

## Original Research Article



# Energy Crisis and the Path to Salvation: Hydrogen, the Driving Force of a Clean Future

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## ABSTRACT

The increasing global demand for energy, the depletion of fossil fuel reserves, and the environmental consequences of their consumption have made the need for transformation in energy supply systems more urgent than ever. In this context, renewable energy sources have emerged as sustainable alternatives, yet each faces challenges such as dependence on climatic conditions, high infrastructure costs, and storage limitations. Among these options, hydrogen has garnered significant attention from researchers and policymakers due to its high energy density, zero harmful emissions, storage capability, and diverse production sources. This study examines the energy crisis, the limitations of renewable energy sources, and the unique properties of hydrogen, analyzing its significance as a modern energy carrier. Various hydrogen production methods, including gray, blue, and green hydrogen, explored, along with the challenges related to production, storage, and distribution. In addition, the role of hydrogen in industries, transportation, electricity generation, and renewable energy storage was evaluated. The results indicate that with advancements in production technologies and cost reductions, hydrogen could become a key component of a sustainable energy future. Achieving this goal requires investment in infrastructure development, improvements in storage and transportation technologies, and the implementation of effective supportive policies. If existing challenges addressed, hydrogen could play a crucial role in reducing greenhouse gas emissions, enhancing energy security, and facilitating the transition to a sustainable, low-carbon energy system.

## Introduction

In the 21<sup>st</sup> century, energy supply has become one of the fundamental challenges facing human societies. The increasing global demand for energy, the depletion of fossil fuel reserves, and the environmental consequences of excessive resource

consumption have raised serious concerns about the future of energy security [1]. Rapid growth of population and industrial expansion have led to unprecedented levels of energy consumption, which in turn has intensified greenhouse gas emissions, contributing to climate change and global warming. Likewise,

the world's reliance on finite and unsustainable fossil fuel resources has resulted in economic instability, severe energy price fluctuations, and geopolitical crises [2-4]. To address this crisis, a fundamental transformation in the global energy system is necessary. In this context, renewable energy sources have emerged as sustainable and environmentally friendly alternatives. Solar, wind, geothermal [5], and biomass energy offer promising solutions to decline dependence on fossil fuels. However, each of these sources faces limitations such as reliance on weather conditions, energy storage challenges, and high infrastructure costs [6]. Among the available alternatives, hydrogen has attracted the attention of researchers and policymakers as an innovative energy carrier [7]. Due to its zero-emission nature, capability of produced from diverse sources, and ease of storage and transportation, hydrogen is considered one of the most viable solutions for sustainable energy supply in the future. This study examines the energy crisis, the role of renewable energy sources, and the potential of hydrogen as the driving force of the future. It highlights how this clean fuel can serve as a viable solution to the global energy crisis [8].

### *Energy crisis: Causes and consequences*

#### *Global dependence on fossil fuels*

Energy is a fundamental necessity for modern societies, essential for industrial growth, transportation, and daily activities. However, a significant portion of the world's energy supply still comes from fossil fuels such as oil, natural gas, and coal. These resources, formed over millions of years through geological processes, are finite. The increasing global energy demand has led to the gradual depletion of fossil fuel reserves, reinforcing the urgent need for alternative energy sources [9].

Besides resource limitations, fossil fuel consumption presents numerous challenges:

#### *Environmental impact*

The combustion of fossil fuels releases greenhouse gases and air pollutants.

#### *High extraction and refinement costs*

As available reserves diminish, extraction becomes increasingly expensive and complex.

#### *Energy price volatility*

Changes in the supply and demand of these resources can lead to instability in global energy markets [10].

#### *Environmental consequences of the energy crisis*

One of the most pressing challenges associated with fossil fuel consumption is its environmental impact. The emission of greenhouse gases, including carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrogen oxides (NO<sub>x</sub>), has detrimental effects on the climate and human health. Some of the major environmental consequences include:

#### *Global warming and climate change*

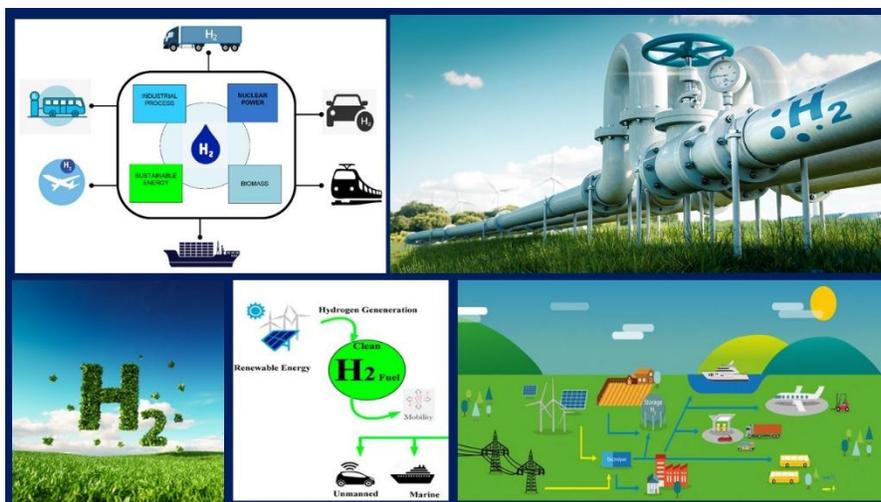
The rising concentration of greenhouse gases is leading to increased global temperatures, resulting in the melting of polar ice caps, rising sea levels, and extreme weather events.

#### *Air pollution*

The combustion of fossil fuels not only generates CO<sub>2</sub>, but also releases harmful pollutants such as sulfur dioxide (SO<sub>2</sub>) and particulate matter (PM), which contribute to respiratory and cardiovascular diseases (Figure 1).

#### *Ecosystem damage*

The extraction and transportation of fossil fuels can result in oil spills and water contamination, negatively impacting plant and animal life [11-13].



**Figure 1:** Energy crisis and the path to salvation: hydrogen, the driving force of a clean future

### *Economic and industrial challenges of the energy crisis*

The energy crisis is not only an environmental issue, but also poses significant economic and industrial challenges. Some of these challenges include:

#### *Rising costs of energy production and consumption*

As fossil fuel reserves dwindle and extraction becomes more complex than, energy prices increase, raising production costs across industries [14].

#### *Low energy efficiency*

Many existing technologies used in energy consumption have low efficiency, leading to significant energy waste, particularly in industrial and transportation sectors [15].

#### *Economic dependence on fossil fuels*

Many economies are still heavily reliant on oil and gas as their primary energy sources, limiting their ability to transition toward sustainable development [16]. Given these challenges, the need for alternative energy sources has become more critical than ever. Expanding renewable energy technologies is an essential step in reducing fossil fuel dependence and mitigating environmental

damage. Among these alternatives, hydrogen emerges as a highly promising energy carrier that could replace fossil fuels. The following sections will explore the hydrogen potential as a viable energy solution [17-19].

#### *Renewable energy: Green alternatives*

Given the limitations of fossil fuels and the environmental consequences of their consumption, the development and adoption of renewable energy sources have become a sustainable solution for energy supply in the 21<sup>st</sup> century. Renewable energy sources are naturally replenished and, unlike fossil fuels, do not contribute to greenhouse gas emissions. Some of the most significant renewable energy sources include solar, wind, geothermal, and biomass energy [20-22]. The following sections will examine and analyze each of these energy sources in detail (Table 1). Each renewable energy source has its advantages and disadvantages, and no single source can fully meet global energy demands (Table 2). However, integrating multiple renewable sources into a unified energy system can significantly reduce greenhouse gas emissions and enhance energy sustainability (Table 3). Hydrogen, as a potential energy carrier, can play a crucial role in storing and transporting renewable energy. The following section will explore hydrogen's characteristics and its potential as the fuel of the future (Table 4).

**Table 1:** Solar energy is one of the most abundant and sustainable sources of renewable energy worldwide. This energy harnessed through sunlight using various technologies, such as photovoltaic (PV) cells and concentrated solar power (CSP) systems, to generate electricity and heat

Challenges and Limitations	Advantages
<i>Dependence on Weather Conditions:</i> Energy generation is reliant on sunlight, making it ineffective during cloudy days and nighttime.	<i>Abundant Resource:</i> Solar energy is available globally and continuously provided by the sun.
<i>High Initial Investment:</i> The installation cost of solar panels is relatively high, although prices have decreased in recent years.	<i>Zero Greenhouse Gas Emissions:</i> Electricity production from solar energy does not generate CO <sub>2</sub> or other pollutants.
<i>Large Land Area Requirement:</i> Large-scale electricity production requires extensive land, which can be a constraint in urban areas.	<i>Low Maintenance Costs:</i> Solar PV systems have minimal operational and maintenance costs.
<i>Limited Energy Conversion Efficiency:</i> The efficiency of photovoltaic cells typically ranges between 15-25%, meaning a significant portion of solar energy is not converted into electricity. New technologies, such as multi-junction solar cells, are improving efficiency but remain expensive.	<i>Versatility in Application:</i> Solar power used in both large-scale power plants and small residential installations.

**Table 2:** Wind energy is one of the most cost-effective and widely used renewable energy sources. It harnessed using wind turbines to generate electricity, with wind speed and consistency playing a crucial role in system efficiency

Challenges and Limitations	Advantages
<i>Dependence on Weather Conditions:</i> Electricity generation fluctuates with wind speed, making it unreliable on calm days.	<i>High Efficiency in Wind-Rich Areas:</i> In regions with strong winds, wind energy can be a stable and cost-effective source of electricity.
<i>Environmental and Noise Concerns:</i> Wind turbines can impact bird populations and wildlife. Additionally, their operation generates noise pollution.	<i>Zero Environmental Emissions:</i> Similar to solar energy, wind energy does not produce greenhouse gases.
<i>Location Constraints:</i> Wind farms require large open areas, making them difficult to implement in densely populated regions.	<i>Low Operational Costs:</i> Once installed, wind turbines have minimal maintenance and operational expenses.

**Table 3:** Geothermal energy derived from the heat stored beneath the Earth's surface. This energy extracted through geothermal wells and used for electricity generation or direct heating

Challenges and Limitations	Advantages
<i>Geographic Constraints:</i> Geothermal energy is viable only in areas with thin Earth's crust, such as volcanic regions.	<i>Reliable and Independent of Weather:</i> Unlike solar and wind, geothermal energy is available continuously.
<i>High Drilling and Infrastructure Costs:</i> Extraction requires deep drilling, which is expensive.	<i>High Efficiency:</i> Geothermal power plants can operate 24/7, providing a consistent energy supply.
<i>Potential Seismic Activity:</i> Geothermal extraction may trigger small earthquakes in some regions.	<i>Small Land Footprint:</i> Compared to solar and wind, geothermal systems require less space.

**Table 4:** Biomass energy derived from organic materials, such as plant waste, municipal solid waste, animal manure, and wood. These materials converted into gas, liquid, or solid fuels for power generation and heating

Challenges and Limitations	Advantages
<i>Air Pollution:</i> Although cleaner than fossil fuels, biomass combustion still releases greenhouse gases.	<i>Reduces Dependence on Fossil Fuels:</i> Biomass can serve as a substitute for fossil fuels in electricity generation and biofuels.
<i>High Land and Water Demand:</i> Large-scale biomass production requires agricultural land, potentially competing with food production.	<i>Waste Recycling:</i> Biomass utilization helps manage organic waste and reduces environmental pollution.

### *Hydrogen: The fuel of the future?*

In the search for a sustainable, efficient, and environmentally friendly energy source, hydrogen has emerged as one of the most promising energy carriers. Unlike fossil fuels, which deplete and contribute to greenhouse gas emissions, hydrogen possesses unique characteristics that make it an ideal candidate for the future of global energy [24-26]. Hydrogen naturally exists in combined forms within water, hydrocarbons, and organic compounds and extracted through various processes, including water electrolysis, natural gas reforming, and biomass decomposition. The most significant advantage of hydrogen is that its consumption produces only water as a by-product, making it a clean and emission-free fuel [27]. This section explores the properties of hydrogen as an energy carrier, its production methods, benefits, challenges, and its role in the future of energy [28].

### *Properties of hydrogen as an energy carrier*

Hydrogen is a lightweight, highly reactive element with the highest energy density per unit mass among all fuels. These properties make hydrogen a key parameter in different industrial sectors, transportation, and energy production. Some of its essential characteristics include:

#### *High energy density (120 MJ/kg)*

Hydrogen provides nearly three times the energy per kilogram compared to gasoline [29].

#### *Zero harmful emissions*

When burned in the presence of oxygen, hydrogen produces only water vapor, eliminating greenhouse gas emissions [30].

### *Usability in fuel cells*

Hydrogen converted into electricity through fuel cells, offering high efficiency.

### *Storage and transport challenges*

Despite its advantages, hydrogen's low volumetric density and its tendency to leak lead to some difficulties in storage and transportation, which discussed further in the challenges section [31].

### *Hydrogen production methods*

Hydrogen produced through three primary methods, each with distinct characteristics, costs, and environmental impacts. These methods are:

#### *Gray hydrogen*

Gray hydrogen is the most common and least expensive production method, utilizing Steam Methane Reforming (SMR). In this process, natural gas (CH<sub>4</sub>) reacts with steam at high temperatures, producing hydrogen [32].

#### *Advantages*

Well-established technology, low production cost [33].

Limitations: High CO<sub>2</sub> emissions, dependency on natural gas resources.

#### *Blue hydrogen*

This technique is similar to gray hydrogen but incorporates Carbon Capture and Storage (CCS)

to trap and store CO<sub>2</sub> emissions, reducing environmental impact [34].

#### *Advantages*

Lower greenhouse gas emissions compared to gray hydrogen.

#### *Limitations*

High costs of carbon capture technology, additional energy consumption.

#### *Green hydrogen*

The cleanest and most sustainable hydrogen production method involves water electrolysis powered by renewable energy sources such as solar or wind energy. In this process, water molecules (H<sub>2</sub>O) split into hydrogen and oxygen [35].

#### *Advantages*

Zero greenhouse gas emissions, renewable and sustainable.

#### *Limitations*

High production cost, need for extensive renewable energy infrastructure.

Currently, over 95% of the world's hydrogen produced through the gray hydrogen method. However, global investments are increasingly shifting toward green hydrogen production to align with sustainability goals [36].

#### *Advantages and applications of hydrogen in the future of energy*

Hydrogen can serve as a versatile energy carrier across various sectors. Some of its most significant advantages and applications include:

#### *Power generation and heating*

Hydrogen used in gas turbines or fuel cells to generate electricity [37]. It serves as a viable alternative to natural gas for heating systems in buildings.

#### *Transportation sector*

Hydrogen used as fuel in fuel cell electric vehicles (FCEVs).

It has high potential for reducing CO<sub>2</sub> emissions in heavy transportation, including trucks, ships, and airplanes.

#### *Energy storage and transmission*

Hydrogen utilized as an energy storage medium for excess energy generated from solar and wind power plants [38]. It has the ability to transport through natural gas pipelines or liquefied for export.

#### *Challenges and limitations in hydrogen development*

Despite its advantages, hydrogen faces several challenges that hinder its widespread adoption:

#### *High production costs*

Green hydrogen production through electrolysis is still expensive and requires low-cost renewable electricity to be economically viable [39].

#### *Storage and transportation issues*

Hydrogen has high gravimetric energy density but low volumetric energy density, making storage and transportation technically complex and costly.

#### *Lack of infrastructure*

Large-scale hydrogen adoption requires new distribution networks and refueling stations [40].

#### *Low efficiency in the supply chain*

The processes of production, compression, transportation, and utilization of hydrogen are energy-intensive, which can reduce overall efficiency [41].

#### *Is hydrogen the fuel of the future?*

Hydrogen is undoubtedly one of the most promising solutions for declining dependence on fossil fuels and decarbonizing the energy sector. However, for hydrogen to become a primary fuel, several key challenges addressed, including reducing production costs, developing storage infrastructure, and optimizing related technologies [42]. In the coming years, advancements in electrolysis, storage technologies, and government support policies could pave the way for the expansion of the hydrogen economy and its replacement of fossil fuels.

### *Hydrogen as an energy carrier: Key characteristics*

Hydrogen, as an energy carrier, possesses unique characteristics that distinguish it from other fuels and energy carriers. These features include high energy density, zero harmful emissions, storage capability, and conversion to electrical energy, and production from diverse sources. Below, these characteristics examined in detail:

#### *High energy density*

One of the most significant features of hydrogen is its exceptionally high energy density per unit mass. Hydrogen has an energy density of 120 MJ/kg, which is nearly three times that of gasoline (44 MJ/kg) and significantly higher than natural gas (53 MJ/kg). This property enables a small amount of hydrogen to generate a considerable amount of energy, making it particularly important for industries requiring high-energy output, such as aviation and maritime transportation [43].

However, despite its high gravimetric energy density, hydrogen has a very low volumetric energy density (0.08 kg/m<sup>3</sup> under standard conditions). This means that storing hydrogen in gaseous or liquid form requires large volumes, which presents significant technical challenges.

#### *Zero harmful emissions*

Unlike fossil fuels, which release greenhouse gases (CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>2</sub>) and other pollutants

when burned, hydrogen combustion produces only water vapor (H<sub>2</sub>O) as a byproduct. This feature makes hydrogen a clean and sustainable fuel, playing a key role in decarbonizing industries and mitigating climate change. However, gray and blue hydrogen production methods still involve significant CO<sub>2</sub> emissions, making green hydrogen (produced via electrolysis with renewable energy) the only truly zero-emission option.

#### *Storage and transportation capability*

One of hydrogen's most crucial attributes is its capability to be stored and transported as an energy carrier. Hydrogen can be stored and transported in several forms:

##### *Compressed gas*

Stored at high pressures (350-700 bar) for applications such as fuel cell vehicles.

##### *Cryogenic liquid*

Stored at extremely low temperatures (~ -253 °C), making it suitable for long-distance transportation.

##### *Metal hydrides*

Absorbed into metal compounds for safer storage with reduced high-pressure requirements.

##### *Liquid organic hydrogen carriers (LOHCs)*

Hydrogen chemically bonded to organic liquids (e.g., toluene) for safer and more efficient transport [44].

Hydrogen's versatility in storage and transportation is crucial for transferring renewable energy (e.g., solar and wind energy) to consumption sites. However, hydrogen storage methods are energy-intensive and costly due to the need for high pressure or cryogenic temperatures. Furthermore, global hydrogen infrastructure not as well developed as natural gas distribution networks.

##### *Conversion to electrical energy in fuel cells*

One of hydrogen's most attractive features is its ability to convert into electricity without combustion using fuel cells. In a fuel cell, hydrogen reacts with oxygen through an electrochemical process, generating electricity, water, and heat.

This process functions like a battery but with continuous operation as long as fuel supplied. The benefits of fuel cells include:

#### *High efficiency*

Fuel cells achieve 40-60% efficiency, compared to ~30% efficiency in combustion engines.

#### *Zero emissions*

The only byproduct is water, making them environmentally friendly.

#### *Versatile applications*

Fuel cells used in vehicles, power stations, and buildings.

However, challenges remain:

#### *High production cost*

Expensive materials like platinum catalysts increase costs.

#### *Limited durability*

Fuel cells typically have shorter lifespans than batteries in some applications.

#### *Production from diverse sources*

A key advantage of hydrogen is that it is produced from various sources, unlike fossil fuels, which are dependent on finite petroleum and gas reserves. Hydrogen production methods include:

Electrolysis of Water (Renewable Energy-Powered) → Green Hydrogen

Steam Methane Reforming (Natural Gas-Based) → Gray / Blue Hydrogen

Coal Gasification → Brown Hydrogen

Biomass Conversion (Biochemical Processes) → Renewable Hydrogen

This flexibility allows hydrogen to produce in different regions using available energy resources. However, cleaner methods such as electrolysis are still costly and require technological advancements. High energy density, zero emissions, storage capabilities, and production flexibility of hydrogen make it one of the most promising energy carriers for the future. However, for it to become a primary global fuel, cost reductions, improved storage solutions, and infrastructure expansion are essential. In recent years, governments and major industrial players have been investing heavily in hydrogen economy development. With advancements in related technologies, hydrogen significantly contributes in the transition to a sustainable, carbon-free energy system.

### **Conclusion and Recommendations**

Hydrogen, as a clean and sustainable energy carrier, has significant potential to decline dependence on fossil fuels and contribute to the decarbonization of various sectors, including energy, industry, and transportation. However, its development still faces challenges such as high production costs, the need for storage and distribution infrastructure, and the efficiency of related technologies. To accelerate the adoption and expansion of hydrogen usage, it is essential to focus on reducing production costs, advancing storage technologies, improving fuel cell efficiency, and establishing appropriate infrastructure. In addition, supportive policies, large-scale investments, and international collaborations can help pave the way for the growth of the hydrogen economy. If these challenges addressed, hydrogen could become one of the key elements in a sustainable energy future, playing a crucial role in power generation, transportation, industry, and the storage of renewable energy.

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