splitting, and photovoltaic electrolysis. The review outlines the benefits of these technologies, as well as the present research hurdles that need to be overcome in order to fully realize their potential.

Encouraging advancements in solar-powered water treatment and hydrogen generation technology can pave the way for global water and energy security. The growing need for clean energy and clean water can be sustainably met by using solar energy, which is abundant and renewable. There are still a number of infrastructure, financial, and technical obstacles to overcome. In order to overcome these challenges and improve the viability, effectiveness, and scalability of solar-based systems for water treatment and hydrogen production, this review also addresses the future research directions that will be required.

1.4. Structure of the Paper

The structure of the paper is as follows: In Section 2, the use of solar energy in water treatment technologies is reviewed, with particular attention paid to solar-powered filtration systems, photocatalytic purification, and solar desalination. In the third section, photovoltaic electrolysis, photoelectrochemical water splitting, and thermochemical techniques are covered as solar-powered hydrogen production processes. The main issues that both industries are facing are outlined in Section 4, along with possible avenues for future research. The article is concluded in Section 5, which highlights the contribution of solar energy to improving water and energy security and summarizes the main findings.

2. Solar Energy in Water Treatment

Historically, energy-intensive techniques fueled by fossil fuels have been used in water treatment operations, which has resulted in environmental deterioration and greenhouse gas emissions. As a renewable and environmentally benign alternative for water purification, solar energy has gained popularity in response to the growing scarcity of water and the global shift toward sustainable practices. Solar-powered water treatment systems use the sun's energy to produce drinkable water in a cleaner, more effective way, especially in areas with limited access to traditional energy sources. The three most well-known solar-powered water treatment technologies that are presently being developed are solar-powered filtration systems, solar desalination, and photocatalytic water purification [13–14].

2.1 Solar Desalination

Using solar energy, the process of "solar desalination" turns brackish or salty water into freshwater by eliminating contaminants and dissolved salts. It provides a sustainable response to the worldwide problem of water shortage because it is a low-carbon and renewable process, particularly in coastal areas where freshwater is limited but seawater is plentiful. Solar stills, multi-effect distillation (MED), and solar-powered reverse osmosis are the main techniques for solar desalination. As seen in Figure 1, the goal of each of these technologies is to use solar energy to evaporate water and then condense the resulting liquid to produce potable, clean water.

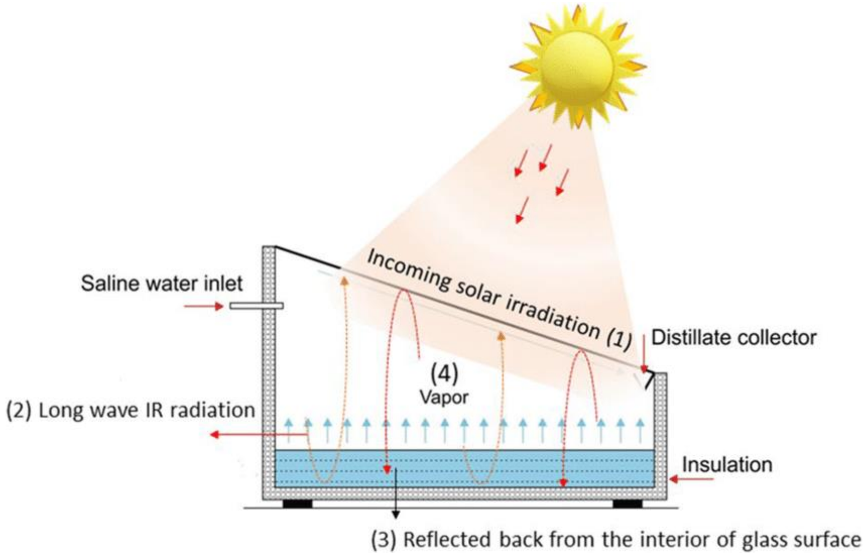

Figure 1. Working Principle of a Solar Desalination System [15]

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2.1.1 Solar Stills

Solar stills work by using evaporation and condensation to simulate the natural water cycle. Salted water is poured into a shallow basin and covered with a clear plastic or glass dome in a solar still. The water evaporates because of the heat from the sun. As the water vapor rises and condenses on the dome's underside, pure freshwater is released into a collection channel. Solar stills are an affordable, easy-to-build solution for small-scale desalination in isolated, off-grid locations. However, the relatively slow procedure, large water losses, and low evaporation rates frequently restrict their efficiency. The goal of current research is to improve the overall water output of solar stills by increasing their thermal efficiency through the use of cutting-edge materials like phase change materials (PCMs) and nanomaterials that absorb and hold heat [16].

2.1.2 Multi-Effect Distillation (MED)

A more sophisticated and effective solar desalination method that is frequently employed in large-scale applications is multi-effect distillation. In order for MED systems to function, heat from solar collectors is used to evaporate water in stages, or "effects." In every effect, the steam produced condenses to create freshwater, and the leftover heat is recycled to further evaporate water in later phases. The system's thermal efficiency is increased by this cascading effect, which makes it more energy-efficient than conventional single-stage distillation. Reliance on non-renewable energy sources can be decreased by combining solar-powered MED systems with concentrating solar power (CSP) facilities to supply the required heat. However, widespread implementation of MED systems is hindered, especially in developing nations, by the high capital expenditures and maintenance requirements of these systems [17].

2.1.3 Solar-Powered Reverse Osmosis

One of the most popular desalination techniques in the world is reverse osmosis (RO), as illustrated in Figure 2. However, the high-pressure pumps that drive water through semi-permeable membranes require a substantial amount of electrical energy to run. Photovoltaic (PV) panels and solar thermal systems are two forms of integrated solar energy that can significantly lower the energy consumption and environmental impact of solar-powered RO systems. While solar thermal systems can produce the heat needed to run the RO system's ancillary processes, solar photovoltaic RO systems use sunlight to directly convert it into energy to operate the pumps.Recent advancements in solar energy harvesting and energy-efficient membranes have increased the affordability and viability of solar-powered RO for large-scale desalination operations. To maximize system performance, however, issues including membrane fouling, sporadic sun availability, and the requirement for energy storage systems must be resolved. Table 1 displayed a comparison of various solar-powered desalination processes.

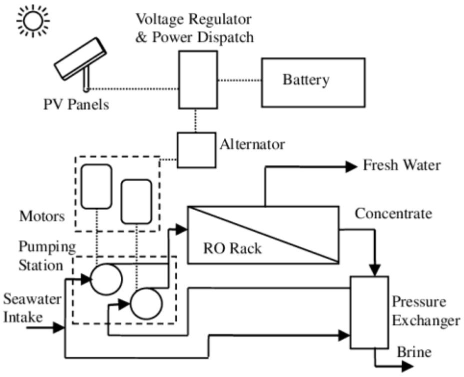
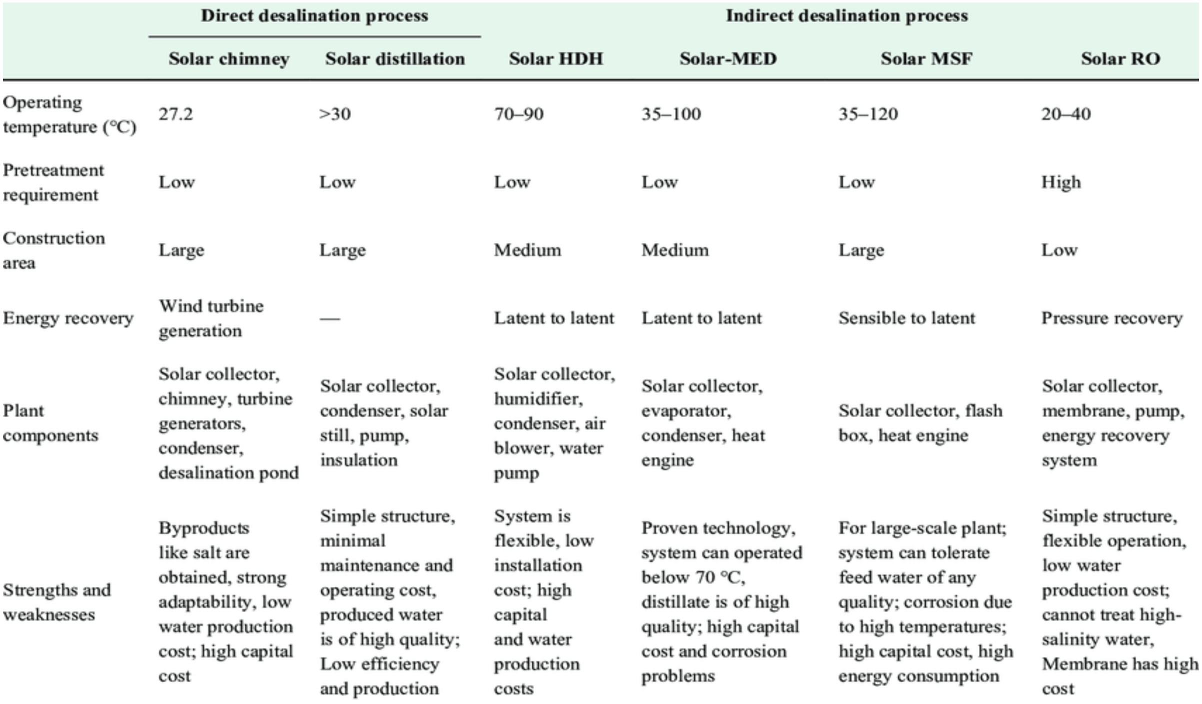


Figure 2. Photovoltaic Powered Reverse Osmosis System [18]

Table 1. Comparison of different solar powered desalination Process [19]



	Direct desalination process		Indirect desalination process			
	Solar chimney	**Solar distillation**	**Solar HDH**	**Solar-MED**	**Solar MSF**	**Solar RO**
Operating temperature (°C)	27.2	>30	70–90	35–100	35–120	20–40
Pretreatment requirement	Low	Low	Low	Low	Low	High
Construction area	Large	Large	Medium	Medium	Large	Low
Energy recovery	Wind turbine generation	—	Latent to latent	Latent to latent	Sensible to latent	Pressure recovery
Plant components	Solar collector, chimney, turbine generators, condenser, desalination pond	Solar collector, condenser, solar still, pump, insulation	Solar collector, humidifier, condenser, air blower, water pump	Solar collector, evaporator, condenser, heat engine	Solar collector, flash box, heat engine	Solar collector, membrane, pump, energy recovery system
Strengths and weaknesses	Byproducts like salt are obtained, strong adaptability, low water production cost; high capital cost	Simple structure, minimal maintenance and operating cost, produced water is of high quality; Low efficiency and production	System is flexible, low installation cost; high capital and water production costs	Proven technology, system can operated below 70 °C, distillate is of high quality; high capital cost and corrosion problems	For large-scale plant; system can tolerate feed water of any quality; corrosion due to high temperatures; high capital cost, high energy consumption	Simple structure, flexible operation, low water production cost; cannot treat high-salinity water, Membrane has high cost

2.2 Photocatalytic Water Purification

By using semiconductor materials to catalyze chemical processes in the presence of sunshine, photocatalysis is a solar-powered technique that successfully breaks down organic contaminants and pathogens in water. Since it doesn't call for the inclusion of hazardous chemicals or result in undesirable byproducts, this technology presents a viable substitute for traditional chemical-based water treatment techniques. The most widely used photocatalyst is titanium dioxide (TiO2) because of its potent oxidizing abilities, chemical stability, and lack of toxicity.

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2.2.1 Mechanism of Photocatalysis

When a semiconductor material is exposed to sunshine, electrons are excited from the valence band to the conduction band, leaving behind positively charged holes in the valence band. This is a common photocatalytic process. Following their interaction with dissolved oxygen and water molecules, these excited electrons and holes produce reactive oxygen species (ROS) like superoxide anions ($O_2^{\bullet -}$) and hydroxyl radicals ($\bullet OH$). Because of their extreme reactivity, these ROS can degrade viruses, organic contaminants, and even heavy metals in water. Wastewater can be effectively treated by photocatalysis to remove pesticides, dyes, pharmaceutical residues, and other organic substances that are difficult to remove [20].

2.2.2 Challenges in Photocatalytic Water Treatment

Even with its potential, photocatalysis has a number of obstacles that prevent broad use. A principal constraint is that the majority of widely utilized photocatalysts, such as TiO2, exhibit activity solely in the presence of ultraviolet (UV) light, which accounts for a minor portion of the solar spectrum. Researchers are looking at creating new photocatalysts that react to visible light, which accounts for most solar energy, in order to increase efficiency. Graphene-based composites, metal-doped TiO2, and perovskite-based semiconductors are among the materials that have demonstrated promise in extending photocatalytic activity into the visible light spectrum. Furthermore, as most photocatalytic reactors are currently only used in lab settings, scalability is still a problem. In order to increase the viability of solar-driven photocatalysis for industrial applications, future research will concentrate on developing large-scale photocatalytic systems and enhancing catalyst durability [21-22].

2.3 Solar-Powered Filtration Systems

One popular technique for purging water of contaminants such as bacteria and suspended particles is filtration. External power sources are needed to run pumps in traditional filtration systems and move water through filter membranes. By using solar energy to power these operations, solar-powered filtration systems do away with the need for grid electricity, which makes them particularly well-suited for off-grid and rural populations with limited access to conventional energy [23].

2.3.1 Membrane-Based Filtration

Because membrane filtration technologies can precisely remove impurities from water, they are frequently used in water treatment processes. Examples of these technologies include reverse osmosis, microfiltration, ultrafiltration, and nanofiltration. Pumps in solar-powered filtration systems push water through semi-permeable membranes by using photovoltaic panels to create electricity. These systems are a good way to supply clean drinking water in isolated areas since they are very good at eliminating germs, viruses, and suspended particles from

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water. Applications for solar-powered membrane filtration can be found in developing country rural communities, military field operations, and disaster relief efforts [24–25].

2.3.2 Recent Advancements and Challenges

New developments in solar-powered filtration systems include the creation of modular, transportable devices that can be rapidly set up in remote or emergency circumstances. Frequently, these devices come with battery storage to guarantee uninterrupted functioning in the absence of sunshine. Furthermore, since modern membrane materials like graphene oxide and nanocomposites provide better filtration effectiveness, less fouling, and longer membrane lifespans, researchers are looking into using them. But obstacles like membrane fouling, which gradually lowers filtration effectiveness, continue to be a major hindrance to widespread implementation. Anti-fouling coatings and self-cleaning membranes are two inventions that have the potential to significantly lower operating costs and extend system life, therefore efforts to decrease fouling through them are ongoing [26–27].

2.3.3 Applications in Remote and Off-Grid Areas

Solar-powered filtration systems are especially promising in isolated locations with limited access to reliable electricity and clean water. These systems can offer a decentralized approach to producing clean water in underdeveloped areas, minimizing reliance on large-scale distribution networks and centralized water treatment facilities. Furthermore, in regions where there is a persistent lack of water, solar-powered filtration systems can be combined with rainwater collection systems or groundwater sources to provide sustainable water supply options [28].

There are distinct benefits and difficulties associated with each of these solar-powered water treatment methods: solar desalination, photocatalytic water purification, and solar-powered filtration. When taken as a whole, they mark a significant advancement toward decentralized, sustainable water treatment systems that help alleviate the world's water shortage and provide access to clean water, particularly in areas with an abundance of solar energy. Future developments in system architecture, scalability, and materials science will be crucial to increasing the effectiveness and accessibility of these technologies [29].

3. Solar Energy in Hydrogen Production

A key component of the worldwide transition to a sustainable energy future is emerging: hydrogen. Hydrogen is a clean fuel that, when used in fuel cells, only creates water, which makes it a desirable substitute for fossil fuels in a variety of uses, including as manufacturing, transportation, and power generation. Unfortunately, carbon-intensive methods like steam methane reforming (SMR) provide the majority of the hydrogen produced today, which adds to greenhouse gas emissions. Research and development efforts are now concentrated on producing green hydrogen, or hydrogen produced from renewable energy sources, in an effort

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to lessen these negative environmental effects. In particular, solar energy provides a plentiful and sustainable energy source for the generation of hydrogen. This section examines photovoltaic electrolysis, photoelectrochemical water splitting, and thermochemical water splitting as the three main solar-driven hydrogen generating techniques. Every technique uses solar energy in a different way to create hydrogen, but in order for them to be widely used, technological obstacles must be removed [30–32].

3.1 Photovoltaic Electrolysis

As seen in Figure 3, one of the simplest and most economically feasible processes for producing hydrogen from solar power is photovoltaic electrolysis. In order to electrolyze water and separate it into hydrogen and oxygen, photovoltaic (PV) solar panels are used to generate power. The electrolysis procedure is carried out by electrolyzers, which use the electrical energy from photovoltaic cells to break the bonds that hold hydrogen and oxygen together in water molecules. This approach is a good choice for creating green hydrogen because of its simplicity and the maturity of PV technology.

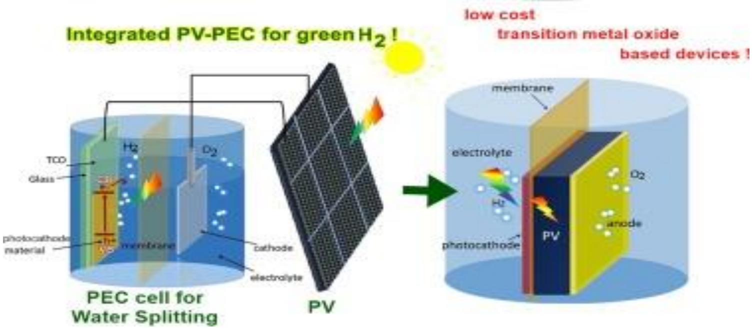

Figure 3. Photovoltaic Electro Catalysis Integration System for Green Hyderogen [33]

3.1.1 Efficiency and Technological Advancements

Both the solar panel and electrolyzer efficiencies have an impact on the total efficiency of photovoltaic electrolysis. With efficiencies of up to 20–25%, modern PV cells—especially those based on silicon and cutting-edge materials like perovskites—are incredibly efficient at converting sunlight into electrical power. But the actual electrolysis process has a lower efficiency, usually between 60 and 70 percent. This leads to a about 15-20% overall energy conversion efficiency, which is a significant technological constraint. During the electrolysis process, there are significant energy losses that are mostly caused by resistive losses within the electrolyzer and overpotentials, which are excess energy needed to drive the reactions [34–36].

Research is still being done to lower these losses by strengthening the electrolyzer's construction and material composition. Advanced proton exchange membrane (PEM) electrolyzers, as demonstrated in Table 2, are a promising field of development since they offer shorter response times and higher efficiency when compared to standard alkaline electrolyzers.

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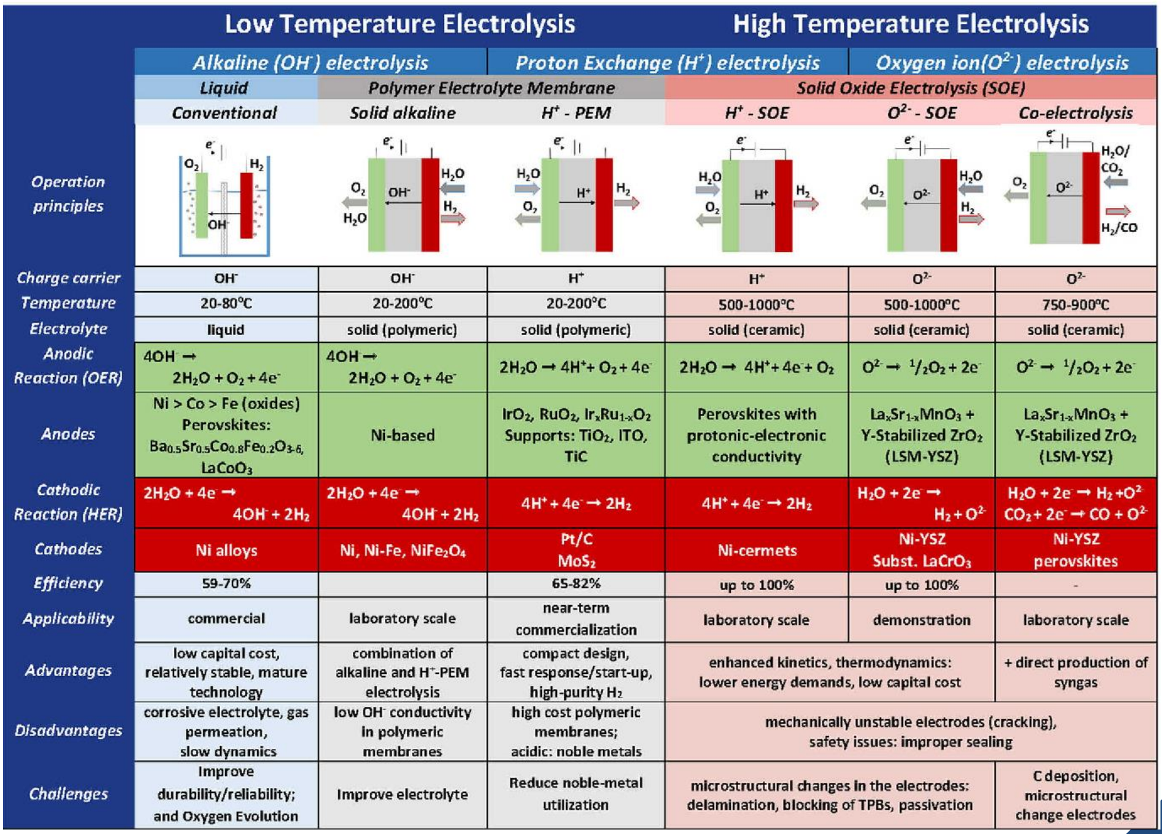
A different strategy is to optimize the integration of PV panels and electrolyzers to reduce energy losses. For example, high-efficiency PV cells can be directly coupled with low-voltage electrolyzers to reduce conversion steps and increase system efficiency [37].

3.1.2 Challenges and Future Directions

Even though photovoltaic electrolysis is a proven technology, there are still a few obstacles to overcome. The intermittent nature of solar energy is a significant problem that impacts electrolyzers' ability to operate continuously. Energy storage devices or hybrid systems that can run on a mix of solar and grid electricity are therefore required. Furthermore, electrolyzer longevity is an issue, especially for large-scale or off-grid applications. Because they are subjected to severe operating conditions, electrolyzer components like electrodes and membranes deteriorate with time, lowering system lifespan and raising maintenance costs [38].

Future studies will concentrate on creating stronger electrolyzer materials, strengthening system integration, and increasing photovoltaic electrolysis systems' capacity for energy storage. Advancements in photovoltaic technology, including the creation of tandem cells that integrate various materials to absorb a wider range of solar radiation, may additionally enhance the overall effectiveness of this process for producing hydrogen [39].

Table 2. Water Electrolysis based on renewable energy for hydrogen production [39]



	Low Temperature Electrolysis			High Temperature Electrolysis		
	Alkaline (OH^-) electrolysis		Proton Exchange (H^+) electrolysis		Oxygen ion(O^{2-}) electrolysis	
	Liquid	Polymer Electrolyte Membrane		Solid Oxide Electrolysis (SOE)		
	Conventional	Solid alkaline	H^+ - PEM	H^+ - SOE	O^{2-} - SOE	Co-electrolysis
Operation principles						
Charge carrier	OH^-	OH^-	H^+	H^+	O^{2-}	O^{2-}
Temperature	20-80°C	20-200°C	20-200°C	500-1000°C	500-1000°C	750-900°C
Electrolyte	liquid	solid (polymeric)	solid (polymeric)	solid (ceramic)	solid (ceramic)	solid (ceramic)
Anodic Reaction (OER)	$4OH^- \rightarrow 2H_2O + O_2 + 4e^-$	$4OH^- \rightarrow 2H_2O + O_2 + 4e^-$	$2H_2O \rightarrow 4H^+ + O_2 + 4e^-$	$2H_2O \rightarrow 4H^+ + 4e^- + O_2$	$O^{2-} \rightarrow {}^1/_2O_2 + 2e^-$	$O^{2-} \rightarrow {}^1/_2O_2 + 2e^-$
Anodes	Ni > Co > Fe (oxides) Perovskites: $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$, $LaCoO_3$	Ni-based	IrO_2, RuO_2, $Ir_xRu_{1-x}O_2$ Supports: TiO_2, ITO, TiC	Perovskites with protonic-electronic conductivity	$La_xSr_{1-x}MnO_3$ + Y-Stabilized ZrO_2 (LSM-YSZ)	$La_xSr_{1-x}MnO_3$ + Y-Stabilized ZrO_2 (LSM-YSZ)
Cathodic Reaction (HER)	$2H_2O + 4e^- \rightarrow 4OH^- + 2H_2$	$2H_2O + 4e^- \rightarrow 4OH^- + 2H_2$	$4H^+ + 4e^- \rightarrow 2H_2$	$4H^+ + 4e^- \rightarrow 2H_2$	$H_2O + 2e^- \rightarrow H_2 + O^{2-}$	$H_2O + 2e^- \rightarrow H_2 + O^{2-}$ $CO_2 + 2e^- \rightarrow CO + O^{2-}$
Cathodes	Ni alloys	Ni, Ni-Fe, $NiFe_2O_4$	Pt/C MoS_2	Ni-cermets	Ni-YSZ Subst. $LaCrO_3$	Ni-YSZ perovskites
Efficiency	59-70%		65-82%	up to 100%	up to 100%	-
Applicability	commercial	laboratory scale	near-term commercialization	laboratory scale	demonstration	laboratory scale
Advantages	low capital cost, relatively stable, mature technology	combination of alkaline and H^+-PEM electrolysis	compact design, fast response/start-up, high-purity H_2	enhanced kinetics, thermodynamics: lower energy demands, low capital cost		+ direct production of syngas
Disadvantages	corrosive electrolyte, gas permeation, slow dynamics	low OH^- conductivity in polymeric membranes	high cost polymeric membranes; acidic: noble metals	mechanically unstable electrodes (cracking), safety issues: improper sealing		
Challenges	Improve durability/reliability; and Oxygen Evolution	Improve electrolyte	Reduce noble-metal utilization	microstructural changes in the electrodes: delamination, blocking of TPBs, passivation		C deposition, microstructural change electrodes

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3.2 Photoelectrochemical Water Splitting

A new method called photoelectrochemical water splitting (PEC) combines the electrolysis and light absorption processes into one unit. PEC systems use semiconductor photoelectrodes that, in contrast to photovoltaic electrolysis, combine the functions of solar panels and electrolyzers. These electrodes not only absorb sunlight but also produce the charge carriers required to propel the water-splitting reaction. Compared to conventional PV-electrolysis systems, this direct conversion of solar into chemical energy has the potential to achieve higher efficiencies [40].

3.2.1 Mechanism and Materials

The semiconductor photoelectrodes in PEC water splitting, as shown in Figure 4, are essential for absorbing sunlight and starting the electrochemical reactions that split water into hydrogen and oxygen. Electrons from the valence band go to the conduction band when sunlight strikes the photoelectrode, forming electron-hole pairs. At the cathode, protons (H^+) are reduced into hydrogen gas by excited electrons, and at the anode, holes cause water to oxidize and turn into oxygen.

The characteristics of the semiconductor materials used in PEC systems have a major role in determining their efficiency. Because of their chemical stability, traditional semiconductors like titanium dioxide (TiO_2) are frequently employed; nevertheless, they are limited to absorbing ultraviolet (UV) light, which makes up a small percentage of the solar spectrum. Researchers are creating novel semiconductor materials with the ability to absorb visible light, which makes up the bulk of solar radiation, in order to increase efficiency. Visible light absorption has been demonstrated by materials including tungsten trioxide (WO_3), bismuth vanadate ($BiVO_4$), and other perovskite-based semiconductors.

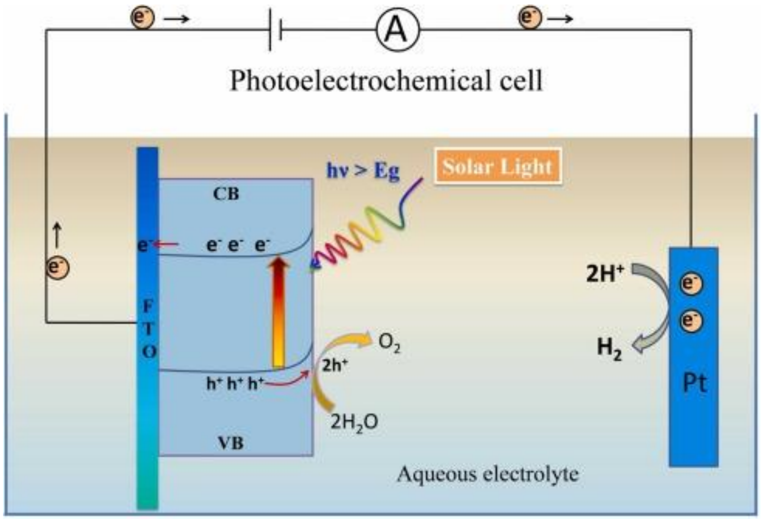

Figure 4. Photoelectrochemical Water Splitting [41]

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3.2.2 Challenges and Innovations

A primary obstacle in PEC water splitting is the photoelectrode stability. Many semiconductors have a tendency to break down quickly under the harsh settings needed for water splitting, such as strongly acidic or basic environments, especially those that absorb visible light. PEC systems' lifespan is shortened by this degradation, which also raises operating expenses. Researchers are looking on protective coatings for photoelectrodes that can increase their stability without lowering their efficiency in order to address this problem.

An additional obstacle is the effectiveness of charge separation. To power the water-splitting reactions in PEC systems, the photo-generated electron-hole pairs need to be effectively separated and transferred to the appropriate electrodes. Nevertheless, before they reach the electrodes, electrons and holes may recombine, decreasing total efficiency. The creation of heterojunctions, which are combinations of various semiconductor materials, and nanostructured electrodes are examples of material design advancements that have the potential to improve charge separation and transport, which will raise the overall efficiency of PEC water splitting [42].

3.3 Thermochemical Water Splitting

Using concentrated solar power (CSP) to reach the high temperatures required for chemical processes that split water into hydrogen and oxygen is known as thermochemical water splitting. Thermochemical water splitting employs thermal energy to drive a series of chemical reactions, in contrast to photovoltaic or photoelectrochemical processes, which rely on solar photons to generate charge carriers. Redox (reduction-oxidation) cycles involving metal oxides are commonly used in this process. Hydrogen is produced when these oxides react with water at high temperatures.

3.3.1 Mechanism and Materials

The process of thermochemical water splitting involves two steps, as illustrated in Figure 5. The first phase involves using concentrated solar energy to heat metal oxides (like zinc oxide or cerium oxide) to extremely high temperatures. The metal oxides experience a reduction reaction at these high temperatures, which releases oxygen and forms a reduced metal oxide. The reduced metal oxide is combined with water at a lower temperature in the second step, which yields hydrogen and regenerates the original metal oxide that can be utilized again in the cycle [43].

Thermochemical water splitting has the potential to be highly efficient because it can use heat and the full range of sun radiation to power the reaction. Furthermore, the system can reach the extraordinarily high temperatures (above 1,000°C) required for the reduction reactions by utilizing concentrated solar electricity. Finding materials that can tolerate these high temperatures without deteriorating over time is the difficult part.

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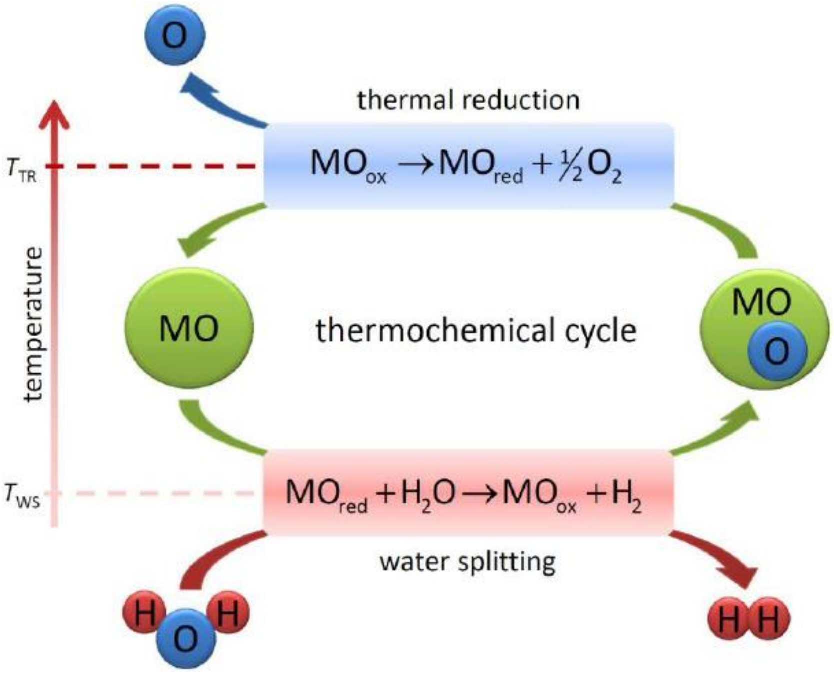

Figure 5. Thermochemical Water Splitting [44]

3.3.2 Challenges and Advancements

In thermochemical water splitting, material stability at high temperatures is a significant challenge. After several cycles, metal oxides utilized in the redox cycles have a tendency to deteriorate, which lowers their efficacy and raises the process's cost. Scholars are examining a range of metal oxide compounds that exhibit cycle stability, including perovskite oxides and cerium oxide (CeO_2). Furthermore, efforts are being undertaken to create novel materials that can operate at lower temperatures, which would lessen the system's thermal stress and increase overall durability.

The system's ability to transport heat efficiently presents another difficulty. To maximize energy use in thermochemical water splitting, careful control of high-temperature processes and effective heat recovery are necessary. Heat transfer efficiency in thermochemical systems is being enhanced by reactor design innovations like the use of solar towers and sophisticated heat exchangers. These advancements are essential to the viability of thermochemical water splitting as a large-scale hydrogen production technique.

These three solar-powered hydrogen generation techniques—thermochemical water splitting, photoelectrochemical water splitting, and photovoltaic electrolysis—each have unique benefits and difficulties. The development of photovoltaic technology is advantageous for photovoltaic electrolysis; however, photoelectrochemical and thermochemical processes have the potential to achieve greater efficiency and lower energy losses. However, in order for any of the three

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approaches to be economically feasible for the large-scale generation of green hydrogen, more progress in the fields of materials science, system design, and scalability is needed [45].

4. Challenges and Future Directions

Solar energy offers an environmentally friendly way to produce hydrogen and cleanse water, but before these technologies are widely used, a number of significant obstacles need to be removed. The immediate scalability and economic viability of solar-powered systems are restricted by these obstacles, which cut across the technical, financial, and operational realms. The widespread implementation of these technologies is still hampered by problems including high capital costs, material deterioration, intermittent solar power, and inefficient systems, even with major breakthroughs in the field. In order to overcome these obstacles, engineers and researchers need to investigate the following future directions, which are outlined in this section [46].

4.1 High Initial Costs of Solar Technologies

The large initial outlay needed is one of the biggest barriers to the use of solar energy in hydrogen generation and water purification. Solar panels, concentrators, and other system components must frequently be installed, which results in a significant financial outlay for solar-powered desalination, water purification, and hydrogen generating systems. While solar photovoltaic (PV) panels have become considerably less expensive in recent years, large-scale solar installations—especially those that make use of cutting-edge technologies like thermochemical reactors or concentrated solar power (CSP)—remain costly. The initial costs of these systems are increased by the requirement for a significant land area [47].

When it comes to producing hydrogen, solar electrolysis systems are less competitive when compared to fossil fuel-based methods because of the high cost of electrolyzers, especially proton exchange membrane (PEM) electrolyzers. Similar to this, the materials required for thermochemical and photoelectrochemical water splitting systems can be costly because they require metal oxides or high-quality semiconductors that can endure high operating temperatures and harsh conditions [48].

4.2 Material Challenges and Durability

The entire cost-effectiveness and efficiency of solar-powered water treatment and hydrogen production systems are significantly influenced by the materials' lifetime and durability. Materials used in solar stills, membranes, and concentrators for solar desalination systems must be able to tolerate prolonged exposure to saltwater and UV light, as these conditions can cause corrosion, fouling, and degradation. Similar to this, materials like membrane filters used in solar-powered filtration systems are prone to fouling, which lowers their performance and calls for regular maintenance or replacement [49].

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Material degradation is a critical concern in the synthesis of hydrogen. The electrolyzer's electrodes and membranes deteriorate over time in photovoltaic electrolysis as a result of exposure to high voltages and reactive intermediates. One of the main challenges in photoelectrochemical water splitting is semiconductor material stability. Many materials that are effective in absorbing visible light, like perovskites and some metal oxides, have a tendency to break down quickly in operating conditions, especially when water and oxygen are present.

Material durability is a problem for thermochemical water splitting as well. The repeated heating and cooling cycles at extremely high temperatures (sometimes over 1,000°C) that the metal oxides used in redox cycles must withstand can eventually lead them to lose their reactive characteristics. Additionally, materials resistant to oxidation and thermal stress are needed for the high-temperature reactors utilized in these processes. A major area of research concentration is the development of affordable, long-lasting materials that can continue to perform well for extended periods of time [50].

4.3 Intermittency of Solar Energy

One of the main issues with all solar-powered systems is the intermittent nature of solar energy. Due to geographical location, time of day, weather, and seasonal variations, solar energy is inherently changeable. For systems that depend on constant energy inputs, like large-scale solar desalination plants or the electrolysis of hydrogen, this fluctuation poses a serious problem.

The variability of sunshine can lead to an unequal output of hydrogen in solar-powered hydrogen production, which makes integration with networks for hydrogen storage and distribution more difficult. For instance, in photovoltaic electrolysis, variations in the power produced by solar panels result in inefficiencies in the electrolyzer's functioning. Solar-powered water treatment and hydrogen production systems may need hybrid setups or backup energy sources in areas with less steady sunlight, which raises the systems' complexity and cost.

Batteries and thermal energy storage are two examples of energy storage technologies that are frequently needed to mitigate variations in solar energy supply. However, these technologies come with added expenses and technical complexity. The intermittent nature of solar electricity presents a significant challenge for thermochemical water splitting, as high temperatures need to be maintained constantly for effective redox reactions. Overcoming this obstacle will need the development of effective, affordable energy storage devices that can store solar energy as heat or electricity [51-55].

4.4 System Efficiency and Scale-Up Challenges

Although solar water treatment and hydrogen generation systems in the lab have shown encouraging results, bringing these technologies to the commercial level will present more difficulties. When operations are scaled up, there is a tendency for system efficiency to

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diminish because of higher heat losses, inefficiencies in energy transmission, and difficulties in maintaining constant operating conditions over large regions or volumes [56-59].

For example, when solar desalination is scaled up, the efficiency of solar stills diminishes, mostly because of increased heat losses and the complexity of maintaining ideal conditions for condensation and evaporation. Upgrading membrane filtration units in solar-powered filtration systems presents problems with water flow rates, membrane fouling, and energy usage. Integrating several solar modules and electrolyzers is necessary for scaling photovoltaic electrolysis or photoelectrochemical systems for the production of hydrogen. This can add inefficiencies and complexity to the process of balancing power output and system integration.

In thermochemical water splitting, where large-scale reactors must sustain high temperatures and effective heat transfer across enormous volumes, scaling up is very difficult. In order to guarantee that the systems function effectively at industrial scales, this calls for the development of sophisticated reactor designs, effective heat exchangers, and thermal storage technologies [60-62].

4.5 Future Directions

To address these challenges, future research and development efforts must focus on several key areas:

Development of Cost-Effective Materials: The development of durable and efficient new materials is crucial to bring down the cost of solar-powered systems. Advanced nanomaterials, corrosion-resistant coatings, and anti-fouling membranes have the potential to greatly increase system longevity and performance in the water treatment industry. Important areas of research in hydrogen production include more robust electrolyzer materials, stable photoelectrodes for PEC systems, and high-temperature resistant metal oxides for thermochemical systems.

Improved System Integration and Design: System design advancements that maximize the integration of electrolyzers, solar panels, and other parts can lower energy losses and boost overall effectiveness. To enhance system performance, energy conversion steps can be eliminated by directly connecting photovoltaic cells to low-voltage electrolyzers or by employing concentrated solar power to power thermochemical cycles. Furthermore, more dependable and constant energy inputs could be provided by hybrid systems that integrate solar energy with other renewable energy sources, such geothermal or wind, reducing the consequences of intermittency.

Energy Storage Solutions: More investigation into effective energy storage technology is necessary to counteract solar energy's erratic nature. Solutions for thermal energy storage, battery storage, and hydrogen storage may make it possible for solar-powered systems to run continuously, even in the absence of direct sunlight. Specifically, hydrogen generated by

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electrolysis offers a flexible way to store and distribute energy since it can be kept and utilized as fuel and an energy carrier.

Scaling and Commercialization: For solar-powered systems to be scaled up for industrial usage, better system designs, standards, and legislation that support commercialization are needed. Manufacturing techniques must also advance. Investment and adoption will be fueled in large part by demonstration projects that highlight the practicality of large-scale solar water treatment and hydrogen production systems. Furthermore, partnerships between government agencies, businesses, and academic institutions can hasten the shift from laboratory-scale research to commercial application.

Solar-powered water treatment and hydrogen production technologies can be key players in the shift to a low-carbon, sustainable future by tackling these issues through creative research, better materials, and sophisticated system designs. By reducing greenhouse gas emissions and achieving climate goals, these technologies have the potential to provide clean water and renewable hydrogen globally [63–65].

5. Conclusion

Solar energy, especially when used for water treatment and hydrogen production, provides a revolutionary, long-lasting response to the world's most urgent problems: water scarcity and the switch to clean energy. Solar-driven technologies offer scalable and environmentally friendly alternatives to traditional processes, as this review has shown. Examples of these technologies include solar desalination, photocatalytic water purification, solar-powered filtration, photovoltaic electrolysis, photoelectrochemical water splitting, and thermochemical water splitting. Significant obstacles still need to be overcome, though, such as the high initial prices, material deterioration, solar power's erratic nature, and the difficulties in expanding these systems. It will take coordinated research and development efforts to address these issues, especially in the fields of material science, system integration, and energy storage. The development of hybrid systems that combine solar energy with other renewable energy sources, as well as the advancement of affordable, long-lasting materials and more effective system designs, will be essential to improving the efficiency, dependability, and financial sustainability of these technologies. Moreover, converting these advancements into widely used, practical applications will require extensive demonstrations and collaborations between government, business, and academia. By doing this, solar-powered water treatment and hydrogen production systems can significantly aid in the global transition to renewable energy sources and water security, promoting climate action and the development of a sustainable future.

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Author Contributions

Doaa Salim Musallam Samhan Al-Kathiri conceptualized the manuscript framework and provided technical insights into solar energy applications in water treatment. Lakshmi Jayanthi Juturi contributed to the literature review and data analysis on desalination and solar-powered filtration systems. Nageswara Rao Lakkimsetty critically reviewed the manuscript and added significant contributions to the sections on photovoltaic electrolysis and photoelectrochemical water splitting. Clement Varaprasad Karu was responsible for drafting the section on thermochemical water splitting and analyzing recent technological advancements. Naladi Ram Babu focused on the environmental implications of hydrogen production and solar-driven water treatment technologies. Amarender Reddy Kommula conducted feasibility studies and provided critical input on cost-benefit analysis. Dadapeer Doddamani contributed to editing, refining, and enhancing the readability of the manuscript. Rakesh Namdeti supervised the project, guided the team, and finalized the manuscript for submission.

All authors have read and approved the final manuscript.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. All relevant data are included in the manuscript and its supplementary materials.

Conflicts of Interest

“The authors declare no conflict of interest.”

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