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A Short Review on Developing Technologies by Hydrogen

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ABSTRACT

Hydrogen is deemed as the most significant fuel of the future, with strong potential to minimise pollution. Hence, there is also growing global interest in reducing the effects of greenhouse gases as well as other pollutant gases. In order to explore the implementation of hydrogen as a fuel or energy carrier, it requires an easily acquired broad-spectrum knowledge on a variety of processes as well as their advantages, disadvantages, and potential adjustments in making a process suitable for future development. Aside from directly utilising the hydrogen produced from these processes in fuel cells, hydrogen-rich streams can also be used to generate high-value of ethanol, methanol and gasoline, as well as other high-value chemicals. This paper presented a brief overview on the remarkable current and emerging hydrogen technologies.

Keywords:
Hydrogen technologies; lower flammability level (LFL); higher flammability level (HFL); hydrogen recovery; fossil fuel

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1. Introduction

In the United States (US), more than 225 million small vehicles drive at least 7 billion miles per day, using 8 million oil drums a day [1, 2]. In regard to the additional demand received by the US as the third largest global oil producer, an increase of up to 60% is anticipated by 2025 [3-5]. The development of alternative fuels as a source of energy for society has drawn many interests since the primary oil embargo of the 1970s [6-9]. However, the oil prices declined as a result of the cutback in embargo have lessened the attention in alternative fuels. Nevertheless, the current considerable uncertainties, especially in the Middle East, have led to increased demand for oil from the developing countries, resulting in a substantial increase in the previous year's oil costs [10-14]. In addition to cost, environmental issues regarding the petroleum usage have also contributed to the decreasing attention received. Recent US studies indicated that the contaminants may be alarmingly high, affecting public health and the environment in the regions where 50% of Americans live [15, 16]. Apart from the great amount of nitrogen oxide (NOx) and carbon monoxide in the US, volatile organic compound (VOC) and carbon dioxide are also emitted from the small vehicles [17]. In order to find the solution for these concerns, various works are being conducted on examining the sources of energy especially in the transportation industries, as well as finding cleaner fuels. However, the application of alternative fuels may

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not be suitable in every area as one area may prefer biodiesel while another may prefer methane, ethanol or gasoline. For the engine to have an effective operation, a majority of the aforementioned fuels require specific technologies. Hydrogen is globally applied due to its production that can be performed using feedstocks [18, 19]. Fig. 1 shows an outline of key production and usage pathways of hydrogen [20]. Hydrogen could be useful in offering flexibility and sector-coupling to energy systems, due to various options in production and applications.

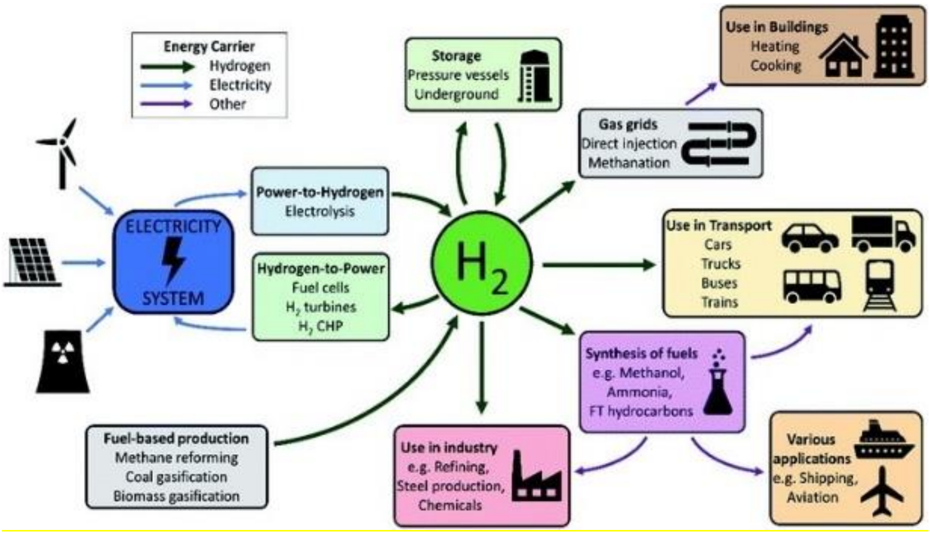

Fig. 1. Outline of key production and usage pathways of hydrogen [20]

Currently, global researchers are developing new hydrogen technologies to resolve the existing concerns as well as for economic and energy security. For example, the US Department of Energy have constructed a multi-year strategy for the development of hydrogen infrastructure, storage technologies as well as fuel cells with ambitious goals and milestones [21, 22]. The cost of hydrogen delivered was estimated at 2 to 4 USD per kilogramme with the energy equivalent to one gallon of gasoline [23, 24]. However, these works are difficult to find in the literature as there are very few works that deal with this subject. The International Energy Agency (IEA) estimated that more than 89 million drums of fossil fuels were currently being utilised. The popularity of fossil fuels is drawn by broad and super improved political, social, and scientific infrastructures. There are various concerns regarding the huge consumption of fossil fuels; for example, the emission of harmful substances, greenhouse gases, and global warming issues [25, 26]. Fossil fuels are an exhaustive resource and can be found only in certain areas [27]. Moreover, its high volatile price is one of the causes of political conflict that threatens human life [28, 29]. These conventional fuels are also oil derivatives that come with a wide variety of formulations in which each can be loaded into certain groups of consumer machinery. The burning of these fuels releases energy content, which results in a large portion of waste heat being released into the atmosphere [30]. Meanwhile, hydrogen possesses a long term viability [31], besides being recognised for its continuous availability. Hydrogen can be synthesised anywhere around the globe, using various techniques [32-34]. This material can be used for a wide range of appliances, from small electrical equipment such as heaters and ovens to industrial unit operations such as fuel cells, combustion engines, and turbines [35]. The requisite conversion rate from mass to energy can be obtained as some of the listed systems have zero mobile components, suggesting a higher life span and efficiency as compared to conventional equipment with similar functions. The production and consumption of hydrogen in micro, macro, and mega scales are convincingly achievable. Its usage comes with minimum emissions of harmful substances, with water as the by-product regardless of the technique employed. Additionally, hydrogen may be added to other fuels, forming an energy-enriched mixture [36].

2. Hydrogen as Energy Tools

As an energy carrier, hydrogen has a high potential to fulfil the global energy demand while also reducing CO2 emissions and their impacts on global warming. The Hydrogen Council was launched during the Davos Economic Forum in January 2017, of which the inaugural members are chief executives from thirteen worldwide companies. The Hydrogen Council aims to focus on the significance of hydrogen energy and to speed up funding for research and commercialisation of hydrogen and fuel cell technologies [37, 38]. Clearly, without the manufacture and use of hydrogen, it is impossible to achieve both the environmental and energetic goals. Therefore, sustainable hydrogen manufacturing techniques must be the key impetus in executing the international capabilities. Maggio et al. claimed that industrial intermediate commodities, such as chemical synthesis could be the first green hydrogen market, followed by stationary power generation, and play a crucial role in the mobility sector [39]. Sgobbi *et al*. addressed the role of hydrogen in decarbonising Europe's energy system by emphasising the potential of hydrogen, particularly in the transport and industry sectors [40]. Besides, hydrogen production is beneficial in providing flexibility and variable electricity, as hydrogen is a conspicuous option in renewable energy storage implementations. Samsatli and Samsatli constructed a model to observe the impact of using hydrogen as inter-seasonal storage in an attempt to decarbonise the heating industry in the United Kingdom (UK) [41]. According to their research findings, using 80% electricity with 20% hydrogen was an ideal alternative to produce heat. This work further clarified the need for a robust supply chain of hydrogen for the carbon capture and utilisation technologies to operate. Meanwhile, Colbertaldo et al. evaluated the contribution of hydrogen to 100% use of renewable electricity in California (through the power-to-gas approach) [42]. This work focused on hydrogen for power decarbonisation to reduce greenhouse gas emissions. Early findings showed that a hydrogen-based power-to-power storage system is more feasible than a battery-based system.

Hydrogen has the potential to be utilised as a substitute fuel for engines intended for other fuels, where its wide range of flammability offers well-regulated engine power [43]. Burning a fuel can only be achieved in either vaporised or gaseous states, and hydrogen reaches its gaseous state at a very low temperature. Flashpoint is the temperature at which a fuel produces sufficient vapour to form a flame in the air, with the presence of an ignition source [44, 45]. For a fuel, the flashpoint value is lower than its boiling point value. Low temperature can reduce vaporisation, meaning that when there is no source of ignition, a fuel flame will not last. Thus, hydrogen-based engines are expected to need less sophisticated ignition and starting equipment in contrast to the engines operating on other types of fuel [46]. This source of energy can also operate normally under "harsh" conditions. For instance, it was known that a hydrogen-powered vehicle would operate even after being kept at low temperatures for several days without the need for ignition [47, 48]. In addition, hydrogen has a distinctive range of flammability. The large difference between the lower flammability level (LFL) and higher flammability level (HFL) of hydrogen contributes to various possibilities for its use in turbine or combustion engine [23]. The estimation of LFL at high pressures is based on the calculation of adiabatic flame temperatures for the mixtures H2 + O2 in CO2 and N2, between 1.0 and 300 bar and 288–348 K, as reported by Piqueras and co-workers (Fig. 2).

HFL and LFL refer to the maximum and minimum levels, respectively, of fuel concentration in the air for the mixture to be flammable. The mixture of fuel and air will not be ignitable if the amount of fuel content exceeds levels below its LFL or above its HFL, due to the absence of oxygen or fuel in the mixture. The latter feature indicates its significance by acknowledging that various manufacturers from industrial, transportation, and automotive parts are required to make improvements, even in the additional systems; for example, turbochargers or custom-designed engines to operate in low pressure situations, such as high altitudes. Nevertheless, the hydrogen consumption leads to simplified design of structural engine in order to operate under different conditions with the same efficiency.

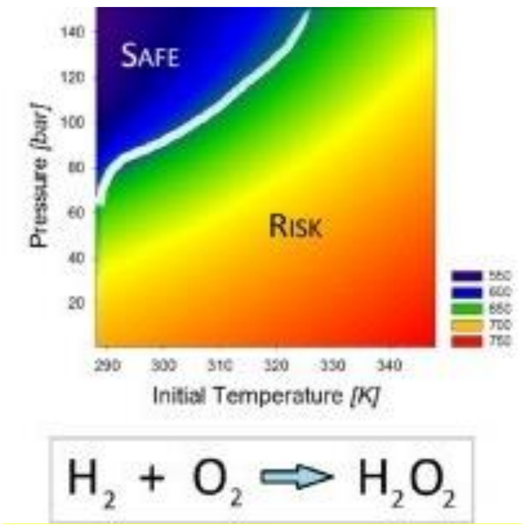

Fig. 2. Calculation of adiabatic flame temperatures for the mixtures H2 + O2 in CO2 and N2 [49]

Apart from the noted benefits of hydrogen consumption, the octane number of hydrogen is also important, indicating the anti-knock features of a fuel [50, 51]. Knock refers to the establishment of a second fuel explosion after primary detonation inside the combustion engine. This explosion occurs because of the temperature that surpasses the level of auto ignition fuel. Octane measures the anti-knock ability of hydrocarbon fuels with ratings up to 100. Higher octane levels indicate further fuel ability in the combustion chambers to avert undesirable auto ignitions. Furthermore, other types of fuel are also subject to various tests to determine their experimental octane levels [52]. The most common technique of global octane rating is the research octane number of a fuel. This number is obtained by flowing fuel at varying compression conditions in a chamber. Many materials present in nature contain hydrogen; for instance, it is found mainly in water such as brine (sea water), river, rain or well. Hydrogen extraction can also take place from biomass, fossil hydrocarbons, hydrogen sulphide or other materials. Following the extraction of hydrogen from fossil hydrocarbon, the process of separating or sequestrating carbon dioxide is conducted to eliminate greenhouse gases or other gases from polluting the atmosphere so that a green process can be implemented. The extraction of hydrogen requires four energy forms from the above mentioned natural resources, namely biochemical, photonic, electrical, and thermal, which can be attained from green energy sources [53, 54]. This work suggests green energy in terms of nuclear energy, renewable energy, and recovered energy; for example incinerated waste, landfill gas, and heat recovered from industrial processes.

Both thermal and electrical energies can be obtained from renewable sources such as biomass, wave, ocean thermal, tidal, wind, geothermal, and solar, or recovered and nuclear energies. Meanwhile, photonic energy can only be found in solar radiation. On the other hand, biochemical energy can be derived from organic substance in the form of sugars, glucose or carbohydrates used by some microorganisms for hydrogen extraction from various substrates or through chemical conversion to form thermal energy. Solar radiation serves as a biochemical energy assistant in generating energy according to the case in hand; for example, dark fermentation or bio-photolysis. There are multiple ways to acquire the driving energy from the green energy sources [55, 56], such as ways to convert energy from green energy to photonic, biochemical, thermal, and electrical energies. Temperature level is a crucial thermal energy parameter. It is noted that there are specific techniques used to produce high, intermediate, and low heat temperatures. High temperature heat is needed in thermos-catalytic, thermochemical, and thermolysis processes, whereas hydrogen sulphide splitting as well as hybrid thermochemical water splitting require the heat of an intermediate temperature. On the contrary, a low grade heat is required in the thermophilic digestion. Biomass and solar energy are capable of generating high temperature heat, while low and intermediate temperature heat can be provided by geothermal and solar energies as well as heat obtained from various processes. Typically, nuclear energy is obtained at an intermediate temperature of ~300 °C. The use of photonic energy, such as photo-electrolysis and photo-catalysis, requires solar energy input with the aid of other forms of green energy. Meanwhile, the biological conversion process requires biological substrate.

3. Upcoming Technologies by Hydrogen

Hydrogen is known as one of the most significant energy carriers in this era. Nevertheless, with fewer options for their substitutes, hydrogen production from unrenewable sources comes with various environmental consequences. The production of hydrogen from renewable sources is essentially the best way out in providing the energy required by a hydrogen community. Sustainable development encourages energy resources because their availability is sustainable at a sensible price with minimal to no negative impact, among which solar energy has the highest potential. Therefore, the widespread use of a light-based hydrogen energy system is critical to achieving worldwide sustainability. Hydrogen energy programmes, policies, and strategies are necessary to assure worldwide sustainability in reducing the adverse effects of unrenewable energy usage. The remarkable benefits of hydrogen energy usage are; high energy conversion efficiency; zero carbon dioxide emissions when combusted or used in fuel cells; lavish water sources in nature; accessibility of various storage substitutes; transportation accessibility for wide distances (e.g., via hydrocarbon blending); multiple fuel selections for conversion (for example, ammonia, methanol, dimethyl ether, and ethanol); high heating value than various conventional fuels (HHV: 141.80 MJ/kg and LHV:119.96 MJ/kg); and can be produced from water, wastewater or seawater using renewable sources with minimal environmental impact [57].

Hydrogen production is possible using various feedstocks from fossil resources (for example, natural gas, coal, char, or uranium in thermochemical cycles) [58, 59], and renewable resources (for example, solar, wind, biomass, and many more) [60, 61]. There are currently multiple routes available for the production of hydrogen, which are divided into unrenewable and renewable sources. Certain types of biochemical substrate stored in sucrose, glucose, cellulose, carbohydrates, and proteins can be used in biochemical hydrogen production. However, these processes have low effectiveness. Biochemical hydrogen generation reactions are possible through anaerobic bacteria and photosynthetic microorganisms, respectively, in both dark and light conditions. Earth energy, also known as geothermal energy can be utilised in the form of thermal energy (thermochemical water splitting) or electrical (electrolysis) energy to produce hydrogen. Arellano-Garcia investigated the production of hydrogen using aqueous methanol electrolysis as compared to the pure water electrolysis in a straight paired solar-PEM electrolysis system [62]. The purpose of this previous study was to verify the economic viability of hydrogen production on a large-scale. A review on the alternative of hydrogen production from algal biomass was conducted by Show and co-workers [63]. This earlier research indicated that the analysis of techno-economic as well as the obstacles that exist as biohydrogen has high potential due to its renewable and clean characteristics. Hydrogen technology along with its broad advancement and deployment insinuations is also known as the hydrogen economy, and has gained numerous attentions ever since its first introduction in the early 1970s. Since then, hydrogen technologies and hydrogen economy are being actively explored along with multiple reviews reflecting on the critical progress achieved at various phases. In the meantime, some roadmaps have been launched in Japan, the European Union and the United States, highlighting the significance of hydrogen in the energy sector [64].

Hydrogen cycle that consists of production, storage, and utilisation, is extensively studied. Water electrolysis is the focus of numerous works related to energy implementations, particularly renewable energy technologies, despite the presence of different manufacturing techniques (for instance, biological production, steam reforming, and so on) [65]. The advancement of both alkaline electrolysis, which is indicated as the most mature technology, and polymer electrolyte membrane (PEM) electrolysis, which is more suitable for dynamic response related to renewable energy technologies, has been widely testified in terms of applications, materials development, and cost trends [66]. Solar electrolysis is also common in off-grid communities [67], while wind-hydrogen energy systems are recognised for their grid-scale and/or microgrid applicability; for instance, frequency control and power [68]. Overall, reviews on the low carbon technologies for hydrogen production along with multiple case studies can be found in the research conducted by Dincer [69, 70] as well as Hosseini and Wahid [71].

In terms of hydrogen tanks, there are wide-ranging analyses of metal hydrides as both volumetric and gravimetric requirements for on-board transportation issued by different bodies, including the US Department of Energy, which have not been achieved through liquid and compressed hydrogen storage [6]. Nevertheless, liquefied and compressed hydrogen storage demonstrated better results on the targets mentioned, specifically for the gravimetric density. While limitations are found in the compressed hydrogen storage at elevated pressure (for instance, requirement of more electricity by an external compressor), this technology continues to be implemented in various stationary pilot plants as well as projects around the world [72]. This consists of hydrogen refuelling sites for transportation purposes as well as PtG systems, whereby these systems use the natural gas network as their storage [73]. The goal of reducing greenhouse gas (GHG) emissions from the transport sector is the driving force of FCs research, particularly the polymer electrolyte membrane fuel cells (PEMFCs), as well as various reviews regarding this technology that have been published for the integration of vehicles [74, 75]. The fuel cell research dealt with different issues such as the materials for degradation, cost reduction, and optimum energy management [76, 77]. Mekhilef et al. compared the features of multiple fuel cell technologies and reported that both solid oxide fuel cells (SOFCs) and PEM are the frontrunners in the micro CHP units field, particularly in South Korea and Japan [78]. SOFCs have also been the subject of numerous articles related to power generation on a large scale [79, 80]. Lastly, major concern can also be seen in the deliberation of hydrogen economy in terms of social and economic impact, in which the reviews normally consist of aspects such as policy, economic, environmental, and technical.

4. Conclusion

Hydrogen is not readily available for usage; nevertheless, this does not inhibit its beneficial features and properties from being recognised as a good fuel or energy carrier. Multiple techniques are utilised in the mass production of hydrogen. Hydrogen extraction can be done using various green and clean techniques from different compounds or materials. On top of that, hydrogen production is possible anywhere on earth. The benefits of hydrogen as an energy carrier can be seen in terms of its excellent energy per mass content, transportation possibilities, storage, safety characteristics, and less emissions of harmful substance. Discussion of this paper covered areas such as hydrogen production via fuel processing technologies as well as from alternative resources; for instance, water and biomass.

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