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A Review on Hydrogen with a Critical Role in Sustainable Energy

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ABSTRACT

Developing sustainable and renewable energies can solve the energy crisis in the world. In this regard, one of the focal points in the energy field is to expand the use of lower-carbon technologies soon. Furthermore, it is necessary to prevent depletion problems of non-renewable energy resources and environmental issues such as climate change. Energy security can be improved by using sustainable and renewable energy sources. Transitioning to sustainable energy is vital, especially in sectors with high energy consumption, such as aviation. Hydrogen can play a critical role in the transition to sustainable energy, as it has enormous potential and can be used as an energy carrier. However, the purity rate of the hydrogen produced and the storage problems of the hydrogen are obstacles to the widespread use of hydrogen. The purity of hydrogen is related to the technology used to produce the hydrogen. In this context, hydrogen production with a renewable energy source is mentioned in this study. Also, the usability of a metal hydride to overcome hydrogen storage problems is discussed. In the literature, many researches and studies exist on sustainable development goals and hydrogen energy. However, studies and analyses on the relationship between hydrogen energy and sustainable development goals are lacking. This review mentions the importance of hydrogen energy in line with sustainable development goals. In addition, it is aimed to create a source for future studies by compiling studies in the literature on sustainable energy sources, hydrogen production methods and hydrogen storage with metal hydrides.

Keywords: *Clean Energy Sources; Sustainable Development; Hydrogen Production with Sustainable Energy; Hydrogen Storage with Metal Hydrides.*

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Sürdürülebilir Enerjide Kritik Rolü Olan Hidrojen Üzerine Bir İnceleme

ÖZET:

Sürdürülebilir ve yenilenebilir enerjiler geliştirmek dünyadaki enerji krizini çözebilir. Bu bağlamda enerji alanındaki odak noktalarından biri de düşük karbonlu teknolojilerin kullanımının yakın zamanda yaygınlaştırılmasıdır. Ayrıca yenilenemeyen enerji kaynaklarının tükenme sorunlarının ve iklim değişikliği gibi çevresel sorunların önlenmesi gerekmektedir. Enerji güvenliği, sürdürülebilir ve yenilenebilir enerji kaynakları kullanılarak geliştirilebilir. Sürdürülebilir enerjiye geçiş, özellikle havacılık gibi enerji tüketiminin yüksek olduğu sektörlerde hayati önem taşıyor. Hidrojen, muazzam bir potansiyele sahip olması ve bir enerji taşıyıcısı olarak kullanılabilmesi nedeniyle sürdürülebilir enerjiye geçişte kritik bir rol oynayabilir. Ancak üretilen hidrojenin saflık oranı ve hidrojenin depolanması problemleri, hidrojenin yaygınlaşmasına engel teşkil etmektedir. Hidrojenin saflığı, hidrojeni üretmek için kullanılan teknoloji ile ilgilidir. Bu bağlamda, bu çalışmada hidrojenin bir yenilebilir enerji kaynağı ile üretilmesine değinilmiştir. Ayrıca hidrojenin depolanma problemlerinin üstesinden gelinebilmesi için bir metal hidritin kullanılabilirliği tartışılmıştır. Literatürde sürdürülebilir kalkınma hedefleri ve hidrojen enerjisi ile ilgili birçok araştırma ve çalışma bulunmaktadır. Ancak, hidrojen enerjisi ile sürdürülebilir kalkınma hedefleri arasındaki ilişkiye yönelik çalışmalar ve araştırmalar eksiktir. Bu derleme, sürdürülebilir kalkınma hedefleri doğrultusunda hidrojen enerjisinin öneminden bahsetmektedir. Ayrıca sürdürülebilir enerji kaynakları, hidrojen üretim yöntemleri ve hidrojen depolanması ile ilgili literatürdeki çalışmalar derlenerek ileride yapılacak çalışmalara kaynak oluşturulması amaçlanmıştır.

Anahtar Kelimeler: *Temiz Enerji Kaynakları; Sürdürülebilir Kalkınma; Sürdürülebilir Enerji ile Hidrojen Üretimi; Metal Hidritlerle Hidrojen Depolanması.*

1. INTRODUCTION

Aydın [1] stated that the energy demand could be supplied from renewable or non-renewable energy sources. Firoz [2] noted that underground minerals and fossil fuels such as natural gas and coal are considered non-renewable energy sources. The preference for non-renewable energy sources such as fossil fuels as an energy source leaves a wearing and negative effect on the environment [3]. Ilker et al. emphasized that non-renewable energy resources such as oil, coal and natural gas may become depleted in the future [4]. According to the 'COP24 Special Report', non-renewable energy sources such as oil and natural gas cause air pollution and climate change [5]. Falehi and Rafiee [6] emphasized that commercial management in the world mostly depends on fossil fuels. Farhad et al. [7] pointed out that the consumption of fossil fuels is increasing globally and that this situation has adverse effects on the environment, such as climate change. Olabi and Abdelkareem [8] stated that despite the harmful effects of fossil fuels, they continue to be used intensively in the energy sector. Zoungrana and Çakmakci [9] emphasized that due to the continuation of the fossil energy consumption model, the world will be challenging to live in due to the environmental impact and the formation of greenhouse gases. Shoaib et al. [10] emphasized that non-renewable energy resources are running out. While greenhouse gas emissions are formed using non-renewable energy sources, greenhouse gas emissions can be controlled using renewable energy sources [11].

Renewable energy is vital to prevent environmental problems such as the depletion of non-renewable energy sources and climate change [12], [13]. Zhao et al. [14] pointed out that in many countries, priority is given to renewable energy studies to reduce environmental pollution and overcome the energy problem. Chehouri et al. [15] stated that there is a tendency towards alternative renewable energy sources due to the ever-increasing energy demand in the world. Renewable energy sources are energy types that do not experience depletion problems and have fewer harmful environmental effects than traditional energy production methods [16]. Barros et al. [17] mentioned in their study that using renewable energy sources can reduce adverse ecological effects. Sadorsky [18] noted that using renewable energy sources can increase energy security, and the effects caused by fossil fuel consumption can be reduced. Han et al. [19] emphasized the importance of incentives for renewable energy sources. Uihlein et al. [20] stated that renewable resources had gained prominence in many areas due to their environmental significance and limited fossil resources. Marks-Bielska et al. [21] mentioned that using renewable resources in energy production is very important to prevent economical problems and ensure energy security.

Dincer [22] stated that renewable energy sources are closely related to sustainable development. Sustainable development is a circular investment or technology that changes to suit our present and future needs [23]. The United Nations recommends producing low-cost sustainable energy resources to ensure energy security and sustainable growth within the scope of the Sustainable Development Goals [24]. One of the sustainable development goals is to make clean energy more accessible [25]. With the widespread use of renewable energy within the scope of sustainable development goals, problems such as climate change can be combated [26].

For this reason, sustainable development must prefer renewable energy sources such as biomass, wind, and sun to supply the energy needed [27]. Kumar and Majid [28] stated that renewable energy sources play a vital role in sustainable energy supply. Rezaei et al. [29] emphasized that using renewable energy resources is one of the most effective and efficient solutions to achieve sustainable development goals. Østergaard et al. [30] stressed that sustainable energy is a prerequisite for sustainable development.

Barreto et al. [31] mentioned that hydrogen-based energy systems could meet sustainability goals and are convenient and advantageous because they are reliable and clean. Falcone et al. [32] pointed out the increasing interest in hydrogen regarding industry development and society's sustainable development. Midilli et al. [33] stated that hydrogen production could also be carried out sustainably since hydrogen can be produced from sustainable and renewable energy sources.

There are many researches and studies on sustainable development goals and hydrogen energy in the literature, but research and analyses on the relationships between hydrogen energy and sustainable development goals are lacking. Environmental problems such as depletion and climate change due to non-renewable energy sources should be prevented. Furthermore, energy security can be improved by using sustainable and renewable energy sources. As a clean and renewable option, hydrogen will play a vital role in building a sustainable energy future.

Hydrogen can be shown among the strongest candidates to ensure the transition to sustainable energy. However, the purity of hydrogen energy needs to be increased. Moreover, there are already storage problems for hydrogen. In this context, since the potential of solar energy is relatively high, hydrogen production from solar energy is one of the methods that can be used for sustainable energy. In addition, the storage problem that limits the use of hydrogen can be solved by using metal hydrides. Therefore, the second part discusses hydrogen production methods with solar energy and hydrogen storage with metal hydrides. This review mentions the importance of hydrogen energy in line with sustainable development goals and examines hydrogen production methods with sustainable energy sources. In this article, studies in the literature about hydrogen production methods with sustainable energy sources have been compiled, and it is aimed to create a resource for future studies.

2. HYDROGEN PRODUCTION USING SUSTAINABLE ENERGY AND HYDROGEN STORAGE WITH METAL HYDRIDES

2.1. Hydrogen Production with Sustainable Energy

Khalilnejad and Riahy [34] stated that hydrogen could be a reliable option in any application where fossil fuels are used. Hydrogen is low-cost, clean, and high-performance [35]. Hydrogen has high specific energy content and a low emission rate [36]. Hydrogen can be used as a fuel and is preferred as an energy carrier in storage and fuel cells [37]. Since hydrogen is the most common ingredient globally, it can be obtained from renewable and non-renewable sources and various processes [38]. Singh et al. [39] stated that hydrogen could be produced with almost any energy source. Ishaq et al. [40] noted that hydrogen production methods could be classified into three basic categories: renewable energy-based, nuclear energy-based, and coal gasification-natural gas based. Wang et al. [41] pointed out that most of the hydrogen production in the world is carried out with fossil fuels. Yu et al. [42] stated that hydrogen is mainly produced worldwide by converting fossil fuels, such as reforming natural gas with steam. Hosseini and Wahid [43] noted that hydrogen production techniques with non-renewable energy sources are widely used. Nikolaidis and Poullikkas [44] stated that hydrocarbon reforming and pyrolysis methods could produce hydrogen from fossil fuels. Harichandan et al. [45] emphasized that hydrogen purity is related to the technology used to produce and use hydrogen. Frowijn and Van Sark [46] stressed that renewable hydrogen production methods should be preferred for a sustainable future.

Since the potential of solar energy is relatively high, hydrogen production from solar energy is one of the methods that can be used for sustainable energy [47]. Agrafiotis et al. [48] emphasized that sunlight can be converted to hydrogen to benefit from solar energy. Solar hydrogen production systems generally include photoelectrochemical, concentrated solar thermal, photobiological, and photovoltaic processes [49], [50]. Table 1 shows the advantages and disadvantages of various hydrogen production methods [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68].

Table 1.The advantages and disadvantages of various hydrogen production methods[51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68].

Method	Advantage	Ref.	Disadvantage	Ref.
Photovoltaic	It is low cost.	[51].	It cannot provide energy in the absence of sunlight.	[52].
	It uses solar energy in an accessible way.	[52].		
	There is no greenhouse gas emission.	[52].		
	No pollution for the environment.	[53].		
	It has no moving parts and has an extensive working capacity.	[54].		
Photoelectrochemical	It is environmentally friendly as it has fewer emissions.	[55].	A large amount of light is needed.	[56].
	It can be installed on large/small systems with simple technology.	[57].		
	It is efficient, low-cost, and straightforward.	[58].		
Photobiological	Its efficiency is high, and it does not cause environmental pollution.	[59], [60].	It should be improved in terms of sustainability and cost.	[61].
	It does not cause greenhouse gas emissions.	[62].	Its use in large-scale production is limited in cost and sustainability.	[63].
	It is an easily applicable method.	[62].		
Concentrated solar thermal	By using high-concentration solar thermal, very high-efficiency rates can be achieved.	[64].	Both economic and technical feasibility should be considered for hybridization.	[65], [66].
	It can store heat energy, and this energy can be used in the absence of sunlight.	[67].		
	It plays an essential role in reducing greenhouse gas emissions compared to traditional heating systems.	[68].		
	It offers the opportunity to hybridize with different systems.	[66].		

In table 1, it is seen that photovoltaic technology is low-cost [51], can benefit from sunlight [52], does not cause environmental pollution [53], does not contain moving parts [54], but cannot produce energy in the absence of sunlight [52]. On the other hand, when photoelectrochemical technology is examined, it is understood that it has less emission [55], can be used in small or large systems [57], is efficient and cheap [58], but requires a high amount of light [56]. When photobiological technology is examined, it is understood that it is highly efficient [59], [60], does not generate greenhouse gases [62], and is easily applicable [62], but needs to be improved in terms of sustainability and cost [61]. Therefore, its use in large-scale production is limited [63]. On the other hand, when concentrated solar energy is examined, it is understood that it can reach high-efficiency rates [64], has heat energy storage capacity [67], plays a vital role in reducing greenhouse gas emissions [68], and offers the opportunity to hybridize with different systems [66]. Still, hybridization's economic and technical feasibility should be evaluated [65], [66].

Khalilnejad et al. [51] stated that photovoltaic systems can be preferred for energy production due to their environmental friendliness, abundance, and low cost. Furthermore, they emphasized that photovoltaic energy can be converted into hydrogen fuel in terms of reliability. In obtaining hydrogen with photovoltaic systems, photovoltaic cells convert solar energy into electrical energy [69]. Figure 1 shows the method of obtaining hydrogen using a photovoltaic system [37], [70], [71].

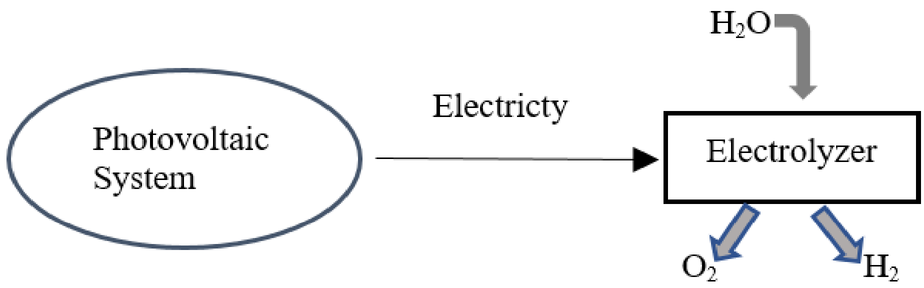

Figure 1: Hydrogen production method using the photovoltaic system [36], [69], [70].

As seen in Figure 1, the first energy is produced by photovoltaic cells, which are used to obtain hydrogen in water electrolysis [46]. Gibson and Kelly [72] found that the efficiency of the photovoltaic electrolysis system increased thanks to the optimization they made using the method of matching the voltage and maximum power output of the photovoltaics with the working voltage of the proton exchange membrane (PEM) electrolyzers. Peharz et al. [73] presented an integrated design combining high-efficiency III-V solar cells with a polymer electrolyte membrane electrolyzer. Thanks to this design, they determined that the conversion efficiency from the sun to hydrogen increased. Dahbi et al. [74] found that the efficiency of the photovoltaic system increased due to their investigation by combining a DC/DC converter and a water flow controller. Bicer et al. [75] established a solar simulator for obtaining hydrogen using photovoltaic cells. They used a reflective mirror in this simulator, and as a result of the investigations, they found that using a reflective mirror reduces efficiency. In another study, Erden et al. [76] examined an integrated system for hydrogen production by electrolysis, consisting of a plate collector, a solar pool, and an organic Rankine loop. As a result of these investigations, they determined that more electricity was produced.

Another preferred method for hydrogen production using solar energy is the photoelectrochemical method. This method obtains the energy needed in water electrolysis using photoelectrochemical cells [53]. The photoelectrochemical system comprises a photo anode, photocathode, and electrolyte [56], [57]. Electron hole pairs are formed when sunlight falls on the photo anodes. These vacancies are separated from the electrons and react with water, thus releasing oxygen and positively charged hydrogen as a result of the reaction. Electrons circulate outside and reach the photocathode. Due to the potential difference between the photoelectrodes, an electric field is created, and the electrons react with the positive hydrogen ions formed by the dissociation of water to form hydrogen gas [57], [77]. Kim et al. [78] stated that perovskite solar cells could be used in photoelectrochemical hydrogen production due to their electrical and optical properties. Licht [79] presented a model for increasing the hydrogen production rate. According to the given model, it is stated that short-wavelength radiations from the sun are used in the photoelectrochemical conversion. In contrast, long-wavelength radiations from the sun heat the reactor and reduce the water-splitting potential. Thus, they stated that solar electrolysis could be performed at high temperatures, where water is the most efficient for hydrogen production. Boudjemaa et al. [80] examined hydrogen production with a photo anode formed with the Fe_2O_3 structure in their study. As a result of this examination, they determined that the system increased the hydrogen production efficiency. Alarawi et al. [81] investigated MoS_2/Si-heterojunction photocathode for photoelectrochemical hydrogen production in their study and found that the MoS_2/Si-heterojunction photocathode had high performance.

The photobiological method of hydrogen production is a method that requires a light source for energy production, a substrate to obtain electrons, and a catalyst to combine protons and electrons [82]. The photobiological hydrogen production method is a promising technique that can replace fossil fuels [83]. Chen [61] states that the photobiological hydrogen production method is one of the most effective green hydrogen energy production methods. Wutthithien et al. [84] also noted that the photobiological hydrogen production method attracts attention due to its high potential and low environmental impact.

Chen et al. [85] reported that the photobiological hydrogen production method had attracted much attention by solving the limiting factors of oxygen scavengers and sulfur deprivation. Biological hydrogen production techniques are divided into two main groups: light-dependent and light-independent processes [86]. Indirect biophotolysis, direct biophotolysis and photo fermentation are light-dependent. But dark fermentation is light-independent [53], [86]. The biophotolysis method involves the decomposition of water by light in the presence of cyanobacteria or microalgae [86]. Many techniques can be used for photobiological hydrogen production. But microalgae, cyanobacteria and purple non-sulfur bacteria stand out among these techniques [87]. The efficiency of hydrogen production with microalgae in processes such as light capture efficiency, oxygen sensitivity and carbon dioxide fixation efficiency is low, which limits hydrogen production with microalgae [88]. Ge et al. [89] stated that adding sulfur is essential in the photobiological production of hydrogen from microalgae. Table 2 shows the advantages and disadvantages of various photobiological hydrogen production methods [44], [86], [90], [91], [92], [93].

Table 2. Advantages and disadvantages of various photobiological hydrogen production methods [44], [86], [90], [91], [92], [93].

Method	**Advantage**	**Ref.**	**Disadvantage**	**Ref.**

Direct biophotolysis	Hydrogen can be produced directly using water and sunlight.	[86], [90], [92], [93].	High-intensity sunlight is needed.	[90], [93].
	There is an increase in energy conversion efficiency from the sun.	[86], [90].	It is susceptible to oxygen.	[90], [93].
Indirect biophotolysis	Nitrogen (N_2) can be fixed from the atmosphere.	[86], [90], [92].	Hydrogenase enzymes must be removed to prevent the degradation of hydrogen.	[90], [93].
	Hydrogen can be extracted from water with the use of cyanobacteria.	[86], [90].	The gas mixture contains 30% oxygen.	[90], [93].
Photo fermentation	The use of intense spectral light energy is possible.	[86], [92], [93].	Oxygen has an inhibitory effect on nitrogenase.	[93].
	Different types of organic waste can be used.	[44], [93].	The conversion rate of sunlight is relatively low.	[93].
	It contributes to the recycling of waste.	[44].	It needs sunlight.	[44].
	It has a high substrate conversion capacity.	[90], [91].	A large reactor surface area is required.	[44], [90].
			The PH value and stretch of the solution affect the hydrogen production rate.	[91].
			It is not suitable for large-scale hydrogen production.	[91].
			Pre-treatment may be required due to the toxic nature of the substrate used.	[90].
Dark fermentation	Hydrogen can be produced without sunlight.	[44], [92], [93].	Hydrogen efficiency is lower.	[44], [93].
	Many carbon sources can be used as substrates.	[86], [92], [93].	Fatty acids are removed.	[44].
	Important metabolites, such as acetic acid, butyric acid, etc., are formed as by-products.	[86], [92], [93].	The hydrogen production rate is affected by the PH value of the solution and the salt content.	[91].
	Problems such as oxygen limitation do not occur.	[44], [91], [93].		
	It contributes to the recycling of waste.	[44].		

Table 2 shows that direct biophotolysis technology can produce hydrogen by directly using water and sunlight [86], [90], [92], [93], increases solar energy conversion efficiency [86], [90], but requires high-intensity sunlight [90], [93] and is susceptible to oxygen [90], [93]. On the other hand, in indirect biophotolysis, nitrogen (N_2) can be fixed from the atmosphere [86], [90], [92]. In this technique, hydrogen can be obtained from water using cyanobacteria [86], [90]. However, in the indirect biophotolysis method, hydrogenase enzymes must be removed to prevent the degradation of hydrogen [90], [93]. Furthermore, in this method, the gas mixture contains a high percentage of oxygen [90], [93]. When the photo fermentation technology is examined, it is understood that it is possible to use intense spectral light energy [86], [92], [93], different organic wastes can be used [44], [93], and it has a high substrate conversion capacity [90], [91]. However, it is understood that photo fermentation technology has a meager light conversion rate [93], requires a large reactor surface area [44], [90], and is not suitable for large-scale hydrogen production [91]. On the other hand, in the dark fermentation method, hydrogen production can be realized without sunlight [44], [92], [93], and many carbon sources can be used as substrates [86], [92], [93]. Moreover, there is no oxygen limitation in this method [44], [91], [93]. However, removing fatty acids is required in dark fermentation [44]. In this technique, the hydrogen production rate is affected by the PH value of the solution and the salt content [91].

Yang et al. [94] stated that the method of energy production using concentrated solar energy is a new technology. This method differs from photovoltaic production regarding thermal energy storage and production technique [94]. With the concentrated solar thermal process, radiation from the solar can be converted into heat and electricity [67]. Storing energy with a concentrated solar thermal method is straightforward [66]. This technique includes processes such as solar thermolysis and solar thermochemical cycles [50]. In solar thermolysis, water is thermally decomposed under high temperatures to produce hydrogen [50], [53]. In the solar thermochemical cycle technique, heat and electrolysis are used together to decompose water into hydrogen and oxygen [95]. Fang et al. [96] emphasized that the efficiency of gasification could be improved by integrating the concentrated solar thermal method and biomass gasification technology. Temiz and Dincer [97] examined integrating the concentrated solar copper-chlorine (Cu-Cl) cycle with thermal energy storage and geothermal systems to obtain products such as hydrogen and electricity. They stated that production improved with this integration.

2.2. Hydrogen Storage with Metal Hydrides

To produce hydrogen, first of all, energy is produced by any method, and then the energy produced is converted into hydrogen. Other processes can be summarized as the storage of hydrogen, it's recycling into various forms of energy transport, and energy consumption [98]. Amirthan and Perera [99] stated that one of the factors that need to be developed regarding hydrogen is storage systems. Excess hydrogen produced by various methods can be stored so that the stored hydrogen can be reused when needed [100]. Zhang et al. [101] stated that hydrogen could be stored in many forms, such as solid, liquid, gas, or derived chemical molecules. Chu et al. [102] emphasized the need for hydrogen storage improvements.

In recent years, research on material-based hydrogen storage has gained importance [103]. Huang et al. [104] stated that metal hydrides could be used for solid-state hydrogen storage.

However, they emphasized that the gravimetric hydrogen storage densities of metal hydrides are low. They stated that amorphous structures could be used to increase the performance of metal hydrides [104]. Edalati et al. [105] stated that magnesium and its alloys could be used in solid-state hydrogen storage as metal hydrides.

Li et al. [106] stated that magnesium hydride (MgH_2) could be used for hydrogen storage due to its advantages, such as being environmentally friendly and having a high storage capacity. However, there are problems to be solved regarding the thermodynamics and kinetics of these materials [105]. Ding et al. [107] emphasized that magnesium-based solid-state hydrogen storage could be used. Still, problems such as low high operating temperature and slow reaction rate of magnesium hydride (MgH_2) must be overcome [107]. Table 3 shows the properties of magnesium hydride (MgH_2) [108], [109], [110], [111].

Table 3. Properties of magnesium hydride (MgH_2) [108], [109], [110], [111].

Properties	**MgH_2**	**Ref.**
H-atoms per (×1022/cm^3)	6.7	[109].
Hydrogen capacity (%)	7.6	[108], [109], [110].
Useable temperature range (°C)	350–450	[110].
T1 bar (°C)	282	[110].
Density (g/cm^3)	1.4	[109].
Energy density (kJ/kg hydride)	2811	[111].

Sui et al. [112] emphasized that nanostructured magnesium-based hydrogen storage can improve the hydrogen storage capacity of magnesium-based materials. They also emphasized that adding a catalyst and alloy can reduce the dehydrogenation temperature of magnesium-based materials [112]. Yahya et al. [113] studied the effect of adding K_2NbF_7 to MgH_2 material in their study. As a result of this review, it was emphasized that positive results were obtained.

Ismail [114] investigated the hydrogen storage capacity of lanthanum chloride ($LaCl_3$) doped MgH_2 material. This study determined that the sorption kinetics of MgH_2 material improved by adding $LaCl_3$. In addition, it was determined that the decomposition temperature of MgH2 material decreased.

Ismail [115] investigated the effect of adding Hafnium Tetrachloride ($HfCl_4$) at specific rates to MgH_2 material. As a result of this examination, it has been determined that the best ratio for MgH_2 material to reduce the decomposition temperature and improve its kinetic performance is 15%.

3. THE ROLE OF HYDROGEN IN BUILDING A SUSTAINABLE FUTURE

In parallel with the recent intensive population growth and rising living standards, there has been a significant increase in global energy consumption [116]. Fossil fuels provide about 80% of the energy needed [117]. The high use of fossil fuels causes global warming and environmental pollution [118]. Because such energy sources face depletion problems and cause climate change, the search for alternative renewable resources has increased in many countries [119]. The transition to low-carbon energy is based on developing renewable and sustainable energy systems [120]. In this context, hydrogen may be the most suitable option to replace fossil fuels [121].

Hydrogen has the advantages of high heating value and non-pollution [122]. Moreover, hydrogen has the benefits of being the lightest element and having a long storage life [123]. Hydrogen is referred to as the 'ultimate energy carrier' [124]. Hydrogen has become the center of attention in sustainable energy due to its high conversion efficiency, high energy density, abundance in nature and environmental friendliness [125]. Hydrogen has come into focus due to its potential use as an energy carrier in fuel cells [126].

Further expansion and improvement of existing work in sustainable energy are essential for the security and stability of our future. Hydrogen, a clean and renewable energy source, will be vital in building a sustainable future. Hydrogen is one of the strongest candidates for sustainable energy use. However, due to our limited hydrogen infrastructure, regular and reliable hydrogen production shortcomings must be urgently addressed. Hydrogen will become a critical resource in the future, as it can reduce greenhouse gas emissions and increase energy efficiency and security. Shortly, hydrogen energy is expected to be used in many areas [127]. One of the most critical problems in the coming years will be the inability to produce enough hydrogen [128]. The focus on hydrogen is no longer limited to the transportation sector; hydrogen has also become a focal point in industries such as heating, steel and chemicals [129].

In recent years, there has been a remarkable increase and diversity in research and studies on hydrogen production. Using non-renewable sources such as fossil fuels for hydrogen production is very high today [130]. Renewable hydrogen production costs must be competitive with other energy sources for sustainable hydrogen production to become widespread. For this, systematic studies that will lead to definitive results are required. Besides the limiting factors of hydrogen production, there are many technical problems to be solved, such as hydrogen storage [131]. In this context, critical breakthroughs such as considering the impact of climate change, designing integrated systems, and accelerating infrastructure and facility works are essential.

3.1. Hydrogen's Role in Sustainable Aviation

Baroutaji et al. [132] emphasized that the aviation sector significantly impacts world energy consumption, with total energy consumption ranging from 2.5% to 5%. It is aimed to reach net zero carbon emissions in the aviation sector by 2050 [133]. Sustainable aviation aims to use renewable energy sources without leaving any environmental footprint [134].

Yusaf et al. [135] stated that hydrogen has a savior role in sectors such as aviation, which cause environmental problems. Musa Ardo et al. [136] emphasized that hydrogen can replace fossil fuels in the aviation sector. Penke et al. [137] stated that renewable hydrogen could be used to produce aviation fuel. The preference for hydrogen in aviation is closely related to the decarbonization of aviation [138]. In addition, using hydrogen in aviation can prevent problems such as climate change [139]. Bauen et al. [140] stated that hydrogen has a much higher gravimetric energy density than kerosene and a lower volumetric energy density than kerosene. These properties of hydrogen are critical to aircraft performance [140].

Nicolay et al. [141] carried out an aircraft design and optimization to examine the potential of liquid hydrogen and fuel cells in general aviation. In this context, they have completed the hydrogen fuel cell-powered aircraft concept. It has been found that this aircraft concept does not generate carbon dioxide emissions, and the performance of this aircraft design is comparable to conventional aircraft performances. However, it was emphasized that this hydrogen aircraft should be developed to show the same performance at higher altitudes [141].

Eissele et al. [142] investigated how a regional aircraft with a capacity of 50 passengers could be hybridized to fly with minimal emissions in 2040. This study stated that liquid hydrogen could be used efficiently by combining it with a fuel cell. They found that this integration is feasible. However, they emphasized that hydrogen production and storage should be improved [142].

Otto et al. [143] stated that hydrogen is a candidate that can be used as an energy carrier in aircraft. However, due to the explosive nature of hydrogen, the use of hydrogen in aviation and flight operations is quite risky [143].

4. CONCLUSION

Renewable or non-renewable energy sources can be used to meet the worldwide energy demand. However, commercial management worldwide primarily depends on fossil fuels [6]. The preference for non-renewable energy sources, such as fossil fuels, causes air pollution and climate change. Nevertheless, despite their adverse effects, fossil fuels are used extensively in the energy sector [8]. If it continues like this, our living standards will become more difficult due to the environmental impact and the formation of greenhouse gases [9]. This negative situation can be controlled using renewable energy sources [11], [17]. In many countries, priority is given to studies on renewable energy to reduce environmental pollution and overcome energy problems [14]. In this context, incentives for renewable and sustainable energy sources are significant. In addition, it is crucial to prefer renewable energy to prevent economic problems and ensure energy security [21].

Renewable energy and sustainable development are closely related. For example, the United Nations recommends using low-cost sustainable energy resources to ensure energy security and sustainable growth [24]. Energy security can be improved by choosing sustainable and renewable energy sources. In this context, hydrogen can be used in the transition to sustainable energy because it has low cost, is very clean, and has high performance [35]. Hydrogen can be used as a fuel, as an energy carrier in fuel cells, or for storage [37]. Hydrogen can be produced using almost any energy source [39]. Worldwide, hydrogen is produced mainly by converting fossil fuels, such as steam-reforming natural gas [41], [42], [43].

The purity of hydrogen is related to the technology used to produce and use the hydrogen [45]. In this regard, using renewable and sustainable energy sources in hydrogen production is essential. Since the potential of solar energy, a renewable energy source, is relatively high, it can be used in hydrogen production. Solar hydrogen generation systems cover photoelectrochemical, concentrated solar energy, photobiological and photovoltaic methods [49], [50]. Photovoltaic technology has advantages such as low cost, no environmental pollution, and no moving parts. However, in the absence of sunlight, hydrogen production is impossible with this technique [51], [52], [53], [54]. Photoelectrochemical technology has advantages such as less emission, being able to be used in small or large systems, and low cost. However, this technique requires much light [55], [56], [57], [58]. Photobiological technology has the advantages of being highly efficient, not generating greenhouse gases, and being easily applicable. However, this technique should be improved in terms of cost [59], [60], [61], [62]. Concentrated solar thermal technology has advantages such as being highly efficient, storing heat energy, and hybridizing with different systems. Economic and technical feasibility must be appropriate for hybridizing the concentrated solar thermal method with other systems [64], [65], [66], [67], [68].

Hydrogen draws attention to sustainable energy due to its high conversion efficiency, energy density, natural abundance, and environmental friendliness. Some advantages and disadvantages of hydrogen production from solar energy are discussed above. In addition, the importance of hydrogen was emphasized in line with sustainable development goals. It is seen that the production of hydrogen with a renewable energy source such as the sun positively affects the purity of the hydrogen.

In sectors with high energy consumption, such as aviation, it is necessary to use sustainable energy sources instead of fossil fuels. In this context, hydrogen is a strong candidate for the transition to sustainability in aviation. However, the factors affecting the use of hydrogen need to be eliminated. The purity rate of the hydrogen produced and the storage problems of the hydrogen are obstacles to the widespread use of hydrogen. In this context, producing hydrogen with a renewable and sustainable method can increase hydrogen purity. This study investigated the hydrogen production method with solar energy to increase the purity of the hydrogen produced. It seems possible to produce hydrogen with solar technology. Moreover, the abundance of sun and the high efficiency of solar technology increase the usability of this technique. Another factor affecting the use of hydrogen is storage problems. In this study, the availability of magnesium hydride (MgH_2) for the storage of hydrogen was investigated. Using MgH_2 for hydrogen storage can be presented as a possible solution. However, some problems must be solved regarding the thermodynamics and kinetics of MgH_2 materials. Some additives can be added to the MgH_2 material to overcome these problems. However, MgH_2 materials still need to be developed.

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