

The Feasibility of a “Hydrogen Society”

Satoshi Matsuda ^α & Hiroshio Kubota ^ο

Abstract- The Japanese government has expressed that Japan intends to become a “hydrogen society” where homes and fuel-cell cars are powered by hydrogen, which is regarded as the CO₂ emissions-free energy source, and has laid out plans for a “hydrogen highway” peppered with fueling stations, all in time for the Tokyo 2020 Olympics [1].

And also, a remarkable development of Fuel-Cell Vehicles (FCVs) has been achieved; for instance, Toyota's FCV, “Mirai,” which launched in 2014 after two decades of tireless research, recently rolled out in the US and Europe.

This situation may give many people an impression that a “hydrogen society” will come true in the near future. But is this really true? In fact, there are so many difficulties to overcome before a “hydrogen society” is realized. This study intends to examine the feasibility of a “hydrogen society” from the stand points of the energy sources (primary energies), energy balance, efficiency, and cost.

I. INTRODUCTION

The Japanese government decided in June 2015 to construct a “hydrogen society,” in which everything from buses to cars to homes will be powered by hydrogen, which is regarded as an environmentally-friendly zero-emission fuel. At first, it is planned that hydrogen-fueled buses will ferry athletes and fans around the 2020 Tokyo Olympic event sites. And in March 2016, the “Fukushima new energy initiative” was announced, in which a hydrogen producing plant using wind power with a capacity of 10 thousand kW will be constructed and will supply hydrogen for the 2020 Tokyo Olympics. Toyota has already developed the hydrogen-fueled car “Mirai” (“Future” in English), which went on sale in Japan in late 2014. Honda and Nissan also have similar Fuel-Cell Vehicles (FCVs) in the works [1]. Many people believe that hydrogen is “environmentally-friendly energy” because “it does not emit any carbon dioxide” just as Japanese Prime Minister Shinzo Abe said. But this is only one side of the story behind hydrogen. It is very important to distinguish clearly between an energy source and an energy carrier; fossil fuels (i.e. oil, coal, natural gas), solar, wind, or nuclear fits into the category of energy source (“primary energy”), whereas hydrogen and electricity are energy carriers (“secondary energy”) which are produced by consuming the primary energies and are used for energy transportation or storage. Thus, whether or not a “hydrogen society” can be realized in the future depends on the following points: Where will the hydrogen for the “hydrogen society” come from? How is

the energy efficient as a whole system? What is the cost of hydrogen? In fact, there are other problems such as security effort and infrastructure improvement due to the characteristics of hydrogen as a chemical substance. In this study, the feasibility of a “hydrogen society” is examined from the viewpoint of science, technology, and economics.

II. THE HISTORY OF THE DEVELOPMENT OF HYDROGEN USE AND FUEL CELL

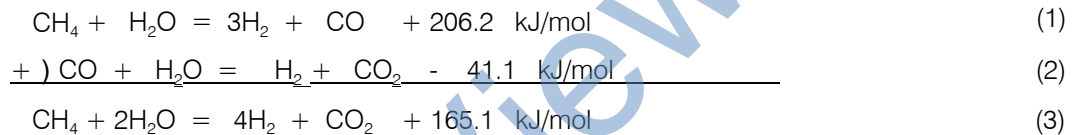
The first research on “hydrogen energy” in Japan started in 1974, the year following the first “oil shock” in 1973, by Japanese government as a part of a new energy-development program called the “Sunshine Project”. There were four major research themes in the project, i.e. solar, geothermal, coal, and hydrogen, which were regarded as alternative energies to oil at that time [2]. Thus, hydrogen energy development has a history of more than 40 years. In 1993, a revised version of the new energy development program called the “New Sunshine Project” was launched, in which six research themes were adopted, i.e. solar, geothermal, wind, coal, power generation by fuel cell, and ceramic gas turbine [3]. In that year, the downsizing of the polymer electrolyte fuel cell (PEFC) was achieved successfully in Canada, which accelerated the development of fuel cells. In the same year, several Japanese auto makers, such as Toyota and Nissan, started the development of fuel-cell vehicles (FCV). In the 2000s, hydrogen received remarkable attention around the world due to the oil price increase and global warming. Several big budgets were spent for hydrogen energy development in Japan, and also in 2000 the transit authorities of several European cities (Amsterdam, Barcelona, Hamburg, London, etc.) decided to participate in a joint fuel-cell bus and hydrogen fleet test to significantly enhance the development of Clean Urban Transport for Europe. They joined with leading infrastructure companies such as BP and Norsk Hydro, and with Daimler Chrysler and its bus subsidiary “Evobus”. In order to strengthen the development of the new technology and to support the efforts of the transport companies, in 2001 the European Commission decided to support this project with one of largest budgets ever for a single research and demonstration project [4]. In addition, the Multi-Annual Work Program(MAWP) for the second phase of the Fuel Cells and Hydrogen Joint Undertaking (FCH2 JU) under the EU's new funding program for research and innovation, Horizon 2020, is now ongoing. The total

Author ^α: Dept. of Appl. Chem. and Biochemical Eng., Faculty of Eng., SHIZUOKA University, e-mail: matsuda.satoshi@shizuoka.ac.jp

Author ^ο: Tokyo Institute of Technology, Tokyo.

investment for this seven-year program is expected to be about 1,330 million Euro [5]. On the other hand, the DOE (Department of Energy) has played a major role in developing hydrogen and fuel-cell technologies in the US. In the 2015 Fiscal Year (FY), congress appropriated approximately \$117 million for the DOE Hydrogen and Fuel Cells Program in addition to \$30 million for solid oxide fuel cell related activities [6]; although, the budget was reduced to nearly half of about \$300 million during the FYs of 2007 to 2009 when the "Hydrogen Fuel Initiative" was driven forward under President Bush [7].

However, the infrastructure construction for a "hydrogen society" is still quite preliminary around the world, e.g. in Japan, in 2015, there were only 15 hydrogen stations, most of which were not commercial facilities but demonstration ones, because the cost for construction as well as operation is very high. The trials of hydrogen use in European and US cities have not been successful so far. This fact would imply that something is wrong with the concept of a "hydrogen society".



The same amount of CO_2 is produced as CH_4 burns ($\text{CH}_4 + 2\text{O}_2 = 2\text{H}_2\text{O} + \text{CO}_2$) in this process, and this is not an exceptional case but a general phenomenon, meaning that hydrogen from fossil fuels or biomass is by no means a "zero-emission fuel." If CCS (Carbon dioxide Capture and Storage) is adopted, in order for the hydrogen produced from these kinds of raw materials containing carbon to be a "zero-emission fuel," the limiting condition for the feasibility of hydrogen use would be naturally stricter than that of a usual situation without CCS. In this case, the total energy efficiency, as well as cost, should be compared between direct use of fossil fuels or biomass resources and their utilization via hydrogen.

The second major source of hydrogen is water, and the "hydrogen from water" system is regarded as the "genuine" zero-emission energy system. So far, there have been many methods to produce hydrogen from water: e.g. electrolysis, photolysis, thermal decomposition, microbial process, and so on. At present, only the electrolysis of water is practically feasible as the hydrogen producing process from the stand point of reaction rate and energy efficiency. That is why the electrolysis of water using wind power was adopted in the "Fukushima new energy initiative" stated above. There is, however, a crucial problem in this process: i.e. electricity as the secondary energy is consumed for hydrogen production, thus the hydrogen produced inevitably becomes "tertiary" energy which is more expensive and inefficient than the secondary one. In addition, the final use of hydrogen is generally a "fuel cell," which is a kind of electricity generator using the

III. THE WHOLE PICTURE OF THE HYDROGEN ENERGY SYSTEM

Since there is no adequate amount of hydrogen gas as an energy source in nature, hydrogen is not a primary energy but a secondary (or even tertiary) one produced from the primary energies, as is stated above. There are two major hydrogen sources; the first one is fossil fuels or biomass resources containing carbon, the other is water.

In the former case, it is usual that the carbon contained in the resources is converted into CO_2 in the process of hydrogen production: e.g. At present the most inexpensive way to produce hydrogen is steam reforming of methane, which is the major component of natural gas, described by the chemical reaction formulae, as the following:

chemical reaction of hydrogen and oxygen, because the energy efficiency of the fuel cell is much better than direct combustion use of hydrogen. Then, a peculiar process appears as a result: electricity \rightarrow hydrogen \rightarrow fuel cell \rightarrow electricity. This cycle is nothing but for the wasteful expenditure of electricity. The only one advantage of hydrogen for electricity is that hydrogen can be stored more easily than electricity. In this case, the energy efficiency of hydrogen use must be discussed as an electricity storage system, not a as zero-emission energy system.

The hydrogen production from water without electricity is possible, at least in principle, e.g. photolysis of water using sunlight. It was reported that the solid solution of GaN: ZnO can act as a photocatalyst of complete decomposition of water using visible light [8]. But, the energy conversion efficiency of solar energy to hydrogen is about 0.2%, and the highest value achieved so far is 1.1% [9]. The simplest way to generate electricity from sunlight is beyond doubt solar cell, of which energy efficiency is usually more than 15% (most practical items). Since the hydrogen from sunlight is converted to electricity via fuel cell, of which energy efficiency is about 60%, the energy conversion efficiency of solar to hydrogen must be more than 25% ($=15/0.6$), meaning that the situation would be far from a feasible condition. In addition, solar cell has more than 200 times higher energy production than thermal power generation with a woody biomass as a means for obtaining electricity from solar energy [10]. The essential reason for this fact is that biomass production is strictly limited by the efficiency of photosynthesis (solar energy

accumulated in biomass / total quantity of solar radiation), which is generally about 1% or less on the basis of the annual average. There is a similar situation of the electricity generation from sunlight via hydrogen. Thus, it is very difficult to find a rational reason for adopting hydrogen production via photolysis of water using sunlight as a means of electricity generation from solar energy.

In short, the hydrogen energy system has four phases: 1) The primary energy: fossil fuels, biomass resources, renewable energies such as solar and wind, or nuclear. 2) Hydrogen production: the source of hydrogen and the method of production, e.g. steam reforming of fossil fuels, or electrolysis of water. 3) Transportation and storage: Since it is very easy for hydrogen to leak and explode, the transportation and storage of hydrogen must be done with extreme caution, which will naturally be the factors for increasing in cost. In addition, since it is difficult to liquefy hydrogen, very high pressure would be necessary, e.g. a 700 atm tank is adopted as a hydrogen storage system of Toyota's "Mirai," of which compression work for this system is naturally very large. 4) Utilization: Generally, fuel cell is used because it is the most energy effective way to use hydrogen, but the final product is electricity, which leads to another aporia if hydrogen is produced by the electrolysis of water (electricity to electricity via hydrogen). These four points must be considered when the whole picture of the hydrogen energy system is discussed.

IV. THE ENERGY EFFICIENCY OF THE WHOLE HYDROGEN SYSTEM

In this section, the energy efficiency of the hydrogen system as a whole is discussed in two cases.

Case 1: Hydrogen is produced by electrolysis of water.

In this case, the energy efficiency of the hydrogen use should be estimated as an electricity storage system, because the utilization of the hydrogen system as an effective way to store electricity is considered as the sole condition for the hydrogen system to be feasible according to the discussion in the previous section.

The energy efficiency of the electrolysis of water (= the energy efficiency of electricity to hydrogen) is usually 60 to 75%, whereas those of recently developed processes with high temperature and pressure would be 83 to 90%, but there will not be a large difference as a net efficiency between them if the energy required for rising temperature or pressure is taken into account. On the other hand, the theoretical maximum energy efficiency of fuel cell is 82%, whereas it is about 52% in practice. Thus, the overall energy efficiency of this hydrogen system would be $0.8 \times 0.8 = 0.64$ in the best-case scenario, under a more realistic assumption, the value would be $0.6 \times 0.6 = 0.36$, which is lower than that

of the pumped-storage power generation, about 0.7 in actual use. In addition, since there are so many electricity storage systems with high energy efficiency being proposed and developed, the hydrogen system using electrolysis of water has little superiority as an electricity storage system. And also, a very huge electricity storage system might not be necessary if a "smart-grid strategy" is established in the future. In short, the hydrogen use as an electricity storage system will be very limited except for a special case, such as isolated island.

There is a concept proposed that hydrogen is generated by the electrolysis of water in remote areas and is transported to Japan. In this case, hydrogen is first converted to other chemical compounds such as methylcyclohexane because liquefied hydrogen is too dangerous to transport using a tanker. In this case, since four steps are required (electricity \rightarrow hydrogen \rightarrow another compound \rightarrow hydrogen \rightarrow electricity), the overall energy efficiency would be $0.8^4 = 0.41$, even if the energy efficiency of each step is ideally 80%; and, if these values are as practical as 60%, the overall value would be $0.6^4 = 0.13$ without energy required for transportation or compression, indicating that there is little feasibility in the system in which hydrogen is produced by the electrolysis of water.

If hydrogen is first liquefied, compression work is necessary; the practical energy consumption for hydrogen liquefaction is about 1 kWh/Nm³-H₂ with the energy efficiency of 30% since the theoretical minimum work is 0.35 kWh/Nm³-H₂. Since the standard combustion heat of hydrogen is - 285.83 kJ/mol, the total energy contained in 1 Nm³-H₂ is 12,769 (=1,000/22.4 \times 285.83) kJ. If the power generation efficiency is 40%, 1 kWh is corresponding to 9,000 (=3,600 kJ/kWh/0.4) kJ. In this case, about 70% (=9,000/12,769) of energy contained in hydrogen will be consumed in the liquefaction process.

As stated above, a 700 atm (70 MPa) tank is adopted as a hydrogen storage system of Toyota's "Mirai" for instance, then the required pressure at a "hydrogen station" is about 80 MPa, and the tank must be cooled to - 40°C to maintain the temperature in the tank during the compression work under 85°C. Therefore, the total energy required at a "hydrogen station" would be at least 60 to 70% of the energy contained in hydrogen, which is almost the same as the energy required for liquefaction, indicating that the concept of hydrogen production by the electrolysis of water at remote areas has very little feasibility as a whole system because the total energy efficiency is too low (or even minus). The low energy efficiency inevitably leads to a high cost of energy.

Case 2: Hydrogen is produced by the steam reforming of methane.

The overall reaction (3) is endothermic, and in addition, heat energy is required to raise the temperature up to around 900 °C, thus the total amount of CO₂ emissions at a practical plant of steam reforming of methane is usually 0.9 kg-CO₂/Nm³-H₂. 0.9 kg-CO₂ is 20.45 (=900 g/44.0 g/mol) mol-CO₂, and 1 Nm³-H₂ is 44.64 (= 1,000 L/22.4 L/mol) mol-H₂, thus 0.458 (= 20.45/44.64) mol-CO₂/mol-H₂ is emitted, and the more the amount of CO₂ would be produced if the heavier hydrocarbon is used as raw material for hydrogen. The standard enthalpy change of formation of CO₂ is -393.5 kJ/mol, and the standard combustion of H₂ is -285.83 kJ/mol, thus, in the case of methane, 63.0 % (= (-393.5)/(0.458)/(-285.83)) of hydrogen energy is consumed in the process of steam reforming of methane. It should be noted that the current purpose of hydrogen production by steam reforming of methane is not to obtain an energy carrier, but to produce raw material for chemicals such as ammonia. If the purpose of hydrogen is for energy carrier, the hydrogen production process using carbon containing materials such as hydrocarbon or biomass must be much more energy-efficient than steam reforming. But, so far, there is no other methods found out, probably because the chemical bond energy of C-H is relatively large (412 kJ/mol) compared with other major chemical bonds such as C-O (360 kJ/mol), C-C (347 kJ/mol), and C-N (280 kJ/mol), meaning that severe conditions (high temperature, etc.) would be necessary for the cleavage of C-H chemical bond, which inevitably leads to large energy input.

If CCS (Carbon dioxide Capture and Storage) is adopted in order for the hydrogen produced from these kinds of raw material to contain carbon to be "zero-emission fuel," the energy balance would be much worse, whereas the cost would be much higher. At present, CCS process is not put into practical use, even in the case that fossil fuels or biomass are used directly due to high cost and low energy efficiency. It is obvious that the hydrogen production with CCS would have almost no feasibility, at least in the near future.

V. COMPARISON OF THE RUNNING COST OF VEHICLES

In this section, the running cost (in Japanese yen/km) of several kinds of vehicles will be compared.

- 1) Fuel-efficient gasoline vehicles: If the fuel consumption is 25 km/L-gasoline, and the price of gasoline is 140 yen/L (100 yen≒1 US dollars), the running cost would be **5.6** (=140/25) yen/km.
- 2) Electrical vehicles (EV): The energy consumption of a practical EV (by Nissan) is 6 km/kWh. Suppose that the average cost of domestic electricity is 24 yen/kWh, and 10 % of the battery charge cost is added, then the running cost would be **4.4** (= (24 × 1.1)/6) yen/km.

- 3) Fuel-cell vehicles (FCV) : Toyota's "Mirai" can travel 650 km on 4.6 kg-H₂, and the price of H₂ was 1,080 yen/kg-H₂ (hearing result at a hydrogen station by the authors), then the running cost would be **7.64** (= 1080/(650/4.6)) yen/km. It should be noted that this current price is the most inexpensive one of hydrogen that is made from natural gas, and the price would be several times higher if hydrogen were made by electrolysis of water. In addition, the major part of the hydrogen cost is occupied by that of the compression process, which cannot be reduced from whatever hydrogen is made.

This comparison of the running cost indicated that FCV is the most expensive vehicle, not only in the manufacturing cost, but in the running one as well. Even though the results of the cost estimation would be varied according to preconditions, the general tendency would not change, because the energy efficiency of EV is the best among these vehicles. The only advantage of FCV at present, is that it has a longer cruising distance than EV; but, this problem would be irrelevant after cartridge type of batteries are developed, which are very quick-release and can be exchanged at gas stations, which exist everywhere, not at hydrogen stations, which are sparsely distributed due to high cost. And the social-infrastructure development for battery charge is much easier than that of hydrogen, which is realized at a rapid rate mainly in European cities. In addition, the superiority of EV would be unchallenged if wireless power transmission technology is put to practical use.

The authors anticipate that fuel-efficient vehicles using fossil fuels (mainly gasoline and natural gas), their hybrid cars, and EV will compete against each other as long as the prices of fossil fuels are relatively low; but, EV will become predominant when the major part of primary energy is electricity from renewable energies such as wind and solar, after fossil fuels are exhausted. Even then, the superiority of EV over FCV will be unchanged, because the direct use of electricity is beyond all doubt much more preferable in energy efficiency and cost than the multistep use via hydrogen. In other words, FCV will have no chance to show off in any period for practical purposes, indicating that hydrogen will be never used, at least as an energy carrier, for vehicles.

VI. CONCLUSION

It should be emphasized that hydrogen is never an energy "source" of CO₂ emissions-free, but only an energy "carrier" that is produced from primary energies. Thus, the feasibility of a "hydrogen society" must be examined from the stand point of whether or not hydrogen is really a good energy carrier compared with other secondary energies, such as electricity, in terms of energy efficiency, cost, manageability, and security: 1) Hydrogen from carbon containing materials such as

fossil fuels and biomass has no meaning as a means of CO₂ emissions reduction, because CO₂ is certain to be released from the hydrogen production processes, and the feasibility will be much worse if CCS is adopted in order to avoid the CO₂ emissions. If fossil fuels or biomass are used as a primary energy, the energy efficiency, as well as the cost, should be compared between the direct use of them, e.g. combustion for thermal energy, and the multistep use via hydrogen. 2) If water is the source of hydrogen, the problem is how to obtain hydrogen from water: In the case that hydrogen is produced by electrolysis of water, the purpose of the hydrogen use must be limited to a means of electricity storage, because the final product of hydrogen use is electricity using fuel cell in almost all cases; and thus, the direct use of electricity is naturally much better than the multistep use via hydrogen. In this case, therefore, the efficiency as an electricity storage system must be examined among many other methods and systems. But, the overall energy efficiency of hydrogen use as an electricity storage system is rather low because of multistep, as shown above. The only possible option is that hydrogen is produced from water without electrolysis, e.g. photolysis, thermal decomposition, and microbial process using solar energy. However, the energy efficiency of hydrogen production in this option must be much higher than that of solar cells in practical use, because the final product of the hydrogen system is usually electricity using fuel cells. So far, it is likely that the technological difficulty in producing hydrogen using sunlight other than electrolysis of water is difficult to overcome.

All data and discussions stated above indicate that the possibility of a "hydrogen society" to be feasible is just about nil. An appropriate energy carrier should be selected, not by illusion or myth, but by solid evidence grounded in science, technology, and the economy.

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Early View