From Sand and Sun
to
Electricity and Hydrogen

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Hydrogen Production from Sand via Silicon

Global reserves of coal, oil, and natural gas are decreasing drastically; global energy requirements, however, are dramatically increasing. Energy generation using nuclear technology could possibly become abandoned, and regenerative energy sources are not able to meet energy consumption in major urban areas. The future lies with hydrogen. However, this gas is essentially totally manufactured from fossil fuels and hence is of limited abundance—not to mention the dangers involved in its utilization. A new approach to solving the energy problem is being sought. Silicon instead of coal and oil: could this be the answer?

The current situation

Our present energy generation concepts are essentially based on carbon (crude oil, natural gas) as a source of raw materials. The resulting energy supply process consequently produces the greenhouse gas carbon dioxide, CO_2. Scientific studies prove that the natural carbon-based resources are becoming dramatically exhausted: “Mankind consumes more carbon- based energy per day than was formed in a thousand years of the earth’s history.” Furthermore, it is expected that energy consumption will double in the next 40 years from improvement in quality of life and increase in population from current 6.5 billions to nearly 10 billions. Projected hydrocarbon energy reserves are; raw oil - 42 yrs, natural gas – 60 yrs, and coal 250 – yrs.

Taking into consideration the reprehending discussions aimed at effecting a reduction in CO_2 emission, it is apparent that the search for and development of alternative energy sources are of eminent importance. This raises the logical question of finding an efficient secondary energy-carrying vehicle enabling permanent energy storage and safe energy transportation, since direct transport of primary electrical energy via long-distance high-voltage power lines is prone to considerable energy losses. According to numerous experts, this future energy-carrying vehicle will be hydrogen, which produces water as the result of the highly efficient energy-delivering combustion process. In spite of huge investments, however, the hydrogen-based energy concept is still controversial due to following factors;

- Hydrogen is currently manufactured using crude oil or natural gas.
- Water can be used as an alternative hydrogen source—possibly involving expensive and hazardous handling during the transport and storage of the hydrogen.
- Energy input necessary to generate hydrogen from water is immense (286 kJ/mol compared to 37.5 kJ/mol for natural gas [methane]).
- Generation, storage, and transport of liquid or gaseous hydrogen involves an enormous expenditure of energy.

The technical feasibility of large-scale activities involving hydrogen thus requires the use of an intermediate storage medium for regenerative energy.

In other words, we are seeking a medium that is capable of decentrally producing hydrogen without the involvement of carbon or carbon dioxide.

These pre-requirements can be met using three materials: silicon, water, and air, where silicon is the energy carrier.

- *The Energy Problem is the problem of Energy Storage and Energy Transportation, thus requiring Energy Carrier.*

- *Our primary goal is; Delivery of secure, safe, reliable, environmentally friendly technology at competitive cost through high-volume manufacturing.*

Silicon: Description, availability, and reactivity

Approximately 75 percent of the accessible earth's crust consists of silicon dioxide, SiO_2 (Si: 26.3 percent; O_2:48.9 percent).

A chemical process that enables a completely carbon-independent production of silicon makes use of the resources "sand" and inexpensive excess energy—ideally renewable forms such as solar energy—to manufacture silicon and thus act as an energy storage medium. Beginning with conventional desert or sea sand, which contains approximately 80–90 percent α-quartz, silicon is obtained using technologically well-established, large-scale processes as a high purity powder.

This process is not in competition with current silicon production via electric arc ovens however, it could certainly develop into an attractive alternative as an option to permit the manufacture of silicon in a future with depleted carbon reserves. The process remains completely free of C/CO_2, and no byproducts are generated. The sole starting material is sand, which, in contrast to the present-day technology, can even be used in low-quality grades. The complementary result of our basic research activities is a second technical process that effectively converts silicon tetra-halide to silicon in a gas-phase reaction. This simplifies the manufacture of silicon to an analog of the so-called Siemens process that is currently employed to produce electronic-grade silicon from chlorinated silicon compounds.

Silicon as an energy carrier

The reduction process sand → silicon generates a permanent energy carrier with an energy density and energy content comparable with that of carbon. Energy content of silicon is 32.6 kJ/g as compared to 32.8 kJ/g for carbon. Energy density of silicon is 75.9 kJ/cm3 while carbon's energy density is 74.2 kJ/cm3.

Silicon proves to be optimal with respect to handling and energy density relative to hydrogen storage and generation. Furthermore, the price of electricity in the sequence SiO_2 → Si → H2 → Electricity decreases proportionally with the costs for the production of silicon. It is expected that for a solar thermally produced carrier manufactured from conventional sand permit us to predict an unbeatable cost profile for silicon in the future.

It is technically possible to generate hydrogen directly from silicon at any location of choice avoiding the transport and storage difficulties encountered with conventional power stations and stationary/mobile fuel cells. Thus, silicon acts as a tailor-made intermediate linking decentralized energy generation with equally decentralized hydrogen-based infrastructure at any location of choice.

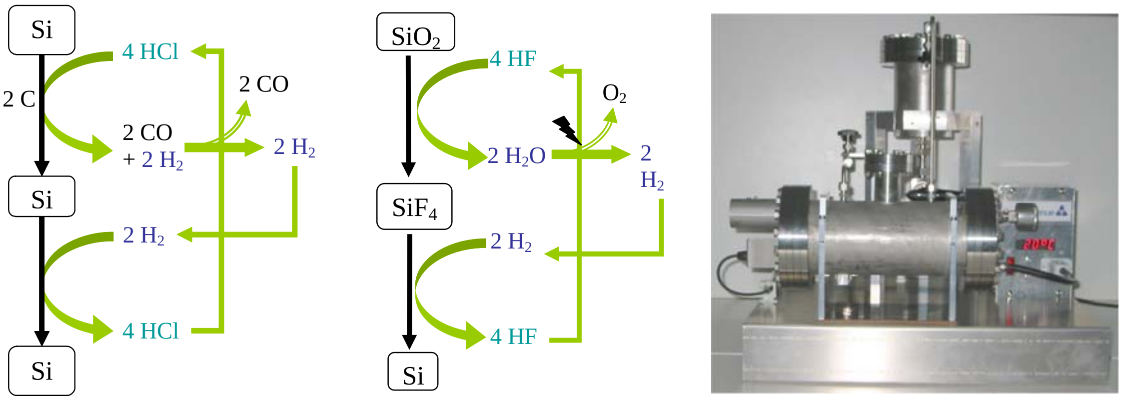

Figure 1: Summary Chemical reactions for Production of Silicon from Sand. Prototype reactor for 1 kg H2 is also shown

Additionally, the hydrogen generated via the sequence Sand → Silicon → Hydrogen directly from silicon and water is “pure.” In strong contrast to oil and in particular hydrogen, the transport and storage of silicon are free from potential hazards and require a simple infrastructure similar to that needed for coal. Whereas the latter material is converted to carbon dioxide, sand is produced from the silicon, which in turn can be used to prepare the silicon carrier material.

Uses of Hydrogen as a Fuel

Non-Burning Reactions – Hydrogen Fuel Cells

When hydrogen is oxidized, there is a reaction between the oxygen and hydrogen which results in water, while energy is released in the form of heat. In a fuel cell, the process is split in two. The two processes take place on each respective side of the electrolyte which keeps the gasses separated, but which transports ions.

The future in Hydrogen production is whereby the hydrogen is ionized and protons and electrons travel concurrently through the membrane. On the permeate side, they combine into hydrogen molecules, whereby electrochemical potential difference drives the reaction, and Water is decomposed on the feed surface (new patent)

The negatively charged electrons move in an outer electrical circuit. With this apparatus a portion of the chemical energy is converted directly to electric energy. Theoretically, 83% of the energy can be generated into electricity. In reality, the efficiency is lower, but compared to traditional technology, the fuel cell is very efficient – 50% compared to 30% in a typical hydrocarbon-based combustion engines.

There are several types of fuel cells. Desirable type is Proton Exchange Membrane (PEM) fuel cell that operates by putting a hydrogen molecule in contact with the platinum catalyst, splitting it into two hydrogen ions (protons) and two electrons. The electrons are conducted by the electrode to the external circuit where they can power for instance an electrical motor. They are then fed onward to the cathode where oxygen from the air splits into two oxygen atoms when it comes in contact with the catalyst. Two hydrogen ions combine with one oxygen atom and two electrons from the conductor, to create a water molecule. The reaction in a fuel cell produces only about 0.7 volts, so several fuel cells are connected in a series to attain a functional level of output. Fuel cells connected together are called a fuel cell stack.

Fuel cells can be manufactured from a few watts to several hundred watts by cascading them in various configurations. One kilogram of hydrogen produces nearly 33 kWh of power in a typical PEM fuel cell, while same amount of gasoline generates only 13 kWh.

When using sand to generate hydrogen via silicon, these fuel cells consume approximately 0.4 kg of sand to produce 1 kWh of electric power.

Burning Reactions – Hydrogen Turbines

The only byproduct of burning hydrogen in oxygen is water that is free from CO_2, NO_x and SO_x emissions. Using hydrogen as fuel, novel combustion technology for a 1,973K-class (1,700°C) turbine is expected to eventually achieve 71% gross thermal efficiency (LHV) with no emissions other than water. Toshiba is developing such technology under WE-NET (World Energy Network). The project's goal is to establish a feasible hydrogen-energy network that can eventually be applied on a worldwide scale.

Hydrogen will be produced from various sustainable-energy sources such as water, solar, geothermal, and wind power in global areas abundant with such sources. Hydrogen will be used as a transportable source of sustainable energies to consuming areas or other nations. Obviously, it is essential to raise the thermal efficiency of such a hydrogen turbine system to minimize not only its total construction cost but also the cost of generating electricity.

It is expected that a hydrogen turbine's efficiency could reach 71% (LHV, gross) if its firing temperature can be raised to 1,973K (1,700°C). In addition to its higher efficiency, a hydrogen-fuel turbine would also provide superior environmental performance as its only byproduct is clean water. Hydrogen turbines can be manufactured in the power ranges of 1-100 MW for local and industrial usage and 250 MW to 1000 MW for power stations. A 1-MW local power generator will consume approximately 30 kg of hydrogen per hour. This amount of hydrogen can be extracted from 420 kg of sand according the proposed scheme in this document.

General Electric is currently advancing combustion technologies for hydrogen fuels to achieve the same type of emissions improvement that have been accomplished for natural gas-fueled turbines. The new Hydrogen turbines will achieves an efficiency increase of 3-5 percentage points over current coal-powered turbine technologies.

Siemens Westinghouse Power Corporation now designs an advanced hydrogen-powered turbine system that employs newly designed system components for improved performance. Newly designed components will include an enhanced cooling subsystem for controlling operating temperatures, increased front-end temperatures for more efficient fuel consumption, and advanced materials and coatings for component durability and reduced operating costs.

Toshiba is currently in the process of developing a hydrogen combustion turbine called "advanced Rankine cycle" because it is a high-temperature, double-reheat Rankine cycle.

It uses two hydrogen-oxygen combustors for heating and reheating. They generate high-temperature steam by combusting hydrogen and oxygen, whereas the conventional Rankine cycle uses a super heater and a re-heater as part of a boiler in which steam temperature must be kept under 600°C because of the boiler material's temperature limit. Use of a combustor instead of a boiler enables significantly higher steam temperatures, which boosts thermal efficiency. Toshiba expects that a hydrogen turbine's efficiency could reach 71% (LHV, gross) if its firing temperature can be raised to 1,973K (1,700°C). In addition to its higher efficiency, a hydrogen-fuel turbine would also provide superior environmental performance as its only byproduct is clean water.

Silicon/Hydrogen fuel Power Plant

The following data are for conversion of Silicon to Hydrogen and the use of Hydrogen in a H2 burning gas turbine to generate electricity. Since many of the process and component efficiencies are not well known, a 50% overall efficiency has been assumed for the entire process. This number maybe on the optimistic side since most fossil-fuel power plants operate at below 40% cycle efficiency.

Silicon Consumption	1MW	10MW	50MW	100 MW
Si consumption per hour	220 kg	2.22 tons	11.1 tons	22.2 tons
Si consumption per day	5400 kg	54 tons	270 tons	540 tons
Si consumption per year	1940 tons	19,400 tons	97,000 tons	194,000 tons

The success of developing hydrogen-fueled turbines requires developing new cooling technologies. Rather than choose between closed- or open-cycle cooling concepts, Toshiba proposes a hybrid cooling concept for cooling 1,973K-class (1,700°C) turbines. In an open-cycle system, after being used to cool internal blades the cooling medium is discharged into the turbine's hot gas path for film cooling, trailing-edge cooling, etc. A closed-cycle system does not discharge the turbine's cooling medium into its hot gas path, but instead recovers it for use in other parts of the system.

Summary

As carbon-based primary energy carriers become increasingly exhausted, it is obvious that the existing reserves should be better used for the production of valuable products as opposed to carbon dioxide. The concept outlined here describes a practical solution to secure the future supply of hydrogen via a "non-carbon" route for a range of applications.

This concept of future energy supply based on hydrogen in effect represents the realization of PowerAvenue's vision described in the introduction: the three- stage solar thermal generation of hydrogen from sand. The use of the element silicon represents an attractive solution to the problems resulting from efficiency losses during the conversion of thermal energy into electrical power as well as the transport and storage difficulties associated with hydrogen.

Figure 2 illustrates the overall infrastructure and transportation means for a silicon based 560 MW power station which could potentially feed vehicles and residential/commercial buildings without the environmental disadvantages of fossil fuel based energy sources. Moreover, figure 2 indicates the reduction in the amount of CO2 emission on a yearly basis for both a silicon fuel based hydrogen hub station as well as a solar energy based hydrogen hub station.

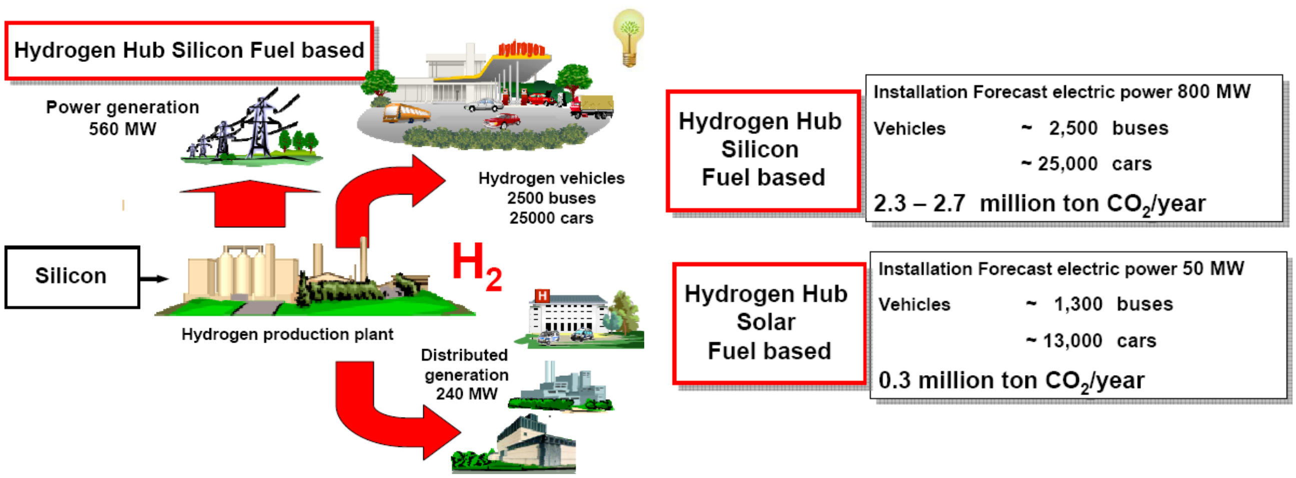

Figure 2: Infrastructure of hydrogen production and distribution as well as the annual reduction in CO2 emissions due to silicon based energy production.

Utilization of this technique will enable nations with abundant sun/sand resources to redirect and modify their energy production schemes to take advantage this non-carbon based alternative. It is noted that the proposed technique of producing hydrogen from sand is not meant to fully replace current or future fossil-fuel based techniques; however, it is possible that as fossil fuels reserves become more limited, the proposed technique offers an attractive alternative to the carbon-based energy production.