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# Hydrogen Production Technologies Overview

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## Abstract

Hydrogen energy became the most significant energy as the current demand gradually starts to increase. Hydrogen energy is an important key solution to tackle the global temperature rise. The key important factor of hydrogen production is the hydrogen economy. Hydrogen production technologies are commercially available, while some of these technologies are still under development. This paper reviews the hydrogen production technologies from both fossil and non-fossil fuels such as (steam reforming, partial oxidation, auto thermal, pyrolysis, and plasma technology). Additionally, water electrolysis technology was reviewed. Water electrolysis can be combined with the renewable energy to get eco-friendly technology. Currently, the maximum hydrogen fuel productions were registered from the steam reforming, gasification, and partial oxidation technologies using fossil fuels. These technologies have different challenges such as the total energy consumption and carbon emissions to the environment are still too high. A novel non-fossil fuel method [ammonia $NH_3$] for hydrogen production using plasma technology was reviewed. Ammonia decomposition using plasma technology without and with a catalyst to produce pure hydrogen was considered as compared case studies. It was showed that the efficiency of ammonia decomposition using the catalyst was higher than ammonia decomposition without the catalyst. The maximum hydrogen energy efficiency obtained from the developed ammonia decomposition system was 28.3% with a hydrogen purity of 99.99%. The development of ammonia decomposition processes is continues for hydrogen production, and it will likely become commercial and be used as a pure hydrogen energy source.

## Keywords

Hydrogen Technology, Hydrogen Production, Steam Reforming, Plasma, Ammonia Decomposition

## 1. Introduction

Energy is the most important needs for the human life and development of the

worldwide. So, energy is the world key consideration in all discussions and meetings of the sustainable energy development. The renewable energy sources, such as solar energy, wind energy, waves, and tides energy are considered eco-friendly. It is expected that the hydrogen fuel and its demand will rise rapidly over the next few decades [1] [2]. The hydrogen energy utilization, as an energy source and storage methods, has been reviewed [3]. The recycling of the waste materials to useful energy sources through waste-to-energy technologies such as hydrogen, biogas, etc., has been reviewed [4]. The importance of hydrogen fuel is known as alternative clean energy and to overcome the fossil fuels depletion due to the high extension usage. In addition, fossil fuels have a bad effect on the environment due to combustion product gases such as carbon oxides, nitrogen, sulfur, etc. which have the main responsibilities of the global warming [5]. Hydrogen fuel is considered the alternative clean energy fuel and it can be produced from eco-friendly sources. In the current state, it is investigated that too little quantity of hydrogen is produced from the renewable energy resources through water electrolysis and the highest quantity is still generated from fossil fuels [6] [7]. Due to the hydrogen fuel advantages and versatility, in the long-term hydrogen will be the alternative of hydrocarbons fuels [8]. Also, hydrogen fuel is considered the highest efficient and clean energy carrier which produced water only as a by-product of its combustion. The worldwide is accepted to use hydrogen fuel as an independent clean energy source and high energy content compared to the fossil fuels, **Table 1** is shown the energy content of different fuels resources [9].

In different energy applications such as fuel cells, hydrogen energy can be utilized as a clean energy source without $CO_2$ products emission to the environment which water is the outlet combustion products. It has been investigated that the nitrogen oxides gases are produced in the high temperature hydrogen combustion, but these environmental pollutants can be removed at the low

**Table 1.** Energy contents of different fuels [9].

| Fuel | Energy content (MJ/kg) |
|---|---|
| Hydrogen | 120 |
| Liquefied natural gas | 54.4 |
| Propane | 49.6 |
| Aviation gasoline | 46.8 |
| Automotive gasoline | 46.4 |
| Automotive diesel | 45.6 |
| Ethanol | 29.6 |
| Methanol | 19.7 |
| Coke | 27 |
| Wood(dry) | 16.2 |
| Begasse | 9.6 |

temperature usage such as fuel cells [10]. The power-to-gas pilot plants have been used to generate electricity from hydrogen fuel or feeding the hydrogen gas into the gas distribution system [11] [12]. Currently, this technology is used for storing power in some European countries as a hydrogen gas [13] [14] [15] [16] [17]. In most power-to-gas pilot plants in Germany, the wind energy, and solar energy is used to produce electricity [18]. Many studies have been developed to evaluate the challenges of transition of using the hydrogen economy [19]-[48]. The steps which involved the implementation of a hydrogen economy have been investigated [49] [50] [51] [52]. The hydrogen energy prospects have been described to avoid the climate change-related problems [53]. The rationale of the hydrogen energy systems and technology has been studied including the present energy systems and their environmental impact [3] [54]-[63]. In this article, the hydrogen gas production technologies from the fossil and non-fossil fuels such as steam reforming process, water electrolysis process... etc. are reviewed. A novel hydrogen gas production method using ammonia decomposition by plasma technology is reviewed. Ammonia decomposition using plasma technology without and with the catalyst to produce pure hydrogen is considered as compared case studies.

### 1.1. World Energy Consumption

As global population increases and the urbanization trend continues, the energy consumers will become ever more and recently, the International Energy Agency report is predicted that the global energy demand will increase by 2030 to 50% [64]. Due to the fossil fuels limited nature and depletion, research and development have extensively started on generating new alternative sources and study the efficiently use of the current fossil fuels. The percentage of the power consumption of different humanities applications such as the building power consumption was considered the main energy usage and acts 51% of the total energy consumption [65]. The world population is estimated that will be triple by 2030. The common Energy Gases begins with natural gas or methane which has only one carbon and four hydrogen atoms. The world has been started to convert energy from one energy form to another form. The transition of solids to liquids to gases has been illustrated in **Figure 1** by GHK Company [66].

Before the mid of 19$^{th}$ century, the most reliance energy of the world was from wood. Coal has still remained the main reliable of the world energy in the 19th century. The energy usage was growing rapidly due to the high increase in world population, the world is directed toward oil fuel which overcomes the coal energy problems. But oil fuel is now facing environmental problems and the world is directed to use natural gas fuel. It has solved most of the environmental problems due to it is cleaner, lighter and more efficiently. Also, the distribution can be through a pipe network that is less conspicuous and more extensive than oil fuel. Nowadays, natural gas fuel became the first choice for generating electricity. The renewable energy ratio generated the electric energy and the renewable

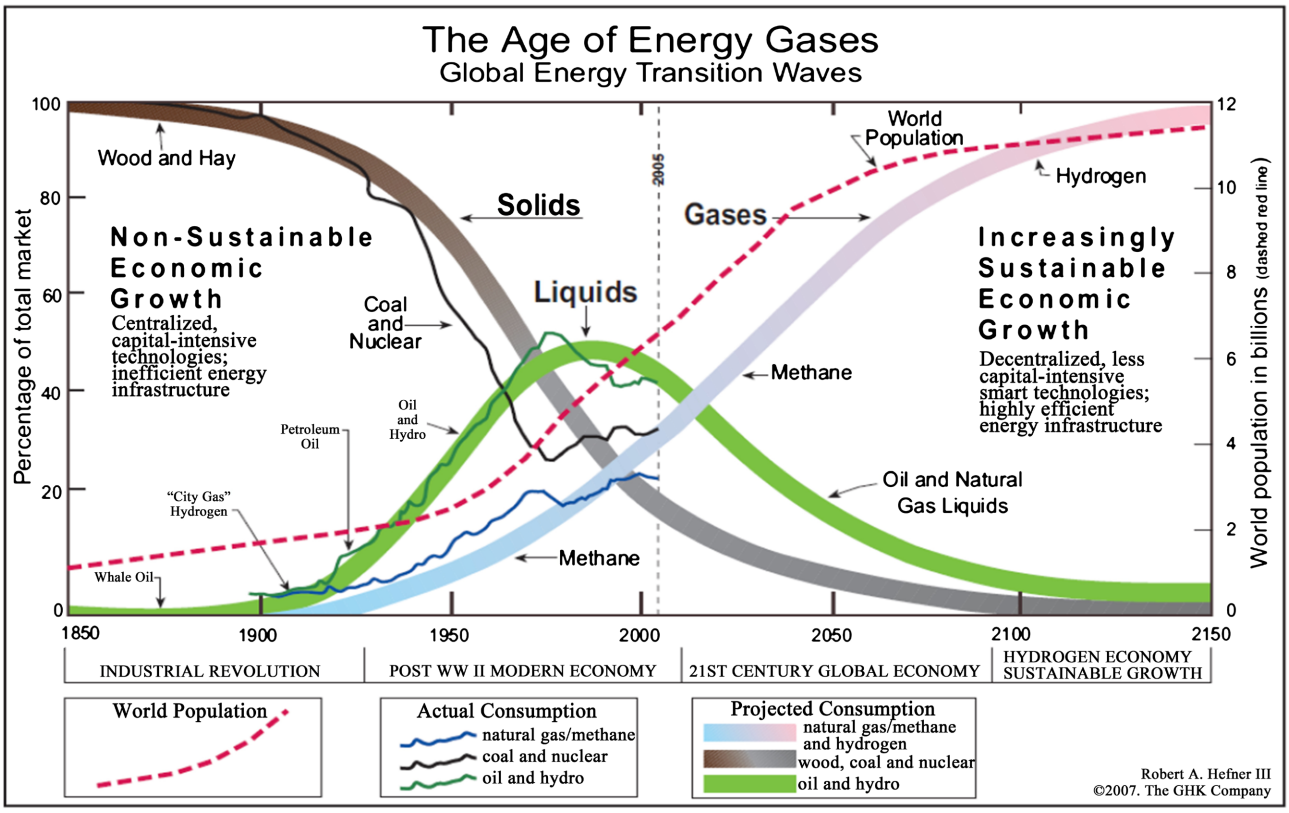



**Figure 1.** Global energy system transition, from 1850-2150 [66].

energy development has been compared by Japan energy 2017 [67]. Firstly, the world energy consumption rate is investigated to show the importance of increasing renewables energy through increasing energy efficiency and switching it to be clean, low carbon resources and economic growth is required. The increasing of fossil fuel usage the increasing of air pollution growing with a possibility of a highly serious economic and negative environmental effect [68] [69].

## 1.2. Environmental Impact

Hydrogen is the highest clean energy carrier which it can be used in the most energy applications such as generates electricity and transportation. Hydrogen fuel energy is expected to be the highest energy carrier's usage in the future; many advantages have been investigated that it can be used in transportation, long time storage and low environmental impact [70]. **Figure 2** is presented the greenization factor (GF), the environmental impact factor (EIF) and the hydrogen content factor (HCF) of the different energy fuels (coal, oil, natural gas, and hydrogen) [71]. In order to take the hydrogen fuel advantages, the hydrogen economy is still the most important hydrogen production issue. So, the renewable energy sources should be used to produce hydrogen at low costs. The assessment methodology for hydrogen production methods has been implemented to study the environmental impact [72] [73]. Hydrogen fuel has been considered that to be the highest clean and renewable future energy source [74]. A comparative

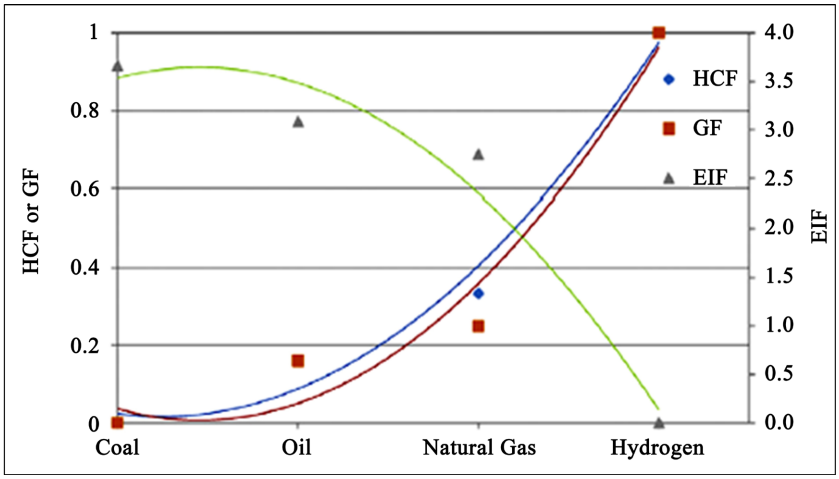



**Figure 2.** Hydrogen Content Factor (HCF), Greenization Factor (GF), and Environmental Impact Factor (EIF) of hydrogen and other fossil fuels [71].

study has been developed to reduce the total environmental emissions from the marine transportations by using hydrogen fuel [75] [76].

## 2. Hydrogen Production Technology

Hydrogen gas became the most important fuel which can be used as an alternative feedstock in industrial application processes. As the utilization of hydrogen fuel grows as the global warming temperature still keeps rising, so, the hydrogen production should be on a large scale. The evaluation of hydrogen production methods has been studied in different reviews [56] [71] [77]-[89]. Currently, the main source of hydrogen production is based on the fossil fuels. It can be presented as a commercial mature technology which it can be applied at low costs and get high efficiencies [90]. The hydrogen production especially using the steam reforming process of methane can get the efficiency range of (65% - 75%). On the other hand, the efficiency of the partial oxidation process of methane is recorded about 50% [54]. Hydrogen gas can also produce from water using the water electrolysis method which acting about 95% of the total quantity of hydrogen produced [91]. In the next section of this article, we will present several methods of the hydrogen production technologies. Recently, Plasma technology is an important method to produce the hydrogen fuel using hydrocarbons or alcohols. Hydrogen production using ammonia decomposition is a novel method can be established to produce pure hydrogen by using the plasma membrane reactor. A comparison of two different ammonia decomposition methods using the plasma technology is developed. The hydrogen production technology can be divided into hydrocarbons reforming and non-hydrocarbons reforming technology [80]. Firstly, a brief review is conducted to describe the hydrogen production from non-hydrocarbons technology.

### 2.1. Water Electrolysis

It can be defined in the simplest form by using two electrodes in water and

passing the electrical current water is converted into hydrogen and oxygen. The water electrolysis method can be divided into three different types of the electrolyte alkaline, proton exchange membrane (PEM), and solid oxide electrolysers (SOE) [92]. **Table 2** has been listed the typical specifications of the water electrolysis technologies methods. The commercial low temperature electrolysers were developed and have efficiencies of (56% - 73%) at conditions of (70.1 - 53.4 $kWh \cdot kg^{-1}$ H2 at 1 atm and 25˚C) [93]. The proton exchange membrane (PEM) electrolysis and solid oxide electrolysis (SOE) units have been studied [94] [95] [96]. Alkaline electrolysis systems are the most commonly compared to other water electrolysis methods. Solid oxide electrolysis (SOE) is the most electrically efficient but still are under development. Corrosion, seals, thermal cycling, and chrome migration are the major challenges faced by the SOE technology. The Proton exchange membrane (PEM) electrolysis systems are more efficient than alkaline electrolyser. Also, the corrosion and seals issues don't exist as (SOE), but the cost of (PEM) is too high compared with alkaline electrolysers systems. Alkaline electrolyser systems have the lowest capital cost and have the lowest efficiency so the electrical energy cost is too high. Recently, electrolysers are used for producing pure hydrogen and high pressure units have been developed [97]. The advantage of using the high pressure operation unit is to eliminate using expensive hydrogen compressors. The hydrogen production using the water electrolysis systems are showed the too high cost to generate hydrogen on large scale using the water electrolysis method. Additionally, the water electrolysis

**Table 2.** The typical specifications of alkaline, PEM and SOE [103].

| Specification | Alkaline | PEM | SOE |
|---|---|---|---|
| Technology maturity | State of the art | Demonstration | R & D |
| Cell temperature, ˚C | 60 - 80 | 50 - 80 | 900 - 1000 |
| Cell pressure, bar | <30 | <30 | <30 |
| Current density, $A/cm^2$ | 0.2 - 0.4 | 0.6 - 2.0 | 0.3 - 1.0 |
| Cell voltage, V | 1.8 - 2.4 | 1.8 - 2.2 | 0.95 - 1.3 |
| Power density, $W/cm^2$ | Up to 1.0 | Up to 4.4 | - |
| Voltage efficiency, % | 62 - 82 | 67 - 82 | 81 - 86 |
| Specific system energy consumption, $kWh/Nm^2$ | 4.5 - 7.0 | 4.5 - 7.5 | 2.5 - 3.5 |
| Partial load range,% | 20 - 40 | 0 - 10 | - |
| Cell area, $m^2$ | <4 | <300 | - |
| Hydrogen production, $Nm^2/hr$ | <760 | <30 | - |
| Stack lifetime, hr | <90,000 | <20,000 | <40,000 |
| System lifetime, yr | 20 - 30 | 10 - 20 | - |
| Hydrogen purity, % | >99.8 | 99.999 | - |
| Cold start-up time, min | 15 | <15 | >60 |

systems are utilized the non-renewable power generation source to produce electricity for the water electrolysis systems [98] [99] [100] [101] [102].

#### 2.1.1. Alkaline Electrolyser

This type is commonly used on the large-scale systems. Alkali solutions are divided into two different electrolyte types. The first electrolyte type is potassium hydroxide (KOH) with a weight percent of (20% - 40%) [104]. Sodium hydroxide (NaOH) and sodium chloride (NaCl) have been used as the other alkaline electrolyte types [105]. The separating diaphragm between the two electrodes is made of the asbestos material with a thickness of 3 mm and due to the usage of the asbestos materials the water electrolyser operation temperature is limited to be 80˚C [103]. Hydrogen and hydroxide are generated at the cathode part, then the hydroxide is moved to the anode part generating oxygen. The anode and cathode part reactions can be expressed as follows:

- Anode reaction:

$$4OH^- \rightarrow O_2 + 2H_2O \tag{1}$$

- Cathode reaction:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \tag{2}$$

- The overall equation is:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \qquad \Delta H = -288\left[\mathrm{kJ \cdot mol^{-1}}\right] \tag{3}$$

The gas-liquid separation unit is used to separate the generated hydrogen gas outside the electrolyser [106]. The alkaline electrolysers process efficiencies have been registered in a range of (50% - 60%) at a current density of (100 - 300 $mA \cdot cm^{-2}$) and at the hydrogen gas lower heating value [93]. The corrosion problem is the main challenge of this method, according to using the alkali solution. So, new materials are also being developed to be used as an alternative diaphragm material.

#### 2.1.2. Proton Exchange Membrane Electrolyser

To overcome the corrosion has happened from the alkaline electrolysers method, the solid polymer membrane has been investigated to use in the PEM fuel cells technology [107]. However, the deionized water with high purity has been required for the water electrolysis process [106]. The oxidation reaction of water is happened at the anode part generating oxygen, electrons, and protons. The electrons and protons are moved to the cathode side through the PEM. The hydrogen gas is generated at the cathode part after the porotons reduced. The PEM reactions are expressed as follows:

Anode reaction:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \tag{4}$$

Cathode reaction:

$$4H^+ + 4e^- \rightarrow 2H_2 \tag{5}$$

The overall equation is same as the alkaline electrolyser Equation (3). The PEM electrolyser system has been investigated that it can be used with the fluctuation power supply source, according to the portons transportation through the PEM membrane is so quickly [103]. The high manufacturing cost is the major challenge of the PEM systems.

### 2.1.3. Solid Oxide Electrolyser

The solid oxide electrolyser (SOE) operation temperature can be reached at 1000˚C compared with the PEM electrolyser. **Figure 3** is illustrated that these systems typically are used the thermal energy instead of a part of the electrical energy [108]. It was investigated that the electrolyser efficiency is increased by increasing high temperature [108] [109]. Therefore, compared to alkaline and PEM processes the SOE process has a higher efficiency. In the SOE system, hydrogen is generated at the cathode part and the oxide anions are passed to the anode where oxygen will form through the solid electrolyte [107]. The following reactions are taking place in an SOE:

At anode:

$$O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^- \tag{6}$$

At cathode:

$$2H_2O + 2e^- \rightarrow H_2 + O^{2-} \tag{7}$$

This method is also used in fuel cells as a solid oxidation electrolysis cells (SOEC).

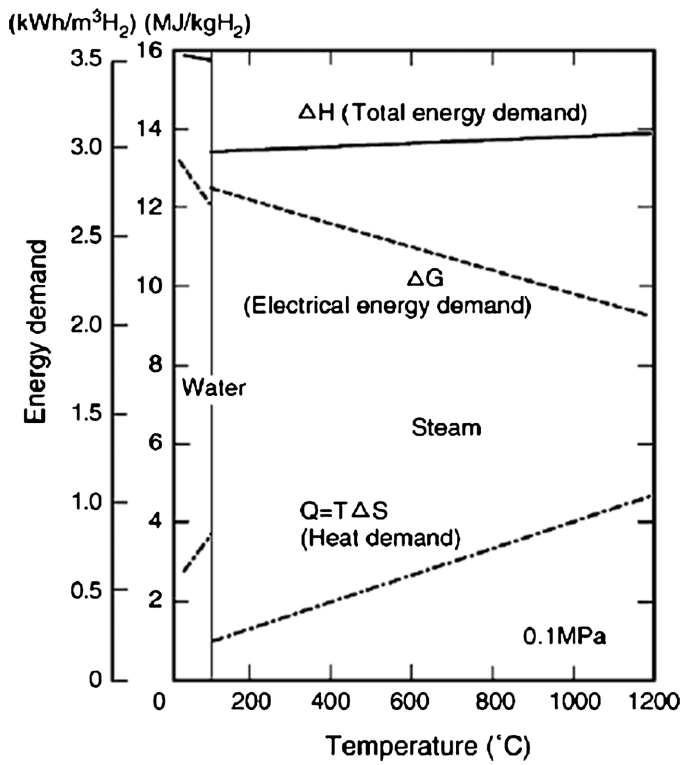



**Figure 3.** Energy demand for water and steam electrolysis [108].

SOEC systems are operated at a high temperature from nuclear reactors and can achieve efficiency up to 60% [102]-[115].

## 2.2. Thermolysis & Thermochemical Water Splitting

### 2.2.1. Thermolysis

In the thermolysis process water is directly split using thermal energy as the energy input or it can be split indirectly using some other chemical materials [113]. The following is the thermolysis chemical reaction equation:

$$H_2O \xrightarrow{\text{Heat}} H_2 + \frac{1}{2}O_2 \tag{8}$$

Thermolysis and thermochemical water decomposition methods can be seemed to be the same methods, regardless of the high temperature source. This means the thermochemical process deals with the chemical reactions and the heat transfer processes. It was investigated that if the temperature reached over 2000˚C, water is started to decompose without using other chemical materials [113]. It was presented that the thermolysis process is a direct thermal splitting of water at too high temperature [92]. This means that the material selection is very difficult to be suited with the high temperature. Also, it has been investigated that the main challenge of the thermolysis process is to develop an effective technique [92] [104] [116] [117].

### 2.2.2. Thermochemical Water Splitting

In the thermochemical water splitting process, it was combining the thermolysis water splitting process and the chemical reactions to reduce the water decomposition temperature to 900˚C [104]. The hydrogen production using the thermochemical water splitting has been involved in different chemical reactions. Many studies have been developed to review the water splitting cycles [106] [118] [119]. Different thermochemical cycles have been studied [105] [120] such as copper-chlorine, Zinc-zinc oxide, nickel-manganese ferrite and the sulfur-iodine process. For example, the sulfur-iodine process as follows:

The first reaction is the sulfuric acid which is decomposed at 300˚C to 500˚C to release water without a catalyst,

$$H_2SO_4(aq) \xrightarrow{300^\circ C - 500^\circ C} H_2O(g) + SO_3(g) \tag{9}$$

Then, $SO_3$ is separated at 800˚C to 900˚C to release oxygen,

$$SO_3(g) \xrightarrow{800^\circ C - 900^\circ C} SO_2(g) + \frac{1}{2}O_2 \tag{10}$$

The next reaction is done at low temperature to produce the sulfuric acid,

$$SO_2(g) + I_2(g) + 2H_2O(l) \rightarrow 2HI(g) + H_2SO_4(aq) \tag{11}$$

Finally, hydrogen is produced from iodine decomposition within a temperature range of 425˚C to 450˚C,

$$2HI(g) \xrightarrow{425^\circ C - 450^\circ C} H_2(g) + I_2(g) \tag{12}$$

The challenge is faced this technology, the efficiency has to be increased by

making scaling up [121].

## 2.3. Photonic

Hydrogen is produced from the photonic process by using the photon energy. It can be divided into two methods the photocatalytic and the photoelectrolysis water splitting (photoelectrochemical water splitting).

### 2.3.1. Photocatalytic Water Splitting

The hydrogen production by the Photocatalytic water splitting process is a direct method to produce hydrogen from water using the ordinary light. The low efficiency has been achieved by the photocatalytic method [122]. The main reactions of this process are as follows [123]:

$$\text{Photo-reduction} \quad 2H_2O + 2e^- \xrightarrow{h\nu} H_2 + 2OH^- \tag{13}$$

$$\text{Photo-oxidation} \quad 2H_2O \xrightarrow{h\nu} 4H^+ + 4e^- + O_2(g) \tag{14}$$

The titanium oxide ($TiO_2$) is used in the photolysis reactions. Different researches are interested in photocatalyst development [124]-[128].

### 2.3.2. Photoelectrolysis

Photoelectrolysis has directly decomposed water into hydrogen and oxygen by using the sunlight. The photoelectrolysis systems are the same as the photovoltaic systems, both technologies are used the semiconductor materials. In photovoltaic, p-type and n-type semiconductor materials are used [94]. The electric current is created, due to the forced movement in the opposite direction of the electron and hole [93] [129]. In photoelectrolysis process instead of generating the electric current water is decomposed into hydrogen and oxygen [93] [94] [100] [129]. The reaction of photoelectrolysis is illustrated as follows [123]:

$$H_2O \xrightarrow{h\nu} H_2(g) + \frac{1}{2}O_2(g) \tag{15}$$

Different photo electrodes materials such as $WO_3$, $Fe_2O_3$, and $TiO_2$ have been investigated to use in photoelectrolysis method as a thin-film [114] [130] [131]. The photoelectrolysis systems performance is mainly based on the utilized materials of the photoelectrodes and the semiconductor. The hydrogen production efficiency has been studied by [93] [94] [100] [129]. It has been investigated that the achieved efficiency of a single band gap is 18.3%, dual-band gap systems over 30% conversions [132].

## 2.4. Biomass

Biomass energy is used to generate hydrogen fuel as a renewable energy source. Biomass energy sources such as agricultural wastes, animal wastes, municipal solid wastes…etc. have been investigated [133]-[151]. A comparison between the fossil fuels and biomass energy is illustrated in **Table 3**. The biomass technologies for hydrogen production can be divided into the gasification, pyrolysis which it was followed by the reforming process [149]. The basic reactions of

biomass gasification process are listed in **Table 4**. The hydrogen production yield of the biomass process has been affected with the biomass characteristics and compositions are affected with a number of process variables such as temperature, heating rate, moisture content, particle size, reactor system…etc. [152] [153].

#### 2.4.1. Biomass Gasification Process

The Gasification process can be commonly used in the biomass and coal gasification processes. It is commercially used in many processes and it has been based upon the partial oxidation process of the materials to get the mixture of hydrogen, carbon monoxide, methane...etc. [145]. Since the moisture has to be vaporized, the thermal efficiency of the gasification process is typically low [133]. Different studies have been presented for the gasification process with and without a catalyst using the fixed bed and the fluidized bed reactor [139] [144] [148] [155]. The recorded performance of the fluidized bed reactors is higher than the fixed bed type reactors [144]. Syngas is produced from steam reforming process when steam or oxygen is added to the gasification process, which it can be utilized for hydrogen production in the water gas shift (WGS) or the Fischer-Tropsch reactor [144] [149]. Biomass is dried by using superheated steam at 900˚C. The high hydrogen production yields can be achieved from the dried

**Table 3.** Advantages and disadvantages of hydrogen production from biomass [154].

| Advantages | Disadvantages |
|---|---|
| 1) Mitigating $CO_2$ emissions | 1) Seasonal availability and high handling costs |
| 2) Crop residues conversion increases the value of agricultural output | 2) Non-total solid conversion and tars production |
| 3) Replacing fossil fuels with sustainable biomass fuel | 3) Fuel process limitations: corrosion, pressure, resistance and hydrogen aging. |
| 4) Cost of getting rid of municipal solid wastes | |

**Table 4.** Basic reactions biomass gasification processes [152].

| Reaction mode | Reaction equation |
|---|---|
| Pyrolysis | $C_6H_{10}O_5 \rightarrow 5CO + 5H_2 + C$ |
| | $C_6H_{10}O_5 \rightarrow 5CO + 3H_2 + CH_4$ |
| Partial oxidation | $C_6H_{10}O_5 + \frac{1}{2}O_2 \rightarrow 6CO + 5H_2$ |
| | $C_6H_{10}O_5 + O_2 \rightarrow 5CO + 5H_2 + CO_2$ |
| | $C_6H_{10}O_5 + 2O_2 \rightarrow 3CO + 5H_2 + 3CO_2$ |
| Steam reforming | $C_6H_{10}O_5 + H_2O \rightarrow 6CO + 6H_2$ |
| | $C_6H_{10}O_5 + 3H_2O \rightarrow 4CO + 2CO_2 + 8H_2$ |
| | $C_6H_{10}O_5 + 7H_2O \rightarrow 6CO_2 + 12H_2$ |

biomass [133]. Based on the lower heating value, the achieved efficiencies of these reactors within range of (35% - 50%) [106] [118].

#### 2.4.2. Biological Hydrogen Production Process

Bio-hydrogen researches are increased last several years, as attention to sustainable development and waste minimization [156]-[186]. This is another biomass method to produce hydrogen gas fuel using the biological technologies. It has been investigated that it can be utilized the anaerobic bacteria which it is grown in the dark fermentation bioreactors or can be used algae in the light in the photo fermentative process [184]. The main processes include the photolytic process to produce hydrogen from water using the green algae, the hydrogen production using the dark-fermentative process of anaerobic digestion, the two-stage dark/fermentative process, the photo-fermentative processes and the WGS method for hydrogen production [160] [165] [185]. The biological methods have been presented with a low environmental impact and high hydrogen production efficiency [78]. By using the anaerobic microorganisms the dark fermentation reaction is carried out to convert the carbohydrate to hydrogen and other final products [105] [186]. The following is the chemical reaction equation:

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2 \tag{16}$$

The low hydrogen production capacity compared with the unit capital investment has been investigated that it was the major challenge of the dark fermentation method [187]. So, different extensive researches have been presented to get additional energy by adding and develop a new other two-stage system [188].

## 3. Hydrocarbons Reforming Technology

The hydrogen production from hydrocarbon fuels using reforming technology is presented. The Steam reforming process of hydrocarbons is considered the manufacturing dominating process of hydrogen production especially, for refineries. The hydrogen production technology using the hydrocarbon fuels can be divided into a steam reforming process, the partial oxidation process, and the auto-thermal reforming process (ATR). **Table 5** is shown as a comparison

**Table 5.** Comparison of reforming technologies [189]-[191].

| Technology | Advantages | Disadvantages |
|---|---|---|
| Steam reforming | Most extensive industrial experience Oxygen not required<br>Lowest process temperature<br>Best $H_2$/CO ratio for $H_2$ production | Highest air emission |
| Auto-thermal | Lower process temperature than POX<br>Low methane slip | Limited commercial experience<br>Requires air or oxygen |
| Partial oxidation | Decreased desulfurization requirement<br>No catalyst required<br>Low methane slip | Low $H_2$/CO ratio<br>Very high processing temperatures<br>Soot formation/handling adds process complexity |

between the reforming processes [189] [190] [191].

In the steam reforming process, hydrogen gas, carbon monoxide and carbon dioxide gases are primarily composed in the gas flow stream; it has been investigated that by improving the operating conditions such as temperature, pressure, etc. in the fuel processing reactors will maximize the hydrogen production and minimize the carbon formation [192]-[199].

### 3.1. Steam Reforming

The steam reforming process is known as the hydrocarbons conversion with steam into hydrogen, carbon oxides, methane, and unconverted steam mixture. The typical feedstock ranges from natural gas and LPG to liquid fuels including naphtha and in some cases kerosene. In recent years steam reforming is also seen as an option for converting the primary feed into a gas suitable for a fuel cell. Different steam reforming reactors types have been used for specific applications [194]. The steam reforming process is considered the preferred hydrogen production process, the steam reforming process reactions are endothermic reactions, the operating temperature is typically lower than the POX and ATR methods while it can be produced a high H/CO ratio [192] [193] [194] [195] [196]. **Table 6** shows the reactions of the steam reforming process.

It was investigated that in the fuel processing, moderate temperatures higher than 180˚C is required [192]-[199]. The limitations of mass and heat transfer have been investigated to enable the kinetics of steam reforming by employing a micro-channel reactor [193] [200] [201] [202]. These systems have been utilized the noble Group VIII metals as alternatives catalysts such as Rh and Co-based catalyst [203] [204] [205]. It was showed a less coke formation and much higher activities compared with the nickel catalysts [200] [206] [207] [208]. The hydrogen production from methane using the steam reforming process is considered the common industrial method where it is given a high thermal efficiencies up to 85% according to the higher heating values [209]. The hydrogen fuel storage and transportation are very difficult due to the hydrogen fuel have a low energy per weight, additionally is a gaseous fuel. Thus, different on-site studies have been developed for steam reforming of hydrocarbons [210]-[216].

**Table 6.** The key reactions of steam reforming process [200].

| Reactions | Reaction description | Standard enthalpy of reactions [kJ·mol$^{-1}$] | |
|---|---|---|---|
| $CH_4 + H_2O \rightleftharpoons CO + 3H_2$ | Steam reforming | 206 | R① |
| $CO + H_2O \rightleftharpoons CO_2 + H_2$ | WGS | -41 | R② |
| $CH_4 + CO_2 \rightleftharpoons 2CO + 2H_2$ | $CO_2$ reforming | 247 | R③ |
| $C_nH_m + nH_2O \rightleftharpoons nCO + \left(\frac{m}{2} + n\right)H_2$ | Higher hydrocarbons steam reforming | 1175* | R④ |

*[Standard conditions at $P = 1$ atm, $T = 298$ K, for n-$C_7H_{16}$].

### 3.2. Partial Oxidation

The reaction of the partial oxidation (POX) method is an exothermic reaction and the reaction equation is presented in Equation (5). In the POX method the hydrogen produced is sent to the water-gas shift (WGS) reactor, and then is purified by using a suitable purification method. Compared with the steam reforming process, it has been investigated that the efficiency of the POX process is low; in addition, the operation cost is too high due to using high quantities of the pure oxygen [217]. The enthalpy of reactions for methane and isooctane are shown in Table 7.

$$C_nH_m + \frac{n}{2}O_2 \rightarrow nCO + \frac{m}{2}H_2 \tag{5}$$

Example of the (POX) reaction:

$$CH_3OH + \frac{1}{2}O_2 \rightarrow CO_2 + 2H_2 \qquad \Delta H = -193.2\left[\mathrm{kJ \cdot mol^{-1}}\right] \tag{6}$$

The hydrogen production from the partial oxidation of hydrocarbon using catalysts has been utilized in commercial applications and automobile fuel cells [218] [219] [220] [221] [222]. The effect of addition ruthenium (Ru) on the molybdenum (Mo) catalysts has been investigated for the production of syngas from methane ($CH_4$) via partial oxidation process [223]. The principles of (CPO) are illustrated in Figure 4.

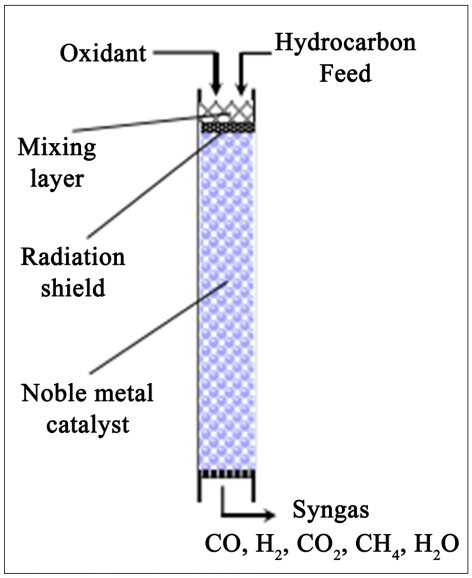



Figure 4. Catalytic partial oxidation principle [200].

Table 7. Standard enthalpies at (298 K, 1 atm), $\Delta H$ in [kJ/mol] [218].

| | Methane | Isooctane |
|---|---|---|
| Partial oxidation | −36.1 | −675.8 |
| Steam reforming | 205.7 | 1258.8 |
| Dry $CO_2$ reforming | 246.9 | 1596.3 |

Several studies have been carried to study CPO at different space velocities (low or moderate) and residence time (from 1 s or above) [224]-[229]. The importance of operating and design parameters has been investigated in another feature of the CPO process to prevent the explosions risk [230]. It is proved that the temperature is hard to be controlled due to the hot spot formation and the reactions nature is exothermic [219] [220] [221] [222]. The POX reactors efficiencies have been recorded based on the higher heating values for methane fuel is 60% - 75% [209].

### 3.3. Auto-Thermal

Auto thermal reforming process has been done at low pressure compared with the POX reforming process. The heat required in the catalytic zone to drive the steam reforming reactions has been generated using the POX process [199] [224] [231] [232]. **Figure 5** is illustrated the auto-thermal reactor components. The combustion chamber reaction equations are shown in **Table 8**.

Compared with the POX process, a significant advantage of the auto-thermal reaction process, it can be produced a large amount of hydrogen gas while the starting and stop are very rapidly. In the auto-thermal reaction process, it was considered that it must be controlled the temperature and preventing the coke formation by using the both of the steam to carbon ratio and the oxygen to fuel ratio [199] [224] [231].

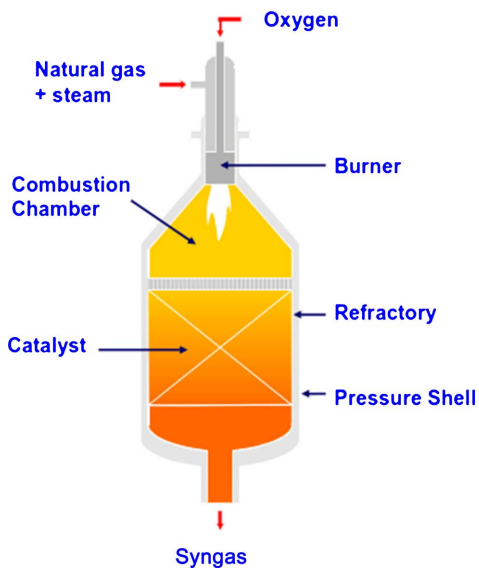



**Figure 5.** Illustration of an auto-thermal reactor [233].

**Table 8.** Simplified reactions in the combustion chamber of ATR [194]

| Reactions | Reaction description | Standard enthalpy of reactions $\Delta H$ [kJ.mol$^{-1}$] | |
|---|---|---|---|
| $CH_4 + 3/2O_2 \rightarrow CO + 2H_2O$ | Combustion | −519 | R⑦ |
| $CH_4 + H_2O \rightleftharpoons CO + 3H_2$ | Steam reforming | 206 | R① |
| $CO + H_2O \rightleftharpoons CO_2 + H_2$ | WGS | −41 | R② |

### 3.4. Gasification

The gasification process is presented to be a sequence of a thermochemical transformations taking place at high temperatures between the organic part such as coal and the gasifying agent, like oxygen, steam, air, carbon dioxide [234] [235] [236]. The heat needed for the gasification process has been made by using the carbonaceous material (so it is called autothermic gasification) [234]. The water gas shift (WGS) process has been used to separate hydrogen and converting carbon monoxide into the carbon dioxide [104]. The gasification process heterogeneous and homogeneous reactions are summarized in **Table 9** and **Table 10** respectively.

The integrations of the coal gasification with other systems have been studied by different researches [239]-[249]. Thermodynamic evaluations using the first and second law of thermodynamics have been conducted on the integrated gasification systems in their analyses [242]-[250].

The hydrogen production from water decomposition using the Bryton cycle and a thermochemical copper-chlorine cycle have been investigated as a novel method to overcome the limitations of the hydrogen production from the coal composition and syngas hydrogen separation [251]. Koppers Totzek Coal gasification process can be produced pure hydrogen up to 97%, it has been investigated that it has the ability in the near and midterm to keep the hydrogen production from the fossil fuel in practice from the solar thermal processes and carbon sequestration application [252]-[261].

**Table 9.** Major heterogeneous reactions taking place in the gasifier [234] [235] [236] [237].

| Reactions | Reaction description | Standard enthalpy of reactions[kJ/mol$^{-1}$] | |
|---|---|---|---|
| $C + CO_2 \rightleftharpoons 2CO$ | Reverse boudouard | 172.4 | R⑧ |
| $2H_2 + O_2 \rightleftharpoons 2H_2O$ | | 131.3 | R⑨ |
| $C + 2H_2 \rightleftharpoons CH_4$ | Methane formation | −74.9 | R⑩ |
| $2C + O_2 \rightleftharpoons 2CO$ | Oxidation of CO | −221 | R⑪ |
| $2C + O_2 \rightleftharpoons 2CO$ | Coke gasification | −393.6 | R⑫ |

**Table 10.** Major homogenous reactions taking place in the gasifier [234] [235] [236] [238].

| Reactions | Reaction description | Standard enthalpy of reactions $\Delta H$ [kJ·mol$^{-1}$] | |
|---|---|---|---|
| $2CO + O_2 \rightleftharpoons CO_2$ | Oxidation of CO | −566 | R⑬ |
| $2H_2 + O_2 \rightleftharpoons 2H_2O$ | Oxidation of $H_2$ | −483.6 | R⑭ |
| $CO + H_2O \rightleftharpoons CO_2 + H_2$ | WGS | −41 | R② |
| $CO + 3H_2 \rightleftharpoons CH_4 + H_2O$ | Methanation/hydrogenation | −206 | R⑮ |
| $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ | Combustion | −802.6 | R⑯ |

### 3.5. Pyrolysis

The Pyrolysis process "can be defined as the decomposition of organic substances by heat" [262]. These decomposition reactions have been performed at 350˚C to 400˚C depending on the coal properties [263]. The other hydrocarbons thermal decomposition have been occurred at high temperatures such as methane thermal decomposition temperature is at 1400˚C or higher. Significantly, the temperature of the pyrolysis process can be reduced by using the transition metal catalyst like (Ni, Fe, Co). It has been investigated that the pyrolysis process can be used the organic material [148] [264] [265] [266], additionally, it can be used for the hydrocarbons production, carbon nanotubes and spheres [148] [266]-[278].

The chemical reaction of the pyrolysis process can be generally expressed as follows [269]:

$$C_nH_m \rightarrow nC + \frac{1}{2}mH_2 \tag{17}$$

The chemical decomposition equation of hydrocarbons using the pyrolysis process, it is showed that water and air aren't used. Consequently, carbon oxides don't appear in the reaction by-products. It was presented that the pyrolysis process has the flexibility to use any organic fuel, in addition to its compactness and the process by-product is carbon-free [152] [265] [266] [269]. Although the pyrolysis process advantages, there is a major potential fouling problem by the carbon formed and it can be reduced by using appropriate reactor design [152].

## 4. Hydrocarbons Reforming Assisted by Using Plasma Technology

Plasma "is known as the fourth state of the material" and it can be defined as an ionized gas. This technology has the challenge to produce hydrogen with the best energetic efficiency. The plasma technology can be classified into thermal and non-thermal plasma (non-equilibrium plasma) based on the energy level (temperature, plasma state, and electronic density). The electrically heated furnaces, combustion, flames, electric discharges, and shocks have been considered the plasma different generated methods [270]. **Table 11** is shown the different plasma systems classifications and properties. The gas components temperature is the major difference between thermal plasma and no-thermal plasma technology [271] [272]. The high energetic densities can be released from the plasma process, so, the hydrogen production from hydrocarbons reforming applications using plasma with and without catalyst case studies have been discussed, in addition, the hydrogen production from ammonia decomposition using non-thermal plasma reactor. The plasma torch (DC) direct current has been used in the first plasma-assisted reformers which it was thermal ones. A comparison between new and old plasmatron for methane and diesel fuels of $H_2$ yield for both kinds It has been shown in **Figure 6** & **Figure 7** respectively [273]. These figures are illustrated that the non-thermal plasma systems have a low en-

ergy consumption compared with the thermal plasma systems. We will briefly describe thermal and non-thermal plasma methods.

### 4.1. Thermal Plasma Technology

Thermal plasma can be applied to different applications which required high temperature such as vehicles ignition systems, lighting applications, gasification

**Table 11.** Classification and properties of various plasma [272].

| Properties | Thermal Plasma (quasi-equilibrium plasma) | Non-thermal Plasma (Non equilibrium plasma) | | | | |
|---|---|---|---|---|---|---|
| Temperature | $Te \approx Ti \approx Tg \leq 2 \times 10^4$ K | $Te \gg Ti \approx Tg \leq 300 \ldots 103$ K | | | | |
| Density | $\geq 1020$ m$^{-3}$ | ~1010 m$^{-3}$ | | | | |
| Classification: | Thermal arc plasma | Gliding arc discharge | Dielectric barrier discharge | Corona discharge | Glow discharge | Atmospheric pressure plasma jet |
| Excitation | DC | DC/AC | AC/RF | Pulsed DC | DC/AC | RF (13.5 MHz) |
| Pressure, bar | 0.1 - 100 | ~1 | ~1 - 3 | ~1 | <10 mbar | ~1 |
| Electron energies, eV | 1 - 10 | 1.4 - 2.1 | 1.0 - 30 | ~5 | 2.0 - 8.0 | |
| Electron density, cm$^{-3}$ | 1015 - 1019 | >1013 | 1012 - 1015 | 109 - 1013 | 109 - 1012 | 1011 - 1012 |
| Breakdown voltage, kV | 10 - 100 | 0.5 - 4.0 | 5.0 -25 | 10.0 - 50.0 | | 0.05 - 0.2 |
| Current, A | 30 - 30,000 | 10-1-50 | 1.0 - 50 | <10 - 5 | 10-5-1 | |
| Tmac, K | $5 \times 10^3$ - $10^4$ | 1000 - 3000 | ~300 | ~400 | ~700 | ~400 |
| Carrier gas | air, $N_2$, $O_2$, etc. | $N_2$, $O_2$, Ar | $N_2$, $O_2$, rare gas | $N_2$, $O_2$, Ar | $N_2$, $O_2$, Ar | He, Ar |

"RF inductivity coupled discharge. Te, Ti and Tg refer to the temperature of electrons, ions, and neutral species (atoms, molecules, radicals and excited species) respectively.

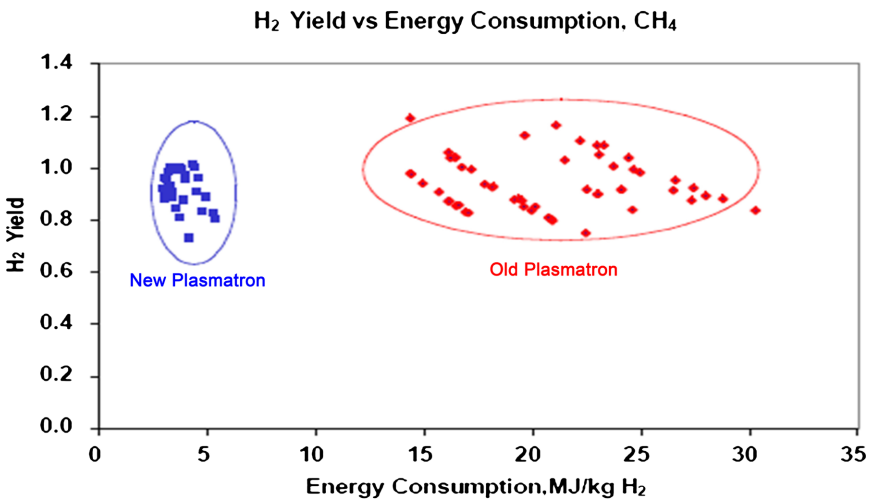



**Figure 6.** Comparisons of energy costs for non-thermal and thermal plasmas reforming of Methane [273].

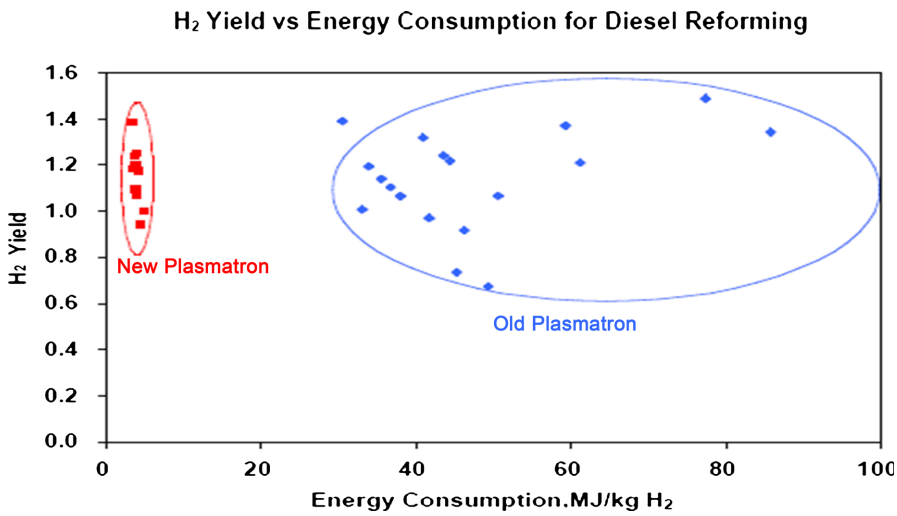



**Figure 7.** Comparisons of energy costs for non-thermal and thermal plasmas reforming of diesel [273].

of solid fuels. Due to the thermal plasma technology high temperature, it has been limited for some liquid fuels reforming due to the electrode erosion. It has been characterized that the thermal plasma technology has a highly degree of dissociation and a substantial ionization degree [274]. Thermal plasma has an important range of application that includes synthesis of Nanopowders, destruction, and treatment of hazardous waste, metallurgy application (smelting operations and re-melting application in large furnaces) surface modification and coating, chemical synthesis [275]. Thermal degradation (gasification) of the organic carbon-based materials have been carried out at a temperatures range of 400˚C to 1500˚C [276]. It has been investigated that the thermal plasma technology can be used in waste treatment such as healthcare wastes, steel making waste….etc. [277]-[283]. The economic studies have been presented that the insufficient control is the main disadvantages of the waste treatment using thermal plasma method [284]. In addition, the reforming process for alcohols using thermal plasma technology has been limited [285].

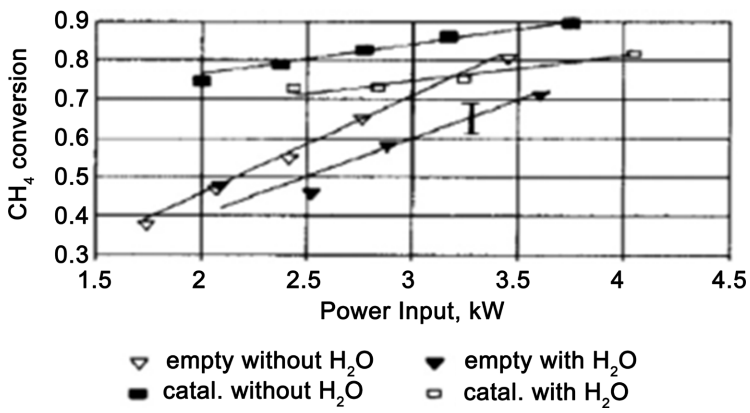
A high electric discharge over 1 kW has been used in hydrocarbons reforming process by using thermal plasma technology; also, the cooling power has been required to decrease the electrode temperature to stop the vaporization of metal [274] [276] [287]. **Figure 8** is shown the methane conversion with the input power to the thermal plasma reactor [274]. The thermal plasma is usually used high temperature, it will increase the energy cost, in addition to unwanted coking and soot. Catalysts have been utilized to reduce the reaction temperature, additionally; the required activation energy of fuel conversion is reduced.

## 4.2. Non-Thermal Plasma Technology

The non-thermal plasma method is more suitable for the hydrocarbons reforming and producing syngas. According to the non-thermal plasma method, the chemical reactions have been happened at low input power and at low temperatures

[288]. In non-thermal plasma technology, the electron temperature can be reached (10,000 to 100,000 K) and at the same time, the gas temperature is at the room temperature [289] [290]. Different reactors have been used for applying the different plasma technologies like the dielectric barrier discharge (DBD) reactors [290] [291], gliding arc discharge [285] [292] [293] [294] [295], corona [290] and microwave [296] [297] [298]. It has been utilized in hydrocarbons reforming such as diesel, methane, and biofuels [274] [291] [299]-[305].

The non-thermal plasma process main effect parameter is the electron temperatures which temperatures are raised higher than 5000 K [285] [286] [306]. Dielectric barrier discharge (DBD), gliding arc discharge plasma, corona discharge and microwave plasma is the non-thermal plasma types [285] [306]-[315]. In the first three types, the dynamic discharge is used to create plasma. The main different parameters between non-thermal plasma types are the controlling method of the current and discharging power, additionally, reactor design, flow rate and the power supplies which have been described [285]. The gliding arc discharge which has a good selectivity and high production rate will briefly describe in this article. **Table 12** differentiates the efficiencies of the non-thermal plasma methods and it is shown that the gliding arc discharge has the highest non-thermal plasma efficiency. **Figure 9** illustrates the gliding arc discharge which has two




"Empty reactor: plasmatron air = 0.4 g/s, fuel = 0.27 g/s, additional air = 0.7 g/s. In the case of water addition, 0.2 - 0.5 g/s $H_2O$ added. Catalytic case: plasmatron air = 0.35 g/s, fuel = 0.25 - 0.5 g/s, additional air = 0.5 - 1 g/s. In the case of water addition, 0.5 - 0.8 g/s water".

**Figure 8.** Methane conversion as a function of power input [274].

**Table 12.** Plasma reformer efficiencies [285].

| Technology | Fuel | Experimental conditions | | | Products (dry vol. %) | | | | Reformate Temperature [K] | Efficiency |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Chemical Reaction | Air Ratio | S/C | $H_2$ | CO | $CO_2$ | $CH_4$ | | |
| Gliding arc non-thermal | Diesel | ATR | 0.4 | 1.8 | 23 | 17 | 6.2 | 1.2 | 1000 - 1300 | 85 |
| Corona discharge + catalyst | Iso-octane | ATR | 0.28 | 1 | 46 | 16 | 16 | - | 900 - 1100 | 55 |
| Gliding arc thermal | Iso-octane | POX | 0.25 | - | 22 | 15 | 2 | 3 | 1200 | 9 |
| Gliding arc thermal | Diesel | POX | 0.25 | - | 23.5 | 23 | 0.1 | 0.03 | 1200 | 9 |
| Microwave | Hexane | SR | - | 2 | 66 | 25 | 4 | - | ? | ? |

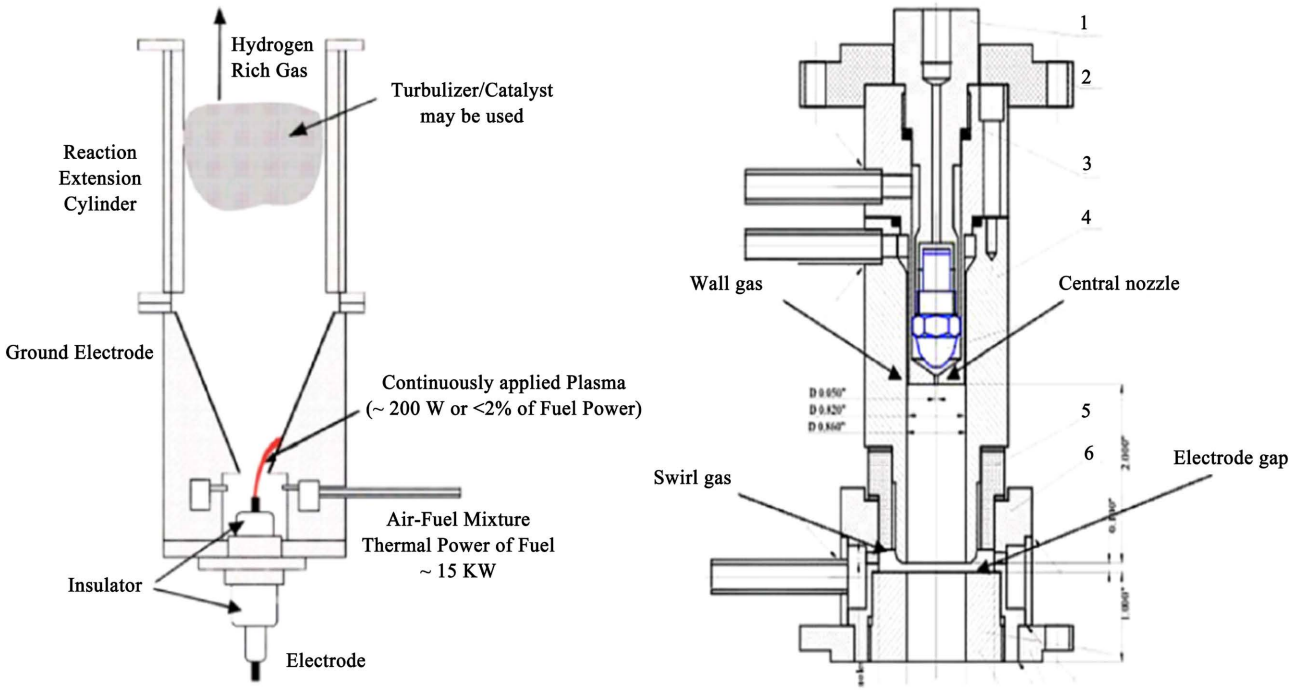



**Figure 9.** Scheme of Gliding Arc reactor [312].

electrodes and a simple feeding electrical system [312]. The arc is formed while the gas enters the reactor and the high voltage is applied. The arc is pushed down by the gas along the reactor length and is turned off at the reactor end, and then the new arc is formed again at the reactor gas inlet. It has been investigated that the gliding arc discharge method can be used the DC or AC currents, in addition, a simple feeding power supply system compared with the other non-thermal plasma systems [285].

## 5. Hydrogen Production Using Ammonia [$NH_3$] by Using Plasma Decomposition

All efforts are made by researchers to provide the World with hydrogen fuel. In a different way, a new hydrogen production method from ammonia decomposition using plasma technology has been investigated. This plasma technology type has the ability to produce a 99.999% of pure hydrogen gas at normal temperature, atmospheric pressure and without using a catalyst. Prof. Shinji Kambara of Gifu University, Japan, Division of Environmental and Renewable Energy Systems is collaborated with Sawafuji Electric Co., Ltd and has been developed a novel hydrogen production method using ammonia decomposition by using a DBD plasma reactor. The newly developed prototype can be applied to fuel cell. Also, it has Low-cost, low environmental impact and highly efficient hydrogen production equipment based on ammonia gas. The flowing ammonia gas is decomposed into hydrogen and diatomic nitrogen through the plasma field as follows:

$$NH_3 + e^- \rightarrow \frac{1}{2}N_2 + \frac{3}{2}H_2 \tag{19}$$

This study confirmed that the power generation by using the hydrogen obtained from the installation as a fuel cell. Hydrogen production equipment that can store and supply hydrogen. It is expected to spread for industrial and domestic fuel.

**Ammonia decomposition case studies**

Hydrogen production from ($NH_3$) using high electron energy obtained by atmospheric pressure plasma is a promising method for producing purified hydrogen from ammonia. A comparison between the two cases of ammonia decompositions has been investigated. Also, the influence of applied voltage, $NH_3$ concentration and $NH_3$ gas residence time on $H_2$ yield has been discussed. According to their study, the hydrogen yield increases as higher applied voltage, longer residence time and lower $NH_3$ concentration [316]. A plasma membrane reactor has been designed as a novel plasma reactor combining $H_2$ separation membrane [317].

## 5.1. [$NH_3$] Decomposition Using a Cylindrical Plasma Reactor without Catalytic Materials

The hydrogen production method from $NH_3$ at atmospheric pressure plasma membrane reactor (PMR) by dielectric barrier discharge has been studied. Figure 10 shows the plasma reactor with the palladium alloy membrane, it is utilized to improve the efficiency of hydrogen production from ammonia decomposition [318]. The PMR has been composed of a quartz glass tube and a palladium separation membrane which has a thickness of 20 μm thickness and welded inside a thin punched metal (SUS 304). The gap length was 1.5 mm. The gap volume is 51.6 $cm^3$, respectively. Figure 11 & Figure 12 showed the PMR before and after firing plasma respectively.

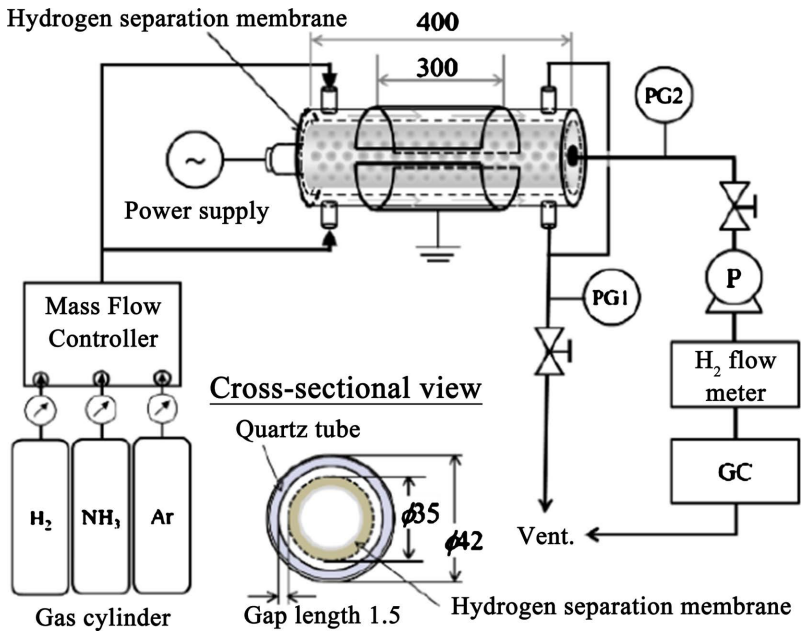



Figure 10. Experimental setup for hydrogen production by PMR [318].

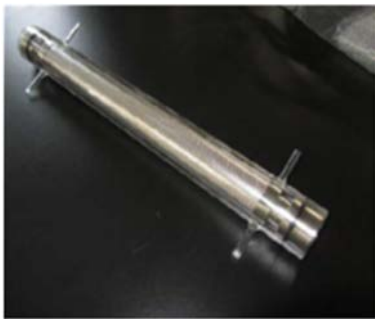


**Figure 11.** PMR before firing plasma.

**Figure 12.** PMR after firing plasma.

**Performance analysis**

Firstly, the PMR has been examined using the pure hydrogen gas to check the hydrogen separation from the reactor. The hydrogen separation characteristics of the PMR via the induced pressure have been investigated [318]. It is known that the hydrogen permeation through the palladium membrane has been affected by the partial pressure [319].

The first attempt of hydrogen production using a cylindrical plasma reactor (PR) has been presented that the hydrogen produced from ammonia flow rate higher than 60 L/h remained constant [318]. **Figure 13** shows the hydrogen production flow rates with the increase in the ammonia gas flow rate. The maximum flow rate of the hydrogen production was 21.0 L/h at a flow rate 30 L/h of the ammonia gas ($NH_3$). The energy efficiency was 4.42 mol$H_2$/kWh which is based on the power supply to the plasma reactor.

## 5.2. Ammonia Decomposition Using PMR Using Catalytic Materials

In this case study, the catalyst has been used as the PMR reactor is continuously developed to produce hydrogen from ammonia gas with a high purity [320]. **Figure 14** is presented the experiment layout of hydrogen production using a catalyst. The catalytic reactor consisted of a stainless tube ($\varphi$18 mm, SUS316), cylindrical ceramic fiber heater and inside the catalytic reactor, 10% Ni/$Al_2O_3$ was packed as a pyrolysis catalyst for $NH_3$.

**Performance analysis**

The development of a system for producing hydrogen from ammonia has been developed by combining a catalytic reaction and a plasma membrane reactor

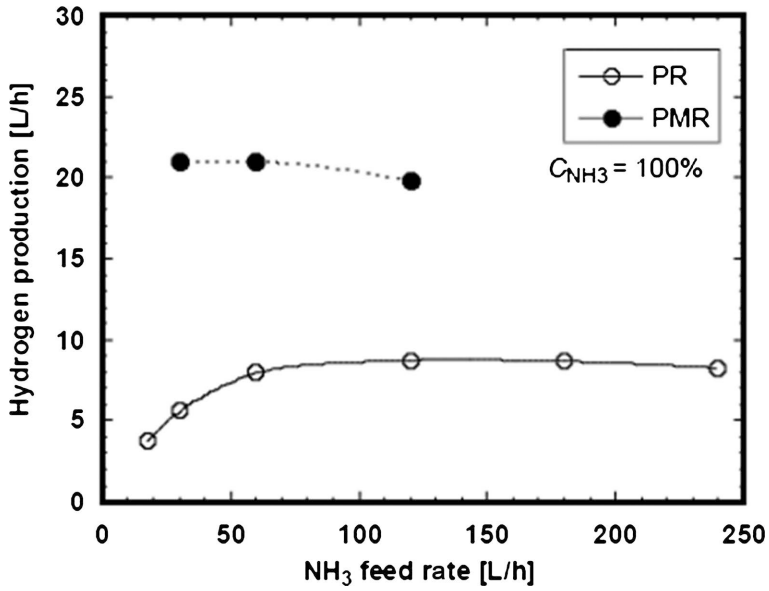



**Figure 13.** Hydrogen production performance of the PMR and PR [318].

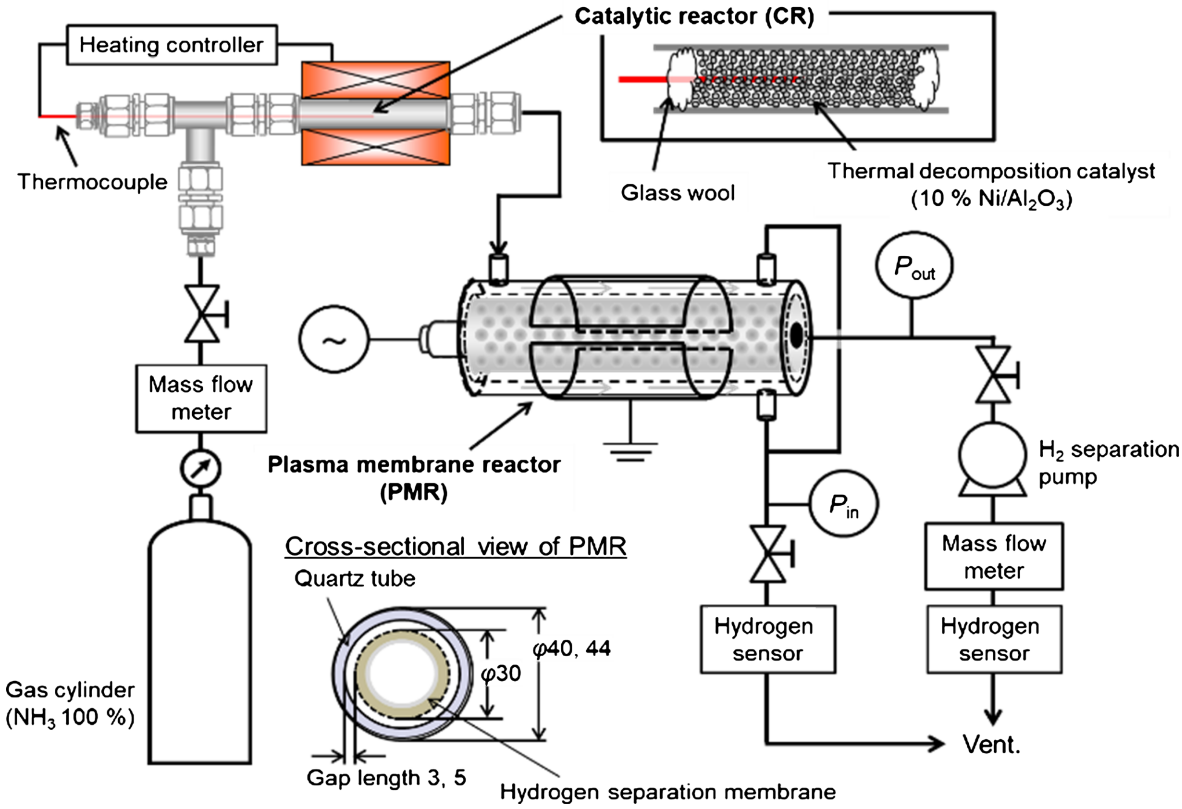



**Figure 14.** Experimental setup for hydrogen production using catalytic PMR [320].

[320]. The gap length between the glass quartz tube and the hydrogen separation membrane effect has been studied. **Figure 15** is shown the gap length effect on the flow rate of the produced hydrogen gas.

The maximum flow rate of hydrogen production was 120 L/h at ammonia gas flow rate 5.0 L/min and a supplied voltage 110 V. The catalytic reactor with 10%

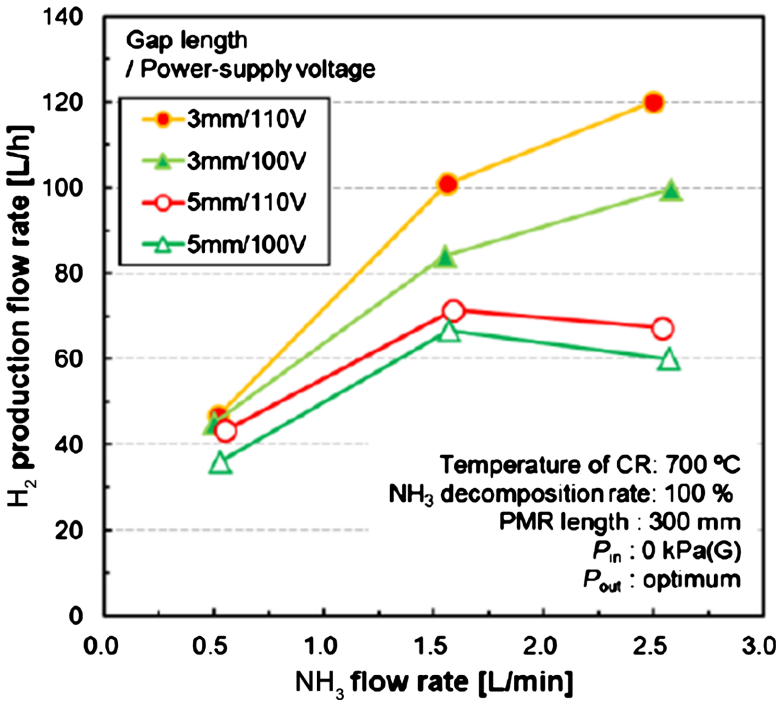



**Figure 15.** The effect of gap length inside the PMR on hydrogen purification [320].

$Ni/Al_2O_3$, ammonia ($NH_3$) has been completely decomposed at 700˚C. The maximum energy efficiency is obtained from the developed hydrogen production system was 28.3%. A comparison between the hydrogen production from the non-catalytic plasma reactor and the catalytic plasma reactor has been presented in Figure 16. It was clear that the ammonia decomposition using catalytic material (10% $Ni/Al_2O_3$) has a higher efficiency than the PMR without using catalyst materials.

## 6. Conclusion

Hydrogen fuel is believed that it will be a promising candidate to lead a new hydrogen economy. In this review paper, the hydrogen production key technologies are reviewed. The hydrogen production different technologies from both fossil and non-fossil fuels such as (water electrolysis, biomass, steam reforming, partial oxidation, auto thermal, pyrolysis, and plasma technology) are reviewed. The reforming and gasification technologies are the most mature hydrogen production technology. Water electrolysis can be combined with the renewable energy to get eco-friendly technology. Additionally, it is important to produce hydrogen from a wide range of feedstock. Currently, the maximum hydrogen fuel productions are registered from the steam reforming, gasification, and partial oxidation technologies using fossil fuels. The hydrogen production technology efficiencies are summarized in Table 13. These technologies still have challenges such as the total energy consumption and carbon emissions to the environment are too high. Ammonia decomposition using plasma technology without and with a catalyst to produce pure hydrogen is considered as a compared

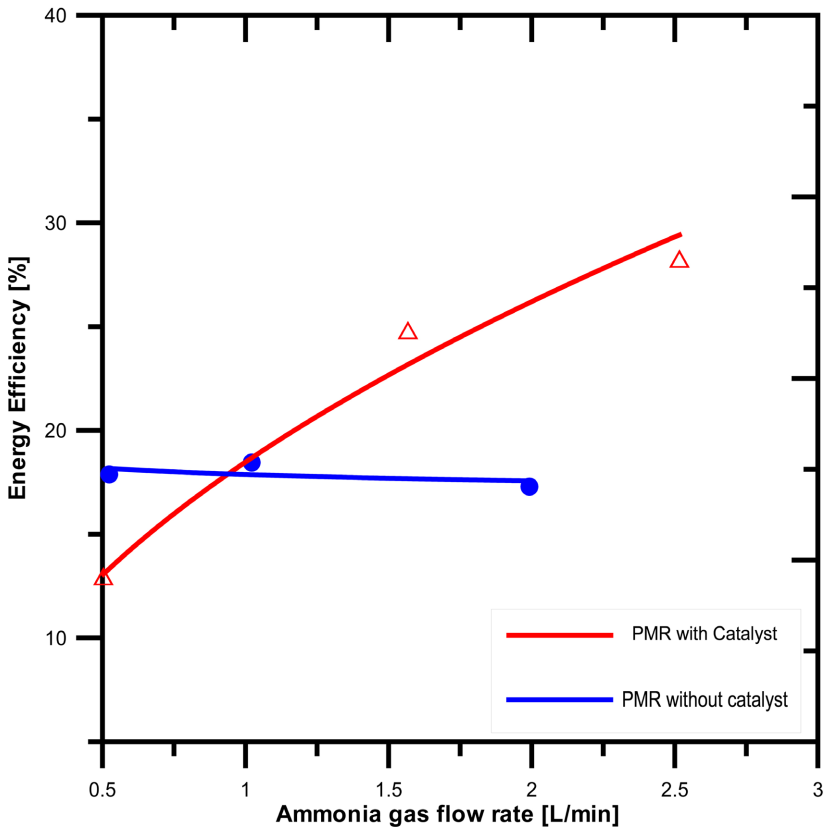



**Figure 16.** Comparison between PMR without and with a catalyst.

**Table 13.** Hydrogen Technology Efficiency summary table.

| Technology | Feed stock | Efficiency | Maturity | Reference |
|---|---|---|---|---|
| Steam reforming | Hydrocarbons | 70% - 85% | Commercial | [209] |
| Partial Oxidation | Hydrocarbons | 60% - 75% | Commercial | [209] |
| Autothermal reforming | Hydrocarbons | 60% - 75% | Near term | [209] |
| Plasma reforming | Hydrocarbons | 9% - 85% | Long term | [285] |
| Aqueous phase reforming | Carbohydrates | 35% - 55% | Med. Term | [321] |
| Ammonia decomposition | Ammonia | 28.3% | Near Term | [320] |
| Biomass gasification | Biomass | 35% - 50% | Commercial | [106] [117] [322] |
| Photolysis | Sunlight + Water | 0.5% | Long term | [323] |
| Dark fermentation | Biomass | 60% - 80% | Long term | [117] [163] |
| Photo fermentation | Biomass +Sunlight | 0.1% | Long term | [117] [322] |
| Microbial electrolysis cells | Biomass+ Electricity | 78% | Long term | [323] |
| Alkaline electrolyzer | $H_2O$ + Electricity | 50% - 60% | Commercial | [93] [322] |
| PEM electrolyzer | $H_2O$ + Electricity | 55% - 70% | Near term | [93] [322] |
| Solid oxide electrolysis cells | $H_2O$ + Electricity+ Heat | 40% - 60% | Med term | [106] |
| Thermochemical water splitting | $H_2O$ + Heat | NA | Long term | – |
| Photo electrochemical water splitting | $H_2O$ + Sunlight | 12.4% | Long term | [93] [129] |

case study. It is shown that the efficiency of ammonia decomposition using a catalyst is obtained 28.3% which is higher than ammonia decomposition without the catalyst. It is concluded that hydrogen production from ammonia decomposition is a promising technology to produce 99.99% pure hydrogen. Hydrogen technologies still have different challenges which require a lot of cooperation between researchers and industrial side to increase the hydrogen production by using the developed technologies.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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