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Hydrogen and Fuel Cell Technologies for Sustainable Future

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Abstract

This paper discusses some crucial energetic, environmental and sustainability issues and the role of hydrogen and fuel cell technologies as one of the potential solutions to these issues. The commercialization plans in various industrialized countries (USA, Canada, Japan, etc.) for these technologies have started by identifying the most likely early markets for hydrogen as an energy carrier and fuel cells as power producing devices from micro- to macro-applications, and set realistic near-term and mid-term goals for selected market penetration. The plans outline the major barriers to achieving those goals and recommends activities to capitalize on the incentives and overcome the market barriers. The paper also presents possible future hydrogen energy-utilization patterns for better environment and sustainable development, and shows how the principles of thermodynamics via energy can be beneficially used to evaluate hydrogen and fuel cell systems and their role in sustainability. Throughout the paper, current and future perspectives regarding thermodynamics and sustainable development are considered.

Keywords: Energy; exergy; fuel cell; hydrogen; life cycle assessment; environment; economics; sustainable development;

1. Introduction

Energy is a key element of the interactions between nature and society and is considered a key input for the environment and sustainable development. Environmental and sustainability issues span a continuously growing range of pollutants, hazards, and eco-system degradation factors that affect areas ranging from local through regional to global. Some of these concerns arise from observable, chronic effects on, for instance, human health, while others stem from actual or perceived environmental risks such as possible accidental releases of hazardous materials. Many environmental issues are caused by or related to the production, transformation, and use of energy, for example, acid rain, stratospheric ozone depletion, and global climate change. Recently, a variety of potential solutions to the current environmental problems associated with the harmful pollutant emissions has evolved. Hydrogen energy systems appear to be the one of the most effective solutions and can play a significant role in providing better environment and sustainability [1].

In the literature, there have been limited studies on sustainability aspects of hydrogen energy systems (including fuel cell systems) undertaken by several researchers [2-10]. Of these Afgan and Carvalho [6] give an overview of the potential on multi-criteria assessment of hydrogen systems. With respective selection of the criteria comprising performance, environment, market, and social indicators the assessment procedure is adapted for the assessment of the selected options of the hydrogen energy systems and their comparison with new and renewable energy systems. Hopwood et al. [8] pointed on that sustainable development, although a widely used phrase and idea, has many different meanings and therefore provokes many different responses. In broad terms, the concept of sustainable development is an attempt to combine growing concerns about a range of environmental issues with socio-economic issues. The sustainable development implies smooth transition to more effective technologies from a point view of an environmental impact and energy efficiency. According to Midilli et al. [9-10], increasing concerns about urban air pollution, energy security, and climate change will expedite the transition to “hydrogen economy.” Kwak et al. [7] indicate that new hydrogen powered fuel cell technologies in both its high and low-temperature derivatives are more effective and cleaner than conventional energy technologies, and can be considered one of the pillars of a future sustainable energy system. Barreto et al. [4] examine future perspectives for fuel cells and develop a long-term hydrogen-based scenario of the global energy system. Their scenario illustrates in Figure 1 the key role of hydrogen in a long-term transition towards a clean and sustainable energy future. Hart [2] states that hydrogen from renewable, coupled with fuel cell

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generation on demand, provides an elegant and complementary solution to this problem. Therefore, it is suggested that not only are fuel cells a future economically competitive option for sustainable energy conversion, they are also a complementary option in the sustainable energy system of the future.

The main goal of this paper is to discuss the role of hydrogen and fuel cell systems for sustainable future, and present a case study on the life cycle assessment of fuel cell vehicles from energy, environment, and sustainability points of views. The role of exergy in performance assessment and sustainability achievement is also discussed..

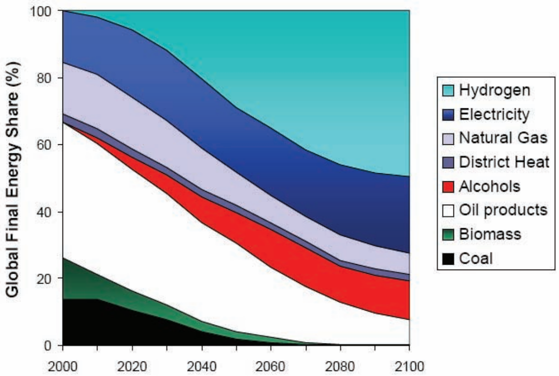


Figure 1. Evolution of global market shares of different final-energy carriers for the period 1990-2100 based on the scenario by Barreto et al. [4]. The alcohols category includes methanol and ethanol.

2. Sustainable Development

Sustainable development requires a sustainable supply of clean and affordable energy resources that do not cause negative societal impacts [5,11-16]. Supplies of such energy resources as fossil fuels and uranium are finite. Energy sources such as sunlight, wind, and falling water are generally considered renewable and therefore sustainable over the relatively long term. Wastes and biomass fuels are also usually viewed as sustainable energy sources. Wastes are convertible to useful energy forms through such technologies as waste-to-energy incineration facilities.

Environmental impact is associated with energy-resource utilization. Ideally, a society seeking sustainable development utilizes only energy resources that release no or minimal emissions to the environment and thus cause no or little environmental impact. However, since all energy resources may somehow lead to some environmental impact, increased efficiency can somewhat alleviate the concerns regarding environmental emissions and their negative impacts. For the same services or products, less resource utilization and pollution is normally associated with increased efficiency.

Sustainability often leads local and national authorities to incorporate environmental considerations into energy planning. The need to satisfy basic human needs and aspirations, combined with increasing world population, will make the need for successful implementation of sustainable development increasingly apparent. Various hydrogen energy-related criteria that are essential to achieving sustainable development in a society follow:

- information about and public awareness of the benefits of sustainability investments,
- environmental and sustainability education and training,
- appropriate energy and exergy strategies for better efficiency,
- promoting environmentally benign technologies,
- clean hydrogen production technologies,
- development of sustainable hydrogen economy infrastructure,
- commercially viable and reliable hydrogen energy systems, including fuel cells,
- availability and utilization of renewable energy resources,
- use of cleaner technologies for production, transportation, distribution, storage and use,
- a reasonable supply of financing and incentives,
- academia-industry-government partnership programs,
- policy development for sustainable energy programs,
- appropriate monitoring and evaluation tools, and
- road maps for future implementation.

Environmental concerns are significantly linked to sustainable development. Activities that continually degrade the environment are not sustainable. For example, the cumulative impact on the environment of such activities often leads over time to a variety of health, ecological and other problems.

Clearly, a strong relation exists between efficiency and environmental impact since, for the same services or products, less resource utilization and pollution is normally associated with increased efficiency. Note that improved energy efficiency leads to reduced energy losses. Most efficiency improvements produce direct environmental benefits in two ways: (I) Operating energy input requirements are reduced per unit output, and pollutants generated are correspondingly reduced. (ii) Consideration of the entire life cycle for energy resources and technologies suggests that improved efficiency reduces environmental impact during most stages of the life cycle. That is why assessing the future hydrogen technologies such as fuel cells over their entire life cycle is essential to obtain correct information on energy consumption and emissions during various life cycle stages, to determine competitive advantages over conventional technologies, and to develop future scenarios for better sustainability.

In recent years, the increased acknowledgment of humankind's interdependence with the environment has been embraced in the concept of sustainable development. With energy constituting a necessity for maintaining and improving standards of living throughout the world, the widespread use of fossil fuels may have affected the planet in ways far more significant than first thought. In addition to the manageable impacts of mining and drilling for fossil fuels and discharging wastes from processing and refining operations, the "greenhouse" gases created by burning these fuels is regarded as a major contributor to a global warming threat. Global warming and large-scale climate change have implications for food chain disruption, flooding and severe weather events, e.g., hurricanes.

It is obvious that utilization of hydrogen and fuel cell technologies can help reduce environmental damage and achieve sustainability. Such technologies essentially do not consume fuel, contribute to global warming, or generate substantial waste as long as hydrogen is produced through clean and renewable energy resources. In this respect, hydrogen and fuel cell technologies can provide more efficient, effective, environmentally benign and sustainable alternatives to conventional energy technologies, particularly fossil-fuel driven ones.

Hydrogen and fuel cell technologies have a crucial role to play in meeting future energy needs in both rural and urban areas. The development and utilization of such technologies should be given a high priority, especially in the light of increased awareness of the adverse environmental impacts and political consequences of fossil-based generation. The need for sustainable energy development is increasing rapidly in the world. In fact, widespread use of these technologies is important for achieving sustainability in the energy sectors in both developing and industrialized countries. These technologies are a key component of sustainable development for four main reasons:

- They have numerous advantages, such as energy efficient and compatible with renewable energy sources and carriers for future energy security, economic growth and sustainable development.
- They generally cause much less environmental impact than other conventional energy sources and technologies. The variety of hydrogen and fuel cell technologies provides a flexible array of options for their use in various applications.
- Hydrogen cannot be depleted because the basic source is water. If used carefully in appropriate applications, it can provide a fully reliable and sustainable supply of energy almost indefinitely. In contrast, fossil fuel and uranium resources are diminished by extraction and consumption.
- These technologies favor system decentralization and local and individual solutions that are somewhat independent of the national network, thus enhancing the flexibility of the system and providing economic and environmental benefits to small isolated populations. In addition, the small scale of the equipment often reduces the time required from initial design to operation, providing greater adaptability in responding to unpredictable growth and/or changes in energy demand.

It is important to note that if we produce hydrogen through conventional technologies using fossil fuels, this will not make hydrogen inherently clean in that they may cause some burden on the environment in terms of pollutant emissions, solid wastes, resource extraction, or other environmental disruptions. Nevertheless, the overall use of these technologies almost certainly can provide a cleaner and more sustainable energy system than increased controls on conventional energy systems. This is in fact clearly shown in the case studies.

To overcome obstacles in initial implementation, programs should be designed to stimulate a hydrogen energy market so that options can be exploited by industries as soon as they become cost-effective. Financial incentives should be provided to reduce up-front investment commitments and infrastructure costs for production, transportation, distribution, storage, and use, and to encourage design innovation, as well as research and development activities along with commercialization practices.

3. Sustainable Development And Thermodynamic Principles

As mentioned earlier, energy is a key element of the interactions between nature and society and is considered a key input for economic development and sustainable development. Energy use is very much governed by thermodynamic principles and, therefore, an understanding of thermodynamic aspects of energy can help us understand pathways to sustainable development [15]. The impact of energy resource utilization on the environment and the achievement of increased resource-utilization efficiency are best addressed by considering exergy. The exergy of an energy form or a substance is a measure of its usefulness or quality or potential to cause change and provide the basis for an effective measure of the potential of a substance or energy form to affect the environment. It is important to mention that in practice a thorough understanding of exergy and the insights it can provide into the efficiency, environmental impact and sustainability of energy systems, are required for the engineer or scientist working in the area of energy systems and the environment. During the past decade, the need to understand the linkages between exergy and energy, and environmental impact has become increasingly significant [17-18]. In one of the recent works, Dincer and Rosen [19] considered exergy as the confluence of energy, environment, and sustainable development and illustrated this in a triangle in Figure 2a. The basis for this treatment is the interdisciplinary character of exergy and its relation to each of these disciplines.

When we look at the general energy efficiency (η) and exergy efficiency (ψ) definitions as follows:

$$\eta = \frac{Energy\ in\ product\ outputs}{Energy\ in\ inputs} = 1 - \frac{Energy\ loss}{Energy\ in\ inputs}$$

and

$$\psi = \frac{Exergy\ in\ product\ outputs}{Exergy\ in\ inputs} = 1 - \frac{Exergy\ loss + Exergy\ consumption}{Exergy\ in\ inputs}$$

It is obvious that reducing losses will increase the efficiency. The relation between exergy efficiency, sustainability, and environmental impact is illustrated in Figure 2b. There, sustainability is seen to increase and environmental impact to decrease as the exergy efficiency of a process increases. The two limiting efficiency cases in Figure 2b appear to be significant:

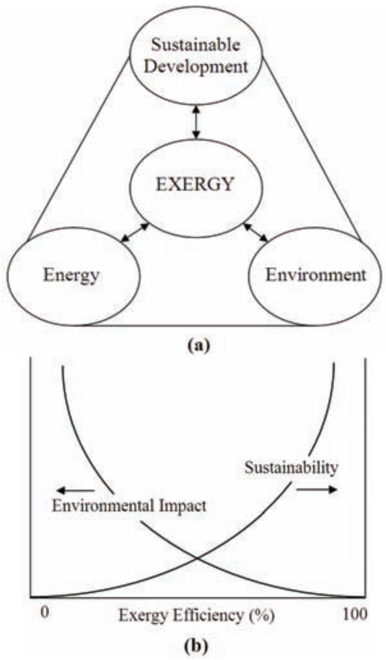


Figure 2. (a) The interdisciplinary triangle of exergy. (b) Qualitative illustration of the relation between the environmental impact and sustainability of a process, and its exergy efficiency.

- As exergy efficiency approaches 100%, the environmental impact associated with process operation approaches zero, since exergy is only converted from one form to another without loss (either through internal consumption or losses). In addition, sustainability approaches infinity because the process approaches reversibility.
- As exergy efficiency approaches 0%, sustainability approaches zero because exergy-containing resources are used but nothing is accomplished. In addition, environmental impact approaches infinity because, to provide a fixed service, an ever-increasing quantity of resources must be used and correspondingly increasing amounts of exergy-containing wastes are emitted.

Although this paper discusses the benefits of using thermodynamic principles, especially for exergy, to assess the sustainability and environmental impact of energy systems, this area of work, particularly for hydrogen and fuel cell systems is relatively new. Further research is of course needed to ascertain a better understanding of the potential role of exergy in such a comprehensive perspective. This includes the need for research to (i) better define the role of exergy in environmental impact and design, (ii) identify how exergy can be better used as an indicator of potential environmental impact, and (iii) develop holistic exergy-based methods that simultaneously account for technical, economic, environmental, sustainability and other factors.

Nevertheless, hydrogen appears to be one of the most promising energy carriers for the future. It is considered an energy-efficient, non-polluting fuel. When hydrogen is used in a fuel cell to generate electricity or is combusted with air, the only products are water and a small amount of NOx, depending on the source of hydrogen and its impurity. Hydrogen that is produced from renewable resources and used in fuel cells can provide sustainable energy to power fuel cell vehicles. The total system, including distribution, refueling and on-board storage of hydrogen may prove superior to batteries recharged with grid power. A hydrogen-powered fuel cell vehicle may offer a market entry for hydrogen and renewable resources in transportation. Attractive transitional applications of hydrogen include use in combustion engine vehicles and production from natural gas. In both case, the environmental and energy policy consequences are significantly less than continued use of oil-derived fuels in conventional combustion engine vehicles. Fuel cells, which employ hydrogen to produce electricity, particularly proton exchange membrane (PEM) fuel cells, can be used to power a wide variety of applications. This is especially true in transportation, where there are several options for providing hydrogen for the fuel cells.

Recently, there has been increased interest in hydrogen energy and fuel cell applications for both stationary and mobile power generation. This interest has been motivated by the fuel cells' high efficiency, even in small-scale installations, and their low waste emissions. Recent legislative initiatives in California, USA aimed at mandating the introduction of zero-emission vehicles, and the failings of other technologies (e.g., the limited range and long refueling times of battery-powered vehicles) have further promoted the investigation of fuel cells in mobile applications.

Thermodynamic principles can be used to assess, design, and improve energy and other systems, and to comprehend environmental impact and sustainability issues. For the broadest understanding, all thermodynamic principles must be used, not just those pertaining to energy. Thus, many researchers feel that an understanding and appreciation of exergy, as defined earlier (see Fig. 2a), is essential to discussions of sustainable development.

Beyond individual behavior, we should think collectively about how society meets its energy needs, including decisions about energy resource selection, efficiency and the role of hydrogen and fuel cell technologies.

An inexpensive and stable energy supply is a prerequisite for social and economic development, in households as well as at the national level. Indeed, energy is essential to human welfare and quality of life. However, energy production and consumption generate significant environmental problems (at global, regional, and local levels) that can have serious consequences and even put at risk the long-term sustainability of the planet's ecosystems. The relationship between energy consumption and production and sustainability is, therefore, complex as shown earlier by Dincer and Rosen [19].

We consider sustainable development here to involve four key factors in terms of environmental, economic, social and resource/energy sustainability under global sustainability, as shown in Figure 3. It is clearly seen that all these factors are interrelated.

4. Fuel Cells as Hydrogen Energy Systems

Fuel cell technology is clean, quiet, and flexible one and is already beginning to serve humanity in a variety of useful ways. Nevertheless, production volume is low and costs are too high. Public support is needed to help generate initial demand to break this cycle. The market for automotive power and stationary generation conversion equipment is the largest market for capital equipment in the world. Fuel cells and fuel cell powered vehicles will be an economic growth leader in the coming decades securing high quality employment for many thousands of people.

Figure 3. Four key factors of sustainable development under global sustainability.

Fuel cells are considerably efficient power producers and create electricity in one simple step, with no moving parts and (at least in the case of PEMFC) at a very low temperature. (Compare this to the combustion process employed by traditional power plants: A fuel is burned at high temperature to create heat, the heat energy is then converted to mechanical energy, and that mechanical energy is finally converted into electricity.) Since fuel cells do not combust fossil fuels, they are known as clean power producers, they emit none of the acid rain or smog producing pollutants that are the inevitable by-product of burning coal or oil or natural gas.

In principle, a fuel cell operates like a battery. Unlike a battery, it does not run down or require recharging, and produces energy in the form of electricity and heat as long as fuel is supplied. The fuel cell converts chemical energy directly into electricity without combustion by combining oxygen from the air with hydrogen gas. It produces electricity as long as fuel, in the form of hydrogen, is supplied. The only by-products are water and heat (Fig. 4). No pollutants are produced if pure hydrogen is used. However, very low levels of nitrogen oxides are emitted, but usually in the undetectable range. The carbon dioxide emissions, which come out from the electrochemical conversion, are relatively low because of high efficiency, and are in concentrated form, facilitating capture Hydrogen can be produced from water using renewable solar, wind, hydro or geothermal energy. Hydrogen also can be extracted from anything that contains hydrocarbons, including gasoline, natural gas, biomass, landfill gas, methanol, ethanol, methane, and coal-based gas.

The type of fuel cells is typically distinguished by the electrolyte that is utilized and can be classified into two main categories, based on their operating temperatures, such as low temperature fuel cells (e.g., 60-250°C) and high temperature fuel cells (e.g., 600-1000°C). Low temperature fuel cells have made significant progress in transportation applications due to their quick start times, compact volume and lower weight compared to high temperature fuel cells. The common types of low temperature fuel cells are proton exchange membrane fuel cells, phosphoric acid fuel cells, alkaline fuel cells, unitized regenerative fuel cells, direct methanol fuel cells. The high temperature fuel cells are more efficient than low temperature ones in generating electrical energy. In addition, they provide high temperature waste heat, which is a benefit in stationary cogeneration applications, but presents a problem for transportation applications. Two common ones are molten carbonate fuel cells and solid oxide electrolyte fuel cells [1].

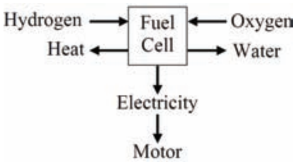


Figure 4. Operation of a fuel cell, converting hydrogen and oxygen (from the air) into electricity, water, and heat.

5. Technical Aspects of Hydrogen Energy

5.1. Hydrogen Production

Although hydrogen is the universe's most abundant 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 source 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). Recognizing this fact is of critical importance. Any analysis of how hydrogen is to be used must also consider how the hydrogen is to be produced. A variety of alternative hydrogen energy production technologies is available in practice, including [1,20]:

- **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%. Hydrogen produced by this technique may cost as little as 65¢/kg.
- **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, with costs typically ranging between 80 and 120 ¢/kg. 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.

5.2. Hydrogen Storage

5.2.1. Bulk Storage in Distribution System

It is expected that any large-scale hydrogen distribution system should address the problem of bulk storage, to provide a buffer between production facilities and fluctuations in demand. Low-cost and efficient bulk storage techniques are a major research goal. One can store hydrogen as either a gas or a liquid. The most widely studied options for storing gaseous hydrogen are underground caverns and depleted underground natural gas formations. Although hydrogen is more prone to leak than most other gases, leakage is shown not to be a problem for these techniques. For example, town gas mixture containing hydrogen) has been stored successfully in a cavern in France, and helium, which is even more leak-prone than hydrogen, has been stored in a depleted natural gas field near Amarillo, Texas. The energy consumed in pumping gas in and out of such storage facilities may be significant, however. Aboveground storage tanks at high pressure are another option.

A certain amount of gaseous storage can be achieved by allowing modest pressure changes in the distribution pipeline system. In the case of natural gas, this technique is used to help manage transient demand fluctuations, such as the morning and evening peaks in residential demand in urban areas. Though the same technique might be useful for hydrogen, its potential is limited, particularly if the hydrogen is to be produced from intermittent sources such as solar or wind.

Storage in liquid form uses tanks similar to those used for liquid hydrogen distribution. For example, Kennedy Space Center uses a 3217 m^3 sphere near the launch pad, and can transfer fuel from this tank to the space shuttle at up to 38 m^3 per minute. Storage at liquefier plants is in vacuum-insulated spherical tanks that usually hold about 1514 m^3 [20]. The energy required for liquefaction may not be a barrier if the hydrogen is to be transported as a liquid anyway, or if the end-use application requires its fuel to be in liquid form.

5.2.2. Hydrogen Storage in End Use

- The difficulty of onboard storage is the main barrier to fueling vehicles with hydrogen. Because it is a gas, hydrogen at room temperature and pressure takes up about 3,000 times more space than an energy-equivalent amount of gasoline. This obviously means that compression, liquefaction, or some other technique is essential for a practical vehicle. So far, storage requirements tend to limit range severely. During the past two decades, several techniques were examined to overcome this problem. The four main contenders are compressed gas, cryogenic liquid, metal hydride, and carbon adsorption. Of these, the first two appear most promising for the short-term. Metal hydrides are also relatively mature, but require further research to be competitive. Carbon adsorption is not yet a mature technique, but it appears very promising if the research goals may be met. Glass micro spheres and onboard partial oxidation reactors are currently under investigation, but as yet are "insufficiently characterized for evaluation at the systems level." It is likely that different techniques will turn out to be most appropriate for different applications, for example buses are less size-sensitive than cars [20].
- Compressed gaseous hydrogen storage is at room temperature in a high-strength pressure tank. Including the weight of the tank, compressed gas storage holds about 1 to 7% hydrogen by weight, depending on the type of tank used. Lighter, stronger tanks, capable of holding more hydrogen with less weight, are more expensive. Compressing the hydrogen gas at the filling station requires about 20% as much energy as is contained in the fuel.
- Cryogenic liquid storage is at 20K in a heavily insulated tank at ordinary atmospheric pressure. As a liquid, hydrogen contains almost three times more energy than an equal weight of gasoline, and takes up only about 2.7 times as much space for an equal energy content. Including the tank and insulation, this technique can hold as much as 16% hydrogen by weight. Furthermore, liquefaction at the filling station requires about 40% as much energy as is contained in the fuel. Another disadvantage is the so-called "dormancy problem": despite the insulation, some heat leaks into the tank, eventually boiling off the hydrogen. A "cryopressure" system stores liquid hydrogen in a pressure vessel like that used for compressed gaseous storage, allowing containment of the boiled-off gas. This helps with dormancy, but increases weight and size.
- Metal hydride systems store hydrogen in the interatom spaces of a granular metal. Various metals can be used. The hydrogen is released by heating. Metal hydride systems are reliable and compact, but can be heavy and expensive. Varieties now under development can store about 7% hydrogen by weight. Unlike the compressed gas and cryogenic liquid techniques, metal hydrides require little or no "overhead" energy when refueling. They do require energy to release the fuel, however. For low-temperature varieties, this energy may be available as waste heat from the fuel cell or engine. For high-temperature varieties, which tend to be the less expensive ones, as much as half of the vehicle's energy consumption may go to releasing the fuel from the metal.
- The carbon adsorption technique stores hydrogen under pressure on the surface of highly porous super activated graphite. Some varieties are cooled; others are operated at room temperature. Current systems store as much as 4% hydrogen by weight. It is hoped to increase this efficiency to about 8%, even for the room temperature variety. Carbon adsorption is very similar to compressed gas storage except that the pressure tank is filled with graphite; the graphite adds some weight but allows more hydrogen to be stored at the same pressure and tank size.
- Glass micro spheres are small, hollow, glass micro-balloons whose diameters vary from about 25 microns to 500 microns, and whose wall thicknesses are about 1 micron. They can be used in large beds to store hydrogen at high pressures. The micro spheres are filled with hydrogen gas at temperatures of 200 to 400°C. The high temperature makes the glass walls permeable, and the gas fills the spheres. Once the glass is cooled to room temperature, the hydrogen is trapped inside the spheres. The hydrogen can be released as needed by heating the spheres. The spheres may also be crushed to release hydrogen. This option precludes sphere recycling, but is desirable for applications where weight is important.

- Onboard partial oxidation reactor is a concept proposed to help bring about a transition from conventional automobiles to cars powered by hydrogen fuel cells. First, a shift would be made from the internal combustion engine to the fuel cell using a conventional hydrocarbon fuel such as gasoline or diesel coupled to an onboard partial oxidation process and a water gas shift reaction process. The partial oxidation process yields 30% hydrogen gas directly and 20% carbon monoxide. Then, the carbon monoxide is chemically reacted with steam to produce additional hydrogen and carbon dioxide gas, which is readily usable by a hydrogen fuel cell. This fossil-to-hydrogen fuel system would be used as a "bridge" until research yields a commercially ready advanced hydrogen storage system or a suitable hydrogen carrier.
- Other techniques are still in the early stages of development. One uses powdered iron and water. At high temperatures, these react to produce rust and hydrogen. Other methods are similar to the metal hydride option, but substitute certain liquid hydrocarbons (also known as "recyclable liquid carriers") or other chemicals for the metal.

5.3. Hydrogen Safety

Hydrogen is intrinsically no more dangerous than many other fuels. Its different characteristics require different safety equipment and procedures, but all fuels have some potential for accidents; if they did not burn, they would not be much use as a fuel. Hydrogen is used worldwide in the petroleum and chemical industries and elsewhere. It was also routinely used in the USA as a fuel (a component of "town gas") before natural gas became widely available. Town gas is still used in some countries. Moreover, hydrogen ranks between propane and methane (natural gas) in safety.

The physical properties of hydrogen make its safety characteristics rather different from those of other fuels. Its low density means that it tends to rise and disperse into the atmosphere in the event of a leak, rather than remaining in a "puddle" near the ground. This increases safety in well-ventilated applications. Its low density also means that a hydrogen explosion releases less energy in a given volume than an explosion of other fuels, and compared to gasoline or natural gas, hydrogen requires much higher concentrations in the air to produce an explosion rather than just a flame. Furthermore, hydrogen's low ignition temperature and flammability over a wide range of concentrations make leaks a significant fire hazard, especially in confined spaces such as a garage. Because it is clear and odorless, leaking hydrogen is more likely to go undetected than a leak of gasoline or most other fuels. Even the flame of burning hydrogen is invisible. Techniques of leak detection have been and continue to be a research priority. A simple approach is to add an odorant like that added to natural gas, or possibly a colorant, or both. Any addition may detract somewhat from the environmental cleanliness inherent to pure hydrogen, however, and additives would need to be chosen with care to avoid destroying other important features. For example, contaminants may reduce the efficiency and/or lifetime of a fuel cell.

As with most fuels, the fire and explosion hazards discussed above are the main safety concerns. In some situations, there may be other safety issues, such as, in applications that involve hydrogen storage under high pressure or at extreme low temperatures. These problems can be minimized with proper equipment design and operating procedures, however, and are generally agreed to be of less concern than hydrogen's flammability.

5.4. Economics of Hydrogen

Hydrogen is currently more expensive than other fuel options, so it is likely to play a major role in the economy only in the long term, if technology improvements succeed in bringing down costs. Higher prices for fossil fuels would not necessarily make hydrogen more cost-competitive in the short term. Since fossil fuels are currently the main source of heat, feedstock, and electricity for hydrogen production plants, rising prices for gas, oil, or coal would also drive up the price of hydrogen. Since hydrogen is produced in many different ways, from many different sources, most hydrogen-related international commerce is likely to be not of fuel but of technology: plant components, engineering services, construction expertise, and so on. These areas could potentially represent new export markets.

5.5. Environmental Aspects of Hydrogen Energy

The use of hydrogen as a fuel is inherently very clean. Hydrogen consumed by either combustion or a fuel cell produces only water as a product. The high temperatures involved in combustion may stimulate some NOx production from nitrogen and oxygen in the air, but this problem is familiar from other fuels and can be controlled. Unlike other fuels, hydrogen contains no other pollutant-producing elements, so it has no potential to produce SO_2, CO, CO_2, volatile organic chemicals, etc. The environmental consequences of hydrogen production should also be considered, however. As mentioned above, production from fossil fuel feed stocks by steam reforming leads to carbon dioxide emissions greater than production from feedstock by itself.. Steam reformers should also somehow dispose of feedstock impurities such as sulfur. Electrolysis is responsible for the emissions of whatever power plants are used to generate the needed electricity. Production of hydrogen from sustainable harvested biomass, solar energy, or other renewable sources might considerably reduce production emissions, but (as described above) such techniques are being fully developed for commercialization. For example, the U.S. Department of Energy (has examined the full-cycle environmental effects of various scenarios for hydrogen production and use. It concludes, "Substantial emissions can be generated when hydrogen is produced from certain energy sources," namely fossil fuels. Thus, the technique of hydrogen production remains crucial.

5.6. Standards and Regulations

Countries have different regulations for hydrogen energy and these regulations are still under development. Area of regulation may include but not limited to commercial truck, bus, passenger plane, pipeline, tunnel, portable fuel container, stationary fuel cell, safety training for operators, and fueling station.

It is obvious that some key, harmonized regulations, codes, and standards are necessary in this regard. Wurster [21] has given the published and draft standards for hydrogen and fuel cells. Some published standards are currently available as follows:

- ISO 13984 Liquid hydrogen – Land vehicle fuelling system interface
- ISO 14687 Hydrogen fuel – Product specification

5.7. Publications and Patents

Thomson ISI Web of Knowledge is one of the most reliable sources to find out detailed information about journals and papers. It includes papers indexed in Science Citation Index-Expanded and patents included in Derwent Innovations Index. According to a query carried out at September 27, 2007; number of publications and patents related to 'fuel cells' and 'hydrogen energy' for all years and the last eight years are shown in Table 1 and 2, respectively.

Table 1. Number of journal papers for various year ranges.

Query keyword	Year range	Number of journal papers
Hydrogen energy	1900-2007	52,576
Fuel cell	1900-2007	14,711
Hydrogen energy	2000-2007	28,258
Fuel cell	2000-2007	11,165

Table 2. Number of patents for various year ranges.

Query keyword	Year range	Number of patents
Hydrogen energy	1963-2007	10,576
Fuel cell	1963-2007	47,120
Hydrogen energy	2000-2007	5,228
Fuel cell	2000-2007	34,756

5.8. Influence of Government and Industry

Two parties may influence the implementation of energy conservation problem. These are hydrogen and fuel cell technologies at the industrial sector, namely the government and the top managers of the industrial organizations. The most important measures that a government can take to implement energy conservation include [22]:

- Pricing policy: In the short term, energy prices influence the way of use of existing equipment and in the long-term energy prices effect the choice of equipment.
- Regulation and legislation: The government can enact a Heat Management Law. For such a law, the companies using more than a certain amount of oil equivalent must submit an annual plan for energy conservation and must employ a manager to monitor its execution for such a plan.
- Publicity campaigns: Government can hold seminars, training workshops for the qualified workers including managers, engineers, and technicians of different companies.
- Financial and fiscal incentive schemes: The government can give awards for the outstanding and successful projects. Tax incentives, such as depreciation allowance might encourage investments in some new equipment.

The main concern of the industry switching to hydrogen economy may be given as follows:

- The top managers resist investing in new technology because they want to acquire large profits in the short term.
- Some managers think that investing largely in new technology might lead to higher selling prices of their products. Hence, their competitiveness in the market will decrease.
- Others may have lack of knowledge about this new technology or they do not know how to implement it systematically.

5.9. Scientific and Technical Challenges

The scientific and technical challenges for the hydrogen economy may be given as follows [23]:

- Lowering the cost of hydrogen production to a level comparable to the energy cost of petrol.
- Development of a CO_2-free route for the mass production of sustainable hydrogen at a competitive cost.
- Development of a safe and efficient national infrastructure for hydrogen delivery and distribution.
- Development of viable hydrogen storage systems for both vehicular and stationary applications.
- Dramatic reduction in costs and significant improvement in the durability of fuel cell systems.

The pathway for the transition from current energy economies to hydrogen economy has some scientific, technological, and economical drawbacks. The most significant milestones for the hydrogen pathway must be mainly based on the intensification of research and innovation programs. Figure 5 shows some research and development priority areas.

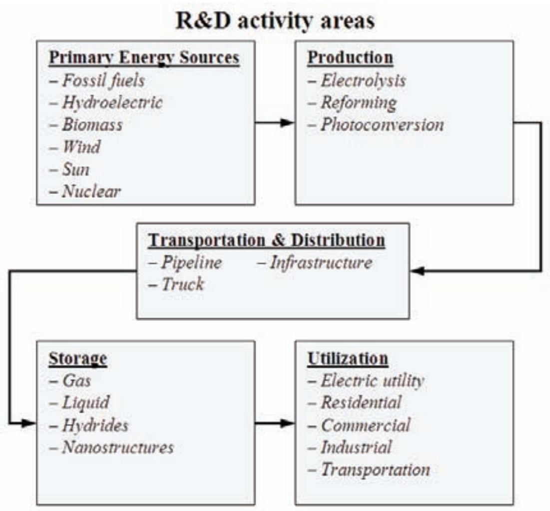


Figure 5. Major R&D activity areas for the pathway to hydrogen economy [31]

It should be noted that universities play an important role in providing the sustainable development of hydrogen and fuel cells through some partnership programs with the relevant industry and government organizations. The output of research conducted in universities is open to other researchers. Hence, being aware of the previous studies and getting benefit of them, new methodologies are developed for better design, analysis, and operation of these technologies. Some challenges to the universities in this issue may be summarized as follows:

- funding challenges,
- coordination of research efforts within and between academic/research institutions, and
- Collaboration between researchers and governmental institutions.

5.10. Priorities that Jordan should consider:

Jordan has limited energy sources such as oil shale deposits, tar sands, a small hydropower potential, a few low geothermal sources, and biogas [24]. It is mainly dependent on imported oil from neighboring countries to cover main portion of its energy demand. In year 2000, 94% of total energy requirement was supplied from imported oil [22]. The major sector of energy consumption is transportation, which is around 41%. Industrial sector, household, and others, which include service and agricultural sectors, follow it, respectively.

Since the oil reserves deplete in the world, alternative energy sources are required to provide the energy need of the world. In the case of Jordan, the transition to the new energy forms should be accelerated since this country is highly dependent on import oil. The priority should be given to the alternative energy sources that could be used in transportation sector since it has the biggest share among the different sectors. For this purpose, renewable energy such as befoul or hydrogen to be used in fuel cells may be considered. Since the main objective of this paper is to discuss hydrogen and fuel cell technologies, the latter one is discussed below.

For vehicle applications, fuel cells are not only preferable since they use hydrogen as fuel but also they have higher efficiency than internal combustion engines (ICEs), which is not restricted with Carnot efficiency; quieter than ICEs; and reduce environmental pollution. Among different types of fuel cells, Proton Exchange Membrane Fuel Cells (PEMFC), also known as Polymer Electrolyte Membrane Fuel Cells has proven to be the most attractive option. This type of fuel cell consists of a proton conducting membrane, such as Nafion, which is chemically highly resistant, mechanically strong, acidic, good proton conductor and water absorbent. Main advantages of this fuel cell may be given as: Fast startup capability since it works at low temperatures, compact since thin Membrane Electrode Assemblies (MEAs) can be made, and no corrosive fluid hazards because the only liquid present in the cell is water. The main disadvantage of this type of fuel cell is the need for expensive catalysts as promoters for the electrochemical reaction. Additionally, carbon monoxide cannot be used as a fuel since it poisons the cell. On the other hand, the main challenge for PEMFC is the water management, which may be summarized as follows: The proton conductivity of the electrolyte is directly proportional to the water content and high enough water content is necessary to avoid membrane dehydration. Contrarily, low enough water should be present in the electrolyte to avoid flooding the electrodes. Hence, a balance between the production of water by oxidation of the hydrogen and its evaporation has to be controlled.

PEMFCs may conquer the market of structured mobility (city buses, postal services, taxis, city cars etc.) where hydrogen can be supplied to the vehicles from central tanks at scheduled intervals. Nevertheless, they may not succeed in the much broader market sector of random mobility (private cars, trucks, tour busses, military vehicles etc.). Some claim that for that market the SOFC is more attractive. These fuel cells may operate between 600°C and 1000°C, respectively. The most common material used for electrolyte is ytrria-stabilized zirconium. The main advantages of this fuel cell are as follows: its fuel flexibility, which means fuel such as methane, propane, butane, JP-8, may be used as fuel, direct reforming at the anode catalyst, and no need for precious metal electro catalysts. The main disadvantage of this fuel cell may be given as the challenges for construction and durability due to its high temperature. Additionally, carbon deposition may be a problem.

In conclusion, the priority for Jordan should be considering fuel cells for transportation applications since it covers the biggest portion among the sectors. Among different fuel cell types, PEMFCs and SOFCs are the most promising ones for this sector.

6. Case Study

Here a life cycle assessment of a PEMFC vehicle, which includes not only operation of the vehicle on the road but also the manufacture and distribution of both the vehicle and the fuel during the vehicle's entire lifetime (Figure 6), is conducted and compared with the one for a conventional gasoline vehicle [25].

As illustrated in Figure 6, the fuel section of the life cycle begins with the primary energy source, e.g., crude oil or natural gas in underground reservoirs. This primary energy is then transported to a manufacturing site, in this case a reforming plant/oil refinery, where it is converted to the fuel suitable for a vehicle, e.g., gasoline or hydrogen. And this fuel has to be distributed from the central reforming plants/refinery by various means to the retail service station where it is deposited in the tanks of vehicles. This sequence constitutes the 'fuel cycle' part of the total automobile technology life cycle.

The vehicle part of life cycle starts with metal ores and other primary materials that eventually converted to components of the vehicle. These primary materials are transported to the vehicle manufacturer (includes manufacture of parts, metals, assembly, and other vehicle constituents). The vehicle itself is fabricated and assembled from these inputs and transported to distributors. Finally, vehicle and fuel cycles come together, which represent the purchaser (user) of both vehicle and fuel. At the end of its lifetime, the vehicle is scrapped or recycled.

The assessment of energy consumption, and greenhouse gases (GHGs) emissions associated with the production and distribution of hydrogen are based on the data published in the literature. Published data are also used to assess the energy consumption, and greenhouse gases (GHGs) emissions associated with producing, manufacturing, and assembling the materials and parts making up the PEMFC vehicle. The assessments of all the phases of each life cycle are then combined to make integrated comparisons with the conventional automobile technology i.e. ICE vehicle.

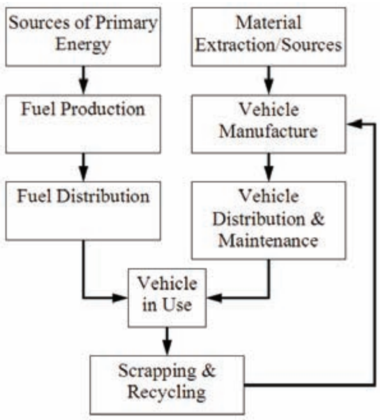


Figure 6. Illustration of life cycle of a vehicle.

6.1. Methodology

The above methodology is used to characterize the following fuel and vehicle cycles [25]:

- Fuels: (i) hydrogen from natural gas and (ii) gasoline from crude oil (for comparison).
- Vehicle Technologies: (i) PEMFC vehicle and (ii) spark ignition internal combustion engine vehicle (for comparison).

The present assessment is a preliminary assessment based on the published data available in the literature [26-27] and like any other assessment, has boundaries on its scope and makes simplifying assumptions. Some assumptions are:

- The boundaries of the physical system are such that secondary energy and environmental effects are not quantified. For example energy consumption and emissions during the operation of a steam reforming plant of natural gas are quantified, but the energy and emissions involved in making the steel, concrete or other elements embodied in the plant itself are not counted.
- Data used for assessment are from mid-size family passenger cars as US experience.
- Other production methods (e.g., electrolysis, nuclear, hydro, etc.) of hydrogen are not considered in the present assessment.

6.2. Results and Discussion

Here, the assessment from fuel cycles includes recovery of the raw material for each (e.g., natural gas for hydrogen or crude oil for gasoline) through conversion to the final fuel (e.g., hydrogen or gasoline) and delivery into the tank of the passenger car. The two characteristics of the fuel cycles are (i) total energy consumed originating from raw materials or other energy sources and (b) total greenhouse gases emitted from raw materials or other sources. The GHGs assessed in the present study are CO_2 and CH_4. N_2O is neglected since its greenhouse contribution for each of the fuel cycles accounts for less than 1% of the other GHGs [28-30].

Figures 7a, b show both the stages classified in both fuel and vehicle cycles. Figures 8a, b exhibit the comparison of energy consumption and GHGs emission during the fuel cycles of hydrogen and gasoline respectively. Here both energy consumption and GHGs emissions during fuel cycle of hydrogen are higher when compared to gasoline fuel cycle. Fuel production stage of hydrogen cycle is the major contributor to total energy consumption and GHGs emissions. The other significant contribution of energy consumption and GHGs emissions during hydrogen cycle comes from the fuel distribution stage which includes primary energy in generation of the electric power used for compressing hydrogen.

The comparison of energy consumption and GHGs emissions during vehicle cycle of PEMFC and internal combustion engine (ICE) vehicle are shown in Figures 9a, b respectively. The largest contributor to energy consumption and GHGs emissions for the ICE vehicle is the usage stage. The energy consumption of ICE vehicle is about three times higher than PEMFC vehicle. Moreover, GHGs emissions during the vehicle cycle of PEMFC vehicles is around 8% of the GHGs emissions of the ICE vehicle, which clearly indicates the environmental friendliness of PEMFC vehicles.

Feedstock Production: Energy consumption and GHGs emissions during the production of natural gas for hydrogen and crude oil for gasoline are quantified in this stage.	**Fuel Production:** Energy consumption and GHGs emissions during refining of crude oil and steam reforming of natural gas are quantified in this stage.
↓	↓
Feedstock Transport: Crude oil and natural gas as the raw materials for gasoline and hydrogen have to be transported to the refineries and reforming plants (decentralized). Energy consumption and GHGs emissions during the transport of raw materials are counted in this stage.	**Fuel Distribution:** Distribution of gasoline follows a chain: from refineries to terminals by ship or pipeline, transfer to road tankers, to service stations and finally to vehicle tank. For hydrogen, natural gas is transported through pipeline or road tankers to decentralized refuelling stations, where it is produced through steam reforming. Moreover, hydrogen fuel distribution also includes the consumption of primary energy and GHGs emissions in generation of the electric power used for compression.

Figure 7a. Stages of fuel cycle.

Vehicle Material Production:
Energy use and GHGs emissions from vehicle materials production are counted in this stage. Typically vehicle incorporates nearly 890 kg of ferrous metals, 100 kg of different types of plastics, roughly 80 kg of aluminium, and about 200 kg of other materials (Weiss et al., 2000). And for PEM fuel cell powered automobile, some additional materials are needed for fuel cell components, e.g., polymer membrane, platinum as catalyst, graphite etc.

↓

Vehicle Assembly:
The energy required and GHGs emissions for transport of vehicles during assembly are quantified here. Because of the complex supply chain in the automobile industry and the associated difficulty in estimating vehicle assembly energy requirements, assembly energy is typically estimated as a linear function of vehicle mass (AE, 1996).

↓

Vehicle Distribution:
The energy needed and GHGs emissions during the transport of a vehicle from the assembly line to the dealership are counted in this stage.

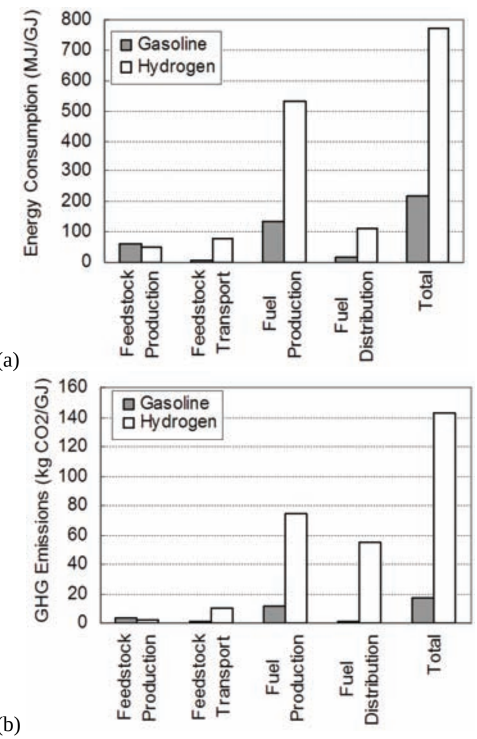
↓

Vehicle Use:
It includes energy consumption (fuel) and GHGs emissions, maintenance and repair during the lifetime, which is assumed to be 300000 km, consistent with Sorensen (2004). In the present analysis, it is assumed that the fuel usage of PEM fuel cell and ICE vehicles are 0.65 MJ/km and 2.73 MJ/km, respectively.

↓

Vehicle Disposal:
After a vehicle's life, the automobile is shredded. The disposal energy is the sum of energy needed to move the bulk from the dismantler to a shredder and the shredding energy (AE, 1997).

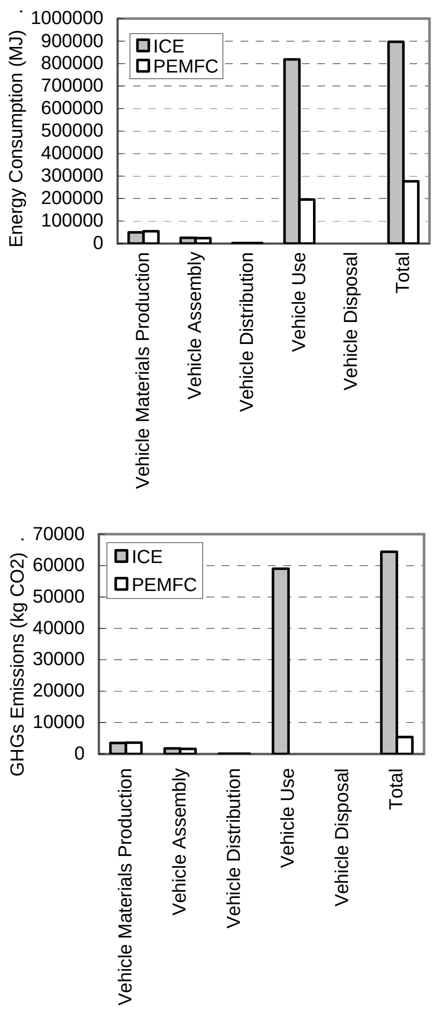
Figure 7b. Stages of vehicle cycle.



(a)

(b)

Figure 8. (a) Energy consumption and (b) greenhouse gases emissions during fuel cycles, using actual data from [32-34].

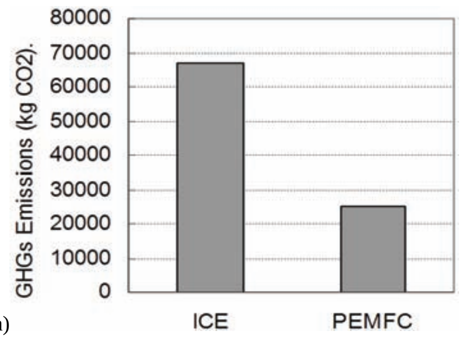


(a)

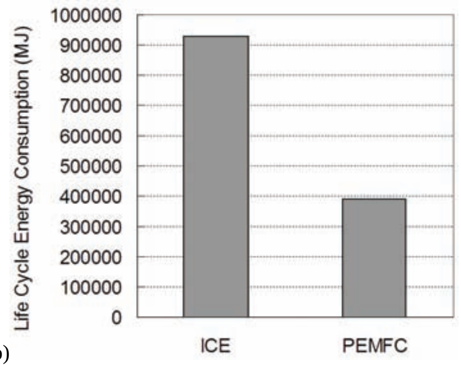
(b)

Figure 9. (a) Energy consumption and (b) GHGs emissions during vehicle cycles, using actual data from [32,35].

Figures 10a, b show the comparison of life cycle energy consumption and life cycle GHGs emissions of the two vehicles technologies considered in the present study. Although the fuel cycle energy consumption of PEMFC vehicle is about 3.5 times higher than ICE automobile, the overall life cycle energy consumption of PEM fuel cell vehicle is about 2.3 times less than that of ICE vehicle, which is due to high efficiency of PEMFC vehicle as compared to ICE vehicle during the vehicle use stage of the vehicle cycle. Similarly, the GHGs emissions of PEMFC automobile is 8.5 times higher than ICE vehicle during the fuel cycle, the overall life cycle GHGs emissions are about 2.6 times lower than ICE automobile, which is again due to no GHGs emissions as compared to ICE vehicle during the vehicle use stage of the vehicle cycle.



(a)



(b)

Figure 10. (a) Life cycle energy consumption and (b) GHGs emissions of vehicle technologies, using actual data from [32-35].

7. Conclusions

The benefits of hydrogen and fuel cell systems is highlighted of using the principles of thermodynamics (particularly exergy) and life cycle assessment to evaluate their key roles in sustainable development. The following concluding remarks, which will likely be useful to scientists, 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. These problems cover a continuously growing range of air pollution, water pollution, solid wastes, pollutants, ecosystem degradation, and extend over ever-wider areas.
- 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. Energy resources such as solar, wind, hydro, and biomass are generally considered renewable and therefore sustainable over the relatively long term. The use of these sources in hydrogen production will be a key factor in sustainable development.
- Assessments of the sustainability of processes and systems, and efforts to improve sustainability, should be based in part upon thermodynamic principles, and especially the insights revealed through exergy analysis.
- For societies to attain or try to attain sustainable development, effort should be devoted to developing hydrogen and fuel cell technologies. Renewable energy utilization in hydrogen production can provide a potential solution to current environmental problems. Advanced hydrogen and fuel cell technologies can provide environmentally responsible alternatives to conventional energy systems, as well as more flexibility and decentralization.
- To realize the energy, exergy, economic and environmental benefits of hydrogen and fuel cell technologies, an integrated set of activities should be conducted including research and development, technology assessment, standards development and technology transfer. These can be aimed at improving efficiency, facilitating the substitution of these technologies and other environmentally benign energy currencies for more harmful ones, and improving the performance and implementation characteristics of these technologies.
- As illustrated in the case study, the results of a comprehensive life cycle assessment of PEMFC vehicles are presented based on the published data available in the literature. The two characteristics, which were assessed, are energy consumption and greenhouse gases (GHGs) emissions during the entire life cycle of an automobile. Moreover, conventional internal combustion engine (ICE) vehicle is also assessed based on the similar characteristics to compare with the PEMFC vehicle.

The results will likely be useful to scientists, researchers and engineers as well as policy and decision makers. The case study presented on the hydrogen and fuel cell systems highlights clearly the importance of the topic and show that these can help achieve better environment and sustainability.

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