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Hydrogen Technologies for Mobility and Stationary Applications: Hydrogen Production, Storage and Infrastructure Development

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Abstract

The present chapter focuses on hydrogen technologies for both stationary and mobility/transportation applications. Hydrogen production from sustainable resources for the generation of pure and low cost hydrogen is described in the chapter. Several potential hydrogen production techniques are introduced and analyzed. The challenges and the advantages of each production method will be discussed. Furthermore, the chapter will introduce hydrogen infrastructure development for mobility applications and will discuss hydrogen storage challenges. Hydrogen production for fuel cell technologies requires an improvement regarding sustainability of the hydrogen supply and an improvement regarding decentralized hydrogen production. Moreover, hydrogen economy as far requires a large scale and long term storage solution to meet the increasing demand.

Keywords: hydrogen production, hydrogen storage, hydrogen infrastructure, hydrogen applications, hydrogen economy

1. Introduction

The establishment of hydrogen economy for mobility applications led to a new movement for energy sector. The ultimate target is to reduce carbon dioxide emission by achieving a transition towards green transport system. There are three main challenges for the global adoption of a hydrogen economy; the production of hydrogen, the storage of hydrogen and the further development of the hydrogen fuel cells. Currently, hydrogen is produced from non-renewable a resource which forms a short term solution. The energy supply sector requires new, reliable and innovative technologies which support green energy supply and achieves the required economy targets. Hydrogen is an energy carrier as it can be extracted from renewable and non-renewable resources which can be converted to electrical power and water by using fuel cells. Hydrogen-powered fuel cells are electrochemical cells that convert chemical energy of hydrogen into electricity via redox reactions. The fuel cells are able to deliver a renewable energy at the point of use with no emission which makes a solution to the problem of greenhouse gases emissions.

| | Natural gas | Gasoline | Hydrogen |
|--------------------------|------------------|---------------------|------------------|
| Energy by weight | 1.2 X > gasoline | 43 MJ/kg | 1.2 X > gasoline |
| Energy by volume | 1.5 X < gasoline | 120 MJ/gallon | 1.5 X < gasoline |
| Boiling point | −162°C | Liquid at room temp | −252.87°C |
| Buoyancy relative to air | 2 X lighter | 3.75 X heavier | 14 X lighter |
| Odor | Mercaptan | Yes | Odorless |
| Toxicity | Some | High | None |
| Color | No | Yes | No |

Table 1.
Physical properties of natural gas, gasoline compared to hydrogen.

Fuel cells have been portrayed as humanity’s solution to the global energy challenge and the answer to the negative environmental impacts from the prevalent energy production methods of today. The current chapter looks at hydrogen as a clean and efficient energy carrier for the future and fuel cells as the power generators, as well as the realistic steps needed to take advantage of the benefits that have been seen in the fuel cells today.

The advantages of hydrogen as fuel over other fuel sources, the several feed stocks available and current methods for hydrogen extraction are discussed, indicating the most commercially-feasible hydrogen production path for fuel cell applications.

While moving from the fossil fuel era towards a greener fuel future, the use of hydrogen as energy carrier is highlighted by a lot of advantages [1]. One of the major advantages that play a major role for hydrogen’s fuel is the high specific energy (Lower heating value per unit mass); as hydrogen is lighter than gasoline or diesel for the same amount of energy (**Table 1**). Moreover, hydrogen has the highest utilization efficiency as compared to the fossil fuels, **Table 1** explains physical properties if hydrogen compared with natural gas and gasoline. It was reported

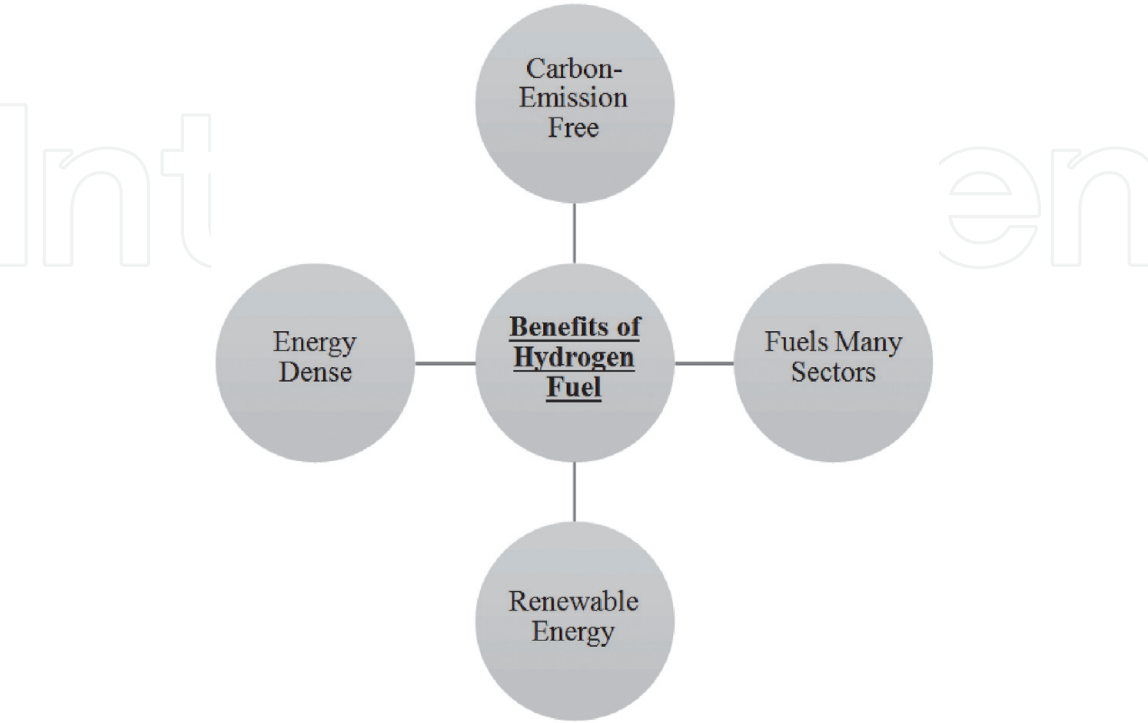


Figure 1.
Benefits of hydrogen energy carrier.

that hydrogen is 39% more efficient than fossil fuels [2]. This means high output energy per unit of mass. Secondly, hydrogen is a clean source of energy, as the product of hydrogen oxidation is only water and heat, independently on the process the oxidation occurs in; whether using it in a combustion engine or a fuel cell, or the type of energy it was converted to; thermal, electrical or mechanical. Thirdly, hydrogen can be produced from different raw materials, and then stored both as compressed, liquefied and via solid state reactions to be used in all types of applications. Finally, hydrogen is a stable non-corrosive element, however, safety aspects needs to be considered. **Figure 1** explains benefits of hydrogen energy carrier.

2. Sources of hydrogen production

Hydrogen is an energy carrier with high potential for green and sustainable applications, as it is carbon-emission free, energy dense, can supply many energy sectors and can be produced form renewable sources. Hydrogen is currently used at many industrial sectors; mainly at chemical industries and refineries. Although, the last two decades, there has been an increased interest from the automotive industry for a low pollution propulsion system. Thus, a carbon emission-free hydrogen method of producing hydrogen is required for automobile applications. In general, as renewable hydrogen, can be defined the hydrogen that is formed from solar, tidal, wind, hydro and supplied by sustainable feedstock. However, sustainable methods are expensive to produce hydrogen and require several technological advances for mass production. **Figure 2** shows that majority of hydrogen used today is produced from fossil fuels. Almost 95% of produced hydrogen is used at the site where it is produced [3]. Renewable hydrogen does not yet contribute to hydrogen market as the cost of renewable power still uncompetitive.

Hydrogen can be produced in large-scale centralized production plants or in small scale distributed production plants, decentralized generation. Currently the hydrogen production via methane reforming in centralized plants is cheaper than the equivalent production in decentralized plants. However, hydrogen distribution (hydrogen delivery infrastructure) and storage technical barriers will make hydrogen production in decentralized plants more feasible as the demand on hydrogen increases. At this early stage of hydrogen energy technology, small scale production is suitable to fulfill the low hydrogen demand and avoid infrastructural unavailability issue. In the long term however, large scale production will be a basic

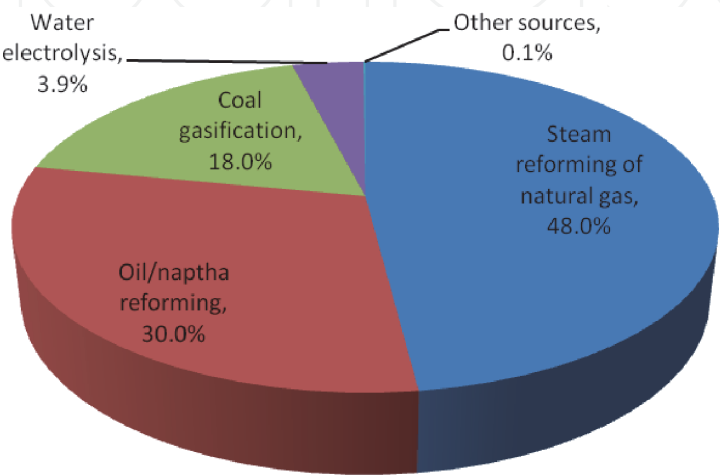


Figure 2.
Global hydrogen production from main sources [6].

requirement to meet the future expected demand, and solutions must be found for the distribution challenge.

The world annual hydrogen production is around 368 trillion m³ [4]. Almost 50% of this amount is produced by steam reforming for natural gas [5]. Hydrogen can be produced in various processes, such as, thermo-chemical, electrochemical, photochemical, photo-catalytic and photo-electrochemical processes. The feed stocks for hydrogen and the production technologies are shown in **Figure 2**. The hydrogen energy feedstock and production routs are explained in **Figure 3**. The main three routes for hydrogen production are; reforming from hydrocarbons, electrolysis and thermal decomposition or cracking.

2.1 Hydrogen from fossil fuels

Hydrogen at commercial usage is obtained from various hydrocarbon feedstocks such as; methane and fossil fuels which can be oil, gas and coal. The extraction method to produce hydrogen is a well-developed technology at large scale production such as steam reformation, fuel oxidation and gasification [7]. The fossil fuel recourses are main contributor to carbon dioxide emissions and the resources for fossil fuels are depleting which makes hydrogen produced from feedstock non-sustainable. Fossil fuels including coal and natural gas are currently the most common way to produce hydrogen. Steam reforming is one example of reforming technology; oxygen is also used instead of steam. Reforming techniques are named depending on the oxidation agent use; this include, steam reforming for light hydrocarbons (methane), partial oxidation for heavy hydrocarbons such as coal and oil and mixed technology known as auto-thermal reforming. After reforming process, the reforming gas mixture must be cleaned to obtain purity of hydrogen required for the application.

2.2 Hydrogen from biomass

One of the emerging technologies for a renewable and sustainable hydrogen feedstock is to use biomass gasification. This method allows the production of

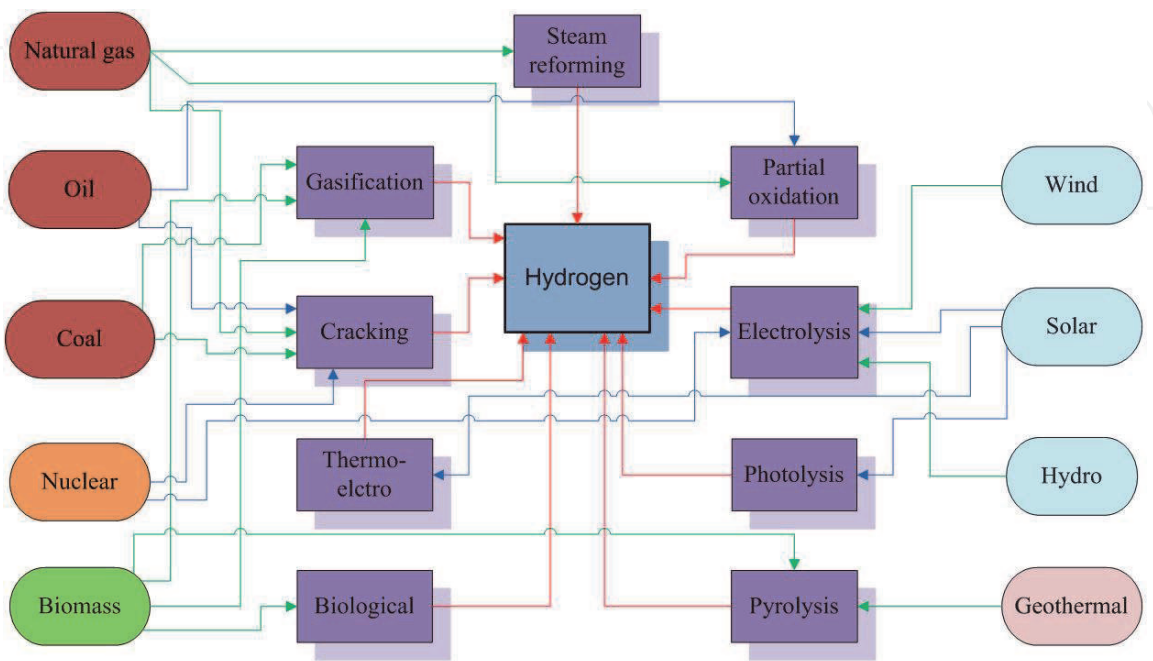
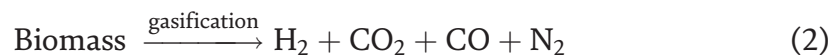


Figure 3.
Hydrogen energy production routes and hydrogen extraction methods [5].

hydrogen with low carbon dioxide emissions. The most popular biomass resources for producing hydrogen are often supplied from agriculture or solid municipal waste [8]. Hydrogen can be extracted from biomass fuels by pyrolysis, biological reactions and gasification [9]. The process used depends on the biomass feedstock. The production via biomass feedstock the most popular method for hydrogen production due to the availability of its gasfires. Further studies are needed to improve catalysts and microorganisms used for pyrolysis and biological reactions to increase the efficiency and hydrogen production rate. Eqs. (1) and (2) are explaining the main mechanism for the pyrolysis (Eq. (1)) and gasification (Eq. (2)).

High temperature gasification is also used to produce hydrogen. The process allows hydrogen production without producing CO₂. The light hydrocarbons are heated in plasma up to 1600°C and converted to carbon and hydrogen. This is also known as high temperature plasma arc gasification.

Biological fermentation process is also used to produce hydrogen using bacterial or algae decomposition of water. The production process can be performed using photo biological at sunlight or at dark conditions.



2.3 Hydrogen from nuclear sources

Mainly, Hydrogen production from nuclear energy can be achieved by using thermochemical processes. Excess heat is generated in a nuclear reactor. Thermal energy will split molecules by applying high temperature. With no catalyst, a steam of 2500°C will dissociate into hydrogen and oxygen. High temperature is considered a problem for material design therefore some catalyst is considered to split water down at 900°C [10].

The by-product heat that is produced during this process is used for hydrogen production method. Several reactor technologies are used to produce hydrogen and the production method is considered economically attractive [11]. The process itself is low carbon dioxide emission. Nuclear generated electricity does not produce CO₂ emissions. There are four methods to use nuclear energy to produce hydrogen; electrolysis, high temperature steam electrolysis, thermochemical water splitting and steam reforming with heat input from a nuclear reactor. The waste heat is utilized in thermochemical water splitting and high temperature electrolysis which both methods are efficient compared to low temperature electrolysis.

In summary, all methods of hydrogen production might be used with nuclear power as a source of electricity and heat to produce hydrogen. The problem with hydrogen production facility at nuclear power plant that hydrogen production facility can be treated as heat sink and flammable substance is in the system which makes a potential hazard for safe operation of a nuclear facility as well as hydrogen safe handling [10].

2.4 Hydrogen from water

Electrolysis process is used to split water electrochemically to hydrogen and oxygen. The hydrogen production from water is considered green upon the electrical supply green routes [12]. The electricity can come from different sources and the electricity source determines whether any CO₂ is produced to generate hydrogen.

For example, wind energy produces no CO₂ but fossil fuel does. Photo-electrolysis is also considered a green hydrogen route as the process depends on sunlight to power the process [13].

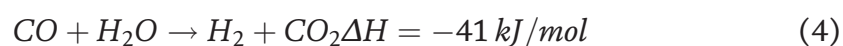
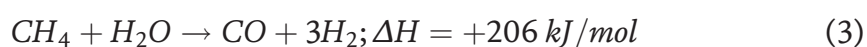
The electrolysis process is performed using an electrolyser; there are three types of electrolyser; alkaline electrolyser, proton exchange membrane electrolyser and solid oxide electrolyser. All consist of two electrodes, water and an electrolyte which is a substance containing free ions that make the substance electrically conductive. The name of electrolyser depends on electrolyte used. Alkaline and proton exchange membrane electrolyser are defined as low temperature electrolyser (less than 100°C) and solid oxide electrolyser is classified as high temperature (900°C). High purity of hydrogen is produced using water electrolysis and the standard potential of a water electrolysis cell is 1.23 V at 25°C.

3. Non-renewable hydrogen production

Currently, this method is the most economical viable for hydrogen production. The current hydrogen production economy is dependent on fossil fuel resources and almost 96% of hydrogen produced is generated from hydrocarbon fuel [14]. Mostly, the hydrogen produced from non-renewable resources is performed in large central chemical plants. The centralized production at large scale chemical plants is used for mass production then hydrogen is transported. Large steam reformers are one of the examples of mass hydrogen production where hydrogen is transported to the location of use via pipelines, road or by ship. For hydrogen produced from non-renewable is a manufactured fuel from fossil fuel including natural gas and coal, methanol and water where electricity is supplied from non-renewable resources.

3.1 Steam-methane reforming (SMR)

Natural gas is used at most common way to produce hydrogen by steam reforming. The process is used for light hydrocarbons. Natural gas is composed of methane (CH₄). Steam reforming is performed at two stages Eq. (3) and Eq. (4) where methane is mixed with water steam at high temperature and heat is absorbed (Eq. (3)), the reaction itself is endothermic and requires a catalyst. The required temperature to perform the reaction is around 850°C. The second step of the process is the water gas shift reaction (Eq. (4)) and this involves a heat release (exothermic reaction). The combination of both reactions results a net of heat addition to the process. The total actual efficiency of the process is rarely above 80% [15]. The process itself is a demanding thermal process where methane undergoes a steam reformation or partial oxidation. The partial oxidation uses oxygen rather than steam as oxidizing agent to perform reaction as this process can maintain a high temperature where it is producing heat [16]. Combination of steam and oxygen for performing the reaction is also used in hydrogen production and the process is known as auto-thermal reforming. **Table 2** compares various reforming methods.



The process of steam methane reforming is performed as a two stage reaction. The first reaction is an endothermic catalytic reaction where methane is reformed using steam to syngas under the existence of catalyst. The process requires steam at

| | Steam reforming | Partial oxidation | Auto-thermal reforming |
|---|---|--|--|
| Steam availability | Steam is part of process | Partially burns a fuel, no steam is required | Both steam and air are required |
| Chemical reaction | $C_nH_mO_z + (n - z)H_2O \rightarrow$ $nCO + \left(n + \frac{m}{2} - z\right)H_2$ | $C_nH_mO_z + \frac{1}{2}(n - z)O_2 \rightarrow$ $nCO + \frac{m}{2}H_2$ | $C_nH_mO_z + yO_2 + 2\left(n - y - \frac{z}{2}\right)H_2O \rightarrow$ $nCO_2 + 2\left(n - y - \frac{z}{2} + \frac{m}{4}\right)H_2$ |
| Maximum percent purity of H2 in the products mix (vol%) | $100 \times \left(\frac{2n+0.5m-z}{3n+0.5m-z}\right)$ combined steam reforming and water gas shift reaction | $100 \times \left(\frac{n+0.5m}{2n+0.5m}\right)$ combined partial oxidation and water gas shift reaction | $100 \times \left(\frac{2n-2y-z+0.5m}{3n-2y-z+0.5m}\right)$ auto-thermal reforming as shown in equation above |
| Maximum H2 yield (mol H2 per mol CnHmOz) | $2n + 0.5m - z$, combined steam reforming and water gas shift reaction | $n + 0.5m$, combined partial oxidation and water gas shift reaction | $2n - 2y - z + 0.5m$, auto-thermal reforming as shown in equation above |
| Heat requirments | Largely endothermic, consume a lot of heat, disadvantage | Exothermic, produce heat, advantage | Must be controlled under slightly exothermic reaction, start-up requires heat, advantage |
| Start-up period for reformer application | Long start-up period, since steam is required, disadvantage | Short start-up period, since no steam is required, advantage | Short start-up period, steady state conditions must be controlled, advantage |

Table 2.
Comparison of different hydrocarbon reforming methods [20].

temperature of 700–1100°C and relatively high pressure range (20–30 bar) [17]. The outcome of the first stage reaction is syngas which is a mixture of hydrogen and carbon monoxide. The second stage requires converting carbon-monoxide to further produce hydrogen. The process is known as water gas shift reaction and it's an exothermic reaction which can occur at two steps, high temperature water gas shift reaction at 350°C followed by a low temperature water gas shift reaction at 200°C [18].

The SMR process has an efficiency of 60–75% and it is well established technology for hydrogen production [19]. One of the main advantages of using MSR for hydrogen production is the product purification using pressure swing adsorption that can produce hydrogen purity greater than 99%. The drawback of such method is that an endothermic process requires heat which is mainly provided by burning natural gas. The SMR produces high yield of hydrogen (50 wt% of CH₄) but with some impurities and the high demand for energy requirements will increase the production cost.

Hydrogen via SMR can be produced at both centralized and decentralized facilities. In the case of centralized production, liquefied or gaseous hydrogen is distributed to the area of application via pipes or tank trailers. For decentralized production, hydrogen is produced and stored at the location of usage. Due to the low hydrogen demand, a design with a capacity of 100 Nm³/h with 65% efficiency (LHV) is commercially available [19]. This process of hydrogen production is currently the most favorable method for both centralized and decentralized production in already developed countries with piped methane infrastructure available and the process' efficiency is relatively high compared to the other methods. However, one drawback for this system is that CO₂ is produced via exothermic water gas shift reaction between CO and excess steam, and this adds the need for gas purification process.

3.2 Methanol steam reforming

Methanol (CH₃OH) is also used for hydrogen production purposes where the reaction temperature required to perform the process (200–300°C) is much less as compared to methane steam reforming [21]. The reformation process produces up to 75% of hydrogen concentration and maximum yield of 18.75 wt% of CH₃OH. The advantage of methanol steam reforming is that methanol is at liquid form which makes this fuel suitable for stationary hydrogen applications where reformation temperature is relatively low. In addition, methanol can be produced from renewable resources [22]; it has low sulfur content and high hydrogen to carbon ratio. The process requires use of methanol where pure methanol is expensive and the hydrogen produced has some impurities which requires further purification. Methanol is currently produced from coal and natural gas. The total world demand for methanol is about 41 million metric tons [22]. Methanol is also produced from bio-based resources as landfill gas, pig manure and paper mill black liquor. The viable method of producing methanol is using hydrocarbon fossil fuels [22]. The methanol reforming is an attractive method as the absence of C-C bonds in methanol allows the reaction to take place at low temperature. Because of low energy chemical bonds, reforming can be granted at faster start up and low material cost. Copper based catalyst is used at methanol steam reforming reaction (Eq.5). In real reaction, reformat gases usually contain CO, CO₂, H₂, H₂O and CH₃O [23]. **Table 3** compares both methane and methanol fuels in hydrogen production.



| Feature | Methane | Methanol |
|---|--|--|
| Maximum percent purity of H ₂ in the products mix (vol%) | 80% | 75% |
| Maximum H ₂ yield | 4 mol/mol of CH ₄ (or 50 wt% of CH ₄) | 3 mol/mol of CH ₃ OH (or 18.75 wt% of CH ₃ OH) |
| Catalyst composition | Nickel based | Copper based |
| Selectivity | Hydrogen and CO | Hydrogen and CO ₂ |
| Size | Large (three purification units and gas cleaning unit) | Small (one purification unit) |
| Phase | Gas | Liquid |
| Temperature | Up to 800°C | Up to 350°C |
| H ₂ produced | High | Low |
| CO produced | High | Low |
| Material | Expansive reactor material | Cheaper material as low temperature design |

Table 3.
Methanol and methane fuels comparison for hydrogen production [20].

3.3 Electrolysis of water

Supplying electrical current to split water into hydrogen and oxygen is known as water electrolysis. The process efficiency is determined by electrical and thermal behaviors of the electrochemical reaction. The electrolysis process produces high purity hydrogen 99.999% with an efficiency of 70% [24, 25]. One major issue with the electrolysis process is that the electrodes tend to degrade overtime causing an increase of resistance, forcing the performance to slow down. The life span of the electrolyser is short and whole reaction process is slow in comparison to the large scale reforming process [26]. Currently, small scale electrolyzers are used to produce hydrogen; however, hydrogen produced via this method is strongly affected by high electricity prices. The main aim for water electrolysis is to use the surplus electricity generated from renewable resources such as, wind, solar, hydropower, geothermal so it can be used in all different applications when stored in hydrogen. Renewable electrical generators need to be further developed to achieve energy sustainability.



3.4 Coal gasification

Gasification is a process where raw materials such as coal, biofuel, biomass and other carbonaceous materials reacts at high temperature under controlled amount of steam and oxygen to produce hydrogen and carbon monoxide. Economically, coal is attractive feed stock for hydrogen production by gasification due to the stability of coal prices compared to natural gas [27]. However, the complexity and high cost of the gasification process makes it a less favorable hydrogen source. The complexity of the process comes from the need of feedstock pre-treatment, multi-stage cleaning of raw syngas and CO conversion. This makes this process only feasible for large scale (centralized) hydrogen production. Coal to hydrogen conversion can achieve 52% of low heating value [28]. The major problem

facing coal gasification process is removing CO₂ from the gas shift reaction, which decreases the overall efficiency and increases hydrogen production cost.



4. Renewable sources and methods

The hydrogen routes where the energy source does not contribute to greenhouse gases are defined renewable. Renewable sources of energy such as solar energy, wind energy, geothermal, tidal, and hydro and biomass energy are the most popular for power generation as well as for hydrogen production. The future potential for hydrogen production will depend on solar energy, wind energy and biomass where it can supply electricity for potential hydrogen production method.

Renewable resources for hydrogen production will include biomass, ethanol, wind farms, tidal energy, solar and hydroelectric. The method of production and whether the hydrogen has been produced without emitting CO₂ is known as green hydrogen. Greener hydrogen routes such as from electrolysis are playing a major role in hydrogen for mobility applications. Decentralized hydrogen production depends on renewable resources where on-demand hydrogen requirements are delivered to end user such as using personal electrolyser for home use.

4.1 Solar energy

Solar energy is used in photovoltaic systems to generate electricity. It is also used on concentrated collectors to collect thermal energy. The solar energy can meet the global energy requirements, if it stored and terraformed into another energy carrier forms. The disadvantage of long sunlight hour's availability makes this technology less attractive for hydrogen production. The cost of implementation of solar capturing system and the space availability when employed at residential area are also drawbacks of such technology [29]. The solar energy can produce thermal energy which can be used to supply energy for hydrogen production methods such as thermolysis process, thermochemical process and steam reformation process. It also can produce photon energy which can supply energy for electrolysis using photovoltaics and photo-electrolysis [30]. Solar photovoltaic has low temperature specification and it is assumed direct solar collection type to produce hydrogen and oxygen using electrolysis and photo-electrolysis. It also can be used to produce hydrogen by photo-biolysis process. The solar thermal has high temperature specification where steam reforming; thermolysis and cracking methods can be used to produce hydrogen from above mentioned routes.

4.2 Solar photovoltaic (PV)

The solar panels are used to generate electricity connected to the main supply grid. Demonstration of such system for hydrogen generation on a small scale has been performed at research level [31]. The system requires special current control unit to perform electrolysis process. The system operation will depend on amount of exposed sunlight where additional electricity from the grid required performing the process. Depending on photovoltaic hydrogen power system alone is a challenging technology and the hydrogen production efficiency is still under research. The PV performance depends on temperature and amount of exposed sun where DC-DC converter requires advanced monitoring system to supply enough power supply for electrolyser.

4.3 Photon-electrolysis

The photon-electrolysis process has low efficiency output [32] that makes this technology not a suitable solution for massive hydrogen production. The technology is under research and development and currently the process itself is not economically attractive.

4.4 Solar steam-methane reforming

The solar steam-methane reforming system applies direct or indirect solar heat to generate the required high temperature demand to fulfill the requirements for the chemical reaction. The thermal energy is harvested at power plant for such technology where heat transfer using a fluid is maintained to supply heat to catalytic reactor tubes. Syngas will be produced in a closed loop reaction to increase the efficiency and to maintain the high temperature requirements of the reaction. For indirectly heated reforming process, the working fluid transfers the heat energy from the solar receiver to the catalyst container at a closed loop system using primary and secondary heat transfer system. The directly heated reformer contains imbedded catalyst container where the thermal energy source will increase the catalyst temperature. This method does not require a secondary loop system, whereas the cost of design can be reduced. The challenges for such hydrogen production method are the requirement for constant solar radiation to maintain the chemical process and the cost for system development [33]. **Table 4** compares most popular hydrogen production methods and **Table 5** summaries current commercial hydrogen production methods.

5. Hydrogen storage

The future of hydrogen as an energy carrier greatly depends on the method at which hydrogen can be stored (**Table 6**). The fact that hydrogen has a low boiling point and a very low density both in gaseous (0.08988 g/L @ STP) and liquid (70.99 g/L) forms makes hydrogen storage complicated and costly [5]. Hydrogen can be stored via changing physical conditions such as its temperature, pressure or phase, or by changing chemical conditions of various solid and liquid compounds. The latter method includes metal hydrides, complex hydrides, carbon nanotubes, Metal Organic Frameworks (MOFs), 2D materials as well as light hydrocarbons as intermediate hydrogen carriers [34].

| Process | Feedstock required | Efficiency | Current use | Renewable or non-renewable |
|-------------------------------|-----------------------|------------|----------------|----------------------------|
| Steam reforming | Hydrocarbons | 60–75% | Commercially | Non-renewable |
| Partial oxidation | Hydrocarbons | 60–75% | Commercially | Non-renewable |
| Electrolysis | Water and electricity | 70% | Commercially | Non-renewable |
| Solar steam Reforming | Hydrocarbons | 60–75% | Commercially | Renewable |
| Photo – electrolysis of water | Water and solar | 12.4% | Under Research | Renewable |
| Thermo – water splitting | Water and heat | 30% | Under Research | Non-renewable |
| Photolysis | Water and solar | 0.5% | Under Research | Renewable |

Table 4.
Hydrogen production process comparison.

| | Steam methane reforming | Methanol steam reforming | Electrolysis of water |
|-----------------------|--|--|---|
| Advantages | <ul style="list-style-type: none">Widely accepted methodA high efficiency of 60–75%Reliable and stable methodCan be used for various industries | <ul style="list-style-type: none">Requires lower temperatures than methane SR to workProduces high efficiency reactions | <ul style="list-style-type: none">It is an on-demand fuel typeCan be used for various industriesProduces high hydrogen purities and efficiency rate |
| Disadvantages | <ul style="list-style-type: none">Carbon capture and storageHigh operating and maintenance costsNon-renewable method, releases greenhouse gases | <ul style="list-style-type: none">Hydrogen impuritiesFeedstock required is costly | <ul style="list-style-type: none">The electrodes are prone to degrading over time requiring replacementElectrolysis solution requires replacing once used up |
| Areas for Improvement | <ul style="list-style-type: none">Production of more efficient catalysts and reduce costsDevelop a viable renewable method of SMR for future use | <ul style="list-style-type: none">To develop on the system integrating a renewable aspect to itTo provide more popularity to the method | <ul style="list-style-type: none">Photo-electrolysis does not yield a high efficiency rateFurther research is required for a faster rate of reaction |

Table 5.
Most popular hydrogen production methods comparison.

| Parameter | Unit | 2017 goal | Ultimate |
|-----------------------------|------------------------------|-----------|----------|
| System fill time (5 kg) | min | 3.3 | 2.5 |
| Cycle life | cycles | 1500 | 1500 |
| Operating temperature | °C | 40/60 | 40/60 |
| System volumetric capacity | kg H ₂ /L system | 0.040 | 0.070 |
| System gravimetric capacity | kg H ₂ /kg system | 0.055 | 0.075 |

Table 6.
Summary on the targets for hydrogen storage systems set by the United States Department of Energy for on-board vehicular applications in year 2017 [35].

Chemical storage methods in high volumetric energy capacity with low cost for on-board hydrogen application are currently under research and development. Nowadays, commercial hydrogen is stored as a gas in high pressure cylinders (350 bar and 700 bar) or as liquid hydrogen at 20 K in cryogenic tanks. The process of hydrogen pressurization and liquefaction consumes energy which adds an extra cost to the hydrogen delivery stage.

Hydrogen storage technologies (**Table 7**) are investigated and mainly hydrogen is stored in three categories; compressed gas storage, cryogenic (liquid) storage and solid storage. The alternatives solutions for high pressure storage are known as; liquefaction, absorption by chemical compounds, metal hydrides, chemical hydrides and carbon nanotube. Hydrogen is good as a gravimetric energy carrier which means it has the most energy of any fuel in proportion to its mass. The problem with hydrogen is its volumetric energy is the worst. When hydrogen is compressed or liquefied, the volumetric capacity increases. The target is to increase both volumetric and gravimetric capacities.

| | Viable capacity (kg) | Market | Commercial availability | Volumetric/ gravimetric ratios |
|--|----------------------|--|-------------------------|--|
| Steel cylinder | 1–100 | Delivered tanks, bundled on trucks or stationary for mass storage | Yes | Medium to high volume. Low weight |
| Carbon fiber compressed gas tank | 0.1–5 | In demonstration fuel-cell cars and on fuel-cell and internal combustion engine busses | Yes | Medium to high volume. Medium weight |
| Carbon fiber-wrapped aluminum gas tank | 0.1–100 | Cars and busses | Yes | Medium to high volume Low to medium weight |
| Cryogenic | 0.1–500 | Stationary storage, tank trucks, | Yes | High volume. High weight |
| Metal hydride | 0.01–1 | Small fuel cells, small vehicles | Yes | Medium to high weight Medium to high volume |
| Chemical hydride | 0.01–1 | Small applications | No | Medium to high weight Medium to high volume |
| Single-walled nanotubes | 0.001–100 | All markets, but too expensive now | No | High weight. High volume |

Table 7.
Current hydrogen storage technologies [36].

5.1 Compressed gas storage

Commercially, two standard pressures (35 and 70 MPa) are used for automotive applications. A high compressive cost and a safety factor for storage medium are some of the main challenges for such storage technology. Currently, there are four types of hydrogen vessels [37, 38], **Figure 4**. Type I; the vessel operates at low pressures, such vessels are the heaviest type of storage vessel. However, single material tank makes those vessels the cheapest to manufacture. Type II vessel is a composite thick tank wrapped with fiber resin. The tank can resist high internal pressure; the tank itself is heavy as metallic wall is thick. Type III is a composite vessel consisting of a thick or thin metallic wall fully wrapped with a fiber resin. The tank provides extra internal pressures resistance. Type IV vessel is a polymeric fully wrapped with fiber resin. It is the lightest storage vessel with a highest pressure resistance. In summary, Type I is the cost effective tank but their weight is the heaviest. Type IV storage tank can hold up to 700 bars with the lightest weight but the cost is two folds of Type I. **Table 8** explains the cost, weight and operation pressure of each tank type.

5.2 Liquefaction of hydrogen

Cryogenic tanks are used to store hydrogen at liquefied form. Hydrogen is at liquid form at 20 K (–253°C) which has a high cost and it requires energy to be maintained at liquid phase. The liquid form is more desirable than gaseous storage. It has higher energy storage density than gaseous form which gives liquefied hydrogen a content advantage. In general, the cryogenic tanks are of cylindrical

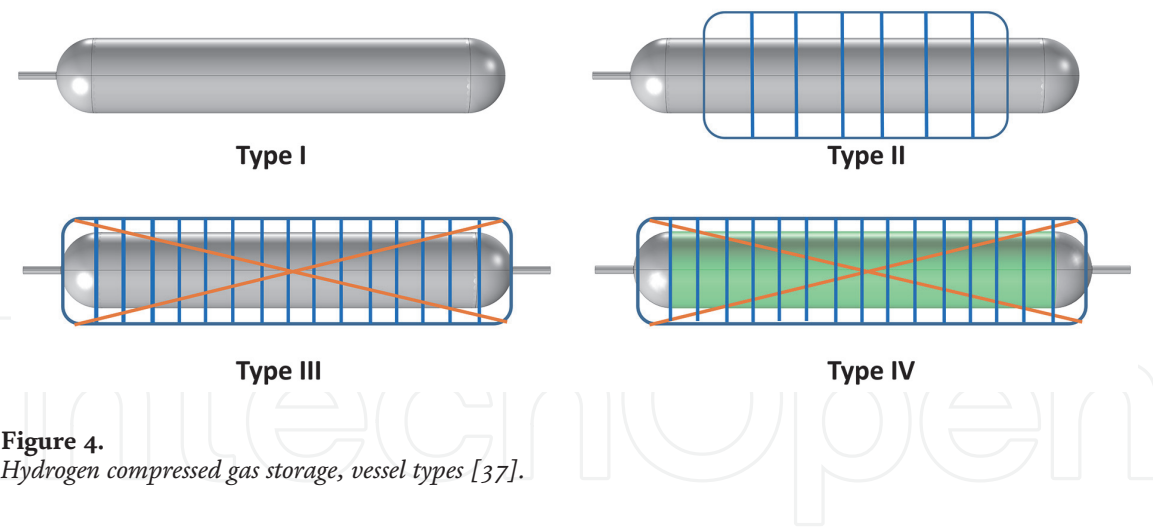


Figure 4.
Hydrogen compressed gas storage, vessel types [37].

| | Type I | Type II | Type III and IV |
|------------------------|--------|---------|-----------------|
| Cost (\$/liter) | 5 | 5.5 | 11 |
| Weight (lb/liter) | 3.0 | 0.9 | 0.75 to 1 |
| Maximum Pressure (bar) | 200 | 263 | 300 to 700 |

Table 8.
Manufacture cost, weight and maximum pressure of four types pressure vessels [39].

| | Compressed hydrogen 200 bar | Compressed hydrogen 350 bar | Compressed hydrogen 700 bar | Liquefied Hydrogen 2 | Single wall nano tube |
|-----------------------------------|--------------------------------|--------------------------------|--------------------------------|-------------------------|-----------------------|
| Storing energy (kJ/kg) | 10,300 | 12,264 | 14,883 | 42,600 | 15,998 |
| Volumetric energy content (MJ/m3) | 714 | 2492 | 3599 | 3999 | 2159 |
| Energy content (MJ/kg) | 1.05 | 8.04 | 7.20 | 16.81 | 3.6 |

Table 9.
Relevant parameters for possible five hydrogen storage forms [41].

shape, as it is easier to manufacture and some of them are of spherical shape. A multilayer material for insulation heat is a current development priority for liquid hydrogen. Hydrogen boil-off or hydrogen loss is a challenge for hydrogen storage [40]. Some multilayers design and polymeric films are used to avoid energy loss.

Table 9 describes five possible hydrogen storage forms, compressed hydrogen at 200, 350 and 700 bar, liquefied form and nanotubes. **Table 9** explains the advantage of storing hydrogen at liquid form. The weight is three times less than compressed gas and it has higher energy storage content.

5.3 Metal hydrides

Hydrogen can be stored in solid state form by either physisorption or by chemisorption. Metal hydrides are chemical compounds that allow hydrogen to be stored at high density and under moderate temperature and pressure conditions [42].

| Safety issues of gaseous storage | Safety issues of liquid hydrogen storage | Safety issues of metal hydrides storage |
|----------------------------------|--|---|
| Loss of containment | Loss of containment | Pyrophoric materials |
| Materials-blistering | Boil off | Explosion and loss of containment |
| Heating effect during filling | Ice formation | Toxicity and heat |

Table 10.
Some potential safety issues of hydrogen storage methods.

The hydrogen storage at such method is safer in comparison to the high pressure gas and liquid hydrogen storage. Metals hydrides exist within metals or alloys, they have physical properties which make them suitable for hydrogen storage such as; low absorption, high volumetric energy density, oxidation resistivity and some of them benefits of good reversibility [35]. The drawback of such storage method can be related to the cost of metal hydrides, metal hydrides being heavy and the reaction kinetic to release hydrogen is slow [43]. The safety issues of hydrogen storage in gaseous, liquefied and solid forms are stated in **Table 10**.

6. Hydrogen energy and fuel cells today

Nowadays, hydrogen energy and fuel cells are still considered as potential candidates to replace fossil fuels, but yet, several steps are necessary to be done towards the commercialization for real life applications. However, an increasing number of companies, big and small alike are investing in the field as they see the future potential for power generation in different applications. It worth mentioning that fuel cell research in its majority is focused on either PEMFC or SOFC, and with time these two types are becoming competitive technologies for some applications.

Hydrogen energy and fuel cell work at the moment can be divided into three major areas; research and development, materials and components supply, and resources training. On the top of that, governmental support and setting laws with incentives for clean energy suppliers and users is raising the awareness of the public and encourages more investments in the field. Some investors in the field of hydrogen energy and fuel cells identified their interest on a particular application, and they have been trying to produce prototypes for products that can be a step towards being a commercial product such as; Transport, Grid support, Domestic CHP, Auxiliary power generation, Portable applications, Educational demonstrations and Testing and measurement systems [44]. Other investors found their interest in identifying a specific component from the fuel cell system and became suppliers to the others working on the system integration and developing prototypes. The market for such companies is already there; however, the demand is quite small at the moment. Most of these investors either hold some research on their own or with collaboration with academia to develop their component or produce new alternatives to compete in a continually advancing field. Components can be one part of the fuel cell or hydrogen production device, hydrogen storage devices, system controllers, and testing and measurement equipment's.

At the moment, PEMFCs and SOFCs are holding the lions share in terms of R&D and commercialization. Together, PEMFC and SOFC cover the whole power generation rate spectrum for all different applications: PEMFC is suitable for mobile, portable, and transport with power rates up to 100 kW, while SOFC is suitable for medium to high power generation in hundred MWs. See **Table 11**.

| Application | Power rate | Fuel cell needed |
|--------------------------|---------------|------------------|
| Portable application | Up to 500 W | PEMFC, DMFC |
| Domestic applications | 5–10 kW | PEMFC, SOFC |
| Transport application | 50–100 kW | PEMFC |
| Central power generation | 100 kW–100 MW | SOFC, MCFC |

Table 11.
Fuel cell applications.



Figure 5.
SOFC applications.

Different types of fuel cells are used depending upon their applications. The operation temperature is the main issue when fuel cell is selected. The most popular fuel cells are solid oxide fuel cell and polymer electrolyte fuel cell. The solid oxide fuel cell designed to operate at high temperatures 700–1000°C. The fuel quality can be a mixture of hydrogen and carbon contained fuel. The main application is stationary power generation and auxiliary power units as shown in **Figure 5**. Polymer electrolyte fuel cell is a low temperature operation fuel cell (below 90- up to 180°C). The low temperature gives a faster start up but this mean a high purity of



Figure 6.
PEMFC applications.

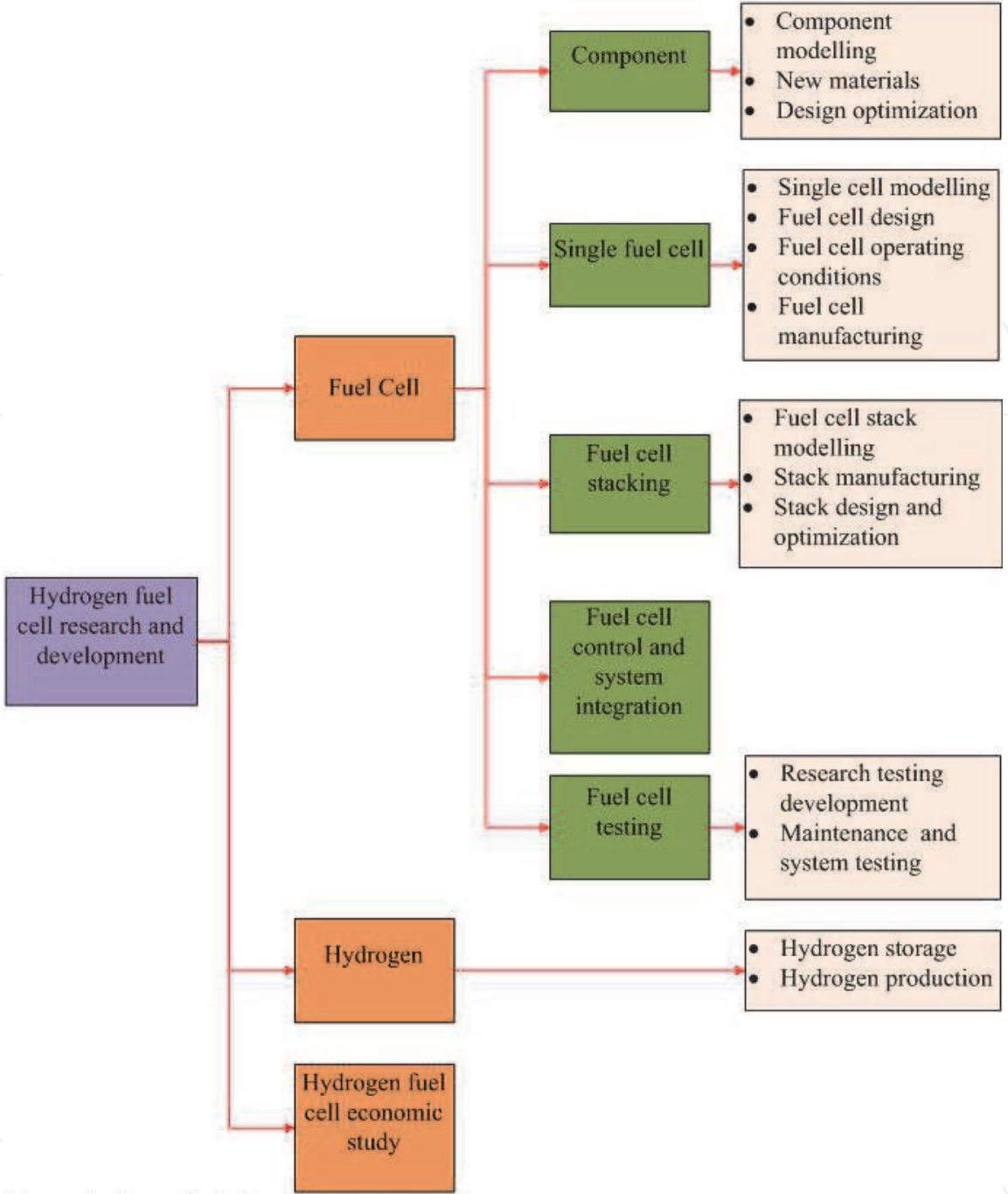


Figure 7.
Hydrogen fuel cell technology developments.

hydrogen must be supplied. The main applications for such fuel cell a portable power generation and fuel cell vehicle are shown in **Figure 6**.

Fuel cells have the advantages of zero end use emissions, no moving parts, quite operation and high efficiency compared to the combustion engine. In addition, different types of fuel cells can provide power generation within various operating conditions that can meet the needs of various applications. However, there are challenges facing fuel cells application (**Figure 7**); these challenges include: hydrogen fuel availability, fuel cell reliability, cost of fuel cell and hydrogen, fuel cell operation durability and wide public acceptance for hydrogen technology [45, 46].

Hydrogen economy has many benefits but it still facing many obstacles and challenges that limit hydrogen of being independent economy. **Figure 8** shows the key limitations.

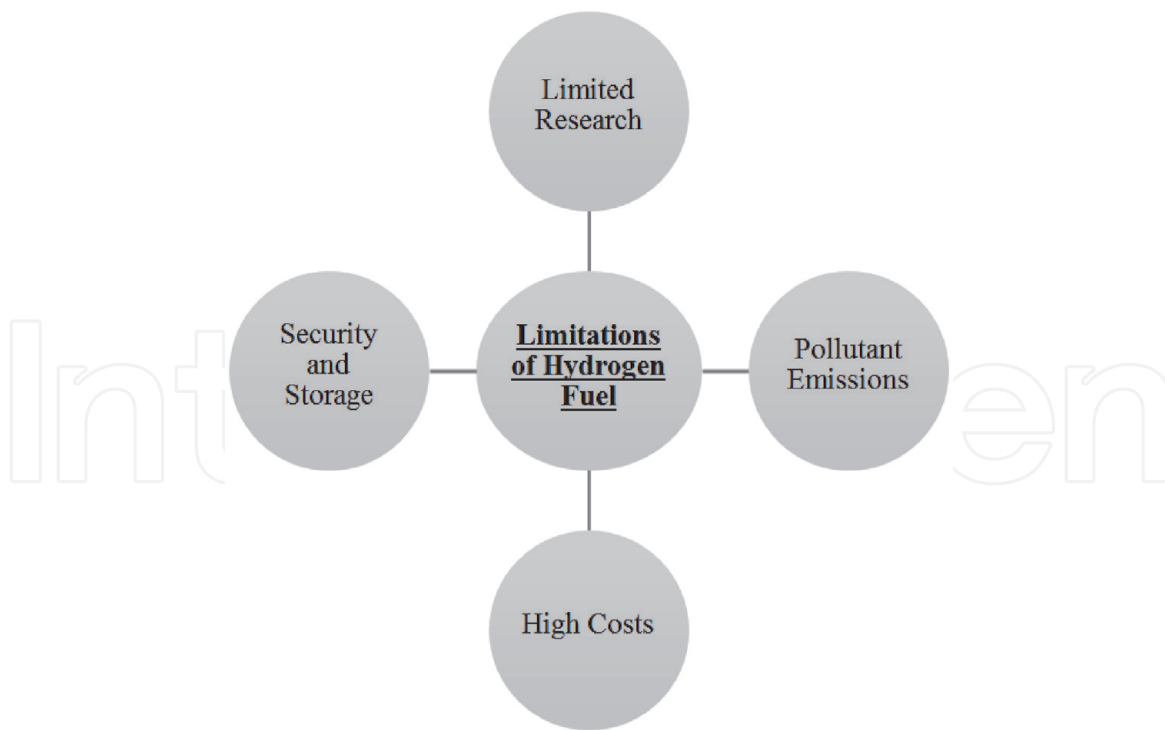


Figure 8.
Limitation of hydrogen fuel cell technology.

7. Steps needed for fuel cell commercialization

To achieve commercialization prospects (**Figure 9**), several technical-technological barriers must be identified. The most important barriers to be addressed are: cost of technology, fuel cell system integration and customer requirements [46].

8. Conclusions

The chapter addressed the main hydrogen production methods and introduced various future green hydrogen routes and opportunities. Hydrogen production for fuel cell technologies requires an improvement regarding sustainability of the hydrogen supply and an improvement regarding decentralized hydrogen production. Electrolysis for on-demand applications can be a potential route when it is coupled with green power supply. Hydrogen can be used for load balancing if stored properly, especially when integrated with renewable energy system. Moreover, hydrogen economy as far requires a large scale and long term storage solution to meet the increasing demand. Hydrogen storage is facing several challenges, such as high pressure storage increase with the size of container; cryogenic storage has a problem with longer and large quantity storage. Solid state storage requires a scale up in case of being used for stationary purposes improve the thermodynamic properties of the materials for storage/release at moderate temperature and pressure.

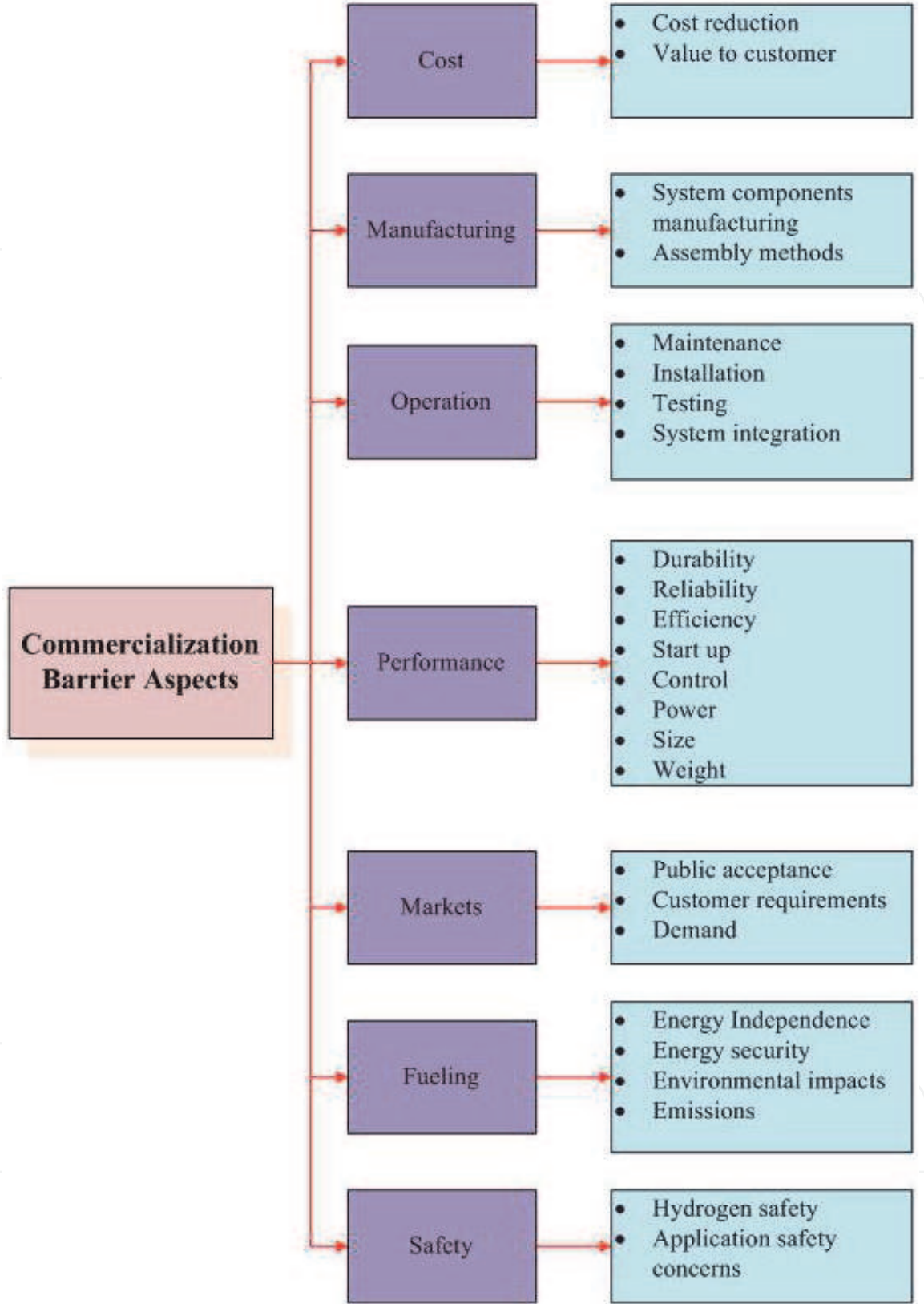


Figure 9.
Commercialization aspects of hydrogen fuel cell technology.

Appendices and nomenclature

| | |
|-------|------------------------------------|
| PEMFC | proton exchange membrane fuel cell |
| SOFC | solid oxide fuel cell |
| DMFC | direct methanol fuel cell |
| MCFC | molten carbonate fuel cell |
| SMR | steam methane reforming |
| PV | photovoltaic |
| DC | direct current |

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