HYDROGEN PRODUCTION, STORAGE, TRANSPORTATION, ITS ECONOMY AND FUEL CELL : A REVIEW

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ABSTRACT

Hydrogen is a soaring quality energy carrier that could be created at global scale, via thermochemical processing of hydrocarbons, such as natural gas, coal or biomass, or water electrolysis using any source of electricity including renewables, such as wind or solar, or nuclear power. Due to air pollution, energy deficiency and climate change, the exploration of cleaner alternative transportation fuel is of vital importance. Hydrogen which has been accepted as a clean energy has the ability to overcome the future energy and environmental troubles, and many projects about hydrogen fuel cell vehicles have been launched in different regions. Hydrogen can be renewed to electricity and heat in fuel cells at high efficiency with zero end-use emissions. In this paper we review the hydrogen production techniques, about fuel cell technology, different types of fuel cells like **MCFCs**, **SOFCs**, **PEMFCs**, hydrogen economy, hydrogen storage and transportation & its use in fuel cell vehicles.

KEY WORDS:- Thermochemical Processing, Renewable, MCFCs, SOFCs, PEMFCs, Fuel cell car, Hydrogen

INTRODUCTION

Due to air pollution, energy scarcity and climate change, the discovery of cleaner alternative transportation fuel is of vital importance. Hydrogen which has been accepted as a clean energy has the ability to rise above the future energy and environmental troubles, and many projects about hydrogen fuel cell vehicles have been launched in different regions. Hydrogen fuel cell vehicles have the likely to be the most energy-efficient vehicles and to decrease polluting emissions and other harmful emissions on a well-to-wheel basis. The hydrogen energy systems for fuel cell vehicles consist of four subsystems in the whole life cycle, namely, hydrogen production subsystem, transportation subsystem, hydrogen refueling station subsystem, and final utilization subsystem . Also, a variety of types of technologies can be used in every subsystem, for instance, there are a variety of materials such as water, methane, and coal to produce hydrogen. There is also a variety of types of hydrogen storage technology including cryo-compressed hydrogen, high-pressure cod gas storage, and metal-organic hydrides. The use of hydrogen in fuel cell vehicles can lead to economically compassionate transportation, but some emissions are related with the different technologies for hydrogen production . Also the effects of different technologies for hydrogen production on environment are different. Similarly, different types of transportation, storage, and consumption of hydrogen in the vehicles will also cause different effects on environmental, economic, and energy aspects. Therefore, the amalgamation of different technologies in hydrogen production subsystem, transportation subsystem, hydrogen refueling station subsystem, and final utilization subsystem will generate different hydrogen energy systems for fuel cell vehicles, and the environmental, economic, and energy performances are also different [4].

Why Hydrogen?

Hydrogen is the perfect fuel because: [8]

✔ it can be produced from a range of energy resources
✔ it satisfies all energy needs—from transportation to electric power generation
✔ it is the least polluting since its use produces water
✔ it is the perfect carrier for solar energy in that it affords solar energy a storage medium.

Likewise, hydrogen is the ultimate partner for electricity, and together they create an incorporated energy system based on distributed power generation and use. Hydrogen and electricity are interchangeable using a fuel cell (to convert hydrogen to electricity) or an electrolyzer (for converting electricity to hydrogen). A regenerative fuel cell works either way, converting hydrogen to electricity and vice versa. Hydrogen and electricity are both energy carriers because, unlike naturally occurring hydrocarbon fuels, they must both be produced using a primary energy source. The primary energy sources available for hydrogen and electricity production are fossil fuels and solar and nuclear power. Solar energy encompasses all renewable resources, including geothermal, wind, biomass, and urban waste. As far as the future transportation is concerned, timing plays a major role in determining which resource and technology is the most feasible for production of hydrogen as automotive fuel. Thus, the question of where the hydrogen is going to come from in the near and long-term future has to be addressed first.

Hydrogen Production

Although hydrogen is the universe's most plentiful element, it is present in the atmosphere only in concentrations of less than one part per million. Most of the Earth's hydrogen is bound up in chemical compounds. Hydrogen for large-scale use should therefore be extracted from a resource such as water, coal, natural gas, or plant matter. It cannot simply be produced from a mine or a well. Since considerable energy is consumed in the extraction process, hydrogen should properly be considered an energy carrier rather than an energy source; the energy released when it is finally used is just the energy that was invested in its original manufacture (minus any losses). A variety of alternative hydrogen energy production technologies is available in practice, including:

• **Steam reforming:** Steam reforming is a chemical process that makes hydrogen from a mixture of water and a hydrocarbon feedstock, usually a fossil fuel. The most common feedstock is natural gas, consisting primarily of methane. When steam and methane are combined at high pressure and temperature, a chemical reaction converts them into hydrogen and carbon dioxide. The energy content of the hydrogen produced is actually higher than that of the natural gas consumed, but considerable energy is required to operate the reformer, so the net conversion efficiency may typically be only about 65-70%.

• Off-gas cleanup: After steam reforming, the next most common source of hydrogen at present is the cleanup of industrial off-gases. Numerous industries give off high concentrations of hydrogen in their waste streams petroleum refineries, blast furnaces, and some chemical plants, for example. Collecting and purifying these gases is often cost-effective. Most off-gas hydrogen is used on-site by the industry that produces it, so although off-gas cleanup is an important feature of today's market, it seems unlikely that it could be expanded enough to meet the increased demand that would result from widespread use of hydrogen as a fuel.

• Electrolysis: Electrolysis means passing an electrical current through water to split individual water molecules into their constituent hydrogen and oxygen. Energy losses during this process are relatively modest: 65% energy efficiency is common, and state-of-the-art large electrolyzers can be 80 to 85% efficient. Electrolysis has captured considerable attention, even though it accounts for only a small fraction of current hydrogen production, because it is a clean process and water is abundant. At present, however, the technique is only used at relatively small plants, with a cost of 2.40-3.60 $/kg of hydrogen produced. This high cost is expected to limit electrolysis to niche markets in the near and mid term. In the long term, could electrolysis become more competitive? At present, natural gas reforming is more than three times more energy efficient than electrolysis if fossil-source electricity is used.

• Photo process: Photo processes use the energy and other special properties of light (usually sunlight) to produce hydrogen from either water or biomass. There are three broad categories of photo process. Photo biological techniques are based on the photosynthesis cycle used by plants and by some bacteria and algae. The efficiency of photo biological hydrogen production is only 1 to 5%, but researchers hope to increase it to 10% or more. Photochemical processes mimic natural photosynthesis using synthetic molecules. This technique is only about 0.1% efficient now, but it can be improved. Photo electrochemical techniques use layers of semiconductor material separated by water. When exposed to light, the semiconductor layers produce an electrical voltage that splits the water into hydrogen and oxygen. The best prototypes yet demonstrated in the laboratory are about 13% efficient, but the maximum theoretical efficiency is believed to be more than 35%. It has been estimated that efficiency in the field of 10 to 15% may be economical, but such estimates depend strongly on projections of equipment costs. Note that since all these photo processes use light as their primary energy source, their efficiencies should not be used directly in cost comparisons with processes that use hydrocarbon fuels or electricity. Photo processes are a major component of current hydrogen research programs.

• Thermo chemical process: This process uses heat to split water into hydrogen and oxygen. The conceptually simplest version of this technique is direct thermal conversion, i.e. heating water to extreme temperatures, perhaps 3400 K. Because of the high temperatures required, however, direct thermal conversion is yet impractical outside the laboratory. Chemical reactions can be employed to reduce the required temperature. Various alternatives have been studied, often involving complex multistep processes. Hybrid techniques that incorporate electrolysis into one or more of the reaction steps are under investigation. There has been little recent work available on thermo chemical techniques.

• **Radiolysis:** This process is the splitting of water molecules by collisions with high-energy particles produced in a nuclear reactor. Since the hydrogen and oxygen atoms thus produced quickly recombine to produce water again, radiolysis would probably be only about 1% efficient. Most experts agree that radiolysis is less promising than other techniques.

• **Solar hydrogen:** In this original and simplest form of hydrogen energy production, the solar hydrogen scenario envisions producing electricity from sunlight using photovoltaic cells, electrolyzing water to produce hydrogen, and substituting this hydrogen for the oil and other fossil fuels in general use today. The term is now often used more broadly to include electrolysis based on other renewable sources of electricity, such as wind. This idea has received considerable attention largely because of the environmental benefits of using hydrogen instead of fossil fuels. It also addresses two barriers to the ultimate achievement of large-scale use of solar energy: that solar electricity cannot be used directly for non-electric applications, such as combustion engines, and that electricity is difficult and expensive to store.

• **Partial oxidation of hydrocarbons:** Hydrogen may be formed from the no catalytic partial oxidation (i.e., gasification) of hydrocarbons such as residual oil. Any hydrocarbon feedstock that can be compressed or pumped may be used in this technology. However, the overall efficiency of the process is about 50% and pure oxygen is required. Two commercial technologies for this conversion are available: the Texaco gasification process and the Shell gasification process.

There are also some other hydrogen production technologies, such as:

- Thermal decomposition of hydrocarbon fuels
- Thermo catalytic CO_2-free production of hydrogen from hydrocarbon fuels
- Super adiabatic decomposition of hydrogen sulfide
- Auto thermal reforming (combining partial oxidation and steam reforming)
- Sorption Enhanced Reaction Process (SERP)
- Production of hydrogen from biomass-derived liquids
- Photo electrochemical hydrogen production
- Biological H_2 from fuel gases and from H_2O
- Two-phase photo biological algal H_2-production system
- H_2 Production from Glucose-6-Phosphate
- Most of the above listed methods are under heavy investigation for implementation and commercialization. The findings show that there is still much to do for achieving those. [7]

Fuel cells

Fuel cells can produce the highest proportion of electricity of any CHP(Combined Heat and Power) technology. They are a flexible, modular technology that can easily be scaled up from serving individual homes to large office blocks and industrial complexes. While some systems are designed to solely produce electricity, the most common stationary application is CHP, which can provide exceptionally high efficiency - up to 95% in total and reduce dependence on centrally-generated power, potentially saving on electricity costs and carbon emissions. Fuel cells are not the only technology for heating with hydrogen, but they are the most prominent because of their electrical efficiency advantage. Similarly, hydrogen is not the only fuel that can power fuel cells, and most currently produce hydrogen internally by reforming a supplied hydrocarbon fuel. For stationary heat applications, natural gas is most widely used, along with LPG and biogas [3].

Types of fuel cells

PEMFCs Proton-exchange membrane fuel cells, also known as polymer electrolyte membrane (PEM) fuel cells (**PEMFC**), are a type of fuel cell being developed mainly for transport applications, as well as for stationary fuel-cell applications and portable fuel-cell applications. Their distinguishing features include lower temperature/pressure ranges (50 to 100 °C) and a special proton-conducting polymer electrolyte membrane. PEMFCs generate electricity and operate on the opposite principle to PEM electrolysis, which consumes electricity. They are a leading candidate to replace the aging alkaline fuel-cell technology, which was used in the Space Shuttle. PEMFCs are built out of membrane electrode assemblies (MEA) which include the electrodes, electrolyte, catalyst, and gas diffusion layers. An ink of catalyst, carbon, and electrode are sprayed or painted onto the solid electrolyte and carbon paper is hot pressed on either side to protect the inside of the cell and also act as electrodes. The pivotal part of the cell is the triple phase boundary (TPB) where the electrolyte, catalyst, and reactants mix and thus where the cell reactions actually occur [11].

REACTIONS

At the anode:

$H_2 \longrightarrow 2H^+ + 2e^-$

At the cathode:

$\frac{1}{2}O_2 + 2H^+ + 2e^- \longrightarrow H_2O$

SOFCs (solid oxide fuel cells) are high-temperature fuel cells used in both large industrial CHP (100-1000 kW) and residential heating systems (1-3 kW), that have recently grown to reach 10% of global sales. A solid oxide fuel cell (or SOFC) is an electrochemical conversion device that produces electricity directly from oxidizing a fuel. Fuel cells are characterized by their electrolyte material; the SOFC has a solid oxide or ceramic electrolyte.
Advantages of this class of fuel cells include high efficiency, long-term stability, fuel flexibility, low emissions, and relatively low cost. The largest disadvantage is the high operating temperature which results in longer start-up times and mechanical and chemical compatibility issues [12].
SOFC benefit from the highest electrical efficiency and greater fuel-flexibility, but operate less dynamically than PEMFC due to their temperature requirements. In particular, start-up and shut-down are sensitive operations taking 12 h or more. It operates at 500-750^{0}C. This allows a wider range of materials to be used, lowering costs and improving dynamic performance [3].

MCFCs Molten carbonate fuel cells (MCFCs) are currently being developed for natural gas, biogas (produced as a result of anaerobic digestion or biomass gasification), and coal-based power plants for electrical utility, industrial, and military applications. MCFCs are high-temperature fuel cells that use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic matrix of beta-alumina solid electrolyte (BASE). Since they operate at extremely high temperatures of 650 °C (roughly 1,200 °F) and above, non-precious metals can be used as catalysts at the anode and cathode, reducing costs[20].
Improved efficiency is another reason MCFCs offer significant cost reductions over phosphoric acid fuel cells (PAFCs). Molten carbonate fuel cells can reach efficiencies approaching 60%, considerably higher than the 37–42% efficiencies of a phosphoric acid fuel cell plant. When the waste heat is captured and used, overall fuel efficiencies can be as high as 85% [13].

Reactions

Internal Reformer:
$CH_4 + H_2O = 3H_2O + CO$

MCFCs benefit from relatively low capital costs due to non-platinum catalysts and simpler ancillary systems, but suffer from low lifetime and low power density [3].

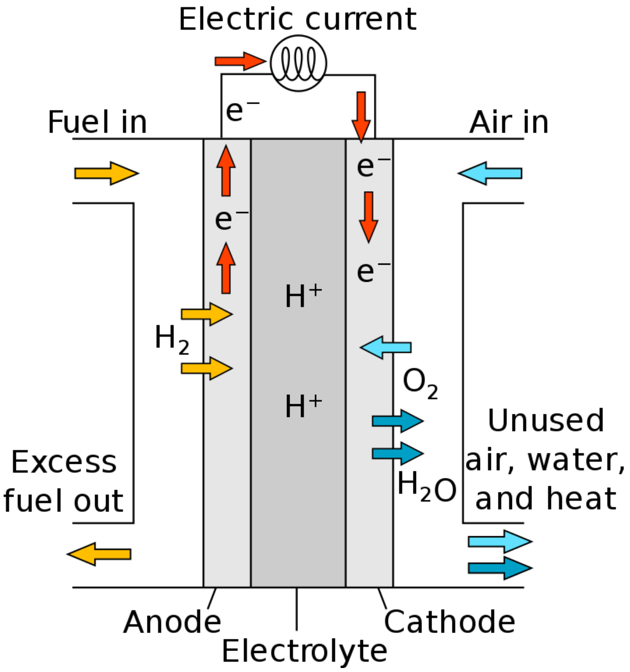


Diagram of a PEM fuel cell

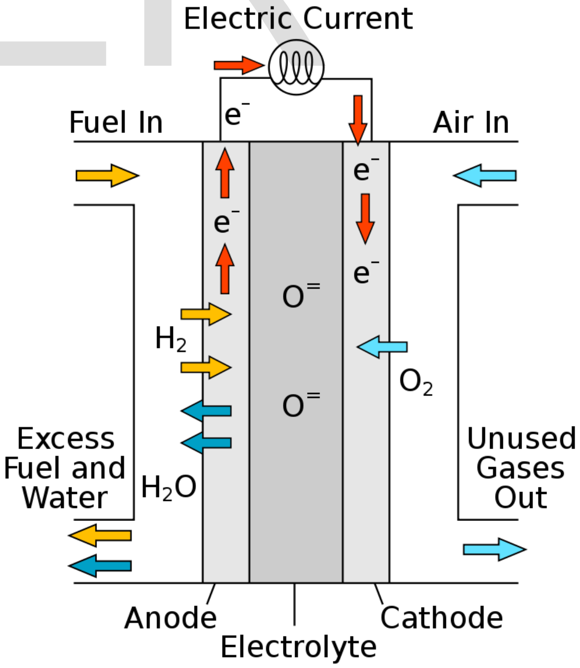


Diagram of SOFCs fuel cell

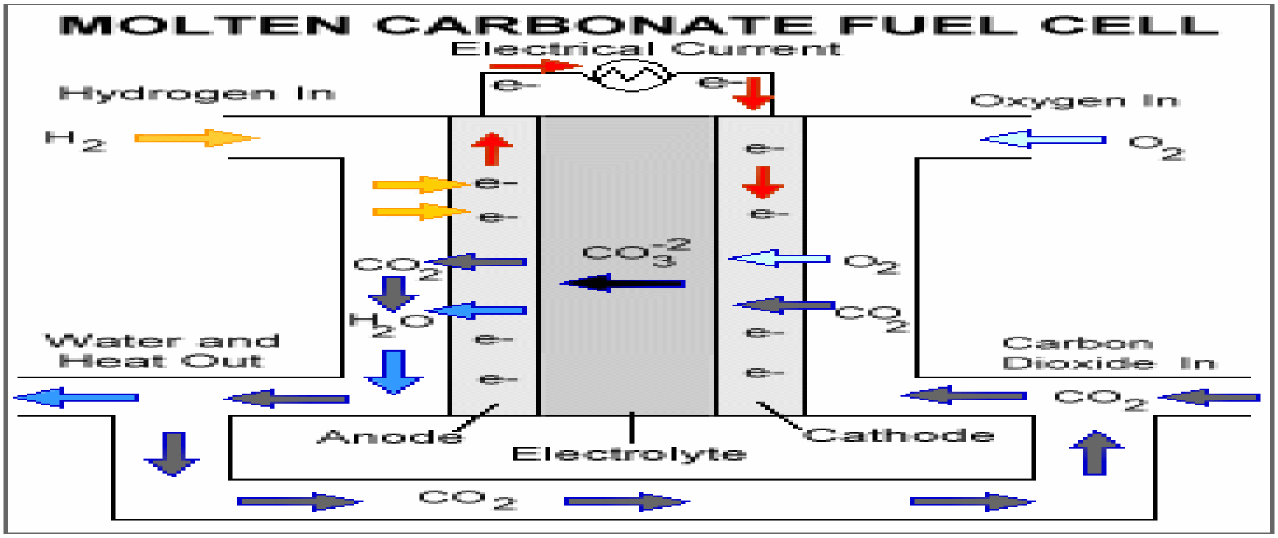
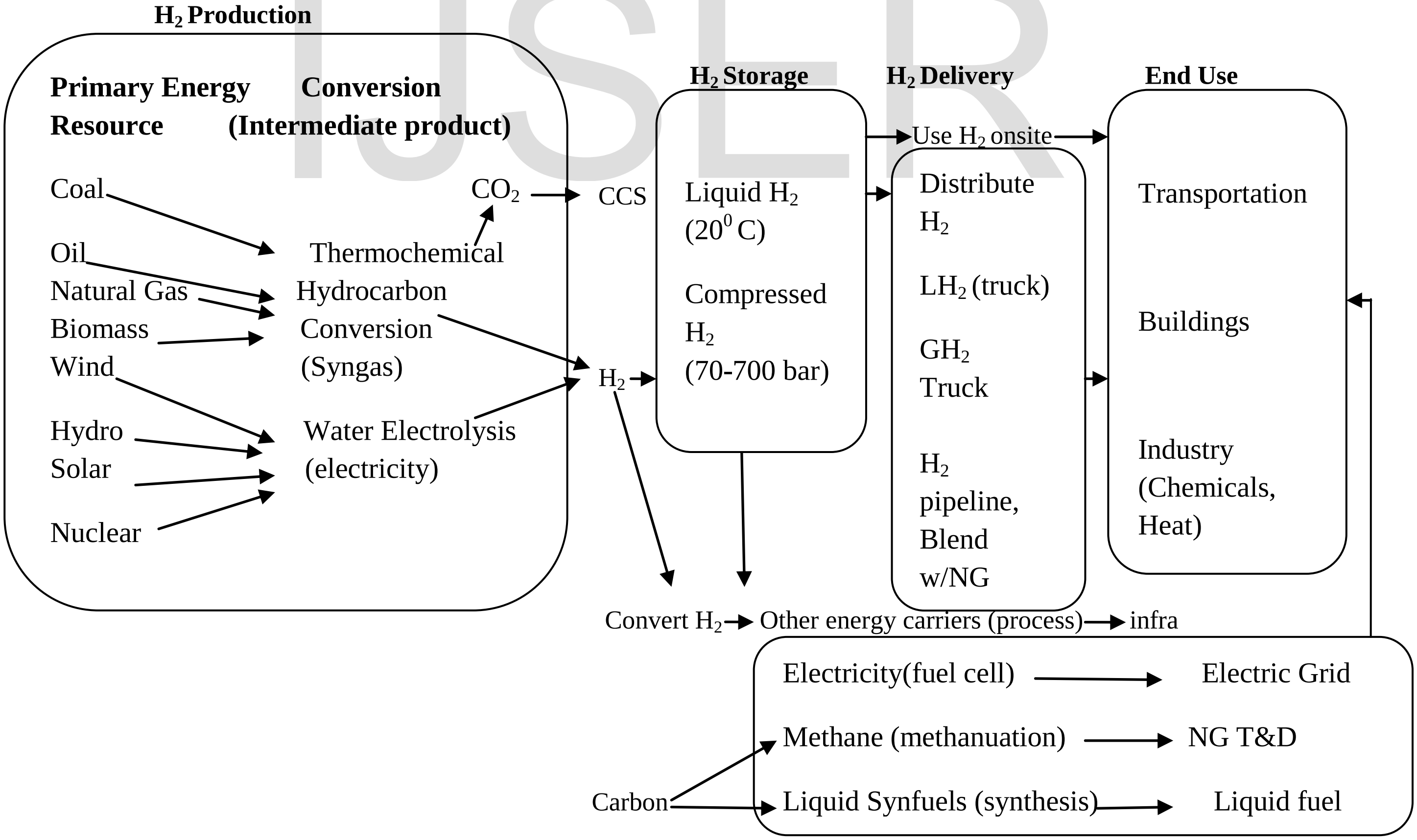
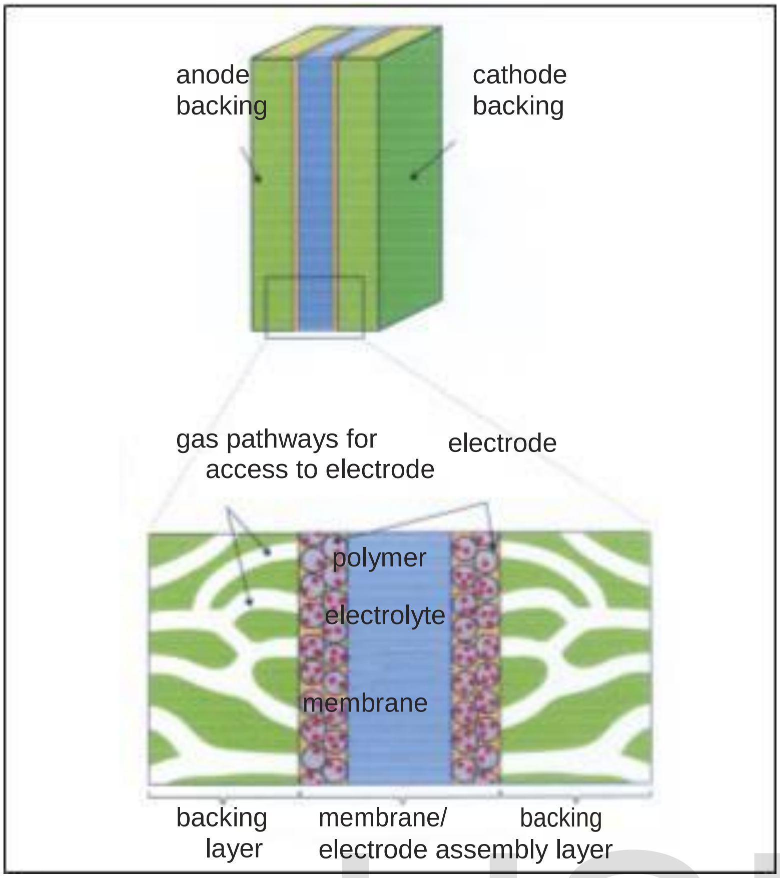
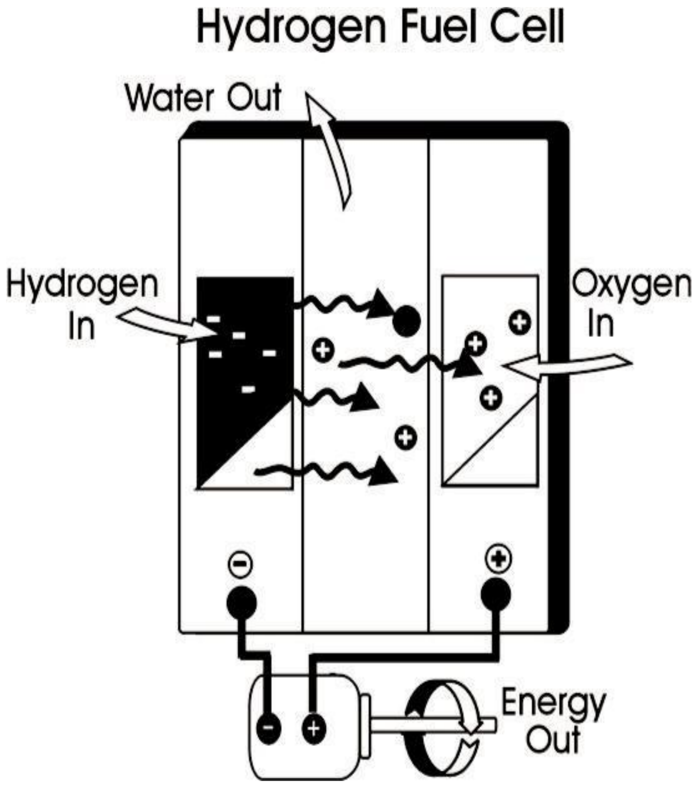


Diagram of a molten-carbonate fuel cell

Pathways for Hydrogen Production, Storage, Delivery and End-use [1]





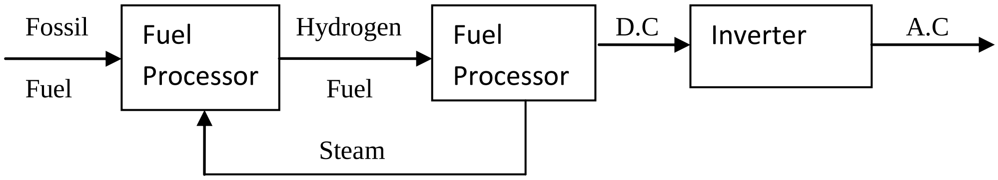


Schematic drawing of the membrane/electrode assembly with backing layers of a PEM hydrogen fuel cell [9]

Image of the hydrogen fuel cell [6]

OPERATION OF FUEL CELL

The following block diagram shows operation of fuel cell [10]:-

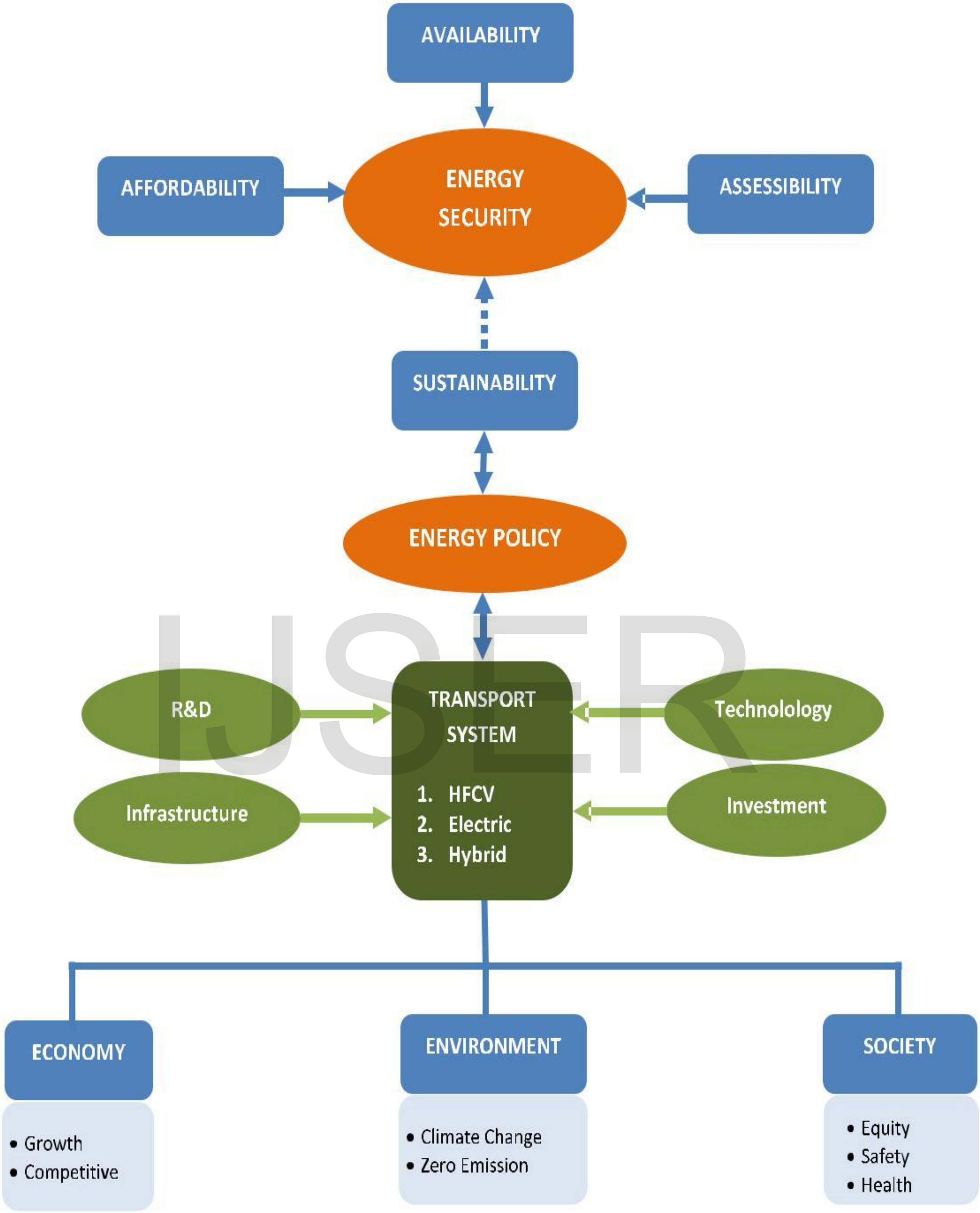


The following reactions takes place in fuel cell [10]:-

Anode: $2H_2 + 4OH_- \longrightarrow 4H_2O - 4e_-$

Cathode: $O_2 + 2H_2O + 4e_- \longrightarrow 4OH_-$

Overall cell reaction: $2H_2 + O_2 \longrightarrow 2H_2O$



Energy policy and sustainable and secure transport system. [2]

	Technology Status	***Capacity***	***Conversion efficiency*** ***H2 out /energy in (HHV)***	***Capital cost***	***Levelized H2 Cost ($/kg H2)***
HYDROGEN PRODUCTION (in MW of H2 output on HHV basis)					
Steam methane reforming (SMR)					
Central production [20]	Commercial	400-700 MW	72%	$380-480/kW	$1.7/kg
SMR w/CCS (central) [20]	CCS Early Market	“	71%	$450-560/kW	$2.1/kg
Distributed production [7]	Early market	0.16-16 MW	51%	$3000-5000/kW	
Coal Gasification (central) [20]	Commercial	160-820 MW	56%	$940-1780/kW	$1.3-1.7/kg
Coal gasification w/CCS [20]	CCS Early market	“	54%	$1200-2200/kW	$1.8-2.4/kg
Biomass gasification (central) [20]	Early market	32-320 MW	48%	$700-1200/kW	$2.1-2.3/kg
Biomass gasification w/CCS [20]	CCS Early market	“	47%	$800-1300/kW	$2.7-2.9/kg
Water Electrolysis					
Alkaline	Commercial	Up to 150 MW[7]	65-82%[7]	$800-1500/kW[7]	$4.1-5.5/kg [20]
Proton exchange membrane	Early market	Up to 1 MW[7]	65-78%[7]	$1500-3800/kW[7]	$4.1-5.5/kg[20]
Solid Oxide	R&D	Laboratory scale[7]	80-90%[7]		$2.8-5.8/kg[20]
HYDROGEN STORAGE AND DELIVERY INFRASTRUCTURE					
H2 BULK STORAGE	Commercial				
Compressed gas (180-340 atm)					
Compressors[20]		-250 kg/h (small) 1-16 MW (large)	Compression Elec input= 5-10% of H2 HHV	$0.15-1.1 million $1.4-8 million	Levelized costs for storage range from $1-10/kg depending on conditions
Above ground pressure vessels		2.5-250 kg [7]		$250-700/kg[207]	
Geologic formations		20-200 million m^3 [20]		$6-30 million[20] $7/kg [7]	
Liquid hydrogen (LH2) (-253 C)[20]					
Liquefiers		25-200 t/d	Liquefaction Elec input =36% of H2 HHV	$50-250 million	
LH2 Storage tanks		500-3500 m^3 (3.5-24.5 t LH2)	<1% loss/day	$2-6 million	
H2 TRANSMISSION AND DISTRIBUTION [20]					
H2 Gas pipelines	Commercial (>1000 mi in use)				
Long distance transmission		10-10000 t/d		$1-2 M/km	$1-10/kg[7] [20]
Local distribution		10 t/d		$0.6-1.2 M/km	
H2 Delivery Trucks Capacity	Commercial				
Gaseous H2		0.5 t/truck		$0.3-0.4 million	
Liquid H2		3 t/truck		$0.7 million	
H2 REFUELING STATIONS[34 35 38 48] (see Table 2 for more details)	Early market intro networks w/ 10s of stations in California, EU, Japan. 100s of stations planned by 2020[35, 51]	0.1-0.35 t/d (now) 0.5-1 t/d (2020)		$1-4 million $1.5-4 million	Dispensed levelized cost of H2 to vehicles ranges from $5-10/kg

Technology Status and Costs for Hydrogen Production, Storage and Distribution Infrastructure [1]

HYDROGEN STORAGE

Hydrogen could serve as flexible energy storage for alternating renewable electricity that might otherwise be shortened, opening the possibility of “greening” both electricity and fuels. Hydrogen’s potential advantage compared to other electricity storage technologies like batteries, compressed air and pumped hydro is its flexibility, enabling concepts like power to gas, seasonal storage as a means of better controlling the grid, and using very low-cost, off-peak power to make hydrogen transport fuel [1]. In the short term, compressed gas storage is the cheapest option; however, the cost of the tank still needs to be reduced. In the long term, hydrogen will be stored using materials such as chemical hydrides, metal hydrides, or sorbents [5].

HYDROGEN TRANSPORTATION

Hydrogen energy supply pathways are categorized as “centralized” production, where hydrogen is produced at large scale and distributed to users through truck or pipeline, and “onsite” or “distributed” production, where hydrogen is produced at the end-use site, typically through small scale electrolysis or steam methane reforming. Hydrogen supply pathways are illustrated in Figure, for hydrogen production from fossil, renewable and nuclear resources with storage and delivery via truck or pipeline. Hydrogen can also be renewed to other energy carriers such as electricity, methane or liquid fuels, which entails conversion costs and efficiency losses, but enables access to existing energy distribution networks, without having to build an extensive hydrogen distribution system. Choosing the best hydrogen supply pathway depends on the scale and location of demand, the relative cost of regional primary resources for hydrogen production, policy (for example, a requirement for renewable hydrogen) and technology developments [1].

HYDROGEN ECONOMY

At first, hydrogen is much more expensive than gasoline, because the first hydrogen stations are small and underutilized. As the hydrogen supply network scales up and matures, we find that the cost of hydrogen decreases. After about 10 years, the fuel cost becomes less expensive for hydrogen than gasoline (on a cent per mile basis). Building an extensive new hydrogen infrastructure is costly, especially during early commercialization when demand is small, market growth is uncertain and technologies are still evolving rapidly. To mitigate risk, early hydrogen fuel supply might “piggyback” on existing energy infrastructures. Hydrogen fuel to consumers at a competitive cost with gasoline on a cent per kilometer basis, estimated to be $10/kg initially, and $5-8/kg for the longer term.

APPLICATIONS

It has wide range of applications such as
Stationary Power
Hydrogen Fuel Cells for Zero Emissions Transportation
Hydrogen as storage for renewable energy (power to gas)

CHALLANGES SCALE.

1) It is more difficult to transform a large market than a smaller system. Further, energy transitions tend to begin at small, local scales that spread to national and eventually global scale.
2) Complexity. The more complex and infrastructure-intensive the system, the slower the transition.
3) End-use innovation is a major driver of energy transitions, and new technologies may be adopted for reasons not emergent from traditional economics.
4) Although a successful transition depends on consumer adoption, it also requires coordination among multiple stakeholders, and institutional and policy support.
5) Risk reduction. Uncertainty about technology and policy can lead to risk averse behavior. Reducing risk to investors is a precondition for success, as demand grows and technology changes .

CONCLUSION

Fuel cell can promote energy diversity and a transition to renewable energy sources. Hydrogen the most abundant element on Earth can be directly used. Fuel cells can also utilize fuel containing hydrogen, including methanol, ethanol, natural gas and even gasoline or diesel fuel. Energy also could be supplied by biomass, wind, solar power or other renewable source. Fuel cell today are running on many different fuels, even gas from landfills and waste water treatment plants. Fuel cells are also ideal candidates for a new trend of power generation called distributed power generation. This paper presented the different hydrogen producing techniques, fuel cell, types of fuel cell, hydrogen storage, hydrogen transportation, hydrogen economy and challenge facing in the development of this techniques. After studying we can say that Hydrogen fuel cell technique is accepted as a clean energy has the ability to rise above the future energy and environmental troubles, and many projects about hydrogen fuel cell vehicles have been launched in different regions.
The following concluding remarks, which will likely be useful to researchers and engineers as well as policy and decision makers, can be drawn from this study:
- Moving towards sustainable development requires that environmental problems be resolved..
- Sustainable development requires a sustainable supply

of energy resources that, in the long term, is sustainable available at reasonable cost and can be utilized for all required tasks without causing negative societal impacts. The use of these sources in hydrogen production will be a key factor in sustainable development.
•. Renewable energy utilization in hydrogen production can provide a potential solution to current environmental problems.

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