Renewable and Sustainable Energy Reviews 30 (2014) 743–757

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Renewable hydrogen economy in Asia – Opportunities and challenges: An overview

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ARTICLE INFO

Article history:
Received 1 April 2013
Received in revised form
21 September 2013
Accepted 12 November 2013
Available online 1 December 2013

Keywords:
Renewable hydrogen economy
Asian countries
Government incentives
Hydrogen infrastructure

ABSTRACT

Renewable alternative energy sources are getting more attention due to the depleting nature of non-renewable fossil fuels. Increasing global warming, caused by the combustion of fossil fuels, triggered the intense research in finding out better energy options with low emission. Among the potential energy options, hydrogen is a clean fuel candidate as it simply produces water as byproducts when burning. Hydrogen can be generated from different renewable sources and Asia is one of the continents which is rich in renewable energy resources. The resources, safety parameters, public acceptability, and proper government incentives are the major factors affecting the implementation of hydrogen as an economical energy source in Asian countries. The present review deals with the necessity of employing hydrogen as an alternative fuel, its production paths, storage issues, transportation and the available sources. Special emphasis has been given to the discussion of renewable hydrogen economy in some Asian countries like, Japan, Korea, China, India and Malaysia. The challenges in the execution of hydrogen as an economical fuel in Asia are also highlighted.

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.11.015

1. Introduction

The primary difficulty faced by the modern world is the scarceness of fossil fuels because of the concomitant use of fuels for daily life [1]. Therefore, it is essential to develop an alternative fuel that can replace non-renewable fossil fuels [2,3]. Substituting hydrogen for fossil fuels in ultimate energy uses could bring this key environmental welfare [4] into accordance with the technical, green and cost challenges, and it is easy to overcome the difficulties in, for instance, production, storage and transport of hydrogen [5–7]. Hydrogen is considered to be the clean fuel of future because it acts as an energy carrier and because only hydrogen provides a method for the storage and transport of energy. The energy storage capacity of hydrogen is excellent because calculations show that one kilogram of hydrogen contains approximately 33 kWh of energy [8]. Hydrogen can be considered to be a secondary energy source, i.e., an energy carrier, because it can be converted to energy in the form of heat or electricity through either combustion or electrochemical reactions. (Secondary energy sources are termed energy carriers.)

Because of the weakness of our gravitational field, pure hydrogen gas is not currently available for use; therefore, hydrogen fuel must be produced from a variety of sources. Because water and natural gas are abundant sources of hydrogen in the universe, the scope is considerable. However, the simultaneous generation of unwanted oxygen with hydrogen limits the scope of large scale hydrogen production through the electrolysis of water [9]. The least expensive method for the production of hydrogen is spraying steam on white-hot coals, but the generation of huge amounts of poisonous carbon monoxide lowers the demand for this method [10]. Therefore, an appropriate substituent for the generation of high hydrogen content should be developed. In 1870, Jules Verne remarked that hydrogen would be a virtuous substitute for coal. Coal gas is another source of hydrogen; the combustion of coal gas produces water gas [11], a mixture of CO and hydrogen, and water gas is highly recommended for the so-called Fischer–Tropsch process, which converts CO and hydrogen to synthetic gasoline and alcohols [12]. In 1920, a huge underground reserve of methane (natural gas) was discovered, and it provided an inexpensive substitute for coal gas [13]. In the modern world, methane can be considered to be the cheapest source of hydrogen. In the production of hydrogen from natural gas, smaller amounts of carbon oxides are produced relative to coal gas. A wide variety of studies are now on-going in the field of the production of hydrogen from natural gas and in lowering the percentages of CO emissions. Many countries in Asia use natural gas as a renewable hydrogen source in industrial scale production of hydrogen by steam reforming or by partial oxidation methods with natural gas and some other hydrocarbons [14].

The main drawback associated with other hydrocarbons is the emission of airborne pollutants and greenhouse gases [15]. Usually, hydrogen is generated by the steam reforming process (SR) of hydrocarbons such as methane, naphtha oil, and alcohols. However, for industrial scale production of hydrogen, more than 85% can be produced from steam reforming of natural gas in conventional fixed bed reactors, and for lab scale applications, partial oxidation reactions and autothermal reactions are applied. Although the mentioned reactions are conducted in the same reactors, the efficiency for the production of hydrogen is different/lower than the efficiency of the steam reforming process [16]. However, by conventional steam reforming reactions, impure hydrogen gas with a high yield was obtained. Among the various technologies connected to the separation and purification of H_2, membrane reactors play an extraordinary role compared to conventional systems and can avoid the thermodynamic constrains associated with the out-dated reactors [17]. The application of membrane reactors for the production and purification of hydrogen was reported by Prof. Gryaznov in the 1960s [18]. Membrane reactors attracted increased attention for the efficient production of hydrogen in subsequent years.

Moving the global energy system onto a viable path is gradually becoming a key concern and strategy objective of the modern world [19,20]. The concept of a shift to hydrogen fuel has been proposed by scientists for more than 50 years [21]. However, there is a concern that hydrogen is a dangerous explosive fuel, but this objection is not true in many respects; hydrogen can explode under some careless conditions, but gasoline and natural gas can explode as well. In 1981, Hoffmann reported that if we handle hydrogen more carefully or properly, use of hydrogen is safer than use of current conventional fuels [22,23]. Midilli et al. [24] reviewed the basic and fundamental knowledge that everyone should know about hydrogen as a fuel, and the importance of hydrogen to the development of a sustainable future. Barreta et al. [25] reported that hydrogen-based fuel cells and technologies that use hydrogen have vital power in the extensive transformation to a diverse energy system with a cleaner and efficient process. This basic transformation in the world energy system brings considerable enhancements in energy systems and hastens decarbonisation of the mix of energy produced to reduce impact on the climate. These criterions for the protection of the climate can be achieved by hydrogen-based technologies, and hydrogen-based technologies satisfy this task. Wide studies have investigated the outlook and possible strategies for a transition toward a hydrogen-based energy system, the "hydrogen economy" [26–29]. It takes a long time to change the basic structure of the energy system, but a transition to a fully established "hydrogen economy" would span several decades. Hence, acceptable quantifications of structural changes and long-term trends for hydrogen technologies are essential for successful implementation. The production and utilisation of hydrogen must be renewed to inspire a hydrogen economy that is expected to enlarge beyond the few initial applications [30–32].

Renewable hydrogen can improve energy confidence throughout the world and can considerably support the basis for global harmony and fortune. Ohi et al. [33] proposed that to achieve victory in the renewable-hydrogen economy, we must consider several factors. These factors mainly consist of good renewable energy resources and how we utilise these resources for the production of hydrogen and electricity in an economically favourable manner. Other factors include the social and ecological benefits from the use of renewable energy; the provisions of domestic policies, which make renewable hydrogen more favourable; extensive public and private support; good international cooperation on hydrogen research for the development in other countries and so on. In this review, circumstantial information on renewable hydrogen pathways is reviewed, especially the economic treatment of hydrogen energy in various Asian countries. Additionally the impact of the hydrogen economy on the situation in Asian countries was outlined. Special attention is given to the challenges that we must overcome to commercialise hydrogen gas

on the bulk scale. The review also outlines suitable hydrogen feedstocks, available production technologies and government incentives to provide a long-term estimate of the use of hydrogen in Asian countries.

2. Renewable hydrogen: an outlook

Traditionally, the central motive for promoting hydrogen as an energy carrier is its exceptional benefits for environmental protection. A renewable energy can fulfil all the energy requirements of a nation [34]. Hydrogen is supposed to the best long-term renewable energy. Hydrogen produced from renewable sources can be considered to be renewable hydrogen and forms the basis for preserving worldwide energy. Orhan et al. [35] reviewed the possible hydrogen production pathways from renewable resources and from nuclear power. Renewable hydrogen can provide a medium for the transportation and storage of energy and acts as a vital connection between the energy and emission-free technologies. The diminution in quantity of and poisoning of the environment by fossil fuels makes the need for a renewable and clean fuel dominant. In the hunt for substitute fossil fuels, committed R&D studies have exposed hydrogen as such a fuel [36]. Hydrogen is an ideal candidate as a clean energy carrier for both transportation and stationary applications. The concept of renewable hydrogen becomes a universal reality through the construction of several resources. The production of hydrogen from renewable energy develops a significant material for solving the intermittency problems associated with the production of non-renewable energy [37]. The value and usage of renewable energy throughout the world can be enhanced by the assimilation of renewable energy with hydrogen.

Zero-emission energy technologies are attractive and economically competitive with the other technologies that use fossil fuels, even without considering the benefits and costs associated with clean-renewable energy [38]. Studies show that the economic savings become more advantageous if we can produce the hydrogen using the same technologies and replacing the fossil fuels [39]. Sorborn et al. [40] treated both hydrogen and electricity as hydricity and reported that these two parameters are energy currency twins because electricity can be produced from hydrogen and hydrogen can be produced from electricity, i.e., both hydrogen and electricity are substitutable. It is noted that hydrogen storage is more economical than storage of electricity in conventional batteries [41]. The production, storage and later use can be considered to be the best alternative to on-going storage forms of energy.

Some countries have many schemes to achieve a renewable hydrogen economy, represented by the International Energy Agency (IEA), the International Partnership for the Hydrogen Economy (IPHE) and some case-studies from North and South America, Europe and Asia. The concept of the hydrogen economy was previously invented by the international policies such as the IEA and IPHE for the growth of a sustainable energy future with zero emissions [42]. The IEA serves as an opportunity to discuss common issues with energy technologies and allows the members to move forward with technology policies. Several implementing agreements, such as collaborative energy studies, are provided by the IEA Framework. The major part of this IEA framework is hydrogen. Over the past few years, considerable achievements have occurred toward the hydrogen future through the IEA Hydrogen Implementing Agreements [43], and hydrogen is quickly developing as a key factor in clean and sustainable energy systems. According to the IEA, hydrogen is applicable to all energy zones and can deliver storage options for alternative renewable tools, such as solar and wind resources. Many Asian countries are now members of the IEA.

The IPHE mainly serves as a device to begin and implement focused international studies related to hydrogen and fuel cell techniques. The IPHE also provides a link to move forward with strategies, common codes and standards, which speed up the economic transition to a global hydrogen economy to enhance energy and environmental safety [44]. Among the various Asian countries in the IPHE, China, India, Japan and Republic of Korea are the prominent members. However, the primary functions include identification, coordination and promotion of potential areas of joint collaboration on hydrogen and fuel cell technologies and analysis of the utilisation of instruments and methods for hydrogen production. From the perspective of the IPHE, a hydrogen economy suggests a probable solution to satisfy global energy desires and reduce greenhouse gas emissions [45].

The Asia Pacific Economic Cooperation Energy Working Party (APECEWP) chiefly focussed on the progress in hydrogen technologies and fuel cell applications in association with the IEA and IPHE for the organisation of hydrogen and fuel cell developments throughout the Asian countries. Clean Urban Transport for Europe (CUTE), which recognised the need for hydrogen power for bus transportation in Asian countries, is one of the collaborative sectors in Asian countries. For hydrogen and fuel cell developments in Asian countries, some investments are also provided by the International Centre of Hydrogen Energy Technologies (ICHET) of Turkey [46].

The transition from the fossil fuel-based economy to the renewable hydrogen economy can happen step by step [47]. To achieve this goal, we must cautiously define future energy scenarios for the industrial scale production and utilisations of hydrogen. Throughout this progress, conservative technologies and the current infrastructure for hydrogen should be maintained for an economically virtuous hydrogen economy [48].

3. Renewable hydrogen systems: infrastructure

Each step, from the production of hydrogen to the handling of hydrogen by the end user and the storage and transportation of hydrogen, has safety parameters, codes, standards and so on. These parameters must be considered to obtain high quality hydrogen in a secure manner. The mentioned parameters, such as hydrogen production, storage and transport, are important to achieve successful development of renewable hydrogen technology. Compared to production from non-renewable fuels, the production of hydrogen from renewable fuels has many positive qualities, which promote the enhancement of the renewable hydrogen economy. The fundamental hydrogen infrastructure shown in Fig. 1 is described by the hydrogen energy roadmap, and describes the production, storage, delivery and end use applications of hydrogen.

3.1. Hydrogen production

A serious problem in the path of the hydrogen economy is hydrogen production in an effective and green pathway [49]. A wide variety of hydrogen production methods are now available

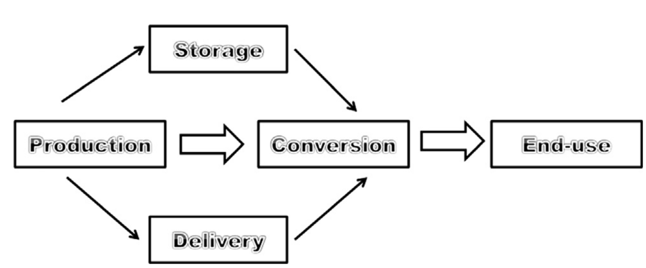

Fig. 1. Hydrogen energy infrastructure adapted from the hydrogen energy roadmap.

in the literature [50–83]. Many of the prescribed methods are only applicable for lab scale production of hydrogen, and only some methods are applicable on the industrial scale. For large scale energy applications, approximately 95% of the hydrogen is produced by reforming of methane [50]. The remaining portion is from the electrolysis of water with the electricity obtained from the combustion of fossil fuels.

A brief description of the different hydrogen production techniques are discussed here. Coal gasification is one of the most advanced methods for hydrogen production on the pilot scale. This process involves the partial oxidation of the coal with oxygen followed by steam reforming in a high-pressure reactor [51]. Hydrogen is produced by the steam reforming of natural gas in large united reformers. Here hydrocarbons are converted to hydrogen and carbon monoxide with catalysts such as nickel-loaded alumina in the presence of steam. This method is the least luxurious method for approximately 90% of hydrogen production. After the generation of CO and H_2, a catalytic water-gas shift reaction takes place, and hydrogen and carbon dioxide (CO_2) are formed through the reaction between water steam and CO. Purified hydrogen gas is the final product [52–55]. Partial oxidation of natural gas is another effective method. In this method, natural gas and oxygen are introduced into a reactor at high pressure. An exothermic oxidation reaction takes place and finally CO and H_2 are formed. One of the limitations of this method is the need for oxygen. The catalysts have been found to be tuned for the partial oxidation of methane. Since the reaction is exothermic, no external heat supply is necessary; the heat evolved reduces the capital cost of the reaction, but the method is less efficient than steam reforming [56–58].

Thermocatalytic cracking method converts hydrocarbons, especially methane, to hydrogen and carbon nanomaterials over nickel-loaded catalysts [59,60]. Research into this method is still on-going. Thermochemical water splitting is the other one, in which hydrogen is produced by water splitting through heat energy and chemicals. Hydrogen can be produced with nuclear heat in the sulphur–iodine cycle. Water splitting with solar heat is similar to the above method, but here, the temperature is achieved by concentrating solar energy [61–63]. An electrical current is used to split water into hydrogen and oxygen. For this purpose, the electricity can be obtained from sources such as nuclear energy, wind turbines, photovoltaic cells, etc. Electrolysis provides only a small fraction of the world's hydrogen, and its scope is limited to the small amount of high-purity hydrogen. To obtain high-purity hydrogen, proton exchange membrane electrolysers or alkaline electrolysers were primarily used. However, the scope of this method is also limited, because only pure water gives high-purity hydrogen. The usage of sea water or alkaline water would produce some by-products such as chlorine gas, NaOH, etc. [64]. In steam electrolysis of water for the production of hydrogen, heat is used instead of electricity for the water splitting. Thus, this process is much more efficient than the conventional electrolysis process [65,66].

Photo-biological hydrogen production process involves the splitting of water by microorganisms in sunlight. Many photosynthetic microbes produce hydrogen directly from water with light energy. Photo-biological technology indicates great potential for hydrogen production [67,68]. Also some semiconducting materials (TiO_2, ZnO) split water to produce hydrogen under sun light. The method integrates a semiconducting material and a water electrolyser in a single device, which produces hydrogen directly from water with light as an energy source [69,70]. Photocatalysts such as spinel cobalt oxide also split water. Some new catalysts for water-splitting reactions are being designed for the efficient, inexpensive and durable production of hydrogen. A device in which light absorption and water splitting are joined in the same apparatus may be the best inexpensive route to produce hydrogen [71,72]. High reaction temperatures also split water. Solar thermochemical water splitting is the method in which intense solar energy can be used to generate very high temperatures at which thermochemical reaction cycles can be used to produce hydrogen through water splitting [73].

Biomass can be converted into hydrogen through many techniques. Recent technologies for hydrogen production from biomass include gasification and pyrolysis of the biomass followed by steam reforming. Other techniques include oxygen-blown gasification, and fermentation in anaerobic conditions [74,75]. Thermochemical conversion of biomass produces hydrogen and other gases, from which hydrogen can be separated. Pure hydrogen can be made from biomass or coal with heat. Thermal treatment of biomass produces bio-oil, which has many components that can be easily separated into chemicals, fuels and hydrogen gas. Reforming technology is also used to convert bio-oils to hydrogen; this process builds on the viable procedures used for the reforming of natural gas [76]. Several photosynthetic microbes such as green algae, cyanobacteria, etc., produce hydrogen from water with light energy by a splitting method in their metabolic activities. The hydrogen production rate from microorganisms is currently too low for marketable feasibility [77,78]. Water splitting with active metals, such as aluminium, zinc, iron etc., is a promising method for hydrogen production. However, the method requires acidic or alkaline conditions for fast reactions and good yields [79–83].

The basic question when we are focussing on the production of hydrogen is the amount of energy needed for the production of hydrogen and how this amount varies with the procedures. It is evident that the production of hydrogen from the electrolysis of water is now more effective than production techniques such as the mining of hydrogen from fossil fuels. If the water splitting is performed by the fossil-based technologies, then extra energy is essential and is needed to address the carbon dioxide and other pollution connected with the fossil-based fuels. Thus, various factors must be included in the consideration of the overall energy loss resulting from the production of hydrogen and also for the concept of a renewable hydrogen economy.

3.2. Hydrogen storage

Hydrogen storage is an important tool for the development of transportation applications with fuel cell power systems. Cost-effective and energy-effective on-board hydrogen storage is needed for portable and mobile applications and throughout the hydrogen transportation network. Hydrogen storage is mandatory at hydrogen production and refuelling stations and in power sites. Hydrogen can be stored in a variety of ways. Salt caverns used for storing natural gas can also be a possible method for the storage of compressed hydrogen [84]. The conventional methods for hydrogen storage are as a gas in compressed form [85] and as a liquid under cryogenic and high pressure conditions in special bulk fuel tanks with appropriate safety precautions [86].

For the cryogenic storage of hydrogen, liquid hydrogen can be obtained by cooling hydrogen to $-253\,^{\circ}C$. This conversion of hydrogen gas into liquid hydrogen supports storage, transfer and delivery by tanker, truck and rail. Approximately 30% of the total energy of hydrogen is needed for the liquefaction of gaseous hydrogen. In addition to this energy cost, highly superior materials are necessary for the tanks and are highly costly. Therefore, improvement in the liquefying process and tank safety must be considered for the development of a renewable hydrogen economy [87]. Many research investigations show that the energy density of hydrogen can be considerably improved by storing hydrogen in a liquid state, and an improved insulation tank is needed to prevent the boiling off of hydrogen. Sludge hydrogen is

a blend of solid and liquid hydrogen acquired by decreasing the temperature to −259 °C, which is much colder than liquid hydrogen; however, applications of sludge hydrogen are currently restricted, but applications of sludge hydrogen in space technology are considerable [88].

Pipeline storage is another important option for effective storage and hence transportation or delivery of the produced hydrogen until it is utilised by the end-users [89]. There are many known ways to store hydrogen in materials, such as absorption, adsorption, and chemical reaction. One option is the adsorption of hydrogen in carbon nanomaterials. Carbon nanotubes store a considerable amount of hydrogen under the appropriate conditions. Carbon-based nanomaterials, such as carbon nanotubes, carbon nanoflowers, carbon nanobamboo and so on, have good storage capacity for hydrogen [90,91]. Carbon microtubes facilitate the storage of hydrogen within the microscopic pores of the tubes. Hydrogen can also be stored in glass microspheres with an appropriate diameter and a thickness of millimetres to micrometres, and the glass is broken to utilise the gas for applications [92].

Additionally, hydrogen can be stored in material forms, such as metal hydrides, where the hydrogen is weakly bonded to a metal [93]. Metal hydrides absorb hydrogen very quickly and release hydrogen when they are heated. Typically, absorbed hydrogen composes approximately 2% of the total weight of the sample. Some metal hydrides have high absorptions of hydrogen, from 5% to 7%, and high temperatures are needed to release the hydrogen in these cases. Additionally, metal hydride storage is also well known for safety. Currently, however, most of the hydrogen in the universe is stored in the liquid or gaseous form by the liquefied or compressed method. Various technologies to store hydrogen on materials are now under development. Among the various materials studied for hydrogen storage, carbon nanomaterials have a prominent role. The storage of compressed hydrogen gas in tanks is the most developed technology in the modern world, and the storing of hydrogen at high pressures can improve the energy density; hence, this storage satisfies utilisation of the limited space on board. The improvement of tank reliability in terms of cost, safety and effectiveness by using good materials and innovative design must be properly considered, especially when considering applications of highly pressurised hydrogen [94]. The storage of hydrogen represents the major technical weakness of a hydrogen economy compared to conformist power generation by fossil fuels.

3.3. Delivery/transportation

The progress in the hydrogen transport and delivery infrastructure has been analysed in detail by the IEA [95]. Hydrogen is presently transported through pipelines and on roads through the use of cylinders, tube trailers, cryogenic tankers and so on. For long distances, hydrogen is generally transported in cryogenic liquid form in super-insulated tankers, railcars, or barges and is then vaporised for use at the customer site. However, for small distances, high-pressure cylinders are used. Reports show that centralised hydrogen production is more economical compared with distributed production of hydrogen throughout the planet. However, the economic feasibility of centralised production is very tight for the development more efficient hydrogen delivery and transport. Compared to all the delivery approaches, pipelines, which link the clients with centralised production plants and transport huge amount of hydrogen, are found to be efficient. Appropriate delivery options based on the distance from the production site are mentioned based on the report [96]. Liquid hydrogen tube trailers are preferred for up to 100–200 miles, and liquid hydrogen tankers or gas hydrogen pipelines are preferred for up to 1000 miles, and long-distance transport is not favoured by these techniques.

3.4. Hydrogen applications

Hydrogen that is produced, stored, transported and delivered must be utilised for energy applications. Hydrogen can be converted into thermal energy through thermochemical reaction processes with combustion engines and turbines or can be converted directly into electrical energy through electrochemical processes with well-developed fuel cells. The by-product of both processes mentioned here for the conversion of hydrogen to energy is water; therefore, the conversion process is greener. However, for the thermochemical processes, other emissions are detected by earlier studies. Fuel cells are potential devices, which modernise the way that the current world uses energy by presenting a cleaner pathway substitute to the fossil fuel-based technologies. Hydrogen has now been used in the main engines of the space shuttle and in rocket engines. Many automobiles with hydrogen internal combustion engines are now in the demo phase, and some automobiles are now developed to a considerable extent in many countries.

Because electrochemical reactions do not need combustion to produce energy, fuel cells are characteristically more proficient and cleaner than combustion engines. The applications of hydrogen based on fuel cells are limitless. Hydrogen, or fuel cells, is used to power all the stationary actions related to industries, residences, all modes of transportation, all types of portable applications and so on. Fuel-flexible and energy-efficient fuel cells play an important role in the renewable hydrogen economy because they have the potential to revolutionise a cleaner alternative to the fossil fuels, have the ability to be an alternative to the internal combustion engine in vehicles and have the power to support stationary and portable applications. The recent progress for fuel cells in transportation applications, such as in vehicles, has been reviewed by Hwang [97]. According to Hwang, fuel cell vehicles have the potential to replace the present vehicles with petroleum-based engines. Many types of fuel cells are now under development; each type has its own benefits, drawbacks, and latent applications [98]. For stationary, portable and transportation applications, polymer-electrolyte membrane fuel cells have been developed, and based on this type of fuel cell, fuel cell cars have previously been manufactured by different companies [99]. Phosphoric-acid fuel cells are the most industrialised option for commercial applications [100]. For military applications, space missions and the transportation applications, alkaline fuel cells have been more commercialised [101]. Molten-carbonate and solid-oxide fuel cells are industrialised for the generation of electricity in stationary applications. Solid-oxide fuel cells may play a vital role in auxiliary power applications, primarily in large-sized trucks. In addition, both renewable hydrogen and all types of fuel cells, or enhanced forms of hydrogen, have no adverse impact on the global climate compared to fossil fuel-based technologies; hence these approaches encourage the greener renewable hydrogen economy [102]. Large numbers of fuel-cell vehicles have been verified in several countries in Asia; many of the vehicles are based on the Polymer Exchange Membrane Fuel Cell (PEMFC) technology because of the low operating temperatures of 80 °C and the higher power to weight ratio of PEMFCs [103].

4. Renewable hydrogen energy resources in Asia – biomass

Asia is well known for its low fossil fuel reserves compared to the other regions of the world and is rich in renewable energy resources. Calculations showed that all Asian countries have more than one exceptional resource for the future production of fuel (hydrogen). Thus, it can be concluded that Asia has a considerable role to play in the development of a renewable hydrogen future. The components for the construction of the renewable hydrogen economy primarily include the availability of renewable resources [104]. The assimilation of renewable energy resource data with

geographic parameters for Asia in the Geographical Information System (GIS) framework sets the stage for the analysis of the development opportunities for renewable hydrogen energy in Asia. Ohi et al. [33] already suggested the various renewable energy resources for provision of the hydrogen economy. According to Ohi et al., Asian regions such as the Himalayan Geothermal Belt, Japan, Eastern China, the Philippines, Indonesia, and New Zealand are well known for geothermal resources whereas hydropower resources are mainly concentrated in southern Asian countries, such as Thailand, Cambodia, Laos, Myanmar, Vietnam, Indonesia, Malaysia, Philippines, India, Nepal and Bhutan. Wind and solar resources are abundant throughout the world, but the areas in which the highest solar resources are situated are in Asian countries [105]. Among the different renewable resources, for the hydrogen energy economy, considerable attention was attracted by biomass resources because of the production of hydrogen from biomass. Asian countries are saturated with biomass resources. Now, we have a forecast for biomass resources in Asian countries. Demirbas et al. [106] reviewed the utilisation of various types of biomass for energy development, which includes hydrogen production for the renewable hydrogen economy in Asia, in a favourable manner.

Biomass and other fuels derived from biomass form the basis for renewable energy sources, which are utilised for the production of sustainable hydrogen [107]. The production of hydrogen from biomass is presently a challenge because it is more expensive than the hydrogen produced from natural gas. The cost for assembling and shipping biomass is fundamentally very high, which results in the construction of small plants for hydrogen production without consideration of the economy. However, it is noted that biomass shows the way to extract energy from domestic and agricultural waste [108]. Biomass is the primary energy source in Asian countries, especially in Malaysia, Vietnam, Indonesia, Philippines and Thailand, and it provides approximately 40% of the energy consumed in the world. The energy policies in Asian countries accept the vitality of biomass for future energy prospects, and renewable energy based on biomass can be assimilated into the economy of a country. Biomass resources are rapidly renewable, are eco-friendly for the production of energy (hydrogen), and are highly sustainable in accordance with the usage of biomass.

Reports show that biomass is the fourth largest renewable fuel that is now in use. Biomass is treated as a renewable energy source, and it is restocked more rapidly than fossil fuels, which take millions of years to form. Different varieties of biomass fuel sources are available in Asian countries. These sources include deposits from agriculture, pulp and paper wastes from industry, wood waste from forests in urban areas, energy crops, landfill methane and wastes from living organisms. Based on the reports of [109], it can be concluded that the distribution of biomass is very high throughout the Asian countries. In some Asian countries, such as Indonesia, Malaysia, the Philippines, Thailand, and Vietnam, 108 million tons of biomass were obtained from the residual deposits from bagasse, rice hulls, palm oil waste and wood waste [110]. In the world, 85% of the biomass is located in Asian countries and is primarily in Malaysia and Indonesia. The various percentages for these residues are shown in Fig. 2 based on [110]. Biomass forms 8.94% of the total electricity production in Asian countries based on the report from Dasappa [111]. Malaysia has a range of biomass residues, which are primarily obtained from the palm oil industry, rice, sugarcane, the wood industry and municipal solid waste [111–113]. Because Malaysia produces a huge amount of palm oil, the amount of biomass obtained from the palm oil industry is very large; this amount constitutes approximately 85.5% of the total biomass available in the country [114,115].

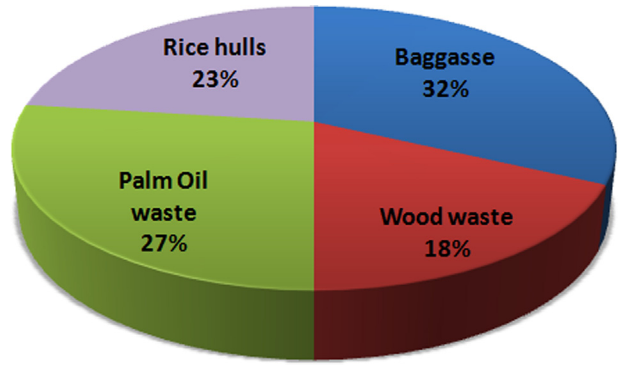

Fig. 2. Percentages of various biomass residues in Asian countries.

5. Renewable hydrogen economy in Asia

The future for the renewable hydrogen economy of a country is greatly influenced by the financial status and the various governmental policies of the country, and favourable policies have a marked influence on the economic feasibility of renewable hydrogen [116]. The costs for the production and use of renewable hydrogen differ based on the source for the energy production and the technology applied in the generation, storage and delivery of the hydrogen fuel. The economics of renewable hydrogen are boosted by the simultaneous production of hydrogen and electricity from renewable resources [117]. The value of the renewable hydrogen economy drastically increases when countries produce hydrogen from renewable resources instead of fossil fuels because renewable energy sources are cost-effective. The governmental policies of each country can significantly participate in the renewable hydrogen economy and can provide economic motivations for renewable hydrogen in a range of cultures [118]. Each Asian country has plenty of its own renewable resources and oil resources are utilised for the production of bio-fuels, which is the other form of a renewable energy, such as hydrogen [119]. The next section will explain previous and recent developments, achievements, various opportunities and the role of governmental and private agencies in each Asian country toward the realisation of a renewable hydrogen economy in Asia.

5.1. *Japan*

Japan is one of the most motivated countries in Asia and throughout the world in the development of a renewable hydrogen economy in the implementation of short-term and long-term plans. The production of hydrogen by reforming of natural gas and water electrolysis were employed as a short-term plan, and water photolysis through the thermochemical route is the long term plan. This country is also considering biomass in the hydrogen production plan.

Short-term storage is generally based on the compression and liquefaction of produced hydrogen gas with metal hydride storage for long-term storage. Hydrogen is utilised by fuel cells for vehicles and stationary applications because Japan intends to use 4 billion dollars for hydrogen usage and expects that by 2020, all road vehicles will powered by hydrogen-based fuel cells [120]. In 2000, the Japanese government apparently paid 25 billion yen for research and development of fuel-cells, and 31 billion yen were utilised in 2004 [121]. The Japanese government also directs some resources to fund Japanese automakers and spends approximately 380 million dollars per year on research, progress, and commercialisation of fuel cells.

In 1973, the initiation of the Hydrogen Energy Systems Society of Japan (HESS) commenced the concept of hydrogen usage for

different energy applications, mainly for transport purposes, with the support of Japanese government [122]. In 1981, the Moonlight project was established for the research, development and commercialisation of fuel cells. In 1991, the Policy Study Group for Fuel Cell Commercialisation was introduced by the Ministry of the Economy, Trade and Industry of Japan (METI) for the commercialisation of fuel cells. The primary public financing for the research and development of fuel cell and hydrogen in Japan comes from METI. The main aim of this ministry (METI) was the execution of fuel cell technologies based on hydrogen, not potential trade benefits, and the promotion of hydrogen R&D based on energy safety, effectiveness and zero emissions [120]. According to Maruta et al. [123], METI aimed to produce a number of hydrogen-based fuel cell vehicles on the road and hoped for 15 million vehicles by 2030. According to Takahara et al. [124], METI spent considerable money on fuel cell and hydrogen research development; this spending grew from 11.7 billion dollar to 35.5 billion dollar within 5 years. The Japanese World Energy Network began in 1993 for the development of hydrogen-based fuel cells for transportation applications. In 2002, the Inter-ministry Official Task Force for Ministries and Agencies was established in Japan to develop practical applications of fuel cells based on a three stage plan; the stages were introduction, diffusion and penetration [125]. The different stages of this ministry dealt with a variety of establishments. Introduction mainly focussed on the evolution, safety and reliability of fuel cell-based vehicles by government organisations. The diffusion stage documented all the fundamentals of hydrogen or fuel cells for self-sustained market development. Finally, the penetration stage suggested a satisfactory hydrogen supply throughout the nation and a considerable level of fuel cell technology [126]. The ministry of the environment in Japan now plans to produce hydrogen from sea water because it is an abundant source of hydrogen; this production will use a power station, which uses electricity generated from wind. Based on international reports, Japan will soon place a hydrogen fuelling power station by spending approximately 20 million dollars by 2020 [120].

In addition to METI, many government organisations in Japan focus on the development of the hydrogen economy. The New Energy and Industrial Technology Development Organization (NEDO) is one example; it was initially recognised by the Japanese government for the development of oil-alternative energy technologies and afterwards, the sector began to focus on the development of hydrogen energy and fuel cell technologies [127]. Certain university research centres in Japan, such as the Japan Automobile Research Institute (JARI), intensely focus on fuel cell-based electric vehicles. The project investigated technical developments for fuel cell vehicles, electric vehicles, and hydrogen energy vehicles [120]. Additionally, research is directed toward fuel competence investigation methods, stack-performance inspection methods, and so on. The Hydrogen Energy Systems Society of Japan (HESS) was specifically established for the promotion of hydrogen energy systems. The head sector is located at Yokohama University, which is the leading hydrogen research university in Japan and primarily focused on hydrogen production from renewable energy sources to improve the atmosphere [122].

HESS has some universities and institutions, such as Yokohama National University, Tokai University, Institute of Applied Energy, Tokyo Institute of Technology, academics from the University of Tokyo, Yokohama National University and some companies such as Honda, Toyota Motor, Advanced Industrial Science and Technology (AIST), Iwatani International, and so on. A large number of vehicle companies, such as Toyota, Honda, Nissan, Mitsubishi, Suzuki, Daihatsu, and Hino are involved in hydrogen fuel cell vehicle activities [126,128]. The Japan Hydrogen and Fuel Cell Demonstration Project (JHFC) in association with the Engineering Advancement Association of Japan (ENAA) have many activities, which are primarily focussed on the development of technology for hydrogen fuelling stations and on improvement of the cost effectiveness for fuel cell vehicles. This project also intends to validate the ordinary usability of fuel cell cars [129]. Laurikko [126] presented the hydrogen energy infrastructure for the renewable hydrogen economy, and in approximately 2030, large scale production of renewable hydrogen is aimed for domestic fuel cell applications through pipeline storage and transportation.

5.2. Korea

The Korean government has already assigned 38 million dollars as an additional budget to develop a greener renewable hydrogen economy [130]. Korea considers hydrogen and fuel cells to be the primary area that makes the country develop in an economical and greener manner. Currently, Korea is mostly concentrated on hydrogen production stations, storage with high pressure tanks, and utilisation of the fuel cells for home power generation, transportation, and portable and stationary applications.

The government of Korea has many programs for the development of hydrogen energy. The hydrogen energy technologies in Korea are supported by the Ministry of Science and Technology (MOST) and by the Ministry of Commerce, Industry and Energy (MOCIE). The MOCIE mainly focuses on the development of large hydrogen technologies in short-term plans, but the MOST is oriented toward the development of long-term plans for basic hydrogen research [130]. In association with R&D programs, these ministries have some projects. Important programs are the High-Efficient Hydrogen Production Program, the Alternative Energy Technologies Development Program and the 21st Frontier Hydrogen Energy R&D Center Program. In addition to these programs, the Korean government has many institutes, universities, and government sectors for the development of the hydrogen economy in Korea. From the report by Song and Chen in 2012 [131], Korea has some public research institutes and many private companies for the development of fuel cell technology, such as Seoul National University, Korea University, Korea Advanced Institute of Science and Technology, Sogang University, Yonse University, Hankuk Aviation University, Chungnam National University, Dong-yang University, Inha University, Kyung-book National University, Hanyang University, Pohang University of Science and Technology, Hannam University, Hong-lk University, Joongang University, the Korea Institute of Energy Research (KIER), the Korea Institute of Science and Technology (KIST), the Korea Electrotechnology Research Institute (KERI) and the Korea Research Institute of Chemical Technology (KRICT) [132]. The Korea Institute of Energy Research (KIER) successfully established a hydrogen-fuelled fuel cell car that can drive farther than 200 km without refuelling [120].

The Korean government strongly supports the creation of hydrogen-based fuel cells in industrial areas. To promote hydrogen energy technologies, the Korean Hydrogen and New Energy Society were developed. This university-based society has a publication named the Journal of the Korean Hydrogen and New Energy Society and is primarily interested in the production, storage and transport of hydrogen from an economical and environmental point of view [131,133]. Some of the contributions for energy initiatives in Korea achieved vital capacity in hydrogen storage through the invention of hydrogen absorption materials. The Samsung energy enterprise in Korea mainly focuses on the development of fuel cells for mobile applications, and Hyundai motor initiatives invented the Sonata fuel cell vehicle [134]. A report by Tak in 2010 shows that the Korean government spends 90 million dollars per year for hydrogen and fuel cell research and developments [135]. In terms of population, Korea is a country that invests a huge amount of money on hydrogen research. In 2004, a new plan was established in Korea; this plan spends

approximately 586 million dollar through 2011 and aimed to develop hydrogen production from, for instance, renewable resources and water electrolysis and to commercialise stationary fuel cells and fuel-cell based vehicles [136].

5.3. China

According to many reports, China is one of the most energy-consuming nations in the world [132]. In all the countries in Asia, especially in China, government incentives and public policies play an important role in the development of the hydrogen economy. China is another country that has a key role in the renewable hydrogen economy in Asia and is also an active participant in the IPHE. Hydrogen production in China is generally based on the residential sources in a cleaner manner without the emission of any greenhouse gases. Many countries reported that hydrogen from natural gas is a low-cost technology, but China reported a viable and inexpensive methanol-to-hydrogen reforming method. Many countries agreed with this pathway; however, the production procedure must be integrated with carbon capture structures to avoid greenhouse emissions in long term usage [46]. One of the research programs in China, named the National Basic Research Program (NBCP), primarily concentrates on hydrogen production, storage and transportation on the industrial scale. Some of the NBCP projects are in the applications of fuel cells and on the lab-scale production of hydrogen from water with solar energy. China utilises fuel cells for light-duty buses, mini-vans and cars in collaboration with some other countries. Another programme, named the National High-Technology Development Program (NHTDP), addresses fossil fuel hydrogen and fuel cell technology and advanced hydrogen generation for motor applications [120].

In 2002, the Chinese government declared that they will finance approximately 18 million dollars for the development of fuel cells, especially PEMFC by funding the Dalian Institute of Chemical Physics (DICP). The Dalian Institute of Chemical Physics in China has some fuel cell R&D that focuses on the development of PEMFC and has many patents for PEMFC technology. In 2003, the DICP provided a new 75 kW polymer electrolyte membrane stack to Tsinghua University, and this stack is utilised in a bus for transportation [126,137]. Additionally, China made approximately 120 million dollars of investments in fuel-cell powered automobiles and has many institutes that specialise in hydrogen-based fuel cells. The Shanghai municipal government in China has some projects for the R&D of fuel cells that spends approximately 12 million dollar per year [121]. The National Development and Reform Commission (NDRC) is a sector of the State Council of China that focuses on sustainable progress in China for a cleaner and pollution-free path to hydrogen.

China has acquired more benefits from the development of the hydrogen economy in various aspects of hydrogen, such as in the production, storage, transportation and delivery etc. It is estimated that in the long run, progress and extensive use of automobiles powered by hydrogen will be of great importance for improving China's energy scarcity crisis, decreasing pollution and encouraging a renewable hydrogen economy. Long-term plans focus on a hydrogen economy that will most likely be realised after 2050. For China, hydrogen energy is included in the national energy system, which is based on the renewable energy terms, and the energy sectors of the state council have responsibilities for the survey of resources, planning developments, cost analysis, economic motivation, and so on for the hydrogen economy [138]. In China, regional diversity may be considered to be a productive sector in the hydrogen economy. Two main cities in China, Beijing and Shanghai, have been nominated for demonstrations of fuel cell buses by the Global Environment Facility (GEF). Shanghai is one of the most important cities in China. It has its own energy developments for the renewable hydrogen economy. Reports show that in Shanghai, current R&D programs are removing most of the barriers to the production of hydrogen from nuclear power, fossil fuels and from renewable energy sources [46]. Short-term plans barely benefit technologies, so R&D policies are needed to fund technologies. One of the policies, named the Green Power System, in Shanghai is mainly focussed on research into renewable hydrogen production [139,140]. One of the top companies in China, named Shanghai Shenli High Tech. Co. Ltd., produces hydrogen power and utilises it in the development of hydrogen fuel cell cars in collaboration with the Shanghai Automobile Industry [141].

Shanghai Shen-Li High Tech Co. Ltd. has developed mini-buses with proton exchange membrane fuel cells. For the development of a renewable hydrogen economy, there are many regional policies in the north eastern areas of China. In Shanghai, a group of fine policy actions suggested for the renewable hydrogen economy includes primarily carbon taxes, motivations and incentives for the developments of hydrogen research, tax exclusions for equipment that uses hydrogen as a fuel and so on. China planned for normal use of hydrogen in the energy development policy and made many investments in hydrogen and fuel cell research. Reports show that the Chinese Ministry of Science and Technology spends approximately 9.4 million dollars for hydrogen-based fuel cell automobiles [142]. Shanghai is working on its own hydrogen infrastructure project and has started to produce hydrogen for fuel cell buses in the city. The supply of hydrogen fuel is very easily available compared with other cities because of the infinite and elastic fuel sources. Some chemical companies in Shanghai produce hydrogen as an industrial by-product, and this production significantly satisfies the needs of short-term users in the city [126].

Tsinghua University in China has some projects and basic research intended for production, storage and transportation of hydrogen, for fuel cell engines and for the development of PEM fuel cells. Hydrogen production is from ethanol [126]. Tianjin University, Fudan University, Tianjin Institute of Power Sources and the South China University of Technology are some other universities in China that focus on the development of PEMFC components. The Fuyuan Company in China works on PEM stacks with sizes of 3–30 kW. In 1998, this company established the first fuel cell-based vehicles in China in association with Tsinghua University with a 5 kW stack. Later, the Fuyuan Company has verified 40 kW PEMFCs for buses and 100 kW PEMFC for electric buses [143,120].

The China Association for Hydrogen Energy also promotes the path to a renewable hydrogen economy by considering hydrogen to be the ultimate fuel for fuel cells for various applications [144]. One important programme in China, known as the MOST 973 program, spends 5.6 million dollars in the development of hydrogen storage materials, membranes and so on. Hong Kong University has collaborations with the programme, and the programme provides many more developments in the field of carbon nanomaterials for hydrogen storage materials.

5.4. India

In India, the marketable energy demand can grow by 4.5% per year until 2020, and after 2020, the economy will grow at 7–8% yearly, based on the present energy consumption calculations. The growth difference between the energy demand and supply depends on imported oil for the increased energy consumption [145]. The oil-based fuel economy in India is a burden because of the high consumption of energy per day or year and the high cost to import oil [146,147]. Thus, replacements for imported oil with renewable energy from India could secure energy supply, and with renewable hydrogen, the major effects of the upcoming energy crises can be minimised. India is a more developing country than the other Asian countries, and India's steps towards a renewable

hydrogen economy have a vital role in the globalisation of and search for an international shift in the direction of the renewable hydrogen economy. India has widespread energy potential from renewable energy sources such as solar energy, hydropower [148], wind energy, and good biomass potential. Reports show that India has begun to utilise these resources for a hydrogen economy [149].

India achieved considerable growth in hydrogen aspects such as production, storage, and applications. The biological production of hydrogen from organic wastes can be established on a pilot plant scale from many sources, and on the lab scale, hydrogen can be produced from bagasse waste materials. Prototype hydrogen vehicles, such as motorcycles, fuel cell cars, three wheelers, vans, etc., have been validated in India with hydrogen-based fuel cells. In association with industry partnerships, these applications will soon arrive in many fields. India has good co-ordination among various government agencies, academic departments, research institutions and industries. It is also one of the active countries in the IPHE. Recently, significant progress has been made in the field of binding hydrogen as a fuel [36]. The Indian hydrogen energy programmes of the Ministry of Non-conventional Renewable Energy Sources (MNRE) act as a key support for future alternative fuels and hydrogen. A huge number of major hydrogen energy programmes are on-going in the various Indian institutes [150].

The role of hydrogen in India has been explored more than in any other Asian country because hydrogen has extensive applications, including power production and transportation. In India, many areas now do not have electricity, which can be provided with regionalised power based on hydrogen. Petroleum-based vehicles can be gradually replaced with hydrogen-based fuel cells. Thus, non-polluting hydrogen fuel can ensure the safety of sustainable energy in India [145]. Calculations show that in India, approximately 3 million mega tonnes of hydrogen is produced commercially per year in petroleum refineries or from fertiliser plants and is transported for applications in various industries and plants through pressurised cylinder storage. A planning process in India named INHERM delivers a long term solution to encounter the growing energy needs of India. In addition, INHERM identifies the various paths for the introduction of hydrogen and hastens the commercialisation of hydrogen by the facile creation of hydrogen infrastructure. The technology development of INHERM is based on three steps: the first step is research and development of different aspects of hydrogen, primarily production, storage, transportation/delivery, application, safety, etc.; the second step is the demonstration of products for hydrogen utilisation; and the final step involves the commercialisation of integrated hydrogen systems for applications [145]. The Indian National Hydrogen Energy Road Map has two major routes: one is the Green Initiative for Future Transport (GIFT), which hopes to establish one million hydrogen-fuelled vehicles. The second route, the Green Initiative for Power Generation (GIP), may generate approximately 1000 MW of power with small IC engine, fuel cell power packs, gas turbine-based power plants and central fuel cell power plants [151].

India is the one of the leading countries in the world for the development of renewable energy and has a devoted Ministry of New and Renewable Energy (MNRE) with a huge number of projects [152]. Through the programme named Hydrogen Vision 2020, India plans to make at least 1000 MW of hydrogen power and 1 million hydrogen-based fuel cell vehicles on the road [153]. There are many universities and research institutes in India that have various projects for the development of the hydrogen economy. Some of the institutes and projects along with their research activities on hydrogen is as follows: (1) Hydrogen Energy Centre, Banaras Hindu University, Varanasi, project for hydrogen production, storage and applications; (2) Barath Heavy Electrics Institute, project for alkaline and polymer exchange membrane fuel cells; (3) Indian Institute of Technology (IIT), Delhi, project for static applications of hydrogen; (4) IIT, Madras, Tamil Nadu, project for hydrogen storage as hydrides; (5) SPIC, Madras, project for PEM fuel cells and applications; (6) MCRC, Madras, project for hydrogen production; (7) Jaipur University, project for hydrogen production; (8) Ranchi project in Jharkhand for hydrogen storage in the form of hydrides; (9) ISRO, IISER Thiruvananthapuram, Kerala, project for liquid hydrogen storage; (10) Bakra project in Punjab for liquid hydrogen; (11) II. Sc., Bangalore, project for direct methanol fuel cells; (12) Madurai University, Tamil Nadu, project for biological photo generation of hydrogen; (13) CECRI, Madras, project for molten carbonate fuel cells; (14) BARK, Maharashtra, Mumbai, project for development of an electrolyser; (15) Jabalpur, RDU, project for hydrogen production; (16) IIT, Kharaangpur, project for hydrogen production; and (17) IIT, Guwahati, project for applications of hydrogen. Ruijven et al. [154] reported that the AMM Murugappa Chettiar Research Center, Chennai, had produced hydrogen from sugar waste materials and the generated hydrogen gas can be utilised for cooking. Banaras Hindu University in Varanasi has developed fuel cell vehicles in which the hydrogen was stored in metal hydride tanks [155].

India had spent 58 million dollar to endow hydrogen and fuel cell projects in various institutes over a period of 3 years. Additionally, India plans to present 1000 hydrogen-powered fuel cell vehicles by the end of this era. Car manufacturers are estimated to provide 116 million dollars for the development of fuel-cell vehicles in subsequent years [136]. According to Ruijven et al. [154], hydrogen will not have any significant role in India without substantial drops in the cost of the fuel cell technology and an energy assessment programme is necessary for the saturation of hydrogen.

5.5. Malaysia

Malaysia is the one of the Asian countries with vast renewable and non-renewable sources of energy. Malaysia is now looking for an enhanced renewable hydrogen economy. The country has oil and gas resources, and some oil resources are utilised in the production of bio-fuels, which are another form of renewable energy such as hydrogen [119]. Malaysia spends considerable money on the development of a renewable hydrogen economy. Because hydrogen and fuel cells are the fundamentals of a renewable hydrogen economy, The Ministry of Science, Technology and Innovation in Malaysia spent 2 million dollars for hydrogen production and storage from 2002 to 2007 and spent 9.7 million dollar for fuel cell research from 1996 to 2007. Iyuke et al. [156] reviewed the different hydrogen production technologies in Malaysia; these technologies are divided into two categories: one from renewable resources and the other from non-renewable resources. Hydrogen production from non-renewable sources mainly includes the steam methane reforming method and production from renewable sources mainly focussed on the biomass resources in Malaysia. The employed technologies are gasification, pyrolysis, fermentation, biological WGS reaction and so on [157]. Yong et al. [157] reviewed the potential use of palm oil biomass as a source in the gasification reaction for the production of hydrogen. Other methods are water electrolysis with the electricity produced by solar and wind resources. Currently, the steam methane reforming (SMR) process is the key development in the production of industrial grade hydrogen in Malaysia. The Malaysian hydrogen economy still is governed by fossil fuels, such as natural gas. A large number of studies on the progress of hydrogen production in Malaysia are on-going. Iyuke et al., Shafie et al., Koh and Hoi, Mekhilef et al., and Mohammed et al. [156,158–161] suggested that biomass is a promising substitute for fossil fuel in accordance with price and eco-friendly issues, in the

current situation in Malaysia. Biomass gasification and dark fermentation techniques for hydrogen production from palm oil waste need additional development.

Some universities in Malaysia, especially Universiti Kebangsaan Malaysia (UKM) and the Universiti Teknologi Malaysia (UTM), primarily address developments in hydrogen energy fuel cells and different storage systems. UKM has a large number of facilities for research programs on hydrogen and fuel cells and these facilities mainly focus on the renewable hydrogen economy. Malaysia's Eco-House is another good example of the activity in Malaysia for the hydrogen economy; the Eco-House focuses on solar-hydrogen technology and is located at the UKM, Malaysia. The Eco-house is generally based on the photovoltaic electricity production and storage with a hydrogen generator and a fuel cell, which stores and regenerates electricity for residential applications [162]. The commencement of a renewable hydrogen economy has already begun at the Fuel Cell Institute at UKM and University Malaysia Terengganu (UMT). These universities are involved in hydrogen production through the autothermal catalytic reforming of methane and methanol and hydrogen storage in nanostructured carbon, and intensive studies have been performed for fuel cell development [163–181]. In association with the Institute Hydrogen Economy, UTM has a considerable role in the research and development of hydrogen and fuel cells. The institute mainly focuses on hydrogen production, purification, storage, applications, demonstrations and other topics related to the development of hydrogen economy. In collaboration with the UTM, the Institute Hydrogen Economy teaches some courses in the educational programme that focus on the operation, safety, and development of materials. Table 1 represents the potential hydrogen production methods in some Asian countries along with the available resources.

6. Regional progress in Asian countries

Based on the economic nature and available resources, most of the Asian countries have its own R&D provisions for hydrogen fuel-based mobile and stationary applications. In addition, some other public–private enterprises have also encouraged progress in hydrogen stations [46]. Table 2 depicts an outline for the different national programs which fastens the route to a renewable hydrogen economy in Asian countries. Some other countries in Asia, such as the Philippines, Pakistan, Indonesia and Singapore have good resources and were found to have poorly advanced policy incentives appropriate for a renewable hydrogen economy. All organised design and potential must reflect the local and economic policies; hence, the effective implementation of the hydrogen economy can be achieved with the aid of a multi-plan and not with a single plan. In Pakistan, there is an effective project for the renewable hydrogen economy named the Solar Hydrogen Production Pilot Project, which intends to deliver the elementary facilities for life to isolated seaside communities. The project produces hydrogen through water splitting with electricity from photovoltaic panels, and the produced hydrogen can be utilised as cooking fuel. This project is generally based on the feasibility of solar-hydrogen for distant areas of the country [182].

Singapore is now advanced in using hydrogen to transport energy in transportation applications. Singapore is optimistic for a cleaner pathway for power generation, and other Asian countries, such as Malaysia and Indonesia, assist the country by providing natural gas because natural gas is a cleaner pathway to hydrogen and power production with reduced air pollution. Additionally, Singapore aimed at a clean future through fuel cells. There are some companies and enterprises, such as Daimler Chrysler and BP, involved in the commercialisation of the hydrogen economy in Singapore. The Synergy program in Singapore mainly focused on the development of clean energy projects for stationary and transportation applications. As described in the Clean Energy Country Report, in Singapore, more than 80% of electricity was produced from methane, and the remaining portion is generated from fuel oils. Because of the pollution issues associated with the mentioned fuels, hydrogen-based technologies must be acceptable in a considered pathway. These issues cause Singapore to concentrate more on research and development for a clean energy technology. Pulau Semakau and Pulau Ubin in Singapore can be considered to be clean energy sites by the National Environment Agency and the Energy Market Authority, respectively, because the energy demand of both sites is primarily met with hydrogen. Singaporean agencies, such as the Agency for Science, Technology and Research, spend 38.5 million dollars for the development of sustainable energy. Fuel cell power options are accessible in Singapore, but because of the cost and technological issues, the applicability of fuel cell power options are limited. Currently, a group in Singapore is working to develop direct methane solid oxide fuel cells for power generation.

Thailand is another Asian country that must be considered in the hydrogen economy. Thailand is gifted with a wide distribution of renewable energy sources, which are primarily biomass, solar, and hydro energy, and all of which can be successfully utilised for hydrogen production and hence applications [183]. The biomass resources of Thailand are primarily derived from the wastes of the rice, palm oil, sugar and wood-related industries. Calculations show the delivery of 60 million tons of biomass residue per year in this country. Methane-rich biogas can be produced directly from this biomass feedstock, can be utilised for the production of hydrogen and can be applied in fuel cells. Russia has some projects for the improvement of hydrogen economy, which mainly focus on the production and storage of hydrogen and fuel cells for the transportation applications. As per the report by Alexander et al. [184], for the research and development of hydrogen and fuel cells, Russia had financed about 40 million dollars in implementing hydrogen as a fuel. They have developed some microreactors for the hydrogen production via the processes like catalytic steam reforming of methanol, catalytic methane partial oxidations, steam reforming of the natural gas, etc. In addition, Russian Academy of Sciences (RAS) and Chemical Automatics Design Bureau has

Table1
Potential hydrogen production methods and prominent resources in some Asian countries [36,46,120,135,156].

Country	Hydrogen production methods and resources
Japan	Natural gas reforming and water electrolysis are the short-term plans and electro-chemical water photolysis is the long term plan. Biomass is the prominent renewable resource for hydrogen.
China	Methanol reformation is the feasible H_2 production route. Residential sources as considered to be the renewable sources of H_2.
India	Biological production of H_2 from biomass especially from organic waste materials (bagasse waste materials) by gasification and fermentation routes.
Malaysia	Steam reformation of methane is the current method for hydrogen production. Biomass is the main resource especially the palm oil mill effluent biomass (POME).
Korea	95% hydrogen is produced from the fossil fuels especially from the natural gas. The remaining 5% is from water electrolysis.

Table 2
Programs available in some prominent Asian countries for Hydrogen Infrastructure Development.

Country	Programs	Objective/specification	References
Japan	1. Hydrogen Energy Systems Society of Japan (HESS) 2. Moonlight project 3. Ministry of the Economy, Trade, and Industry of Japan (METI) 4. Interministry Official Task Force for Ministries and Agencies 5. Japanese World Energy network 6. New energy& Industrial Techno- logy Development Organization (NEDO) 7. The Japan Hydrogen and Fuel cell Demonstration project	1. For transport applications 2. R&D and commercialisation of fuel cells 3. R&D and commercialisation of fuel cells 4. Practical applications of fuel cells 5. Fuel cells for transport applications 6. Development for the hydrogen and fuel cell technologies 7. Development of hydrogen fuelling stations	[122,123,125,127]
Korea	1. Ministry of Science and Techno-logy (MOST) 2. Ministry of Commerce, Industry, and Energy (MOCIE) 3. High Efficient Hydrogen Production program, Alternative Energy Technologies development Program, 21st Frontier hydrogen Energy R&D center program 4. Korean Hydrogen and New Energy Society	1. Development of long term plans of the hydrogen research 2. Development of short term plans in hydrogen research 3. All of these are intend for development of hydrogen based fuel cell technologies 4. Promotion of the hydrogen energy technologies	[130,131]
China	1. National basic research program (NBCP) 2. The National high technology Development Program (NHTDP) 3. The National Development and Reform Commission (NDRC) 4. Global Environmental Policy 5. Chinese Ministry of Science and Technology (CMST) 6. The china Association for the hydrogen Energy 7. MOST 973 program	1. Industrial scale production, storage and transportation of Hydrogen 2. Development of Fuel cells for motor applications 3. Sustainable and pollution free production of hydrogen 4. Demonstration of fuel cell buses 5. Development of hydrogen based fuel cell automobiles 6. Promotion of fuel cell applications 7. Development of hydrogen storage materials	[120,121,138,142,144]
India	1. The Indian national Hydrogen energy Road map (INHERM) 2. Green Initiative and Future Transport (GIFT) 3. Green initiative for Power Generation (GIP) 4. Hydrogen vision 2020	1. Speed up the commercialisation of hydrogen (development of Hydrogen infrastructure) 2. Development of Hydrogen fuelled vehicles 3. Development of fuel cell power stacks 4. Hydrogen based fuel cell vehicles	[145,151,153]

designed a microwave system for the H2 production and they had made considerable developments in the field of different fuel cells in collaboration with the Joint Institute for High Temperatures. LADA Antel-2 Hydrogen-Air AFC (60 kW) AC motor and the ZIL-5301-HYBRID combined hydrogen power drive are the other prominent examples showing the utilisation of hydrogen and fuel cells for the renewable energy in Russia. The Institute of Physics and Power Engineering and Institute of Structural Macrokinetics under Russian Academy of Sciences are mainly focused on the R&D and commercialisation of hydrogen and fuel cells for the renewable hydrogen economy [184].

7. Challenges – renewable hydrogen economy in Asian countries

Asian countries face the following common challenges in the development of a renewable hydrogen economy. Marketing challenges for the renewable hydrogen economy include the costs of production of the fuel cells, fuel cell performance and government plans for the effective utilisation of hydrogen. Technological challenges mainly include hydrogen storage technology, fuel cell systems and development of fuel production systems. Additionally, infra-structure expansion must be considerably developed for enhanced hydrogen production. Safety management is the other important challenge for the development of the hydrogen fuel economy. The largest questionable challenge for the renewable hydrogen economy is the development of new delivery networks because of appropriate hydrogen infrastructure is non-existent [185]. Many industrial scale hydrogen production methods are now available for many Asian countries, but all of these production methods are highly luxurious compared to the predictable fossil fuel-based forms of energy. The storage and transportation of hydrogen for industrial scale applications are more expensive because of the low volumetric energy density of the hydrogen fuel. The technical challenges associated with the hydrogen economy in Asian countries mainly focus on the durability and dependability of fuel cells. Currently, fuel cells operate at high temperatures, so the probability of a breakdown for a fuel cell within a short period is much higher than it is for the conventional equipment. However, this is a minor problem because many studies and technological developments are ongoing to overcome the barrier and to ensure the technology is applicable for future users.

Many reports show that China and Korea have some common challenges that must be overcome for a renewable hydrogen energy economy. One of the main challenges is the deficiency of advanced technologies in the field of hydrogen because of the achievement of a renewable hydrogen economy and the requirement for more technical support. Therefore, significant improvements in hydrogen research are necessary for a proper hydrogen economy. The research must be focussed on the production, storage, and appropriate use of hydrogen for green and facile applications. The second most important challenge faced by these Asian countries is the lack of policy support. For the development of a hydrogen economy, governmental incentives for an integrated hydrogen energy policy are important. Effective commercial models for hydrogen energy applications are also important to show

the long-term sustainability of a hydrogen economy. In Shanghai, reports show that the number of hydrogen and fuel cell establishments is actually decreasing because of declining funding [46]. Participants in other meetings noted that, where there is potential, existing infrastructures and networks should be leveraged. Lack of human resources is another important challenge faced by China and Korea and should be overcome. It would be promising for the hydrogen economy in these countries if China and Korea built a joint progress sector to overwhelm these common challenges.

Although India has achieved many aspects of the renewable hydrogen economy, it is also facing some challenges. As in other countries, the cost of hydrogen is the main challenge. India must considerably reduce the cost of hydrogen and must increase the rate of production of hydrogen from renewable sources through different types of favourable methods. Another important challenge is storage of hydrogen, and India must develop a suitable, compact, inexpensive storage system with high capacity and develop high pressure cylinders for storage. If we consider the future of the hydrogen economy in India, the hydrogen pipeline network system must be established in a reliable manner. For the efficient utilisation of hydrogen fuel, improvements in the fuel cells are necessary to achieve higher efficiency and better fuel cell stacks must be developed for transportation applications in vehicles. The development of hydrogen-fuelled IC engines with long lifetimes is a major challenge that must be overcome. All other Asian countries have the same challenges as India, China and Korea.

Regardless of the various types of challenges mentioned earlier, many governments, heads of industry, individuals and so on, take a strong role in the realisation of the hydrogen economy. Financing progress in the hydrogen economy delivers insurance against an unreliable energy future. For the shift to the hydrogen economy, vital government action is needed in the research, development and demonstration of hydrogen technologies and also in the incentives to improve the assets of the hydrogen infrastructure and to commercialise the fuel technologies [186].

The hydrogen economy must move quickly through incremental developments, and it significantly promotes the energy security and delivery based on the zero emission concepts. Hydrogen essentially replaces fossil fuels through its production from renewable resources, and it has the potential for a sustainable energy future. As a clean energy carrier, hydrogen is produced from primary resources and will resolve all of the problems of conventional fuels, such as energy security, pollution and environmental changes, and it has the potential to reduce climate change; thus, it is hoped a renewable hydrogen economy will be developed very soon. The frame of the hydrogen research schedule differs for each country, with communication and with cooperation. The major challenge or hurdle associated with the hydrogen economy is the cost. Bringing hydrogen and fuel cells to a high level of impact is the most rewarding challenge for the scientific fields. The ultimate alteration to a hydrogen economy will be greatly reliant on the solution of technical challenges, reduction of costs, confirmation of safety, and attainment of public acceptance. Thus, we must overcome industrial and cost challenges associated with the hydrogen infrastructure to make the hydrogen economy a reality. Compared to the cost of energy generation by normal methods, the cost of hydrogen energy is very high, and some technical problems must be fixed. To realise a renewable hydrogen economy, more developments are necessary in the fields of fuel cells and the production, storage and delivery or transportation of hydrogen, and government incentive are necessary to initiate the growth in technology. In addition to innovation in inexpensive hydrogen production, the hydrogen infrastructure must be developed. Additionally, minor public acceptability concerns must be overcome about the safety issues and the financial security for the implementation of renewable hydrogen energy. The development of a hydrogen economy will overcome many challenges and open new prospects. Various hydrogen foundational technologies must be established, and agreeable and knowledgeable depositors are required to endow these technologies.

8. Conclusion

Hydrogen is an attractive energy carrier due to its unique benefits to the environmental protection and also for the preservation of worldwide energy. The zero emission concept forms the basis of a renewable hydrogen economy for future. Energy efficient hydrogen based fuel cells have the potential to revolutionise a clear alternative to the fossil fuels. For the realisation of renewable hydrogen economy in Asian countries, some schemes are available targeting the research, development and commercialisation of hydrogen over the fossil fuel based techniques. IEA and IPHE are the prominent hydrogen economy international policies, which are pointed to the implementation of hydrogen and fuel cell technologies for the economically worthy renewable hydrogen. For the successful transition to the renewable hydrogen economy, step by step increment in the development of hydrogen infrastructure must be considered in a suitable manner, especially in the hydrogen production, storage, delivery and its end use. Production of hydrogen from the biomass resources such as from waste materials of palm oil, rice, sugarcane and wood industries by the processes like thermochemical pyrolysis, gasification or biological dark fermentation have the potential to provide substantial production of hydrogen. Even though each of the Asian countries have their own hydrogen resources, proper financial status and governmental policies play a role in the economic viability of the renewable hydrogen. Moon light project, METI, NEDO, JHFC and HESS of Japan, MOST, MOCIE and KIER of Korea, NBCP, NHTDP, NDRC, CMST and MOST 93 PROGRAM of China stimulates the route to a renewable hydrogen economy. MNRE, MNES and INHERM of India oriented for the development of hydrogen infrastructure and its commercialisation. Solar hydrogen production pilot project in Pakistan enhances the applicability of hydrogen in isolated seaside communities. Marketing and technical challenges with the cost of hydrogen infrastructure and the lack of governmental policies must be overcome to achieve the hydrogen economy. In short, the shift from fossil fuel based economy to the renewable hydrogen economy required governmental action for the proper demonstration and implementation of hydrogen technologies.

Acknowledgements

This project is financed by Universiti Kebangsaan Malaysia under grant DIP-2012-04 and INDUSTRI-2012-040. The authors would like to thank the university administration for the financial support.

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