Hydrogen Fuel: Opportunities and Barriers

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The fact that 65% of the oil use is by the transportation sector, the increasing gap between the oil supply and demand, and the need to reduce greenhouse gas emissions make the introduction of alternative fuels, together with large energy efficiency gains, a key to sustainable mobility, both nationally and globally. The history of alternative fuels has not been very successful. Various economic, social, and technological barriers have impeded the acceptance of energy carriers such as hydrogen as a major transportation fuel. An effective interaction between the societal system of vehicle owners and a supply infrastructure of alternative fuels is needed for mass adoption of these future technologies. However, hydrogen due to its production pathways, particularly from renewable resources, inexhaustible, and clean nature, an ubiquitous presence and its promise of a sustainable transportable energy source give it a strong edge to be fuel of the future. This paper discusses the economical, social, and technological implications on the use of hydrogen as a future transport fuel. Furthermore, three cases based on UK Department of Transport studies showing the penetration of high efficiency vehicles, fuel cell vehicles (FCVs), and hydrogen fuel internal combustion engine vehicles (H_2-ICEs) into the future transport fleet are discussed. With some assumptions, it indicates clearly that by the end of 2050 the H_2-ICEs will play a major role in the UK transport sector whereas more time is needed for FCVs due to their less compelling consumer value possibility. Also, it can be inferred that the emissions from hydrogen's full life cycle are about half those of the direct emissions from nonrenewable fuels such as the natural gas from which it is produced, thereby showing a promising future of hydrogen fuel to cope with the problem of climate change and the continuously increasing scarcity of conventional/fossil fuels.
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1 Introduction

Energy sources are needed for transport, electricity generation, heating in buildings, and industrial processes. About 90% of primary energy comes from fossil fuels and the transportation sector alone consumes ~30% of the total energy [1]. The transportation sector is a major contributor to greenhouse gas (GHG) emissions, an inevitable result of hydrocarbon fuel combustion. The research communities are continuously seeking sustainable, durable, and cheaper options for replacing conventional fuels to reduce vehicle pollution and to preserve the natural fuel resources (e.g., oil and coal). The European Commission's White Paper "A European Transport Policy for 2010" [2,3] predicts that a viable way of reducing greenhouse gas emissions is the introduction of cleaner alternative fuels. This would also lower the present dependence (about 98%) of the European transport sector on oil [4]. The history of alternative transportation fuels such as methanol, compressed natural gas, and ethanol has not been very successful. Lack of any private benefits, need of major infrastructural changes for their mass acceptance has contributed to this failure. However, depending on the fuel supply and storage infrastructure and the application in present day vehicles, natural gas and biofuels are seen to be the short-term option for meeting the above mentioned goals, whereas hydrogen and the fuel cell technology are expected to contribute in the long run [5].

Hydrogen is a colorless, odorless, nontoxic flammable gas, with no local pollutant effects. It can be used as a transport fuel, in internal combustion engine (ICE) or fuel cell vehicles (FCVs). It contains more energy per unit mass than any other fuel and produces low emissions when combusted and essentially no emissions when electrochemically converted to electricity in a fuel cell [6]. Recently, hydrogen has been considered as a "fuel of the future" because it is a clean energy carrier and is abundantly available under certain conditions. However, the means to deliver the hydrogen in sufficient quantities in a sustainable manner and the various social, technical, and economical barriers it has to face still leaves its acceptance as a major transport fuel in debate. This paper highlights the future prospects of renewable hydrogen (that is hydrogen produced from renewable sources), its availability, its penetration and acceptance in the future transport sector.

2 Hydrogen and Its Future Opportunities

The use of hydrogen as a fuel has many advantages. First, the use of hydrogen in fuel cell propulsion systems with low temperature fuel cells (membrane fuel cells: PEMFC) completely eliminates all polluting emissions. Moreover, according to the NAE and BEES study [7], hydrogen has a potential for dramatic reductions in its cost of production, distribution, and use, which makes it a reliable and sustainable carrier of energy for application in the transport industry. Also, hydrogen fuel cell vehicles appear to be a superior consumer product desired by the automotive industry, thus making their societal acceptance easy once the other technical problems in their storage and distribution are sought out. Some of the advantages of hydrogen as a major energy carrier are summarized next.

2.1 Multiple Sources and Energy Security. According to the New York State Energy Research and Development Authority (NYSERDA), hydrogen can be produced from a wide range of sources, which includes various thermal, electrochemical, and biological processes [8]. The processes such as steam reforming of natural gas, thermo chemical water splitting, gasification, and pyrolysis are some thermal processes which require carbon sequestration to minimize GHG emissions. Processes such as electrolysis of water to release hydrogen are virtually zero emission processes if the source of electricity is renewable such as wind or ocean

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energy; renewable resources such as wind, solar, biomass, and biological energy sources are the emerging methods of hydrogen production [9]. Use of hydrogen in conjunction with fuel cell empowers countries to invest in a sustainable energy infrastructure that is matched with their energy production capabilities and demands. Many countries such as United States, Japan, and European Union (EU) are currently emphasizing on developing hydrogen infrastructure. Moreover, the use of hydrogen fuel cells in a distributed generation system enables individual homes and communities to manage their own energy supply. This reduces dependence on energy infrastructure such as large-scale power stations, national grids, and long-distance pipelines [10]. Use of hydrogen fuel will help to secure the incredibly valuable resources of fossil fuels. However, hydrogen is not currently used as a fuel outside prototypes, and demo plants and its introduction as a commercial product would be a significant leap forward.

2.2 Environmental and Economic Benefits. Hydrogen is a carbon-free fuel, and when produced using renewable energy, the whole energy system becomes carbon neutral or even carbon free. Therefore, hydrogen fuel provides long-term environmental benefits and can contribute in reducing the production of many toxic pollutants along with GHG emissions [9]. The air that comes out of the exhaust pipe of a combustion engine running off hydrogen is cleaner than it was when it went in; this is called "minus emissions." A transition to a hydrogen economy will feature a variety of processes from a diverse resource base, beginning with fossil fuels and nuclear fuel in the near and midterms and eventually featuring renewable in the long term.

However, the leakage problem of hydrogen needs to be addressed so that no harmful effect is done to the strastrophic zone by the leaked hydrogen. The new alternative fuel technologies need to be able to integrate and compete with existing technologies, which have had the benefit of many years of mass manufacturing and distribution. To overcome this problem, transition measures such as positive regulatory frameworks, effective codes and standards, financial incentive, improving availability, creating demand, and reducing cost will be helpful [9].

2.3 Fuel Cell Vehicle Technology. Fuel cells convert hydrogen and oxygen into electricity and water. They offer higher conversion efficiencies and lower emissions than most simple electricity generation methods. Proton exchange membrane (PEM) and phosphoric acid fuel cells (PAFCs) use hydrogen produced by reforming the fossil fuels [11]. The success of hydrogen in the transportation sector will be dependent on the development and commercialization of competitive FCV technology. However, the challenge is to develop automotive fuel cell systems that are lightweight and compact (i.e., have high power densities by both mass and volume), tolerant to rapid cycling and on-road vibration, reliable for 4000–5000 h or so of noncontinuous use in cold and hot weather, able to respond rapidly to transient demands for power (perhaps by being hybridized with a battery or ultra capacitor for electrical storage on the vehicle), and able to use hydrogen of varying purity.

2.4 No Natural and Political Enemies. Hydrogen is highly inclusive; it can be made from any energy feedstock, including coal, nuclear, natural gas, biomass, wind, and solar. The political or economical enemies are the most important factors that hydrogen perhaps does not have. The oil industries are the massive energy companies and can act as a key for developing the hydrogen economy. It opposes the battery-electric vehicles because they see no business for themselves. In the case of hydrogen, they prefer fuel cell vehicles, which convert gasoline into hydrogen. But they also anticipate large financial losses in the future when hydrogen use becomes widespread. Without government support during the low-volume transition stage, oil companies are unlikely to be early investors in the construction of hydrogen fuel stations. Since hydrogen fuel cells are a more palatable way to address air pollution than calling for stricter fuel efficiency or tailpipe emissions standards, it will become favorable for the political community to support it [12].

2.5 Safer and Cleaner Than Conventional Fuel. Hydrogen is an extremely light molecule, therefore, it rises and disperses quickly in the atmosphere. If a leak were to occur, the hydrogen gas would quickly become so sparse that the risk of it burning would decrease just as rapidly. It is a nontoxic compound as most of the petroleum products are poisonous to humans. Hydrogen has been produced, transported, and used in industry for over 100 years. The codes and standards developed for this industrial use to ensure the safety of all involved are being adapted for public or commercial adoption, and new codes are being developed where required. When produced from renewable energy sources, hydrogen is the cleanest transportable fuel we have at our disposal. When used in a combustion engine, reaction takes place at lower temperatures and so the only waste product from a hydrogen-fueled fuel cell is water vapor, pure H_2O, even safe enough to drink.

3 Economical, Technical, and Societal Barriers

There are some economic and technological barriers that limit the use of hydrogen in the transport sector. Economic barriers include the cost of hydrogen production and distribution, cost of materials and components, and the competition with the current developed market of fossil fuels. The problems of hydrogen storage, compressor and distribution networks, lack of durable fuel cell technologies, and integration with the existing infrastructure are the technological barriers, which need to be considered for the future. A societal barrier to hydrogen development is awareness, familiarity, and general acceptance of the technologies. The majority of consumers, as well as product developers, are cautious about adopting new technologies until they have proven to meet their needs. Overcoming this barrier would involve educating these groups about the capabilities and accomplishments of hydrogen technologies.

The transition to new fuels and/or energy carriers is especially problematic in the transportation sector because of the diffuse nature of the system and its complex public-private composition. Considering land vehicles only, there are more than 750×10^6 passenger cars and commercial vehicles worldwide, with an annual production rate of 56×10^6 units [13]. The geographically diffuse distribution of vehicles favors fuels that are easy to transport and store, i.e., the fuels that are liquid at room temperature. Consider, for instance, that natural gas fuels and electricity are generally less expensive (on a per unit of energy basis) and tend to be "cleaner" than liquid fuels are, but they are much more difficult to transport, in the case of natural gas, and much more difficult to store, in the case of electricity. Most vehicular fuels continue to be gasoline and diesel fuels. The convenience of the petroleum-based fuel distribution system is a key factor in the continuing dominance of vehicles running on liquid fossil fuels.

The process of using hydrogen fuel comprises the production of molecular hydrogen using coal, natural gas, nuclear energy, or renewable energy (e.g., biomass, wind, and solar), the transport and storage of hydrogen in some fashion, and the end use of hydrogen in fuel cells, which combine oxygen with the hydrogen to produce electricity and some heat [7]. From the environmental point of view, the abatement of local emissions (i.e., NO_X, CO_2, VOCs, particles, etc.) related to transport is not the only issue for promoting hydrogen [14,15]. An equally important challenge is the transformation of a transport system based on exhaustible resources to a system relying on renewable energy sources and, furthermore, achieving a drastic reduction of transport-related GHG emissions. There are mainly *two* reasons that led to all previous alternate transportation fuels to ultimate failure. First of all, the private benefits from compressed natural gas, ethanol, methanol, propane, and early battery-electric vehicles were nil, whereas

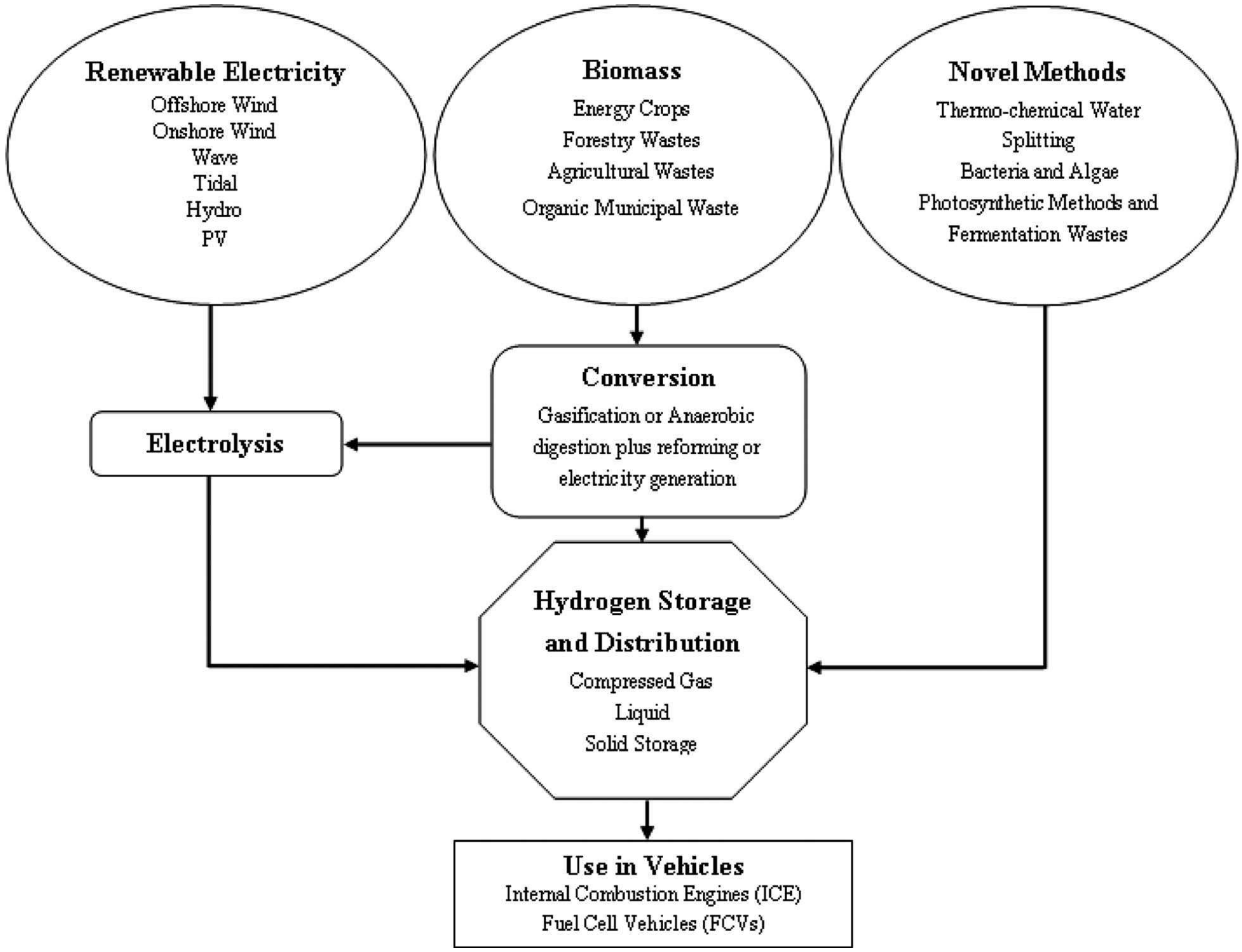

Fig. 1 Schematic showing the sources, production, and use of renewable hydrogen [17]

the petroleum-fueled vehicles have different safety and performance attributes. Second, the claims of large public benefits regarding pollution and energy security proved to be overestimated [10]. And even if they were, few consumers purchase a vehicle for reasons of public good. It seems unlikely that hydrogen will succeed in the near or medium term future on the basis of environmental and energy advantages alone. It will be difficult for hydrogen to compete with the existing developed infrastructure of petroleum fuels and the internal combustion engine. Hybrid electric vehicles, cleaner combustion engines, and cleaner fuels will provide almost as much energy and environmental benefit on a per-vehicle basis for some time. During the next decade or so, advanced gasoline and diesel vehicles will be more widespread and deliver more benefits sooner than hydrogen and fuel cells ever could. Hydrogen is neither the easiest nor the cheapest way to gain large near- and medium-term air pollution, greenhouse gas, or oil reduction benefits [10]. However, in the long term, it appears to have a highly promising future because of its broader and deeper societal benefits than any other options; it is cost effective as fossil fuel become increasingly scarce.

4 Hydrogen Fuel and Its Future Perspective for the UK: Case Study

The technical assessment of hydrogen fuel from renewable resources in the UK up to 2050 is discussed in this section. In the United Kingdom, at present, transport is the third largest source of carbon dioxide (CO_2) and according to the UK Climate Change program (Department of the Environment, Transport and the Regions (DETR) [16]) forecasts carbon dioxide emissions from the transport sector shall increase from 40.0 MtC (million tons carbon) in 2000 to 45.4 MtC in 2010. The chapter on transport focused on increasing the efficiency of road vehicles and reducing their use to move toward the commitment to cut greenhouse gas emissions by 12.5% below 1990 levels by 2008–2012 and the goal of achieving a 20% reduction in CO_2 emissions below 1990 levels by 2010. In the long term, the use of hydrogen energy in the transportation sector could substantially reduce the carbon dioxide and other pollutant emissions.

4.1 Sources and Production Methods of Renewable Hydrogen Production in the UK. There are various methods of hydrogen production; however, some of them are not especially relevant in the UK context (e.g., geothermal energy). Therefore, this analysis will be restricted to the production sources, shown in Fig. 1. Renewable electricity, biomass energy crops, such as short rotation coppice (SRC), and miscanthus were identified the major potential renewable hydrogen energy sources for UK [1,3]. The hydrogen production technologies, currently at research and demonstration stage (e.g., photosynthesis, fermentation, photochemical, and thermochemical processes) could be important in future. The cost of different renewable hydrogen fuel options, including distribution and 5% profit margin, by the year 2020 is shown in Fig. 2. The cost of supplying renewable hydrogen from wind or biomass resources are likely to lie above the current pump price of untaxed petrol and diesel, though some costs are very close to this level. It is also expected that, based on mature technologies, the production costs of hydrogen from biomass will be lower than hydrogen from wind electricity. The production costs of hydrogen from biomass may be close to those of hydrogen produced from

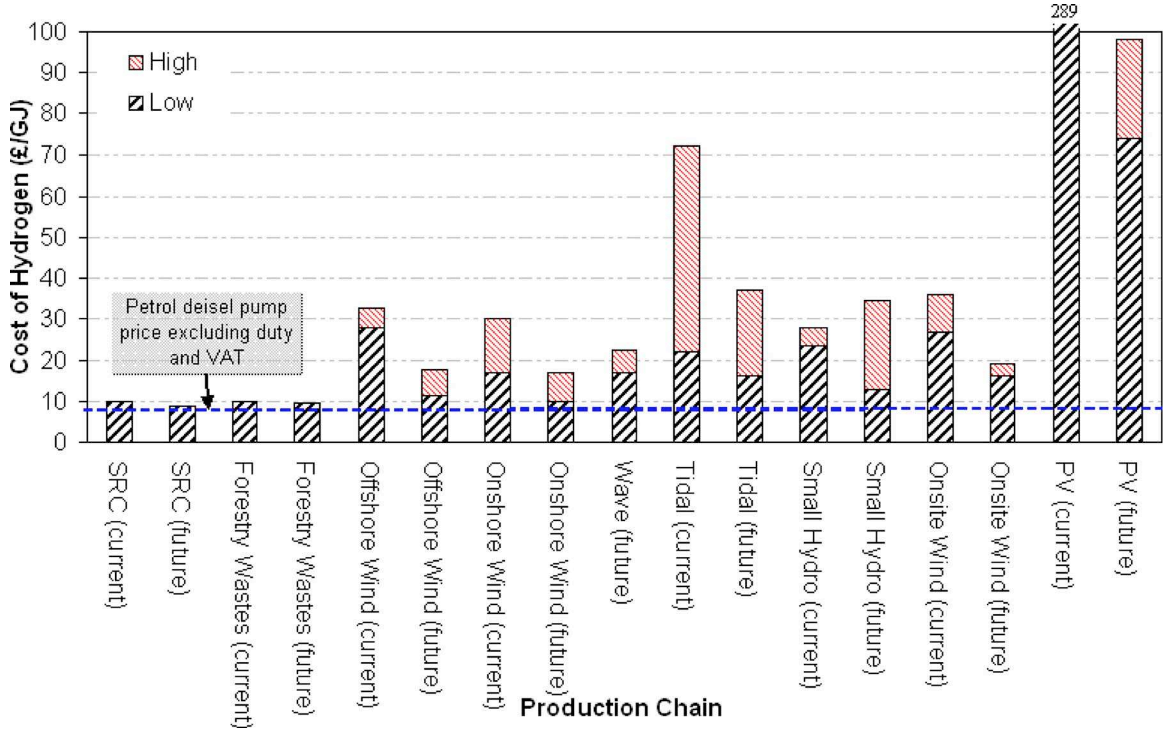

Fig. 2 Comparison of estimated current and midterm costs of hydrogen production in UK, as delivered to user. Figure produced by using the data taken from Refs. [18,19].

the steam reforming of natural gas. However, GHG and other emissions are likely to be higher for hydrogen produced from biomass than that produced from wind energy [17].

4.2 Future Hydrogen Scenarios for the UK. In this context, a study was conducted by Hart et al. [16] for the UK Department of Transport, which examined the potential implications of a large-scale introduction of hydrogen-fueled vehicles into the transport fleet in the UK over the period 2000–2050. Three cases have been considered based on the penetration of different vehicle class (i.e., high efficiency vehicles (HEVs), FCVs, and H_2-ICEs) into the market at different spans of times under Global Sustainability[1] (GS) and World Market[2] (WM) scenarios.

4.1.1 Case 1. This is a base case in which it is assumed that the hydrogen is produced from renewable energy sources, and the GS and WM scenarios are intended to investigate the renewable resources required to supply hydrogen, thus estimating the potential for the UK to supply it using its indigenous resources. Within the two base case scenarios, a high uptake of some form of HEVs is assumed from 2004, as shown in Fig. 3. The number of vehicle kilometer traveled (vkm) is used as a proxy for the number of vehicles on the *Y*-axis, as it enables energy use and CO_2 emissions to be calculated and a comparison to be made against the best expected conventional technology. These factors combine to produce a highly positive environmental base case under the GS scenario, though a less positive one under WM scenario.

4.1.2 Case 2. In addition to HEVs, as included in Case 1, the penetration of FCVs in the market by the year 2020 is also considered in this case. The FCVs are assumed to have become sufficiently attractive that consumers wish to buy them in all vehicle

[1]The scenario in which vehicle distance driven increases gradually from 2000 but then peaks and drops slightly to 2050.

[2]The scenario in which vehicle distance driven increases throughout the period up to 2050.

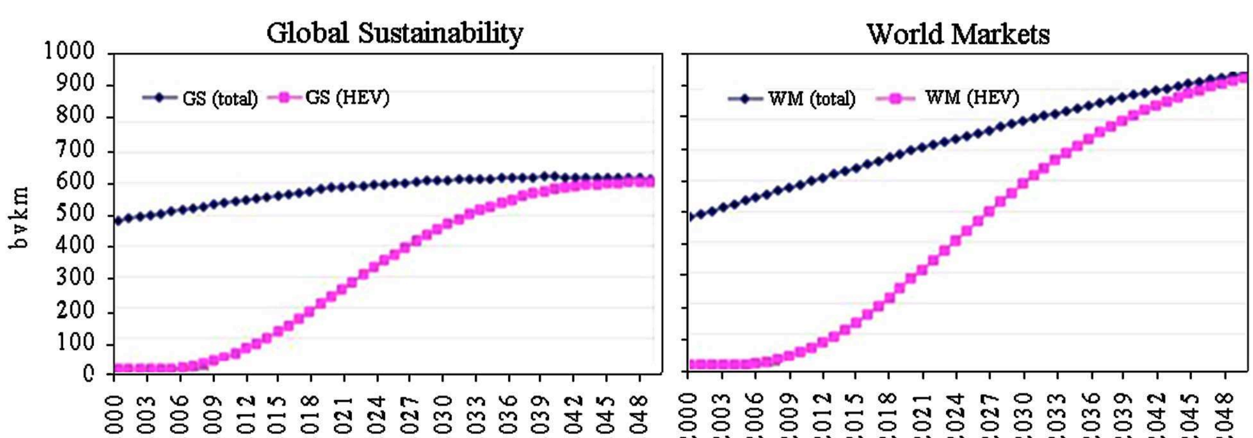

Fig. 3 Total vehicle kilometer traveled under the base case (representing Case 1) penetration of HEVs in the GS and WM scenarios [17]. This figure is based on the assumption that the penetration of the HEVs into the world market is from 2004.

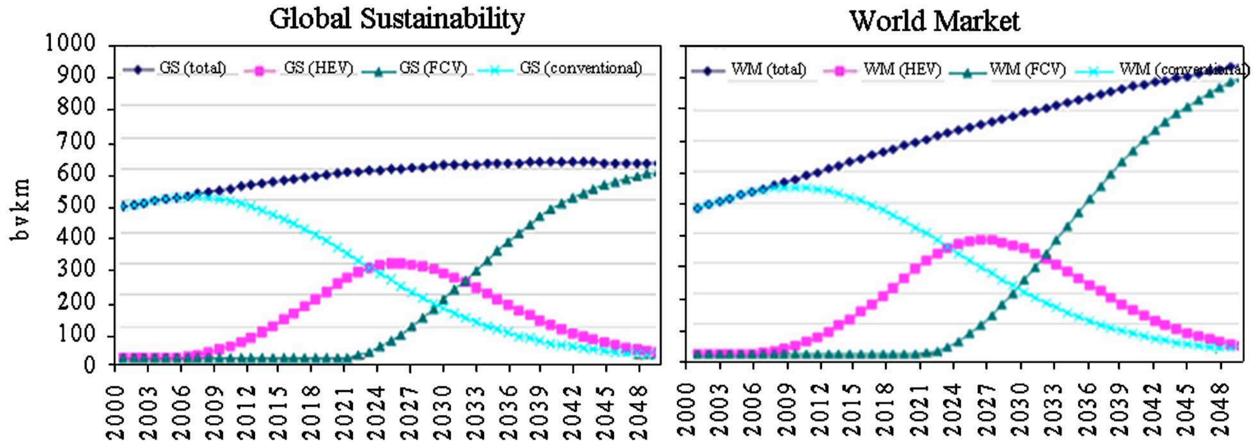

Fig. 4 This figure represents the Case 2 where the penetration of HEVs and FCVs in the GS and WM scenarios is considered [17]. It is assumed the HEVs falls from 2020 onward due to their substitution by FCVs, and FCVs are assumed to achieve a penetration close to 100% of the vehicle stock by 2050.

categories, though heavy goods vehicle uptake occurs later than other vehicle classes, as the advantages of fuel cells are less clear cut in the near term. All fuel vehicles are fueled by hydrogen from renewable resources, and all other vehicles by conventional fuels. The effect under GS and WM scenarios is shown in Fig. 4, which demonstrates that the fall of HEVs from 2020 onwards is due to their substitution by FCVs. The FCVs are assumed to have a very rapid penetration, enabling them to achieve close to 100% of the vehicle stock by 2050.

4.2.3 Case 3. In this case, the hydrogen is introduced in internal combustion engines only by the year 2008, and the analysis is performed under the GS and WM scenarios. It is on the assumption that FCVs do not meet the cost and performance targets required for their future uptake, but the hydrogen is introduced for environmental policy reasons. The effect under both scenarios is shown in Fig. 5, which shows the increase in H_2-ICEs and decrease in conventionally fuelled vehicles. While H_2 ICEs also provides nearly 100% of the vehicle stock in 2050, about ten more years are required for the FCVs due to the less compelling consumer value proposition. Vehicle classes (HEV, FCV, and H_2-ICE) modeled in the above cases are cars, light good vehicles (LGVs), heavy good vehicles (HGVs), and public service vehicles (PSVs). The average energies use by car, PSV, LGV, and HGV are assumed as 2.79 MJ/km, 8.80 MJ/km, 3.30 MJ/km, and 9.74 MJ/km, respectively, for the base case in 2004 [17].

4.3 Renewable Hydrogen Production Potential and Vehicle Fuel Demand. To realize a transformation to a major hydrogen economy and for long-term solution of GHG emissions, it is desirable to produce hydrogen from renewable energy sources. The hydrogen production potential from renewable resources (see Fig. 1 for resources) in conjunction with the energy requirements under WM and GS scenarios are shown in Fig. 6. It shows that a significant proportion of the energy potential is used for fuel under these scenarios, though under GS using FCVs remains 1000 PJ in 2050 [17]. Since this is hydrogen resource, converted at an efficiency of approximately 50% over the fuel chain, the raw renewable energy is around double that amount at 2000 PJ (see Fig. 6).

5 Prediction of CO_2 Emissions From Various Transportation Fuels Using GHGenius Model

The GHGenius model is used for analyzing the emissions of many contaminants associated with the production and use of conventional and alternative transportation fuels. This model was developed by Dr. Mark Delucchi for Natural Resources Canada, for the life-cycle assessment of various transportation fuels. The ap-

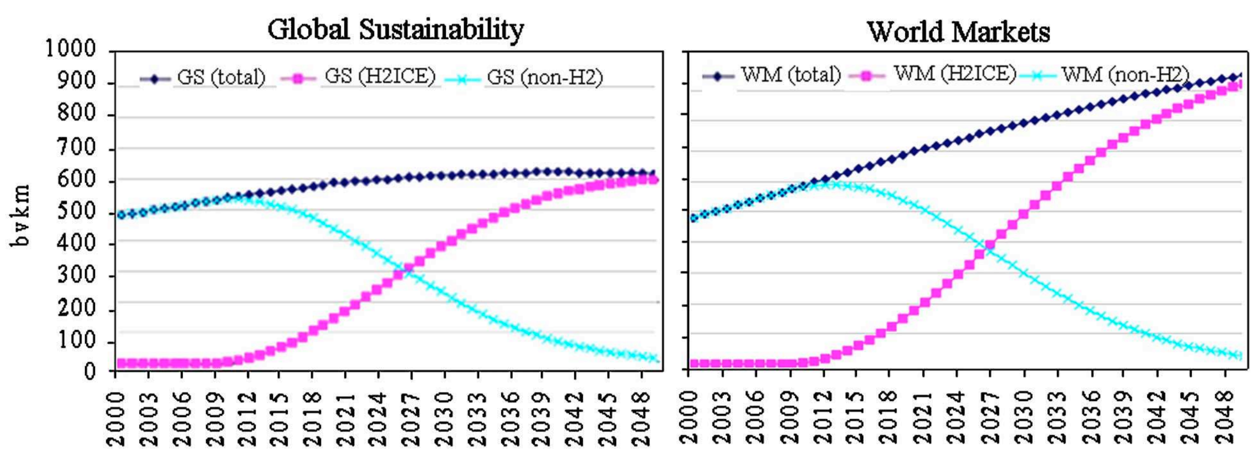

Fig. 5 This figure is representing the Case 3 where the penetration of H_2-ICEs and replacement of conventionally fueled vehicles under the GS and WM scenarios is considered [17]. This figure shows that H_2-ICEs provide nearly 100% of the vehicle stock in 2050, whereas FCVs require ten more years than H_2-ICEs due to the less compelling consumer value proposition.

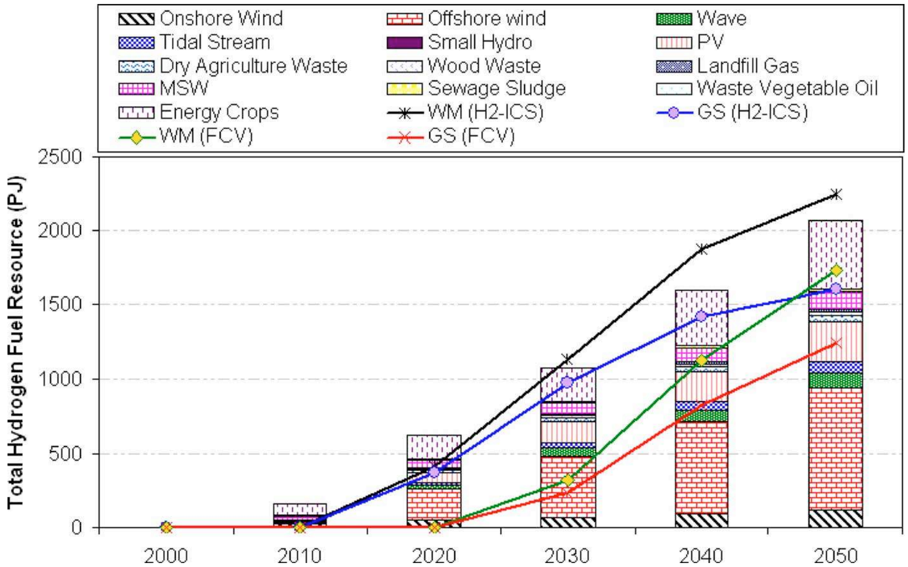

Fig. 6 Renewable hydrogen production potential compared with fuel requirements of hydrogen vehicle under WM and GS scenarios. The data have been taken from Ref. [17]. The energy crop potential in 2050 corresponds to planting 4 Mha of land with lignocellulosic crops with an average yield of 15 odt/ha/y and an energy content of 18 GJ/odt.

proximate CO_2 emission trends were estimated considering various factors such as vehicle operation, fuel dispensing, fuel production and distribution, feedstock transport and production, and vehicle assembly and production for various transportation fuels, viz., gasoline, methanol, mixed alcohol, natural gas, hydrogen, and hythane. The CO_2 equivalent emissions for various fuels and various life-cycle processes are shown in Fig. 7. Also, the percentage change in life cycle emissions (g/km) from alternative-fuel vehicles relative to conventional gasoline vehicles can be inferred from Fig. 7. In the case of hydrogen produced by reforming natural gas, there is an improvement of around 22.3% GHG emissions relative to gasoline life cycle. Other renewable fuels such as natural gas and methanol shows an increase in GHG emissions by 23.4% and 10%, respectively, thereby showing that in long run hydrogen seeks out to be a solution for increasing GHG emissions.

6 Conclusions

This paper discussed the various economic, technical, and societal barriers in the introduction of hydrogen in the future transport sector. Hydrogen is emerging as one of the most promising

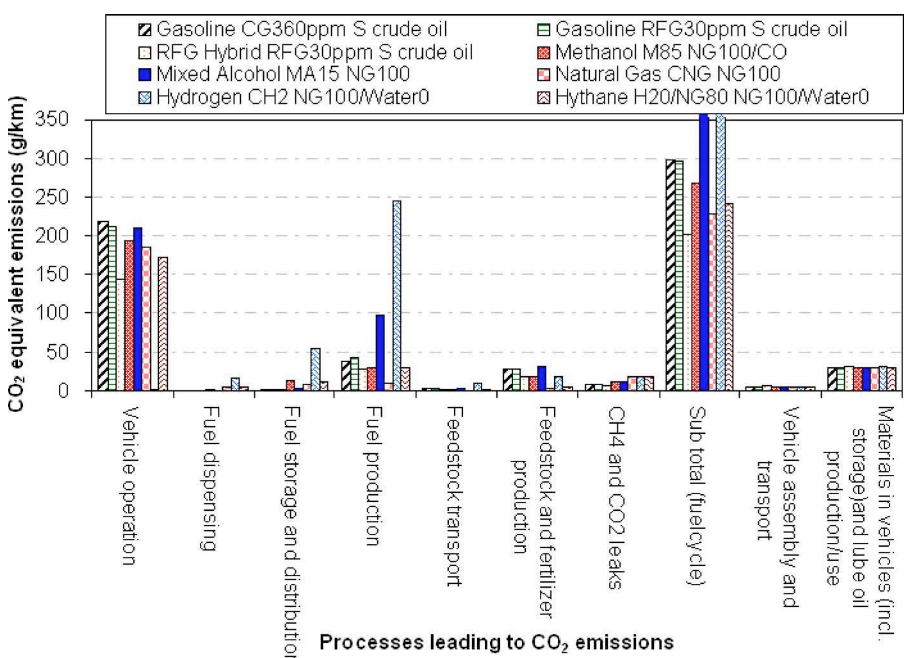

Fig. 7 Comparison of equivalent CO_2 emissions for light duty ICEV's with the other transportation fuels. The data have been taken from GHGenious model, which calculates the CO_2 emissions for various fuels taking into consideration their production life cycle and use.

fuels in the future energy mix. There is no alternative fuel option available with the same advantages that could be introduced in the future transport sector. The analysis showed that a substantial decrease in the average energy consumption of the transport fleet is a necessary condition if the long-term GHG reduction targets essential to combating climate change are to be met. Although all the three cases discussed under GS and WM scenarios are based on many bold assumptions, the results can be considered as indicative. If significant reductions in road transport carbon dioxide are sought, then biofuels and renewably generated hydrogen are two key options that could be pursued. Despite the probable slow uptake of such options, they could lead to very low carbon dioxide emissions from the transport sector in the very long run. In the short- or medium-term, low carbon hydrogen use in transport will be limited because of number of barriers discussed above. However, (a) to develop and introduce cost-effective, durable, safe, and environmentally desirable fuel cell systems, (b) to improve the hydrogen storage and transport facilities, (c) to develop the infrastructure to provide hydrogen for the light-duty-vehicle users, (d) to reduce sharply the costs of hydrogen production from renewable energy sources over a time frame of decades, and (e) to improve the storage and transport facilities are the fundamental, technological and economical challenges for hydrogen-fueled transportation. The results from life-cycle assessment of various fuels using the software GHGenius also gives a promising future for hydrogen production using nuclear or fossil feed stocks. It can be inferred from the study that there is an improvement of about 22.3% in life-cycle emissions for hydrogen fuel compared to the gasoline fuel life cycle. In long term, other renewable fuels such as natural gas and methanol are found to have greater GHG emissions for their life cycle. It is hard to say if and when hydrogen will penetrate the energy market but it can be said that the development under constrained conditions, which leads to higher energy conversion efficiencies and energy savings, will be an advantage for the introduction of hydrogen in the future transportation sector. Also, switching to renewable hydrogen fuel in the transport sector seems an attractive option, which will mitigate the threat of climate change.

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