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A Concise Review of Hydrogen Production from Renewable Energy Sources with Focus on Solar, Wind, Tidal, Geothermal, and Biomass

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ABSTRACT:

Hydrogen production from renewable energy sources has gained significant attention as a sustainable and low-carbon alternative to traditional fossil fuel-based methods. The present review presents a concise analysis of hydrogen production technologies from solar, wind, tidal, geothermal, and biomass sources. Also, it discusses the principles and methods of hydrogen production, including electrolysis, thermochemical processes, and biomass gasification. It then delves into the specific characteristics and advancements in each renewable energy source for hydrogen production. Solar energy, a widely available and abundant resource, has led the integration of advanced materials, efficient electrolyzers, and solar concentrators to significant improvements in solar-to-hydrogen conversion efficiency. Wind energy, with its scalability and reliability, enhances advances in wind turbine technology, grid integration, and energy storage solutions to the feasibility and cost-effectiveness of wind-to-hydrogen systems. The review examines the challenges and opportunities in harnessing tidal power, including technological advancements in tidal turbines, resource assessment, and environmental considerations. The review also explores the geothermal-to-hydrogen potential, geothermal resource mapping, and innovative technologies for geothermal-based hydrogen production. The review discusses the role of biomass in the biohydrogen sector, biomass feedstock options, and advancements in biomass-to-hydrogen conversion technologies. Furthermore, the review paper discusses the research gaps, challenges, and prospects in hydrogen production from renewable energy sources.

Keywords*:* Hydrogen, Solar, wind, Tidal, Geothermal, Biomass

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INTRODUCTION:

Hydrogen has emerged as a versatile and environmentally friendly energy carrier, garnering considerable interest as a potential solution to combat climate change and reduce reliance on fossil fuels. Despite being the most abundant element in the universe, pure hydrogen is rare on Earth and is typically obtained through extraction from other compounds [1,2].

Various methods are employed for hydrogen production, with steam methane reforming (SMR), electrolysis, and biomass gasification being the most prevalent. SMR entails reacting methane, the primary component of natural gas, with steam at high temperatures to yield hydrogen and carbon monoxide. Although SMR is currently the most cost-effective for large-scale hydrogen production, it still hinges on fossil fuels and emits carbon dioxide. Conversely, electrolysis employs electricity to split water molecules into hydrogen and oxygen, and it can be powered by renewable sources like solar, wind, or hydroelectric power, rendering it a sustainable alternative.

Electrolysis exists in two forms: (i) alkaline electrolysis, a well-established and widely used method, and (ii) proton exchange membrane (PEM) electrolysis, which is more efficient and suitable for smaller-scale applications. Another avenue for hydrogen generation is biomass gasification, wherein biomass feedstock such as agricultural residues, wood, or energy crops undergoes a thermochemical process to produce synthesis gas (syngas) containing hydrogen, carbon monoxide, and other gases, which can then be refined to obtain pure hydrogen [3,4].

Research into hydrogen production from renewable sources like solar, wind, tidal, geothermal, and biomass has advanced significantly in recent years. However, there are still notable research gaps and areas necessitating further exploration. Key research gaps in renewable energy-driven hydrogen production encompass enhancing efficiency, reducing costs, improving energy storage and grid integration, considering resource availability and geographic factors, conducting lifecycle assessments for sustainability, exploring hydrogen applications, and addressing policy, regulatory, and market dynamics [5]. Addressing these research gaps is imperative for expediting the shift toward a sustainable and low-carbon hydrogen economy based on renewable energy.

HYDROGEN PRODUCTION FROM RENEWABLE ENERGY SOURCES:

Hydrogen production from renewable sources such as solar, wind, tidal, geothermal, and biomass is gaining momentum due to its potential to reduce carbon emissions in key sectors like transportation, industry, and power generation. Leveraging these renewable inputs allows hydrogen to be generated without adding to greenhouse gas emissions, paving the way for a more sustainable and environmentally friendly energy paradigm. However, challenges persist in scaling up renewable hydrogen production, enhancing efficiency, reducing costs, and establishing infrastructure for hydrogen storage, transportation, and utilization. Ongoing

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research and development endeavors are focused on tackling these challenges and unlocking hydrogen's full potential as a clean energy solution in the shift toward a low-carbon future [6].

Solar Power:

Harnessing hydrogen from solar energy involves using photovoltaic cells or solar thermal systems to convert sunlight into electricity or heat, respectively. This generated electricity or heat can then be employed in electrolysis processes to split water into hydrogen and oxygen.

Wind Power:

Utilizing wind energy can generate electricity, powering electrolysis systems for hydrogen production. Wind turbines capture the kinetic energy of wind, converting it into mechanical energy, which is further transformed into electricity through generators.

Tidal Power:

Extracting energy from ocean tides, tidal energy can generate electricity through tidal turbines or tidal barrages. This electricity can then be used in electrolysis to produce hydrogen.

Geothermal Power:

Geothermal energy, sourced from Earth's crust heat, can generate electricity for hydrogen production via electrolysis processes.

Biomass:

Converting biomass like organic waste or dedicated energy crops into hydrogen involves processes such as gasification or pyrolysis. These methods break down biomass into gases, including hydrogen, which can be isolated and refined for use.

While each renewable source presents advantages and challenges for hydrogen production, they collectively contribute to a more sustainable and low-carbon energy system. Solar and wind power, although abundant, may require energy storage solutions due to intermittency. Tidal power, while predictable, is constrained to coastal regions. Geothermal energy provides continuous power but is limited geographically. Biomass offers a steady feedstock but requires efficient conversion technologies. Combining these sources with hydrogen production can enhance sustainability in energy systems [7].

SOLAR TO HYDROGEN:

Solar-to-hydrogen technology, also known as solar hydrogen production, is a process that harnesses solar energy to produce hydrogen gas through water electrolysis. This method is a key component of the renewable hydrogen economy, aiming to create a sustainable and clean energy source for various applications [8].

The solar hydrogen production process typically involves several steps:

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Photovoltaic (PV) cells or concentrated solar power (CSP) systems are used to capture solar energy. PV cells directly convert sunlight into electricity, while CSP systems focus sunlight onto a receiver to generate heat. The captured solar energy is either converted into electricity (in the case of PV cells) or heat (in CSP systems). This energy is then used to power the electrolysis process. Electrolysis is the process of splitting water (H2O) into hydrogen (H2) and oxygen (O2) using electricity. There are two main types of electrolyzers used in solar-to-hydrogen systems: (i)

Alkaline Electrolysis is a well-established technology that uses an alkaline electrolyte (such as potassium hydroxide) and operates at relatively high temperatures, which suitable for large-scale hydrogen production; and (ii) Proton Exchange Membrane (PEM) electrolyzers use a solid polymer electrolyte membrane and operate at lower temperatures, making them more efficient and suitable for smaller-scale applications. Finally, the produced hydrogen gas is typically purified to remove impurities and moisture, ensuring high-purity hydrogen suitable for various applications [2].

Solar-to-hydrogen technology offers following advantages [9]: (i) Solar energy is abundant and renewable, making it an environmentally friendly option for hydrogen production; (ii) The process produces no greenhouse gas emissions if powered by renewable energy sources, contributing to a cleaner environment; (iii) Hydrogen can be stored and used as a flexible energy carrier, helping to balance supply and demand in energy systems; and (iv) Hydrogen can be used in fuel cells for electricity generation, as a fuel for transportation (e.g., hydrogen fuel cell vehicles), and in industrial processes. Table 1 provides the summary of literature on solar to hydrogen process.

Table 1. Summary of literature on solar to hydrogen process

Focus	Key Points	Reference
Photosynthesis, water splitting, electrocatalysis, hydrogen fuel cells	Bridge gap between ideal concepts and practical implementation	[8]
TiO2 photocatalysis, dopants for enhanced hydrogen generation under solar light	Noble metals and nitrogen dopants improve photocatalytic activity for renewable energy	[9]
Designing efficient photocatalysts using atomic-level doping and co-catalyst modulation	Enhanced charge separation and transfer for improved solar-to-hydrogen conversion	[10]
Fabrication of highly efficient photocatalysts, micro-nanostructures	Promoting solar-to-chemical energy conversion for sustainable energy production	[11]

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RF resin powders as active photocatalysts for H2O2 generation	Enhanced charge separation and efficient solar fuel production through P3HT doping	[12]
Cost-effective III-V-based photoelectrodes for efficient solar-to-hydrogen conversion	Addressing material cost and stability challenges for practical application	[13]
Regression fusion model for predicting hydrogen production rates	Understanding TiO2 photocatalysis and renewable energy generation using machine learning	[14]
Study on 2D nanostructured films for high-efficiency hydrogen production	Importance of contact properties in photocatalytic processes	[15]
PV-EC and PEC strategies for solar-to-hydrogen conversion	Need for efficient water-splitting electrolyzers for large-scale hydrogen production	[16]
Exploration of BPV cells for renewable energy generation	Potential of biological systems in sustainable energy production	[17]
Review of solar hydrogen production technologies	Efficiency, viability, and potential for addressing climate change through renewable energy	[18]
Novel full-spectrum photo-thermo-catalysis technique for efficient H2 production	Synergistic effects from photon and thermal energy for high-efficient solar fuel production	[19]

Qi et al. (2018) discuss photosynthesis in plants, laboratory-based water splitting strategies, electrocatalytic reactions for hydrogen and oxygen evolution, and their application in hydrogen fuel cells, emphasizing the gap between ideal concepts and practical implementation [8]. Ismael (2020) explores dopants' impact on TiO2 photocatalysis, focusing on noble metals and nitrogen dopants for enhanced hydrogen generation under solar light, crucial for renewable energy production [9]. Zhu et al. (2022) present insights into designing efficient photocatalysts using atomic-level metal ion doping and co-catalyst modulation, improving solar-to-hydrogen conversion through enhanced charge separation and transfer [10]. Sun et al. (2020) fabricate a highly efficient photocatalyst with micro-nanostructures and structural defects, promoting solar-to-chemical energy conversion, which is vital for sustainable energy production [11].

Shiraishi et al. (2021) demonstrate RF resin powders as active photocatalysts for H2O2 generation, enhanced by P3HT doping, showcasing a promising approach for liquid solar fuel production [12]. Varadhan et al. (2019) introduce cost-effective III-V-based photoelectrodes for efficient solar-to-hydrogen conversion, addressing challenges in material cost and stability

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for practical application [13]. Liu et al. (2023) develop a regression fusion model for predicting hydrogen production rates using machine learning, aiding in understanding TiO2 photocatalysis for renewable energy generation [14]. Balocchi et al. (2023) study 2D nanostructured films for high-efficiency hydrogen production, emphasizing the importance of contact properties in photocatalytic processes [15].

Li et al. (2023) investigate PV-EC and PEC strategies for solar-to-hydrogen conversion, highlighting the need for efficient water-splitting electrolyzers for large-scale hydrogen production [16]. Carbas et al. (2023) explore BPV cells using organic organisms for renewable energy generation, showcasing the potential of biological systems in sustainable energy production [17]. Song et al. (2022) review solar hydrogen production technologies, evaluating their efficiency, viability, and potential for addressing climate change through renewable energy [18]. Li et al. (2022) propose a novel full-spectrum photo-thermo-catalysis technique for efficient H2 production, leveraging synergistic effects from photon and thermal energy for high-efficient solar fuel production [19].

The challenges in solar hydrogen production process are as follows:

However, challenges such as intermittency (due to variations in solar irradiance), cost of electrolysis technologies, and infrastructure development for hydrogen storage and distribution need to be addressed to fully realize the potential of solar-to-hydrogen technology in the transition to a sustainable energy future [10]. Ongoing research and technological advancements aim to improve efficiency, reduce costs, and overcome these challenges.

WIND TO HYDROGEN:

The urgency to transition towards sustainable and renewable energy sources has never been more pressing. Renewable energy, such as solar, wind, hydroelectric, and geothermal power, offers viable alternatives that can reduce our reliance on fossil fuels and curb carbon emissions. Embracing these clean energy technologies not only promotes energy security but also fosters economic growth, job creation, and technological innovation. Additionally, it aligns with global efforts to achieve the United Nations Sustainable Development Goals (SDGs) and fulfill commitments under international agreements like the Paris Agreement.

Limitations of Traditional Energy Storage:

While advancements have been made in renewable energy generation, such as solar and wind power, these sources are often intermittent and cannot always meet fluctuating energy demands. Traditional energy storage methods like pumped hydropower storage have limitations, including geographical restrictions, environmental impacts, and high capital costs. This necessitates the development of efficient and versatile energy storage solutions to bridge the gap between renewable energy generation and consistent energy supply [22-23]. In response to the challenges outlined above, wind-to-hydrogen (WtH) technology emerges as a

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promising solution. WtH integrates wind energy generation with hydrogen production, offering several advantages [24-25]:

WtH utilizes wind, a clean and renewable resource, for hydrogen production, significantly reducing greenhouse gas emissions compared to traditional fossil fuel-based energy sources. This contributes to mitigating climate change and air pollution, leading to a cleaner and healthier environment [26]. Unlike wind and solar power, which are variable and dependent on weather conditions, hydrogen offers flexible energy storage capabilities. It can be stored efficiently and utilized to generate electricity or power various applications when needed, overcoming the intermittent limitations of renewable energy sources [27].

WtH technology has the potential to de-carbonize various sectors beyond just electricity generation. Hydrogen produced using wind energy can be used as a clean fuel for transportation, such as electric vehicles and hydrogen-powered aircraft, replacing fossil fuels and reducing emissions in these sectors. Additionally, it can be used for industrial processes, further contributing to overall decarbonization efforts [28]. Therefore, WtH technology presents a compelling solution for addressing the need for clean energy, flexible storage, and reducing carbon emissions across diverse sectors, paving the way for a more sustainable future.

Wind Energy Integration:

This section describes how wind farms generate electricity and the challenges associated with intermittent wind power availability [29].

Electricity Generation from Wind Farms:

Wind farms consist of numerous wind turbines, which are essentially large windmills. These turbines utilize the wind’s kinetic energy to rotate their blades, which in turn, drive a shaft connected to a generator. The generator converts this mechanical energy into electricity, feeding it into the power grid. Wind farms offer a clean and renewable source of energy, contributing to a sustainable energy future [30].

Challenges of Intermittent Wind Power:

While wind energy holds significant potential, its inherent variability presents a significant challenge. Wind speed and direction are not constant, leading to fluctuations in electricity generation by wind farms. This intermittency can cause [31]:

Grid Instability:

Fluctuations in electricity supply can disrupt the stability of the power grid, potentially leading to blackouts or brownouts.

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Unpredictable Power Availability:

The inability to predict and control wind power availability makes it difficult to match electricity supply with fluctuating demand, creating challenges for grid operators.

Integration with Existing Infrastructure:

Integrating wind energy into existing grid infrastructure requires additional measures to manage the variability and ensure stable power supply.

These challenges highlight the need for effective energy storage solutions, like WtH technology, to bridge the gap between intermittent wind power generation and consistent energy supply.

Integrating WtH Systems with Wind Farms

To address the challenges of intermittent wind power and facilitate smoother, more efficient power generation utilization, several methods for integrating WtH systems with wind farms are being explored [32-33]:

Direct Coupling:

In this approach, wind turbines directly power electrolyzers for hydrogen production during periods of high wind power generation. The produced hydrogen is then stored and used to generate electricity during periods of low wind or high electricity demand. This method offers real-time utilization of wind energy but requires careful management of grid stability and electrolyzer operation.

Battery Buffering:

This method utilizes batteries to temporarily store excess wind energy during periods of high generation. This stored energy can then be used to power the electrolyzers and produce hydrogen when wind power is low. Batteries can help smooth out short-term fluctuations in wind power, facilitating a more stable integration with the grid.

Hybrid Systems:

Combining the above methods, hybrid systems utilize both batteries and electrolyzers for hydrogen production. Batteries manage short-term fluctuations, while hydrogen storage provides longer-term energy storage solutions. This approach offers increased flexibility and can be tailored to specific wind farm characteristics and grid requirements.

Economic Considerations:

Integrating WtH systems with wind farms involves significant capital investments for electrolyzers, hydrogen storage infrastructure, and grid upgrades. Therefore, economic

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feasibility is crucial for widespread adoption. Several factors influence the economic viability of WtH, including [34-36]:

Cost of Electrolyzers:

Electrolyzers are currently a major cost driver. Ongoing research and development efforts aim to reduce the cost of electrolyzers through technological advancements and economies of scale.

Hydrogen Storage Costs:

The cost of hydrogen storage depends on the chosen method (compressed gas, liquefaction, etc.). Research is ongoing to develop more cost-effective and efficient storage solutions.

Carbon Pricing Mechanisms:

Implementing carbon pricing mechanisms, such as carbon taxes or emission trading schemes, can incentivize WtH adoption by reflecting the environmental benefits and external costs associated with traditional energy sources.

Government Subsidies and Incentives:

Government support through financial incentives, subsidies, and tax breaks can play a crucial role in making WtH technology more economically attractive and accelerating its deployment. By addressing these economic considerations and promoting cost reductions through technological advancements and supportive policies, WtH can become a more cost-competitive and attractive solution for integrating renewable energy sources like wind power into the grid.

Smart Grid Integration:

Integrating WtH systems with smart grid technologies can further optimize their operation. Smart grids employ intelligent automation and communication technologies to monitor and manage the flow of electricity throughout the grid. This allows for real-time adjustments to optimize hydrogen production, storage, and utilization based on wind power availability and grid demand.

By implementing these integration methods, WtH systems can effectively utilize excess wind energy, mitigate the challenges of intermittent, and contribute to a more stable and efficient power grid.

Hydrogen Production from Wind Energy:

This section describes different methods for producing hydrogen using wind energy, such as water electrolysis powered by wind turbines (Figure 1). Wind energy serves as a clean and renewable source of power for producing hydrogen through various methods [37-41]:

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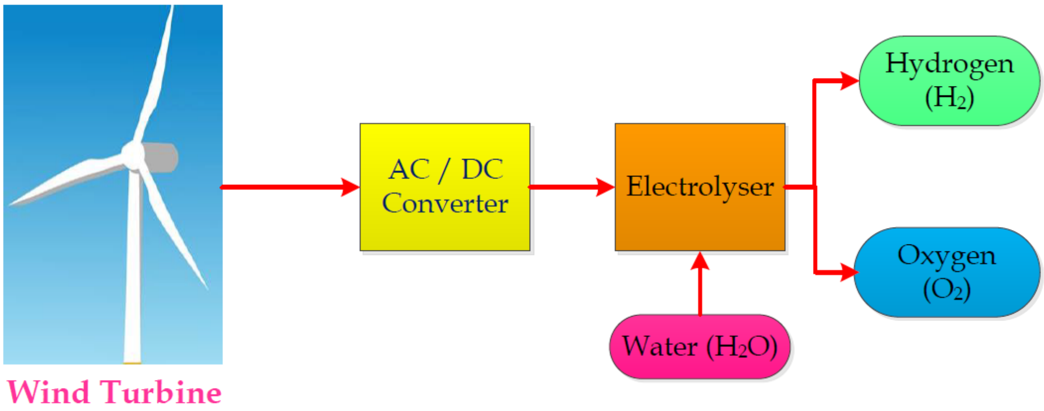

Figure 1. Wind to hydrogen process

Water Electrolysis:

This is the most common and well-developed method for WtH technology. It involves passing electricity, generated by wind turbines, through water (H2O) in an electrolyzer unit. The electricity splits the water molecules into hydrogen (H2) and oxygen (O2) through a chemical reaction:

2H2O (l) + Electricity → 2H2 (g) + O2 (g)

The produced green hydrogen, derived from renewable wind energy, has minimal environmental impact compared to hydrogen produced from fossil fuels.

Thermochemical Water Splitting:

This method utilizes heat to split water molecules into hydrogen and oxygen. The heat can be sourced from concentrated solar power, nuclear reactors, or geothermal energy. While not directly powered by wind energy itself, it can be integrated with WtH systems where excess wind energy is used to generate the heat required for thermochemical water splitting. This offers an alternative approach for hydrogen production, potentially increasing overall efficiency and resource utilization.

Photoelectrochemical (PEC) Water Splitting:

This emerging technology utilizes sunlight and a specialized semiconductor material to directly split water into hydrogen and oxygen. PEC cells are still under development but hold promise for a direct conversion process from sunlight and water to hydrogen, potentially eliminating the need for separate electricity generation from wind turbines. Integrating PEC technology with WtH systems could create a more efficient and sustainable hydrogen production pathway in the future.

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Biological Hydrogen Production:

This method utilizes specific bacteria or algae that can produce hydrogen through biological processes. These processes often involve sunlight and organic matter as feedstock, potentially integrating with renewable resources like wind energy for auxiliary power needs or specific applications. While still under research and development, biological hydrogen production offers a potentially sustainable and carbon-neutral pathway for hydrogen generation.

These methods showcase the diverse approaches for producing hydrogen using wind energy, each with its own advantages, limitations, and development stage. Continued research and development efforts aim to improve the efficiency, scalability, and cost-effectiveness of these methods, paving the way for a more sustainable hydrogen production future [42-43].

Comparison of Hydrogen Production Technologies

Table 2 shows the efficiency, maturity, and scalability of different hydrogen production technologies are compared, including those mentioned in the previous section [44-51]:

Table 2. Comparison of efficiency, maturity, and scalability of different hydrogen production technologies

Technology	Efficiency	Maturity	Scalability
Water Electrolysis	60-80%	High	High
Thermochemical Water Splitting	20-40%	Medium	Medium
Photoelectrochemical (PEC) Water Splitting	Low (currently)	Low	Low
Biological Hydrogen Production	Low (currently)	Low	Low

The efficiency of the various methods is discussed below [52-53]:

Water Electrolysis offers the highest efficiency among the listed methods, typically ranging from 60% to 80%. However, the efficiency depends on the type of electrolyzer used and the operating conditions. Thermochemical Water Splitting shows lower efficiency compared to electrolysis, with estimates ranging from 20% to 40%. This is due to the additional energy losses involved in generating the high temperatures needed for the process. Currently, PEC technology suffers from low efficiency, typically below 10%. However, ongoing research aims to improve the efficiency of these systems. The biological Hydrogen Production method also exhibits low efficiency at present, with estimates around 1-10%. Transporting hydrogen safely and efficiently is crucial for its widespread adoption. While challenges exist, ongoing research, development of safety protocols, and establishment of clear regulations will pave the way for a robust hydrogen transportation infrastructure [54-56].

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Diverse Applications of Wind-to-Hydrogen (WtH) Technology

Wind-to-hydrogen (WtH) technology offers a versatile approach to utilizing clean and renewable wind energy for various applications beyond just power generation. Here are some of its diverse applications [57-61]:

Power Generation:

- Peak Demand Management: During periods of high electricity demand, WtH systems can be used to generate electricity by converting stored hydrogen back into electricity through fuel cells. This helps to address peak demand challenges and optimize grid operation.
- Dispatchable Power: Unlike variable wind power, WtH enables dispatchable power generation. This means that electricity can be generated from stored hydrogen whenever needed, even when wind power is unavailable, ensuring a reliable and consistent power supply.

Transportation:

- Fuel Cell Electric Vehicles (FCEVs): WtH can provide clean hydrogen fuel for FCEVs, offering a zero-emission alternative to gasoline and diesel vehicles. This contributes to reducing greenhouse gas emissions and air pollution in the transportation sector.
- Heavy-Duty Transportation: WtH can be a potential solution for decarbonizing heavy-duty vehicles like trucks, ships, and airplanes, which are challenging to electrify directly due to battery weight and range limitations.

Industrial Applications:

- Industrial Processes: Specific industries like steel production or chemical manufacturing require high-temperature heat. Hydrogen derived from WtH can be used as a clean fuel source for these processes, replacing fossil fuels and reducing carbon emissions.
- Feedstock for Renewable Chemicals: Hydrogen can be used as a feedstock for producing various renewable chemicals like ammonia or synthetic fuels, creating greener alternatives to traditional fossil fuel-based products.

Grid Balancing and Stability:

- Energy Storage: WtH systems act as large-scale energy storage solutions, allowing for the storage of excess wind energy and its utilization when needed. This helps to balance the grid by smoothing out fluctuations in renewable energy generation and contributing to grid stability.
- Ancillary Services: WtH systems can provide ancillary services to the grid, such as frequency regulation and voltage control, by quickly adjusting hydrogen production and electricity generation based on grid requirements.

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Remote Power Generation:

♦ Off-grid Applications: WtH systems can provide a reliable and clean source of power in remote locations with limited or no access to the electricity grid. This can be crucial for powering communities and infrastructure in remote areas.

♦ As WtH technology continues to develop and costs become more competitive, its applications are expected to expand further, potentially impacting various sectors beyond those mentioned above. Implementing WtH solutions requires careful consideration of factors like infrastructure development, policy frameworks, and economic feasibility to ensure its successful integration into existing energy systems by unlocking the diverse applications of WtH, this technology holds significant potential for creating a cleaner, sustainable, and more secure energy future [62-66].

Key Challenges Facing WtH Technologies:

Despite its potential for clean and sustainable energy, WtH technology faces several key challenges [67-71]:

Cost:

♦ High capital costs: Currently, the cost of electrolyzers, hydrogen storage infrastructure, and grid upgrades for WtH systems is high, hindering widespread adoption.

♦ Electrolyzer cost: Electrolyzers are a major cost driver. Advancements in technology and economies of scale are crucial to bring down their cost.

Efficiency:

♦ Electrolyzer efficiency: While improving, the overall efficiency of converting wind energy into usable hydrogen and back to electricity through fuel cells still needs further improvement.

Storage:

♦ Energy losses: Hydrogen storage, whether compressed gas or liquefied, involves energy losses during compression, decompression, or boil-off, reducing overall efficiency.

♦ Limited storage options: Scalable and cost-effective storage solutions are still under development, particularly for large-scale energy storage needs.

Infrastructure:

♦ Limited hydrogen infrastructure: Existing infrastructure is primarily designed for fossil fuels, and significant investments are needed to develop a dedicated hydrogen infrastructure, including pipelines, storage facilities, and refueling stations.

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♦ Repurposing existing pipelines: While modifying existing natural gas pipelines for hydrogen might seem cost-effective, challenges like material compatibility, leakage, and energy efficiency need to be addressed.

Policy and Regulation:

♦ Lack of clear policies and regulations: Consistent policies and regulations for hydrogen production, transportation, and use are needed to encourage investment and ensure safety standards.

♦ Carbon pricing mechanisms: Implementing carbon pricing mechanisms, such as carbon taxes or emission trading schemes, can incentivize WtH adoption by reflecting the environmental benefits and external costs associated with traditional energy sources.

Public Perception:

♦ Safety concerns: Addressing public concerns about the potential safety risks associated with hydrogen production, storage, and transportation is crucial for gaining public acceptance.

♦ Raising awareness: Educating the public about the benefits and safety measures of WtH technology can help promote its adoption and overcome potential societal resistance.

TIDAL TO HYDROGEN

Global total energy demand is rising from around 630 exajoules (EJ) in 2022 to 670 EJ by 2030 according to the Stated Policies Scenario (STEPS) [72]. As per the International Energy Agency (IEA), the global energy demand will continue to rise through 2050 in almost all scenarios. While fossil fuels still make up most of our energy use now, their share is expected to shrink from 80% to around 69% by 2030, opening the door for clean energy sources to take over according to the Announced Pledges Scenario APS and 62% in the net zero emission NZE scenario. Hydrogen emerges as a critical clean energy player, with consumption doubling in the faster-decarbonization scenario, especially in sectors like aviation and shipping.

Tidal energy, driven by the gravitational pull of the moon and sun, offers a promising source of clean and reliable energy that is predictable. According to the IEAs 2023 Offshore Renewables Technology Report, the global technical potential of tidal energy stands at a staggering 1,000 GW – enough to meet almost 10% of current global electricity demand. Notably, a 2022 study published in Environmental Science & Technology Letters estimates a more accessible potential of 500 GW, focusing on areas with higher resource density and existing infrastructure. One of the technologies that needs to be expanded for the energy system to achieve complete decarbonization is ocean energy (IRENA, 2023) [73]. Ocean energy can supply coastal nations and island people worldwide with clean, localized, and predictable electricity by 2050 which represents a 350 gigawatt (GW) global market.

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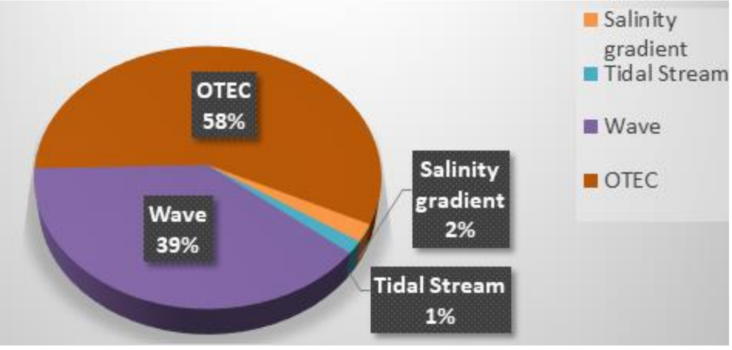

Figure 2. Ocean Energy global resource potential (TWh/year)

[Source: IRENA (2020a), based on Nihous, 2007; Mørk et al., 2010; Skråmestø et al., 2009; OES, 2017.]

Ocean energy technologies are typically classified based on the energy sources they utilize for power generation. Among these, tidal stream and wave energy converters stand out as highly promising solutions with potential applicability in various geographic locations. Other technologies also exist, capable of harnessing energy from temperature differentials, variations in salinity levels, and the kinetic energy of ocean currents (IRENA, 2020a). Global ocean energy potential and deployment are illustrated in Figures 2 and 3, as reported by the International Renewable Energy Agency (IRENA) [74].

Even if the use of ocean energy fell short of initial expectations, things are starting to change. With its cutting-edge technology and expanding farm operations, tidal energy is ready for market adoption. Even though it is still in its infancy, wave energy pursues various objectives, including both large-scale arrays and specialized uses. Although OTEC and salinity gradient are relatively new, increased investment and planned projects indicate that all technologies will grow. Driven by cooperative initiatives from nations like Finland, France, and Canada, by 2030, tidal energy could account for more than 10 GW of clean ocean technology. We are ready to harness the limitless power of the ocean [74].

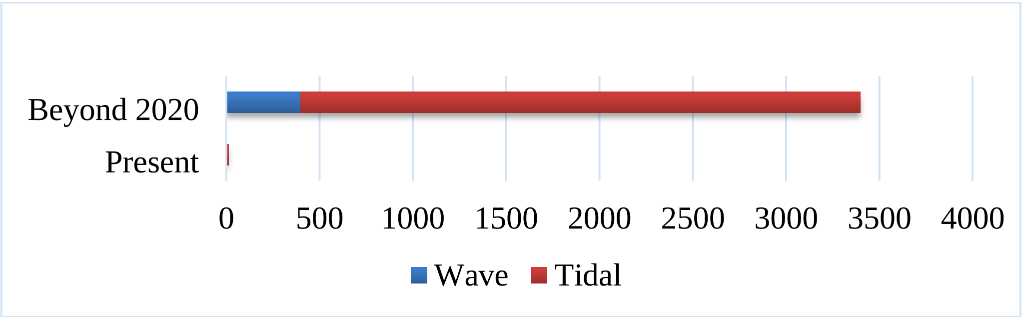

Figure 3: Present and future tidal stream and wave capaity beyond 2020 (in MW)

[Source: IRENA ocean energy database]

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There are two distinctly different strategies for taking advantage of tidal energy. The first involves deploying barrages to take advantage of the sea levels cyclical rise and fall. In contrast, the second involves harnessing local tidal currents in a way that's similar to wind power [75]. Ocean Energy sources such as Tides, waves and currents could be used to generate electricity.

Ocean technologies with promising potential, still undergoing research and development without commercial availability, include: (i) Wave energy converters, which harness the energy from ocean waves to generate electricity. These converters encompass various types such as oscillating water columns that capture air pockets to drive turbines, oscillating body converters utilizing wave motion, and overtopping converters utilizing height differentials. (ii) Tidal energy generation methods, which can employ hybrid applications, tidal-current or tidal-stream technologies, and tidal-range technologies utilizing a barrage (like a dam or barrier) to harness power between high and low tides. (iii) Salinity gradient energy production, which occurs when freshwater from a river mixes with the ocean, leading to varying salt concentrations. Demonstrative projects include pressure retarded osmosis, where freshwater passes over a membrane to increase pressure in a saltwater tank, and reverse electrodialysis, where salt ions move through alternating saltwater and freshwater tanks. (iv) Ocean thermal energy conversion, a process utilizing the temperature contrast between warm surface saltwater and deep, 800- to 1,000-meter seawater to generate power.

Different tidal energy technologies include:

- Enclosed Tidal Basin System: Water enters a closed tidal basin during high tide and is released at low tide, passing through turbines to generate electricity.
- Horizontal Axis Turbines: Blades radially attached to a horizontal shaft rotate underwater, similar to a wind turbine, with the hub or blades needing to turn 180 degrees during reverse flow.
- Vertical Axis Turbines: Blades parallel to a vertically rotating shaft generate power regardless of the flow direction of tidal water.
- Enclosed Tips/Open Center Technology: Tidal water velocity increases as it concentrates in a funnel-shaped structure or duct, where a turbine produces energy.
- Reciprocating Device/Oscillating Hydrofoil: Tidal water flow lifts an oscillating hydrofoil attached to an arm, causing up-and-down movement that generates energy through a shaft or pistons.
- Archimedes Screw/Spiral: A tidal water stream turns the spiral of a helical-shaped impeller, converting this rotation into energy.
- Tidal Kite: A kite attached to the seabed or floating platform moves in an eight-shaped or linear trajectory through the tidal stream, generating electricity due to the increase in its relative velocity.

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Hydrogen production from marine resources:

The integration of electrolysis with marine energies is very beneficial since it allows the storage of electrical energy that is produced in excess in the form of green hydrogen. Rather than directly storing ocean energy, we can unlock its long-term potential by employing electrolysis to convert it into hydrogen fuel. This green hydrogen production, coupled with ocean energy, can take two forms: centralized electrolysis plants nestled offshore or onshore facilities offering greater flexibility. By transforming the ocean's power into storable hydrogen, we bridge the gap between renewable energy capture and convenient, versatile usage [76]. When it comes to creating hydrogen from water using electricity, we have four main options: alkaline electrolysis (AE), the classic workhorse; proton exchange membrane electrolysis (PEME), known for its speed and purity; high-temperature solid oxide electrolysis (SOE), offering efficiency and diverse feedstock; and the intriguing newcomer, direct electrolysis seawater (DES), bypassing freshwater purification altogether. Each technology boasts unique strengths and challenges, offering a spectrum of choices for producing electrolytic hydrogen tailored to specific needs and resources.

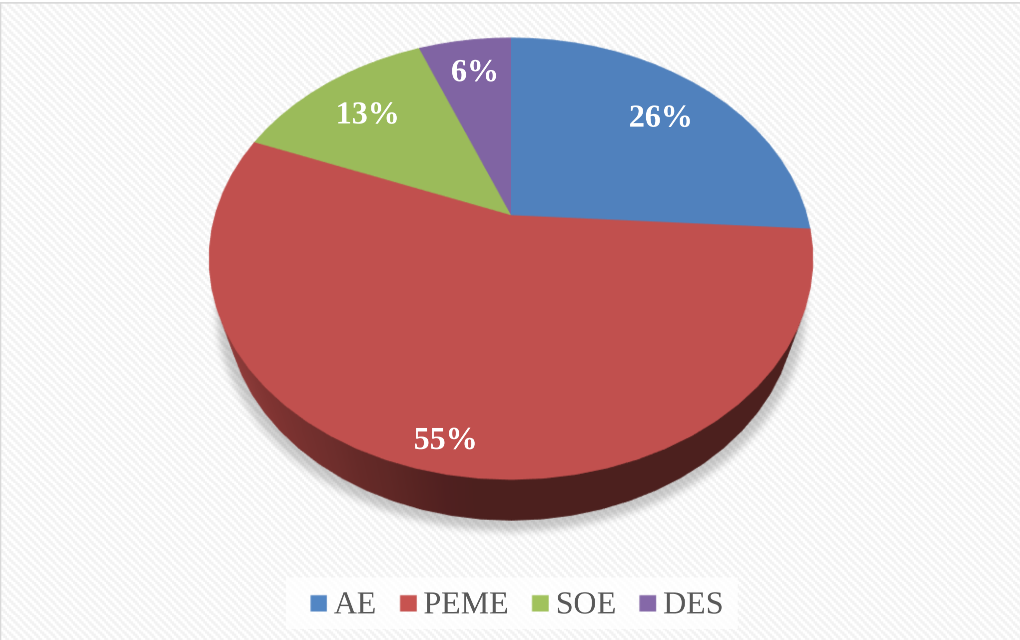

Figure 4: Commonly used electrolyzers to produce green hydrogen by marine energy

[Source: Feasibility analysis of green hydrogen production from oceanic energy sources [76]

The most frequently used electrolysers to produce green hydrogen using oceanic energy are PEME and AE, with 55% and 26% preferences, respectively, as shown in Figure 4. This is primarily due to their technology and their higher efficiency with long useful life and cost efficiency. PEME and AE are suitable for generating green hydrogen using marine energy

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sources. The comparison between AE and PEME for green hydrogen production from ocean energy shows AE has a better resistance to impurities in the seawater, a longer life span, and a proven track record. However, its slow response leaves it lagging behind PEME. Whereas PEME is most suitable for green hydrogen production using ocean energy sources due to its quick response to the energy input, but this comes at the cost of rapid membrane degradation, corroding electrodes, and a shorter lifespan. Efficiency-wise, AE takes the lead in offshore scenarios, with some studies reporting figures exceeding 72%. PEME generally trails behind at around 66%, though a remarkable 93% was achieved in one instance. Ultimately, the choice between these technologies depends on priorities – prioritize long-term stability and resistance to harsh conditions, choose AE; need a nimble performer who excels with variable energy input, PEME may be your champion [76].

Unleashing the vast potential of seawater for green hydrogen production holds the key to unlocking a sustainable future with a dramatically reduced global water footprint. While only 2.5% of Earths water is fresh, the remaining 97.5% slumbers in the salty embrace of oceans and seas. This seemingly limitless resource can be tapped through various purification methods like desalination, opening doors for its use in electrolyzers. For ocean energy sources, the proximity to seawater presents a unique advantage – integrating desalination plants into their green hydrogen production becomes a tantalizing possibility. This synergistic approach not only tackles the freshwater scarcity challenge but also leverages the dependable ocean currents and tides to power an eco-friendly hydrogen revolution.

Site selection for ocean energy projects and installation characteristics:

Choosing the perfect spot for an ocean energy project is like finding the sweet spot in a symphony - everything needs to harmonize. Geographical features, grid proximity, water depth, accessibility, environmental impact, and even public opinion all play their part in creating a harmonious energy system.

Researchers like Rediske et al. have identified key factors for onshore wind farms, and by adapting these to the ocean, we can create a three-stage selection process: (i) Identify areas with strong ocean currents or waves; (ii) Exclude areas that clash with shipping lanes, protected environments, or migration routes; and (iii) Choose the sites that offer the most benefits and least limitations, considering factors like port access, water depth, and construction ease. This is not the end.

The oceans depths pose their own challenges. Deeper waters call for floating turbines, like the stable semisubmersible platforms, which boast promising economic viability. Accessibility also plays a crucial role, as remote locations drive up maintenance costs. Ultimately, finding the perfect ocean energy location is like composing a masterpiece - considering every note, every factor, to create a symphony of sustainable energy production.

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Technical aspects of marine farms for energy and green hydrogen production:

Harnessing the ocean's power depends on two key factors: turbine efficiency and capacity factor. how efficiently the device converts the resource into electricity (device efficiency) and how often it can operate at peak capacity (capacity factor).

Storage of green hydrogen:

Capturing the ocean's power through green hydrogen brings us to the next challenge: storing this valuable fuel. The method for storing hydrogen depends on its form: gas, liquid, or solid. Gaseous hydrogen can be stored in underground caverns, pressurized tanks, or pipelines, with salt caverns offering the most cost-effective solution for large-scale applications. Liquid hydrogen, suitable for long distances or limited space, requires energy-intensive liquefaction and cryogenic storage. Solid hydrogen storage through metal hydrides is still under development, while adsorption onto nanomaterials shows promise for future advancements. Ultimately, the choice of storage method depends on factors like capacity, application, and cost.

Compressed gas and cryogenic liquids are the most common ways to store hydrogen. Chemical and physical methods using ammonia, nanotubes, and more are in the pipeline, aiming to overcome limitations like cost and security for mobile applications. Research suggests improvements through material innovations like metal hydride alloys and catalytic techniques, promising a brighter future for portable hydrogen solutions.[76]

Transportation of green hydrogen:

The transportation of marine-generated hydrogen to land depends on distance and economics. For short trips close to shore, it's cheapest to send electricity via underwater cables and convert it to hydrogen on land. Ships take over for longer distances, with liquefied hydrogen offering the lowest cost but compressed gas requires more energy. Pipelines are ideal for long hauls but repairing ruptures is tough, making them less attractive than cables. Ultimately, the choice depends on factors like pipeline resilience and the suitability of using liquid organic hydrogen carriers for distribution.[76]

Economic feasibility:

Evaluating the economic viability of a marine system producing hydrogen requires considering various factors. The Levelized Cost of Hydrogen (LOCH2) plays a crucial role, with lower values indicating better prospects. Studies estimate LOCH2 values ranging from 20 €/kg to 89.43 €/kg, heavily influenced by energy production and technology development risks. Net Present Value (NPV) analyses suggest a 30% reduction in capital cost is key for success, with hydrogen prices reaching feasibility around 5 €/kg by 2030. Distance from shore significantly impacts costs, with both CAPEX and LCOE increasing exponentially. Wind farm capacity, on

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the other hand, affects CAPEX and OPEX proportionally, while exhibiting a decreasing LCOE trend due to economies of scale. While off-grid options currently boast the lowest LCOH2, long-term viability points towards offshore wind becoming a competitive option for isolated consumers in the future. Ultimately, a comprehensive analysis encompassing all economic factors is crucial for determining the financial feasibility of any marine hydrogen production system.[76]

Environmental aspects:

Marine hydrogen production shows remarkable environmental benefits. Compared to traditional methods, electrolysis generates far less greenhouse gas emissions, with studies estimating up to 94% reduction. PEME technology dominates as the cleanest option, eliminating concerns of caustic electrolyte leaks associated with alternatives like AE. By switching from gasoline to electrolytically produced hydrogen, significant carbon footprint reductions are achievable, reaching 268 tons per vehicle for fuel cell electric cars. Green hydrogen from offshore wind offers substantial emissions reductions compared to grid-electricity-derived hydrogen or coal gasification. Several studies showcase how marine hydrogen can significantly curtail pollution in specific contexts, such as replacing diesel buses with hydrogen vehicles in Sicily and reducing emissions at the Port of Damietta. However, environmental hurdles exist. Concrete elements in construction contribute heavily to the environmental impact, and certain marine power systems can harm aquatic life. Despite these challenges, the environmental strengths of marine hydrogen, coupled with potential for technological advancements and societal benefits, present exciting opportunities for the future of clean energy.

In conclusion, green hydrogen production from oceanic sources like offshore wind and marine currents holds promise for clean energy. The key to success lies in efficient systems: high-capacity factors, fast-responding PEME electrolyzers, and proximity to the coast for cost-effectiveness. While transportation options depend on distance, with electric cables for short hauls and ships for longer journeys, salt caves offer the best large-scale hydrogen storage. Economically, hydrogen production becomes preferable to electricity sales when prices range from 5 to 13 €/kg, highlighting the potential profits. Despite initial emissions from construction, the long lifespan and clean operation of these systems make them environmentally sound. Moreover, the transition to a hydrogen economy opens exciting economic opportunities for countries rich in renewable resources, as production costs decrease with technological advancements. Further research, incorporating a wider range of ocean energy technologies and detailed analysis of integrated marine systems, is crucial for optimizing this promising clean energy path.

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GEOTHERMAL TO HYDROGEN:

Geothermal-to-hydrogen technology involves using geothermal energy, which is heat derived from the Earth's interior, to produce hydrogen gas through various processes. This approach combines renewable geothermal resources with hydrogen production, offering a potentially sustainable and low-carbon energy solution [77].

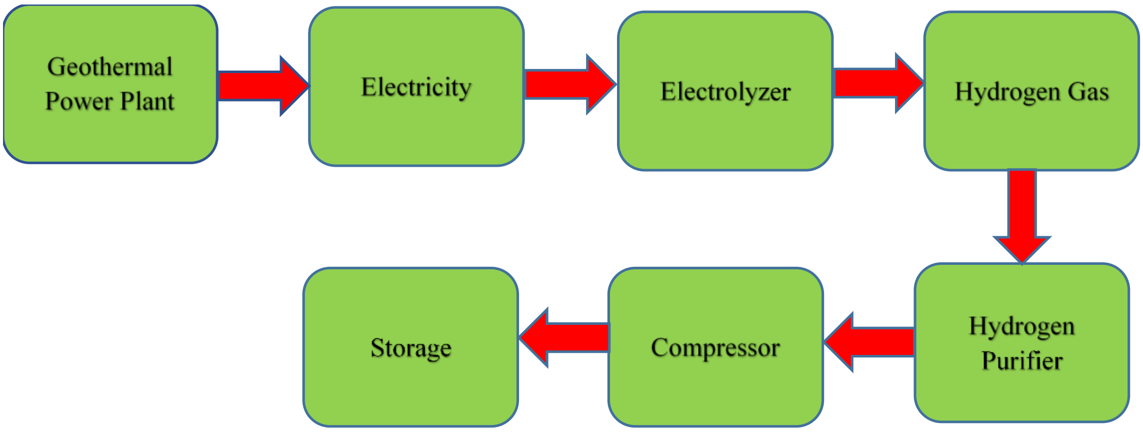

Figure 5: Geothermal to hydrogen process

Figure 5 shows the process of hydrogen production from geothermal sources. An overview of geothermal-to-hydrogen production process is as follows: (i) Geothermal Energy Extraction: Geothermal energy is harnessed from hot rocks or reservoirs of steam and hot water beneath the Earth's surface. This heat can be accessed through geothermal wells or by tapping into naturally occurring geothermal features. (ii) Electricity Generation: The primary application of geothermal energy is often electricity generation. Geothermal power plants use the heat from underground reservoirs to produce steam, which drives turbines connected to generators to generate electricity. (iii) Hydrogen Production: Geothermal energy can also be utilized for hydrogen production through various methods: (a) Electrolysis: Geothermal electricity generated from steam or hot water can power electrolysis processes to split water molecules into hydrogen and oxygen. This can be done using alkaline electrolysis or proton exchange membrane (PEM) electrolysis technologies. (b) Thermochemical Processes: Alternatively, geothermal heat can directly drive high-temperature thermochemical processes to produce hydrogen from water or other feedstocks. For example, thermochemical water splitting involves using heat to drive chemical reactions that release hydrogen from water molecules. (iv) Hydrogen Purification: The produced hydrogen gas may undergo purification processes to remove impurities and ensure high-purity hydrogen suitable for various applications [78].

Geothermal-to-hydrogen technology offers several advantages [79]:

- Continuous and Reliable Energy: Geothermal energy is a continuous and reliable renewable resource, providing a stable source of heat for hydrogen production.

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- Zero Emissions: When combined with electrolysis powered by geothermal electricity, the process can produce hydrogen with zero greenhouse gas emissions.
- Local Energy Production: Geothermal resources are often found in specific regions, allowing for localized energy production, and reducing dependence on imported energy.

However, there are challenges to consider [80]:

- Location Constraints: Geothermal resources are not evenly distributed globally, and suitable sites may be limited to certain geological conditions.
- Cost and Efficiency: The cost of developing and operating geothermal power plants and hydrogen production facilities can be significant, requiring ongoing advancements in technology and cost reduction efforts.
- Infrastructure Development: Infrastructure for hydrogen storage, transportation, and utilization needs to be developed and integrated into existing energy systems.

Despite these challenges, ongoing research and development in geothermal-to-hydrogen technology aim to improve efficiency, reduce costs, and increase the scalability of this approach, contributing to the transition towards a more sustainable and diversified energy mix.

BIOHYDROGEN:

Biomass-to-hydrogen technology involves converting biomass, which includes organic materials such as agricultural residues, forestry waste, energy crops, and organic municipal waste, into hydrogen gas through various processes. This approach leverages renewable biomass resources to produce hydrogen as a clean energy carrier [81].

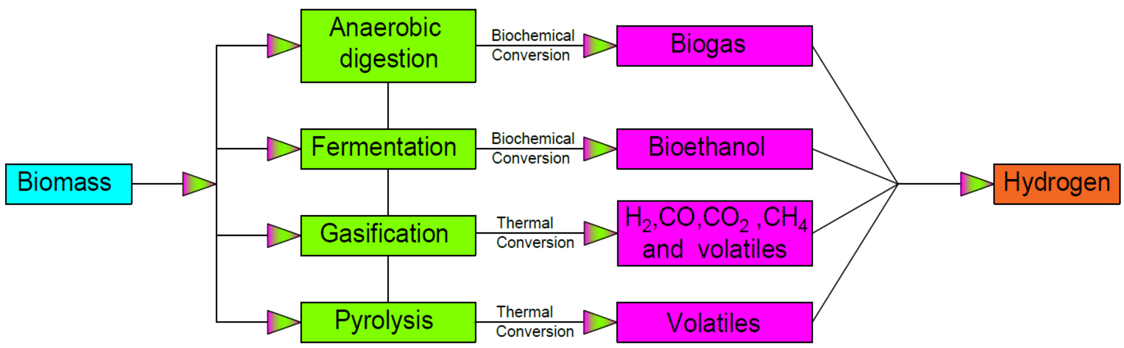

Figure 6: Major pathways of producing hydrogen from biomass.

Figure 6 shows the major pathways of producing hydrogen from biomass. An overview of biomass-to-hydrogen production is as follows: (i) Biomass Feedstock Collection: Biomass feedstock, which can include agricultural residues like crop stalks, forestry waste such as wood chips or sawdust, energy crops like switchgrass or miscanthus, and organic municipal waste, is collected and prepared for processing. (ii) Thermochemical Conversion: Biomass can be

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converted into hydrogen gas through thermochemical processes, such as gasification or pyrolysis: (a) Gasification: Biomass gasification involves heating the biomass feedstock in a low-oxygen environment to produce a mixture of gases known as syngas, which contains hydrogen, carbon monoxide, methane, and other gases. The syngas can then be processed to separate and purify hydrogen. (b) Pyrolysis: Pyrolysis is a process that involves heating biomass in the absence of oxygen to break down the organic materials into gases, liquids (bio-oil), and solids (biochar). Hydrogen can be extracted from the gases produced during pyrolysis. (c) Biological Conversion: Alternatively, certain microorganisms can be used in biological processes such as fermentation or anaerobic digestion to produce hydrogen gas from biomass. This method, known as biohydrogen production, involves microbial fermentation of biomass sugars or organic compounds to generate hydrogen as a metabolic byproduct. (iv) Hydrogen Purification: The produced hydrogen gas undergoes purification processes to remove impurities and ensure high-purity hydrogen suitable for various applications [82,83].

Biomass-to-hydrogen technology offers several advantages [84]:

- Renewable Resource: Biomass is a renewable and potentially abundant resource, offering a sustainable source of feedstock for hydrogen production.
- Waste Utilization: Biomass-to-hydrogen processes can help in the management and utilization of agricultural residues, forestry waste, and organic municipal waste, reducing landfill waste and greenhouse gas emissions.
- Energy Security: By utilizing biomass resources locally, biomass-to-hydrogen technology can contribute to energy security and independence.

However, there are challenges to consider [85]:

- Feedstock Availability: The availability and cost of biomass feedstock can vary depending on factors such as geographic location, seasonality, and competing uses (e.g., food production).
- Efficiency and Economics: Biomass-to-hydrogen processes may require advanced technologies to improve efficiency and reduce costs, as well as addressing challenges related to scale and commercial viability.
- Environmental Impact: While biomass-to-hydrogen is considered a renewable and low-carbon option, the environmental impact of biomass cultivation, harvesting, and processing must be managed to ensure sustainability.

Ongoing research and development efforts focus on improving the efficiency, scalability, and environmental sustainability of biomass-to-hydrogen technology, aiming to contribute to a more diversified and sustainable energy portfolio.

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CONCLUSION:

In conclusion, hydrogen production from renewable energy sources such as solar, wind, tidal, geothermal, and biomass presents a promising pathway towards a sustainable and low-carbon energy future. This review has provided a comprehensive analysis of the principles, methods, advancements, and challenges in harnessing these renewable resources for hydrogen generation. Solar energy offers abundant opportunities for hydrogen production through photovoltaic and solar thermal systems, with ongoing advancements in materials, efficiency, and integration technologies. Wind energy, known for its scalability and reliability, contributes to electrolysis-based hydrogen production, supported by innovations in wind turbine technology and energy storage solutions. Tidal energy provides a predictable and continuous source of power for electrolysis-driven hydrogen production, with emerging technologies enhancing the efficiency and viability of tidal-to-hydrogen systems. Geothermal energy, derived from the Earth's heat, offers a sustainable and constant energy supply for hydrogen production through electrolysis or thermochemical processes. Biomass, including organic waste and energy crops, can be converted into hydrogen through gasification or pyrolysis, contributing to the biohydrogen sector and supporting circular economy principles. However, challenges such as cost, efficiency, infrastructure, and policy frameworks remain to be addressed for widespread adoption and commercialization of renewable hydrogen technologies. Future research and development efforts should focus on technological innovations, cost reduction strategies, grid integration, energy storage solutions, and policy support to accelerate the transition to a hydrogen-based economy. Collaboration between industry, academia, government agencies, and stakeholders is crucial for unlocking the full potential of hydrogen production from renewable energy sources and achieving sustainable energy goals. In total, the review underscores the importance of renewable hydrogen as a clean, versatile, and efficient energy carrier, paving the way for a more resilient and environmentally friendly energy system in the years to come.

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