Briefing on the state of the art of Hydrogen Technology (prepared by R.Chahine/Hydrogen Research Institute, UQTR)

Vision & Transition: A sustainable energy system using electricity and hydrogen as carriers and providing safe, reliable and secure energy supply. This vision is built on meeting two expectations: 1- that on the supply side hydrogen can be produced cleanly and economically from primary energy sources; and 2- that on the demand side hydrogen applications, like fuel cells for transportation, can effectively compete with the alternatives. Unlike other energy systems, both expectations should be met; one will not work without the other and there are major challenges that must be overcome before they become a reality. The transition to the hydrogen economy will not be simple or straightforward, its course will be dictated on one hand by our ability to overcome the major economical and technical hurdles spread across the whole spectrum of the hydrogen economy namely production, storage & distribution and use; and on the other hand by advancements in competing technologies that are not hydrogen dependent.

Challenges of the hydrogen economy: In a recent exhaustive report[1] published by National Academy of engineering and emphasizing hydrogen-fuelled transportation, the four most fundamental technological and economic challenges were resumed as follows:

1. [illegible]
[illegible]

case, production costs for small production units

Hydrogen as energy carrier: Hydrogen does not occur in nature as the fuel H_2. Rather, it occurs in chemical compounds like water or hydrocarbons that must be chemically transformed to yield H_2. Hydrogen, like electricity, is a carrier of energy, and like electricity, it must be produced from a natural resource. At present, most of the world's hydrogen is produced from natural gas by a process called steam reforming. However, producing hydrogen from fossil fuels would rob the hydrogen economy of much of its raison d'être: Steam reforming does not reduce the use of fossil fuels but rather shifts them from end use to an earlier production step; and it still releases carbon to the environment in the form of CO_2. Thus, to achieve the benefits of the hydrogen economy, we must ultimately produce hydrogen from non−fossil resources, such as water, using a renewable energy source.

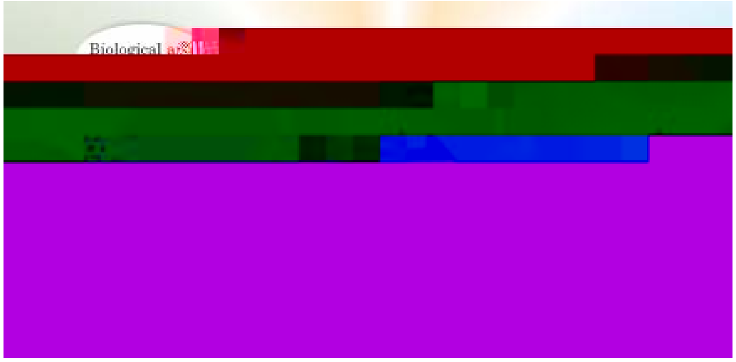

Figure 1. The hydrogen economy as a network of primary energy sources linked to multiple end uses through hydrogen as an energy carrier. Hydrogen adds flexibility to energy production and use by linking naturally with fossil, nuclear, renewable, and electrical energy forms: Any of those energy sources can be used to make hydrogen.

Figure 1 depicts the hydrogen economy as a network composed of three functional steps: production, storage, and use. There are basic technical means to achieve each of these steps, but none of them can yet compete with fossil fuels in cost, performance, or reliability. Even when using the cheapest production method—steam reforming of methane—hydrogen is still four times the cost of gasoline for the equivalent amount of energy. And production from methane does not reduce fossil fuel use or CO_2 emission. Hydrogen can be stored in pressurized gas containers or as a liquid in cryogenic containers, but not in densities that would allow for practical applications—driving a car up to 500 kilometers on a single tank, for example. Hydrogen can be converted to electricity in fuel tETu5(e) quantities from non−fossil natural resources. The most promising route is splitting water, which is a natural carrier of hydrogen. It takes energy to split the water molecule and release hydrogen, but that energy is later recovered during oxidation to produce water. To eliminate fossil fuels from this cycle, the energy to split water must come from non−carbon sources, such as the electron−hole pairs excited in a semiconductor by solar radiation, the heat from a nuclear reactor or solar collector, or an electric voltage generated by renewable sources such as hydropower or wind.

The direct solar conversion of sunlight to H_2 is one of the most fascinating developments in water splitting. Established technology splits water in two steps: conversion of solar radiation to electricity in photovoltaic cells followed by electrolysis of water in a separate cell. The two processes, however, can be combined in a single nanoscale process: Photon absorption creates a local electron−hole pair that electrochemically splits a neighboring water molecule. The efficiency of this integrated photochemical process can be much higher, in principle, than the two sequential processes. The technical challenge is finding robust semiconductor materials that satisfy the competing requirements of nature.

Water can be split in thermochemical cycles operating at elevated temperatures to facilitate the reaction kinetics. Heat sources include solar collectors operating up to 3000°C or nuclear reactors designed to operate between 500°C and 900°C. More than 100 types of chemical cycles have been proposed. At high temperatures, thermochemical cycles must deal with the tradeoff between favorable reaction kinetics and aggressive chemical corrosion of containment vessels. Separating the reaction products at high temperature is a second challenge: Unseparated mixtures of gases recombine if allowed to cool. But identifying effective membrane materials that selectively pass hydrogen, oxygen, water, hydrogen sulfate, or hydrogen iodide, for example, at high temperature remains a problem. Dramatic improvements in catalysis could lower the operating temperature of thermochemical cycles, and thus reduce the need for high−temperature materials, without losing efficiency.

Bio−inspired processes offer stunning opportunities to approach the hydrogen production problem anew. The natural mechanisms for producing hydrogen involve elaborate protein structures that have only recently been partially solved. …The hope is that researchers can capitalize on nature's efficient manufacturing processes by fully understanding molecular structures and functions and then imitating them using artificial materials.

Storing hydrogen: Storing hydrogen in a high−energy−density form that flexibly links its production and eventual use is a key element of the hydrogen economy. The traditional storage options are conceptually simple—cylinders of liquid and high−pressure gas. Industrial facilities and laboratories are already accustomed to handling hydrogen both ways. These options are viable for the stationary consumption of hydrogen in large plants that can accommodate large weights and volumes. Storage as liquid H_2 imposes severe energy costs because up to 40% of its energy content can be lost to liquefaction.

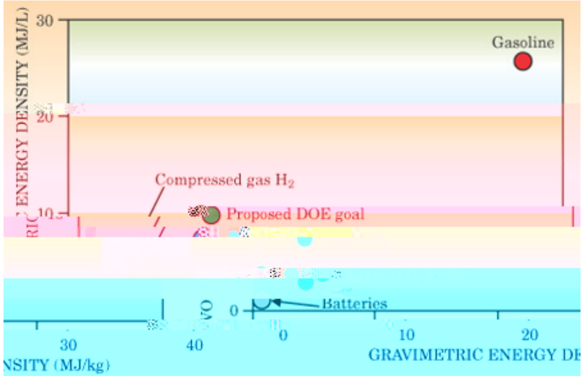

Figure 2. The energy densities of hydrogen fuels stored in various phases and materials are plotted, with the mass of the container and apparatus needed for filling and dispensing the fuel factored in. Gasoline significantly outperforms lithium−ion batteries and hydrogen in gaseous, liquid, or compound forms. The proposed DOE goal refers to the energy density that the

energy use. Coupling fuel cells to electric motors, which are more than 90% efficient, converts the chemical energy of hydrogen to mechanical work without heat as an intermediary.

Although fuel cells are more efficient, there are also good reasons for burning hydrogen in heat engines for transportation. Jet engines and internal combustion engines can be rather easily modified to run on hydrogen instead of hydrocarbons. Internal combustion engines run as much as 25% more efficiently on hydrogen compared to gasoline and produce no carbon emissions. BMW, Ford, and Mazda are road− testing cars powered by hydrogen internal combustion engines that achieve a range of 300 kilometers, and networks of hydrogen filling stations are

Beyond the oxygen reduction reaction, fuel cells provide many other challenges. The dominant membrane for PEM fuel cells is perfluorosulfonic acid (PFSA), a polymer built around a C−F backbone with side chains containing sulfonic acid groups (SO_3−) (for example, Nafion). Beside its high cost, this membrane must incorporate mobile water molecules into its structure to enable proton conduction. That restricts its operating temperature to below the boiling point of water. At this low temperature—typically around 80°C— expensive catalysts like platinum are required to make the electrochemical reactions sufficiently active, but even trace amounts of carbon monoxide in the hydrogen fuel stream can poison the catalysts. A higher operating temperature would expand the range of suitable catalysts and reduce their susceptibility to poisoning. Promising research directions for alternative proton−conducting membranes that operate at 100−200°C include sulfonating C−H polymers rather than C−F polymers, and using inorganic polymer composites and acid−base polymer blends.

Solid oxide fuel cells (SOFCs) require O^{-}_{2} transport membranes, which usually consist of perovskite materials containing specially designed defect structures that become sufficiently