

## FUEL CELLS AND HYDROGEN ECONOMY

*Fuel cells with applications ranging from power generation to transportation need hydrogen as fuel. Hydrogen is not a source of energy, and hydrogen is not a readily available fuel. Hydrogen is more like electricity – an intermediary form of energy or an energy carrier. However, while electricity infrastructure is already in place, hydrogen infrastructure is practically nonexistent. It is this lack of hydrogen infrastructure that is considered to be one of the biggest obstacles to fuel cell commercialization. Commercialization of fuel cells, particularly for transportation and stationary electricity generation markets, must be accompanied by commercialization of hydrogen energy technologies, i.e., technologies for hydrogen production, distribution and storage. In other words, hydrogen must become a readily available commodity (not as a technical gas but as an energy carrier) before fuel cells can be fully commercialized. On the other hand, it may very well be that the fuel cells will become the driving force for development of hydrogen energy technologies. Fuel cells have many unique properties, such as high energy efficiency, no emissions, no noise, modularity, and potentially low cost, which may make them attractive in many applications even with a limited hydrogen supply. This creates what is often referred to as a "chicken and egg problem" – does the development and commercialization of fuel cells come before development of hydrogen energy technologies or must hydrogen infrastructure be in place before fuel cells can be commercialized?*

*Hydrogen as fuel cannot compete in today's market with the very fuels it is produced from (including electricity). Also, as any new technology, hydrogen energy technologies, such as fuel cells, are in most cases initially more expensive than the existing mature technologies, even when real economics is applied. Hydrogen energy technologies are expensive because the equipment for hydrogen production and utilization is not mass-produced. It is not mass-produced because there is no demand for it, and there is no demand because it is too expensive. This is a closed circle, or another chicken-and-egg problem. The only way for hydrogen energy technologies to penetrate into the major energy markets is to start with those technologies that may have niche markets, where the competition with the existing technologies is not as fierce and/or where they offer clear advantage over the existing technologies regardless of the price. Another push for commercialization may be gained through governmental and/or international subsidies for technologies that offer some clear advantages. Once developed, these technologies may help reduce the cost of other related hydrogen technologies, and initiate and accelerate their widespread market penetrations. This article discusses the role of fuel cells in the future Hydrogen Economy, and explores possible transition paths and strategies.*

*Key words: hydrogen, economy, fuel cell.*

PEM fuel cells need hydrogen as fuel. Hydrogen is not a source of energy, and hydrogen is not a readily available fuel. Hydrogen is more like electricity – an intermediary form of energy or an energy carrier. Just like electricity, it can be generated from a variety of energy sources, be delivered to the end users, and at the user end, it can be converted to useful energy efficiently and cleanly. However, although electricity infrastructure is already in place, hydrogen infrastructure is practically nonexistent. It is this lack of hydrogen infrastructure that is considered one of the biggest obstacles to fuel cell commercialization. Commercialization of fuel cells, particularly for transportation and stationary electricity-generation markets, must be

accompanied by commercialization of hydrogen energy technologies, that is, technologies for hydrogen production, distribution, and storage. In other words, hydrogen must become a readily available commodity (not as a technical gas but as an energy carrier) before fuel cells can be fully commercialized. On the other hand, it may very well be that the fuel cells will become the driving force for development of hydrogen energy technologies. Fuel cells have many unique properties, such as high energy efficiency, no emissions, no noise, modularity, and potentially low cost, which may make them attractive in many applications even with a limited hydrogen supply. This creates what is often referred to as a "chicken and egg problem" – does the development and commercialization of fuel cells come before development of hydrogen energy technologies or must hydrogen infrastructure be in place before fuel cells can be commercialized?

**TRANSITIONS IN ENERGY SUPPLY**

Many scientists consider hydrogen the fuel of the future in the post-fossil fuel era. When and how hydrogen energy technologies will be commercialized is probably beyond the scope of this book. Nevertheless, some clues may be obtained by looking into the history of energy use and transitions in energy supply.

Figure 1 shows the ever-growing global demand for energy, and how it has been met by a variety of energy sources. At present, more than 85% of world energy demand is met by fossil fuels—coal, petroleum, and natural gas [1]. These fuels are readily available and convenient to use. Humankind has learned to exploit them relatively efficiently to satisfy its energy needs. The tremendous economic growth of modern industrialized society has been based on utilization of fossil fuels.

However, energy technologies, particularly those related to fossil fuel extraction, transportation, processing, and end use (which is almost always combustion), have harmful impacts on the environment, which in turn cause direct and indirect adverse effects on the global economy. Those environmental impacts may be on a local level, such as air pollution due to emissions, water and soil pollution due to spills and leaks, or on a regional level because of pollutants dispersion and acid rains, and even on a global level as a result of carbon dioxide accumulation in the atmosphere with threatening consequences such as global warming, climate changes, and rising sea level.

If environmental stress does not force a shift to other, cleaner energy sources and fuels, the finite supply of fossil fuels will mandate such a change eventually. Reserves of fossil fuels are finite—that is an indisputable fact—yet it is often a subject of vigorous arguments. What is arguable is not whether the reserves are finite, but rather when they will be depleted, or at what level of depletion the global economy will become noticeably affected. Furthermore, the demand for energy will continue to rise because of the continuing increase in world population and the growing demand on energy resources by the developing countries in order to

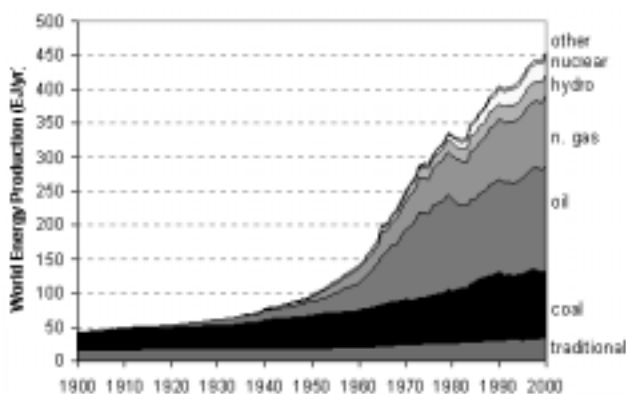


Figure 1. History of world energy production [1].

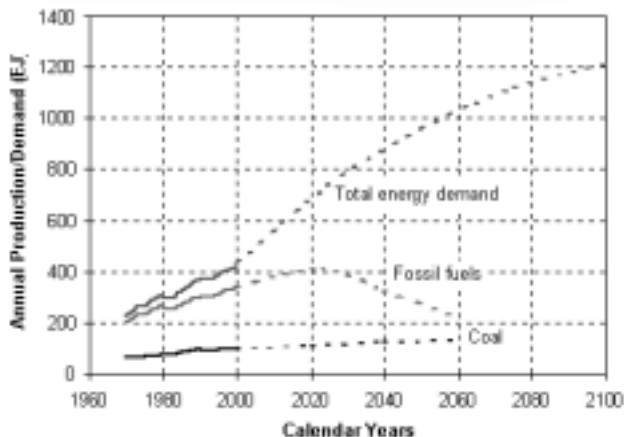


Figure 2. Projections of energy demand and supply. (Sources: Historical data from [1]; World energy demand forecast from [2]; Fossil fuels and coal forecasts extrapolated from [3,4].)

improve their standard of living. Figure 2 shows a gap between the energy demand and fossil fuels availability. This gap represents an opportunity for non-fossil fuel energy sources.

The present energy system, based on utilization of fossil fuels, is clearly not in balance with the environment, and therefore cannot be sustainable. It relies on a finite source of stored energy, converts that energy into useful forms primarily through a combustion process, and discharges the products of combustion, such as CO<sub>2</sub> and a myriad of pollutants, into the environment (Figure 3). From Figure 3 it is obvious that such a system can only run as long as there is enough stored energy or as long as the environment is capable of absorbing pollution, whichever event occurs first.

It is clear that our civilization is facing an unavoidable transition from convenient but environmentally not so friendly, and ultimately scarce energy sources to less convenient, but preferably clean and nonexhaustable ones. There are several known energy sources that satisfy cleanliness and abundance

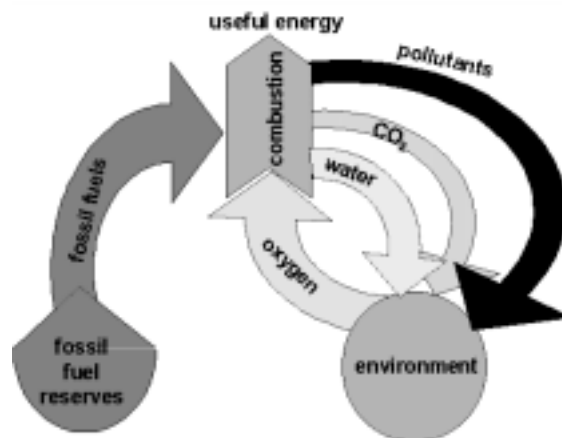


Figure 3. Present unsustainable energy system.

requirements, such as direct solar radiation, various forms of indirect solar energy (wind, waves, ocean currents, ocean thermal, biomass), and geothermal, tidal, and nuclear energy. Technologies for utilization of these sources are at various stages of development and their (direct economic) competitiveness with existing energy technologies varies from case to case. Human ingenuity may add new sources to this list in the future.

Regardless of the energy sources of the future, there will always be a need for convenient, clean, safe, efficient, and versatile energy carriers or forms of energy that can be delivered to the end users. One such carrier is electricity, which is already being used worldwide. Electricity is a convenient form of energy—it can be produced from various sources, it can be transported over large distances, it can be distributed to the end users, it is clean (although its production from fossil fuels is not), and at the user end it may be very efficiently used in a variety of applications.

Hydrogen is another clean, efficient, and versatile energy carrier, which supplements electricity very well. Together, these two carriers may be able to satisfy all future energy needs, and form a permanent energy system that would be independent of individual primary energy sources. Hydrogen has some unique properties that make it an ideal energy carrier, namely:

- It can be produced from and converted into electricity at relatively high efficiencies.
- Raw material for hydrogen production is water, which is available in abundance. Hydrogen is a completely renewable fuel, because the product of hydrogen utilization (either through combustion or through electrochemical conversion) is pure water or water vapor.
- It can be stored in gaseous form (convenient for large-scale storage), in liquid form (convenient for air and space transportation), or in the form of metal or chemical hydrides (convenient for surface vehicles and other relatively small-scale storage requirements).
- It can be transported over large distances through pipelines or via tankers (in some cases more efficiently and economically than electricity).
- It can be converted into other forms of energy in more ways and more efficiently than any other fuel, that is, in addition to flame combustion (like any other fuel), hydrogen may be converted through catalytic combustion, electrochemical conversion, and hydriding.
- Hydrogen as an energy carrier is environmentally compatible, because its production from electricity or directly from solar energy, its storage, transportation, and end use do not produce any pollutants (except small amounts of NO<sub>x</sub> if hydrogen is burned with air at high temperatures), greenhouse gases, or any other harmful effects on the environment. Hydrogen itself is not toxic.
- Hydrogen is a relatively safe fuel if handled properly. Several in-depth studies suggest that

hydrogen has many properties that make it at least as safe as other fuels used today (gasoline, natural gas, or propane) [5,6]. More on hydrogen safety can be read in the following section, Hydrogen Energy Technologies.

## HISTORY OF HYDROGEN AS FUEL

The first vision of the energy system based on hydrogen was provided by science fiction writer Jules Verne in his novel *The Mysterious Island* [7]:

*Water decomposed into its primitive elements... and decomposed doubtless, by electricity... will one day be employed as fuel,... hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable,... Water will be the coal of the future.*

After investigating the electrochemical process first described by Sir William Grove in 1839, Ostwald in 1894 predicted that the twentieth century would become the Age of Electrochemical Combustion, with the replacement of steam Rankine cycle heat engines by much more efficient, pollution-free fuel cells [8].

In 1923 Haldane predicted that hydrogen-derived from wind power via electrolysis, liquefied, and stored—would be the fuel of the future [9]. This view was repeated in more technical detail, some 15 years later, by Sikorski [10], who realized hydrogen's potential as aviation fuel. He predicted that introduction of hydrogen would bring about a profound transformation of aeronautics.

Lawaczek [11] in the early 1920s outlined the concepts for hydrogen-powered cars, trains, and engines; collaborated in developing of an efficient pressurized electrolyzer; and was probably the first to suggest that energy could be transported via hydrogen-carrying pipelines, similar to natural gas. In the 1920s and 1930s, Erren and his team of engineers converted more than 1000 cars and trucks to multifuel systems using both hydrogen and gasoline as fuel [12].

The concept of a solar-originated hydrogen economy was first set down by Bockris (1962), developed and diagrammed by Justi (1965), named a Hydrogen Economy by Bockris and Triner (1970), formulated by Bockris (1971) and Bockris and Appleby (1972), and quantified by Gregory (1972) and Marchetti (1972) [13].

Bockris proposed a general plan of supplying American cities with solar-based energy via hydrogen. He suggested the use of floating platforms containing photovoltaic devices, producing hydrogen by the electrolysis of seawater, and piping hydrogen to land [14].

A similar concept, but for Japan, called PORSHE (Planned Ocean Raft System for the Hydrogen Economy) was later proposed and elaborated by Ohta [15].

Justi Š16Ć made the first diagram of the solar hydrogen economy. He proposed the thermoelectric conversion of solar energy into hydrogen in the Mediterranean area, and transportation of hydrogen to Germany through a pipeline. He envisioned hydrogen as a fuel for households and industry, large-scale and localized electricity generation and transportation (in electric vehicles).

Bockris and Veziroglu [17] outlined the solar hydrogen energy system and discussed the real economics of potentially competitive energy systems of the future. They showed that if hydrogen utilization efficiency advantage and total fuel costs (i.e., cost of production plus the cost of environmental damage done in every step of the fuel cycle) are taken into account, the solar hydrogen energy system is the most economical energy system possible.

Scott and Hafele [18] addressed the issue of the global climatic disruption caused by excessive use of carbon fuels and concluded that hydrogen energy system is a practical technological pathway that can mitigate and then reverse energy-sector contributions to greenhouse gas climatic disruption, and at the same time bring economic growth and improvements to the quality of life. They provided a vision of the transition to the hydrogen energy system as two sequential but overlapping waves: integrated energy systems (i.e., the mix of fossil fuel and hydrogen) and neat hydrogen technologies.

Winter feared that the point of transition to hydrogen and solar energy could be another "lost moment of history" [19]. Timely transition to these clean forms of energy would lead toward new direction in development of human civilization, qualitatively and quantitatively different than the path based on utilization of fossil fuels.

**HYDROGEN ENERGY SYSTEM**

Hydrogen is not just a fuel. Hydrogen is a fuel that will allow the imminent transition from fossil fuel economy. The energy system in which hydrogen has a prominent role is often referred to as the Hydrogen Economy (although a title such as Electricity and Hydrogen Economy would be more accurate).

A global energy system in which electricity and hydrogen are produced from available energy sources and used in every application where fossil fuels are being used today—in transportation, residential, commercial, and industrial sectors—is depicted in Figure 4. In such a system, electricity and hydrogen are produced in large industrial plants as well as in small, decentralized units, wherever the primary energy source (solar, nuclear, and even fossil) is available. Electricity is used directly or transformed into hydrogen. For large-scale storage, hydrogen can be stored underground in ex-mines, caverns, or aquifers. Energy transport to the end users, depending on distance and

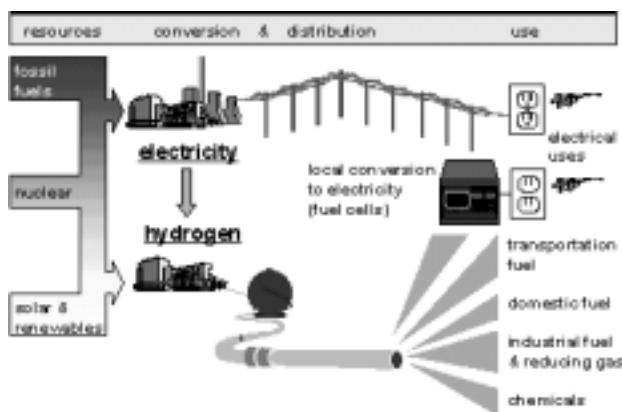


Figure 4. Hydrogen/electricity energy system.

overall economics, is in the form of either electricity or hydrogen. Hydrogen may be transported, by means of pipelines or supertankers. It is then used in transportation, industrial, residential, and commercial sectors as a fuel. Some of it may be used in fuel cells to generate electricity, depending on demand, geographical location, or time of day.

Production of hydrogen from fossil fuels may be justified only in cases where it results in higher efficiency or lower emissions, or where fossil fuels cannot be used at all. These technologies will not help reduce dependency on fossil fuels and will not reduce CO<sub>2</sub> generation. They may be used in a transition period and help in bringing hydrogen to the market cost-effectively and in establishing hydrogen infrastructure.

Full benefits of hydrogen will be realized only in conjunction with renewable energy sources. Both hydrogen and electricity complement the renewable energy sources and allow their indirect utilization in almost every imaginable application. Such a system is in complete balance with the environment, as shown in Figure 5, and can run as long as the energy source is available.

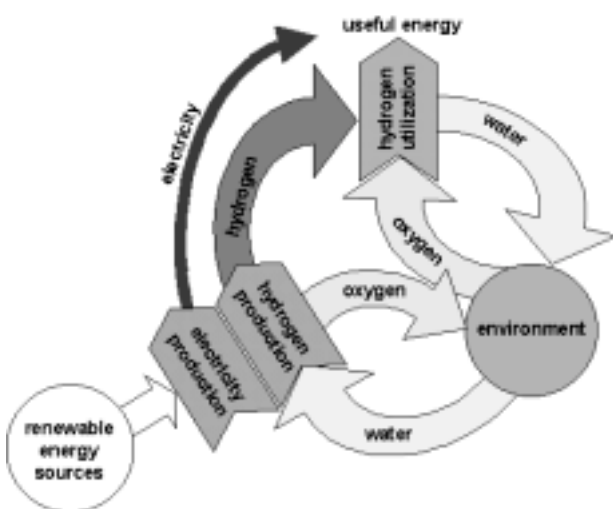


Figure 5. A sustainable energy system based on renewable energy sources.

**PREDICTING THE FUTURE**

As discussed earlier, hydrogen is considered a fuel that will make a transition from fossil fuels possible. When will this transition happen? Is it imminent? Hydrogen technologies seem to be technically feasible. When will they become economically feasible? To answer these questions, we would have to take a peek at the future.

Predicting the future is, of course, impossible. However, all systems behave in accordance with established laws of physics, and if enough information is available, their future behavior may be predicted, at least to some extent. For example, if we throw a ball in the air, we can with great certainty predict that the ball will initially go up, reach its peak, and then come back down. If we want to predict how high the ball will fly and when and where it will fall down, more information is needed.

All systems in nature require energy. Their behavior, therefore, may be studied and predicted based on their energy use and available energy resources. The same applies to the global economy. As mentioned before, the tremendous economic growth of modern industrialized society has been based on utilization of fossil fuels, a convenient and concentrated form of energy. Although all economic models are based

on growth, from a thermodynamic point of view it is clear that no system based on finite energy sources can continue to grow forever. Such a system does go through exponential growth during periods when the resources are plentiful, but eventually reaches its peak and then declines as the resources become depleted, as shown in Figure 6. If we want to calculate how high the peak will be and when it will happen, much more information about the system and its energy use would be needed. The diagram in Figure 6 and accompanying equations are based on Odum's energy language [20-22], originally developed to describe energy flows in ecological systems, but subsequently applied to any complex system, including human economic systems on a global, national, or regional scale.

A system based on utilization of a constant flow of incoming energy (such as solar energy) behaves differently. It does not go through a peak, but continues to grow and eventually it reaches a steady state (Figure 7). The rate of growth and the steady state level, which a system can obtain, depend on the rate of utilization of available solar energy and the effort required to convert solar energy into more useful forms of energy (hydrogen and electricity being only the intermediary steps, i.e., energy carriers).

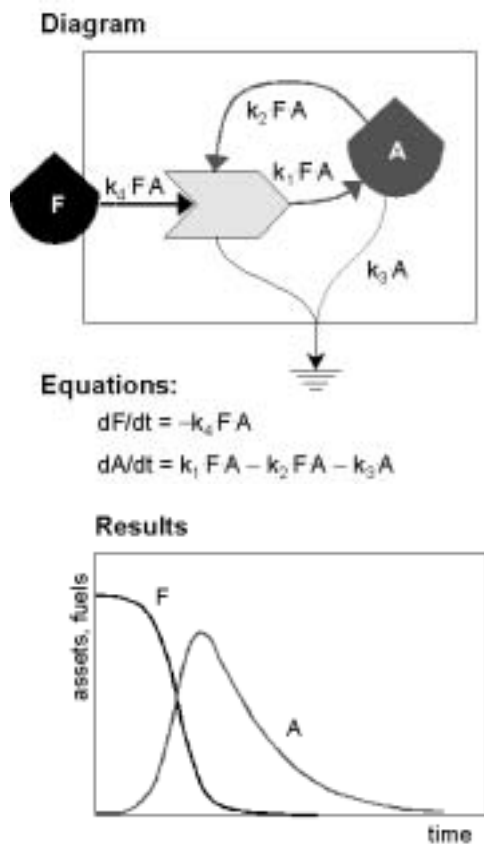


Figure 6. A simple model of a system based on nonrenewable energy sources.

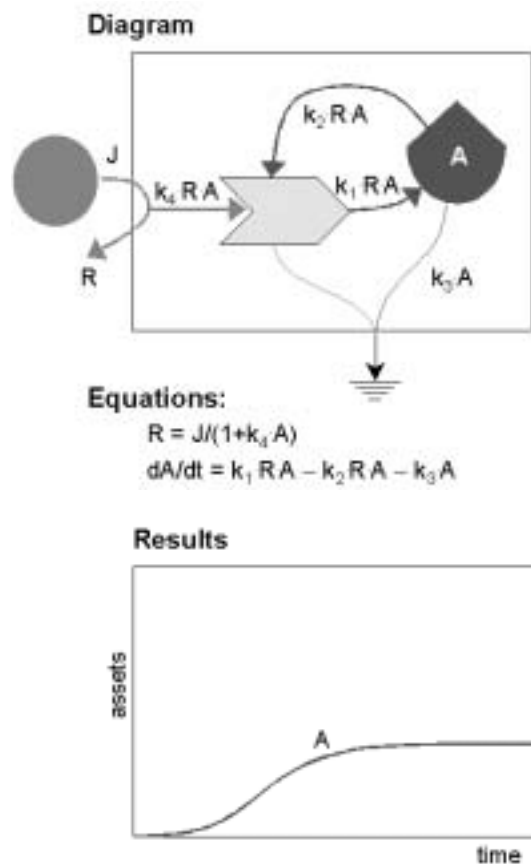


Figure 7. A simple model of a system based on a constant flow (renewable) energy source.

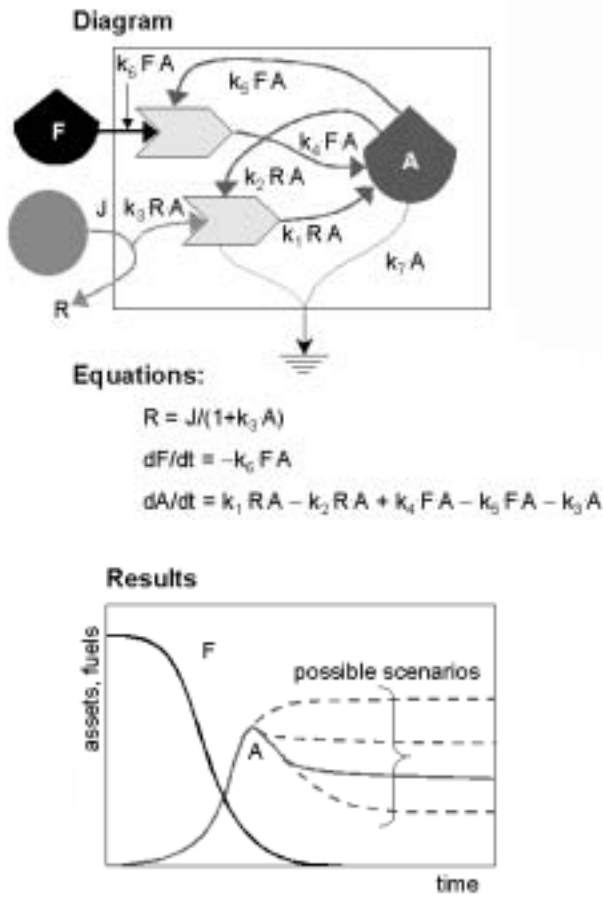


Figure 8. A simple model of a system based on renewable and nonrenewable energy sources.

Human civilization is actually a system that is based on both renewable and nonrenewable energy sources (Figure 8). The renewable energy sources could have never provided the growth enabled by the use of fossil fuels. The problem is that the finite reserves of fossil fuels cannot perpetuate this growth indefinitely. What cannot be predicted by such a simple model is at which level the system would reach a steady state after the nonrenewable, stored energy has been depleted. The steady state level depends on the effort required to convert renewable energy into more useful forms of energy, that is, net energy gain from renewable energy sources.

Various modeling studies, such as those conducted by an MIT team [23,24], indicate that the global economy will peak sometime in the first half of the twenty-first century, and after that will continue to decline. The main reasons for that would be environmental stress and depletion of natural resources (including fluid fossil fuels). A modeling study conducted at the University of Miami [2] has come up with similar results, although using a different method. Both studies, however, concluded that it would be possible to reverse the negative trends by timely introduction of clean, new

technologies that will ease, and actually reverse the burden on the environment, and that will not depend on exhaustible natural resources. Although the MIT study was not specific about those technologies, the University of Miami researchers have identified hydrogen economy based on renewable energy sources as a solution to global economic and environmental problems [2]. This study indicated that the timing and the rate of introduction of a new energy system might be critical. As shown in Figures 9 and 10, early introduction of the solar hydrogen energy system will have long-term beneficial effects on both the global economy and the environment. If this transition starts when the economy begins to decline, it may be too late to reverse the trend, because the economy would no longer be able to afford investing in a long-term project such as establishing a new energy system.

Historically, in the context of a longer time span, the fossil fuels era may well be considered just a short interlude between the solar past and the solar future. In that short period (about 300 years) fossil fuels made possible a tremendous development of human

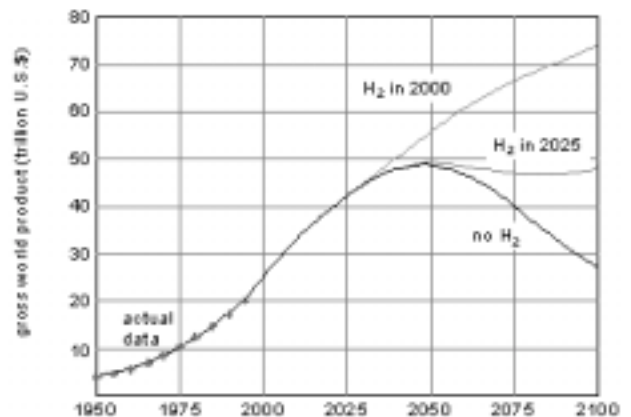


Figure 9. Effect of timeliness of transition to hydrogen energy system on global economy (1990 US \$) [2].

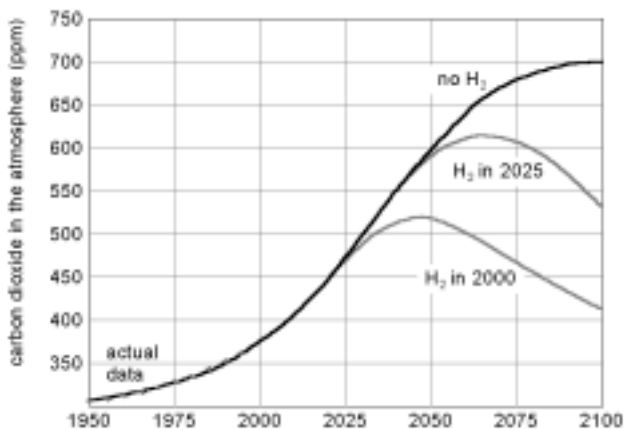


Figure 10. Effect of timeliness of transition to hydrogen energy system on CO<sub>2</sub> concentration in the atmosphere [2].

civilization. If fossil fuels are used to support the establishment of a permanent energy system such as the solar hydrogen energy system, they could be considered a spark that provided a transition from the low-level solar energy past to the higher-level solar energy future. Solar energy is steadily available in quantity that exceeds human needs by several orders of magnitude. However, solar energy (both direct and indirect) is so dispersed that it requires a lot of effort (high-quality energy) to convert it to usable energy forms. The rate at which renewable energy can support the growth of the economy and the eventual steady state depends on the magnitude of efforts required to harvest it and present it to the end users. In economic terms this is equivalent to the cost of energy at the user end. More studies are required to determine the net energy gain of solar electricity and solar hydrogen technologies.

### TRANSITION TO HYDROGEN ECONOMY

A transition from convenient but environmentally not so friendly, and ultimately scarce energy sources (fossil fuels) to less convenient, but clean and nonexhaustable ones (renewable energy sources) seems to be imminent. Hydrogen may play a significant role in this transition by allowing renewable energy sources to be used in virtually any application.

Replacement of a global energy system will not and cannot happen overnight. There is an enormous capital tied in the existing energy system. Building another energy system that would compete with the existing one is out of the question. The new energy system must gradually replace the existing one. Because businesses are too often concerned with short-term profits, governments and international organizations must realize the long-term benefits of the hydrogen energy system and support the transition both legislatively and financially. Introduction of "real economics" and elimination of subsidies for the existing energy system would help in that transition. The term "real economics" refers to economics that takes into account past, present, and future environmental damage, associated with use of particular energy source or fuel, depletion of environmental resources, military expenses for keeping energy resources accessible, and other hidden external costs.

The most difficult would be the initial penetration of hydrogen energy technologies in the existing energy markets. First, hydrogen as fuel cannot compete in today's market with the very fuels it is produced from (including electricity). Also, as with any new technology, hydrogen energy technologies, such as fuel cells, are in most cases initially more expensive than the existing mature technologies, even when real economics is applied. Hydrogen energy technologies are expensive because the equipment for hydrogen production and

utilization is not mass-produced. It is not mass-produced because there is no demand for it, and there is no demand because it is too expensive. This is a closed circle, or another chicken-and-egg problem. The only way for hydrogen energy technologies to penetrate into the major energy markets is to start with those technologies that may have niche markets, where the competition with the existing technologies is not as fierce or where they offer clear advantage over the existing technologies regardless of the price. Another push for commercialization may be gained through governmental or international subsidies for technologies that offer some clear advantages. Once developed, these technologies may help reduce the cost of other related hydrogen technologies, and initiate and accelerate their widespread market penetrations. One example is fuel cell buses in major third-world cities, where hydrogen can be produced from clean and renewable energy sources. These buses replace heavy-polluting diesel buses in regular service, and the difference in price between a fuel cell bus and a regular bus is covered by the World Bank's Global Environment Facility.

Another major difficulty is interrelation and interdependence between hydrogen technologies. For example, it is extremely difficult if not impossible to introduce hydrogen-powered automobiles or hydrogen-powered airplanes into the market without reliable and economically feasible technologies for hydrogen production, distribution, storage, and refueling. On the other hand, significant development of hydrogen production, distribution, and storage technologies will never happen without a large demand for hydrogen.

### COMING ENERGY REVOLUTION?

Recent history of human civilization is characterized by technological revolutions (Figure 11). The industrial revolution started with the invention of the steam engine, which allowed utilization of coal and revolutionized manufacturing with a profound effect on economic and social systems. The electricity revolution brought convenient energy to almost every home and allowed the development of many electrical devices and gadgets, which in turn caused remarkable changes in lifestyle. The automobile revolution started with Ford's mass-manufactured, affordable Model T automobile. Automobiles changed city layout, and the way of living. Most recently, the information revolution, which is still ongoing, started with the invention of computers. Although originally invented for computing only, computers are now being used in everyday life for storing and disseminating information, communication, entertainment, art, and so forth. In a short time, life without a computer has become unimaginable.

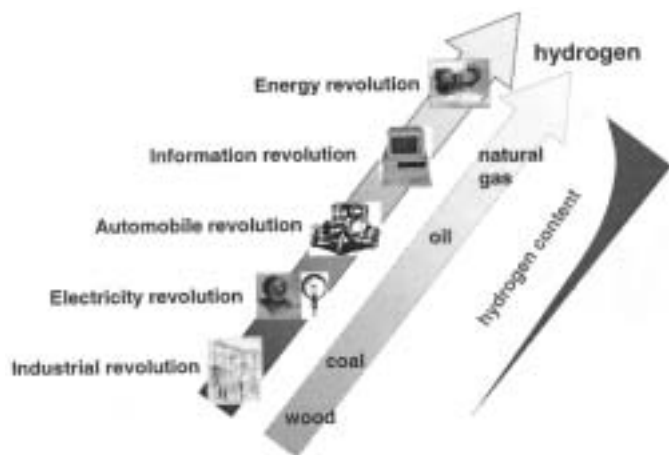


Figure 11. History of technological revolutions and history of fuels.

What is common to all of these revolutions is that each started with a technological invention so powerful that it made changes in everyday life, and allowed development of new products and services unimaginable before its implementation. The fuel cell is likely one of those powerful technologies that could create the next revolution—the energy revolution. It will change the way energy is converted to useful power. It will allow greater utilization of renewable energy sources, it will promote rational use of energy, it will decentralize power generation, and it will allow power generation at various scales, while at the same time without harming the environment.

At the same timescale, it should be noted that different fuels have been used alongside the technological revolutions. Before the industrial revolution, the main fuel was wood and other traditional forms of energy. With the coming of the industrial revolution, coal became the main fuel for more than a century until it was replaced by oil, the main energy source that fueled the automobile revolution. In recent years, natural gas has become more and more significant. The trend is clear—each fuel has been substituted by a fuel with higher hydrogen to carbon ratio. Whereas wood is primarily carbon, coal has the ratio of hydrogen to carbon ~1:1, oil or gasoline ~2:1, and natural gas 4:1. Therefore, it can be extrapolated that the logical choice for an ultimate fuel is pure hydrogen—the fuel of the forthcoming energy revolution.

## CONCLUSIONS

- Transition from the fossil fuel-based energy system seems to be inevitable, due to depletion of liquid fossil fuels (oil and natural gas), and due to environmental concerns.

- Hydrogen and electricity are the most probable energy carriers of the future, because they can be produced from any energy source, and they are clean

and versatile. Produced from renewable energy sources, they result in a permanent energy system.

- Hydrogen technologies, that is, technologies for hydrogen production, storage, and utilization, have been developed. Although these technologies are not mature, there are no major technological obstacles for widespread utilization of hydrogen.

- Transition to a hydrogen energy system will be difficult for a variety of reasons, such as competition with an established infrastructure, lack of policies favoring "real" economics, interdependence of hydrogen technologies, dependency on the renewable energy technologies, and so forth.

- More analyses of solar hydrogen and solar electricity net energy gain are required.

- Fuel cells may be the first hydrogen technologies commercialized on a large scale, with applications ranging from power generation to transportation. This technology has a potential to revolutionize the energy business.

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