<u>Transition to a Nuclear/Hydrogen Energy System</u>

Leon Walters, David Wade, and David Lewis
Argonne National Laboratory

Abstract

The paper explores the motivation for the transition to a nuclear/hydrogen system. For such a transition to be successful the technologies employed must be able to generate enough hydrogen to displace a significant fraction of the petroleum fuels used in the transportation and process heat sectors. This hydrogen must be generated in a manner that is compatible with the environment and independent of foreign fuels.

Nuclear energy, along with contributions from wind, solar, and geothermal resources meet the criteria of environmental compatibility and resource independence. However, nuclear energy is the only one of these sources that has a high enough energy density to generate copious quantities of hydrogen.

The status of the relevant nuclear and hydrogen technologies are discussed and how they are coupled to bring about a transition to a nuclear/hydrogen system. Should the world adopt such a system then the growth rate of nuclear energy would greatly accelerate. With an accelerated growth for nuclear energy the uranium resources would be depleted in a few decades with the once through fuel cycle currently in use. It is pointed out that deployment of fast breeder reactors would become important in the nearer term.

Motivation for a Nuclear/Hydrogen Energy System

Peter Hoffman used a quote from Jules Verne's, "The Mysterious Island" to conclude his book, "Tomorrow's Energy, Hydrogen, Fuel Cells, and the prospects for a Cleaner Planet" [1]. That quote, written in 1874 was; *Yes, my friends, I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light…As long as the earth is inhabited, it will supply the wants of its inhabitants, and there will be no want of either light or heat as long as the production of the vegetable, mineral or animal kingdoms do not fail us.*

Jules Verne, although astonishingly prophetic, could not have imagined the extent to which, in a century, the earth's inhabitants have grown dependent on sources of fossil fuel that are exhaustible and hold the potential to disrupt the environment such that the "the vegetable and animal kingdoms" may fail us indeed.

The technology of producing hydrogen from water has been available for development and exploitation for more than a century. Why have we not used it as a major fuel supply? Simply said, the internal cost of fossil fuel production is cheaper. Internal costs exclude the price that society must pay for the impact to health and the environment. The processes for hydrogen manufacture are energy intensive. When we make hydrogen from fossil fuels, gas, oil or coal, we use up part of the energy in the fossil fuel to make the hydrogen. In all cases the energy we use to manufacture the hydrogen is greater than the energy that we get back from the hydrogen when we use it. For example we can make hydrogen from water by electrolysis using electricity, but we need to put in at least twice as much energy from fossil sources to make the electricity than we will get out when we use the hydrogen as fuel.

Thus, for the past century as we have relied on energy use to grow our economy and enrich our standard of living, we have become more and more dependent on direct use of fossil fuels and more and more dependent on the decisions of a very few countries and corporations that control its production and distribution. All the while we may have been unwittingly disrupting the environment with the by-products of our growing consumption of fossil fuels. These observations are becoming increasingly evident and underscored with the troubled situation in the Middle Eastern countries that threatens the stability of much of the world's supply of oil. The threats to stability in the supply of oil along with recent summit conferences that seek to forestall the growing insult to the environment from the growing use of fossil fuels have caused society to seek alternatives.

Hydrogen, as Jules Verne predicted, may be that alternative that can provide humankind the answer to energy security and environmental compatibility. In the U.S., despite political arguments over energy policy, there is general agreement that hydrogen will play an important part in our energy future. Hydrogen has properties that promise clean, efficient transportation – emitting only water, as a product of its use, to fuel our vehicles. No greenhouse gases, no smog-forming NO_X, no particulates—just water. The fuel cell technology that uses hydrogen as a fuel gives even further environmental benefit with high efficiency conversion of hydrogen to electricity and the advantages that come from an electric-motor vehicle.

More than a third of U.S. CO_2 emissions come from the transportation sector. Use of hydrogen, as fuel will give better fuel efficiency without being environmentally destructive. What more could we want? Well -- how about an environmentally friendly, energy-efficient affordable way to MAKE the hydrogen?

Hydrogen is the third most abundant element on the earth's surface, where it is found primarily in water (H_2O) and organic compounds. But unlike fossil fuels such as coal, oil and natural gas, molecular hydrogen (H_2) needed for fuel does not exist in nature. We don't mine it and we don't pump it out of the ground. We have to manufacture it.

Today we make hydrogen almost exclusively by methane steam reforming. Natural gas is reacted with water at high temperature to form hydrogen and carbon dioxide. The carbon dioxide, which is produced during hydrogen manufacture, must be considered in any discussion of environmentally friendly hydrogen. Greenhouse gas emission reductions won't count if all we do is relocate the place where they are emitted – from the vehicle to the hydrogen manufacturing plant. This is why renewable or nuclear sources are being researched to replace steam methane reforming for hydrogen manufacture. Devising an effective hydrogen future demands that we address two questions:

- Does the process of manufacture possess sufficient scale to supply the world with its energy needs?

- Does the full cycle of a hydrogen economy from harvesting of energy resource to hydrogen production, distribution, use, and cleanup meet our environmental standards?

Only when we have reached a level of comfort with the answers to these two questions have we created an effective energy strategy that includes hydrogen.

Energy demand growth is a global issue, but to get a feel for numbers, let's begin with the scale of energy use in the U.S. alone. The U.S. vehicle fleet accumulated 2600 billion miles in 1997 [2]. Assuming success in building hydrogen powered automobile fleet, we would need 0.013kg of hydrogen for every mile driven to replace the gasoline and diesel fuel [3]. If we were to manufacture the hydrogen by electrolysis we would need 240 gigawatts of new electrical generating capacity. That's almost exactly one half of the total electrical generating capacity of the U.S.

For perspective recall that a typical new large coal fired or nuclear generating plant produces about 1 gigawatt. Gas-fired plants are about half that. Not unexpected in light of the scale of the existing petroleum industry, we are talking about a massive scale of energy infrastructure development to replace oil with hydrogen for the U.S. transportation sector.

Recalling that we want to do more than merely relocate where CO_2 is emitted, we need a nonemitting source of energy to manufacture the hydrogen. Can we make this electricity with windmills? A state-of-the-art 0.0015 gigawatt windmill requires a footprint of about 70 acres. You can place 9 of them on one square mile. To generate 240 gigawatts of electricity you would need 640,000 windmills (with a capacity factor of 0.25) and an area of 71,000 square miles

(Indiana is 35,000 square miles and Ohio 40,000). The land use for windmill based hydrogen production would be remarkably large. The land costs and disruptions would be larger still, but hydrogen is a storable energy carrier suited to the intermittence of the wind. Wind power will likely pay a role.

Can biomass meet the need? The transportation sector would require the American farmer to grow an additional four times as much plant material as he does at present in order to provide enough biomass to produce the needed hydrogen – all the while continuing to feed the American public. Biomass continues to fuel the undeveloped world, but remember the higher energy density of fossil was required to enable the industrialization of the West.

What about solar? The capital cost for solar generated electricity is between $20 and $25 per watt. The 240 gigawatts of generating capacity needed to replace the transportation fuel would cost more than $4.8 trillion for the equipment alone. The 240 gigawatts of solar electric panels would occupy about 3,000 square miles, the purchase of which would add to the cost. Development is warranted on more cost-effective photovoltaic panels, especially to contribute in remote, off grid locations of small demand.

While new renewables (biomass, solar and wind) power will contribute to local power needs, fill niche opportunities, and initiate the electrification of developing countries, they rather clearly fail to meet the scale requirement for manufacturing hydrogen for industrialized America's transportation needs. The U.S. choices for a majority of the energy to manufacture hydrogen at the required scale come down to coal and nuclear.

That takes us to the second question. Does the full cycle, from mining, to production, to distribution, to use, to clean up, meet our environmental standards? Again, consider the situation for the U.S. as an example.

There is certainly enough domestic coal to fire the electrical plants that could provide both the electricity and the clean hydrogen needed to power the U.S. transportation system for several hundred years. Building 240 new power plants is a big job – but not unfeasible. The full hydrogen demand will develop over several decades. At only 3.5% annual growth rate we already double our electricity production every 20 years. Growth rates for energy of 6-8% are not unfeasible for industry to achieve. But coal power plants will generate carbon dioxide and other emissions requiring recovery and sequesterization; otherwise, they will be discharged into the atmosphere at a different location from our automobiles and will continue to contribute to global warming. A number of schemes are proposed for collecting and sequestering the carbon dioxide. Some, such as injecting it into oil reservoirs, have been reduced to practice; they are costly and energy-intensive. Others such as those where the carbon dioxide would be sequestered on the deep ocean floor are energy intensive and might create unanticipated forms of environmental damage. Yet others are simply short-term solutions.

The U.S. is left with nuclear energy as a logical choice. Safe, reliable energy production with a secure domestic fuel supply already mined and sitting in storage sufficient for at least the next several thousand years. No reliance on a foreign trading partner controlling the energy resource, no greenhouse gases or NO_X emissions – and scant increase in cost. The U.S. situation is similar to numerous of the OECD countries where nuclear is an established industry and an important segment of the electricity supply infrastructure.

What's the problem? The problem is the public's perception of the "unsolved" nuclear waste issue. The ironic thing about waste is that the cost of disposing of nuclear waste is already included in the cost of generating electricity from reactors – whereas the cost of disposing of the "waste" CO_2, NO_X, etc. from other energy sources is not. Even renewables generate waste emissions over their life cycle – e.g., emissions and waste from energy use to manufacture the windmills and solar panels, gasoline and diesel used to plant and harvest biomass, etc. What would be the result of adding all the costs of waste management to all energy sources?

A ten-year study by the European Community was designed to quantify the external costs of electricity production [4]. It showed that the cost of producing electricity from coal or oil would more than double. The cost of electricity production from gas would increase by at least 30% if external costs such as damage to the environment and to health, which is currently not included in the price of the energy, were taken into account (this excludes the cost of global warming). Currently, such costs are not billed to consumers, but are none-the-less an expense for society at large. According to the study, the costs to the environment of producing electricity from natural gas, coal and nuclear—taking into account the entire fuel cycle and covering costs not currently accounted for such as damage to the environment and health—would add 1-4¢/kWh for gas, 3-10¢/kWh for coal, but just 0.2-0.5 ¢/kWh for nuclear. These are not numbers from a nuclear advocacy group but from the decade long EXTERN-E study conducted by the European Community. In their view just 0.2-0.5¢/kWh will pay all of the external environmental costs of nuclear power, which are not already included. That is by far the smallest added expense among all the options. When linked to the vision of a clean non-emitting hydrogen future, the notion of affordable, non-emitting hydrogen production from nuclear energy can become an attractive alternative in a thoughtful comparison of alternatives.

The discussion of required scale has focused on industrialized nations, but the dramatic growth of energy use will be in developing economies – most of which currently use energy per capita at one tenth or less of the rate in industrialized nations. In his keynote speech at the World Hydrogen Congress in Montreal last June Geoffrey Ballard said [5]:

- "For society to continue its progress in medicine, social responsibility, science, education and quality of life we must assure that there is an ever increasing supply of energy per capita."

  and he said:

- "It is also paramount that Europe and North America develop and export economically sound, clean technologies to emerging nations. –Carbon-based economies, supplying energy in the quantities necessary to assure progress in developing nations would completely destroy Earth's fragile atmosphere."

Hydrogen is unquestionably the transportation fuel of the future. As we move forward in the next several decades it must be adopted worldwide to make any significant impact on reductions in greenhouse gas emissions. In the near term it will be manufactured from coal, oil, natural gas and electricity generated primarily from fossil fuels. However, the energy to manufacture hydrogen must come increasingly from nuclear power. If the world is to achieve energy security and protect the global environment, then nuclear is the least costly and cleanest option that can meet the scale of deployment required.

Status of the Relevant Technologies & Technical Feasibility of a Nuclear/Hydrogen Economy

Technologies for Hydrogen Production

Hydrogen has been produced for more than a century by a vast number of schemes. All that is needed is water or some other chemical compound containing hydrogen and a source of energy in the form of electricity, heat, or radiation to extract the hydrogen. Today, the steam reforming of natural gas generates 95% of all hydrogen. The heat to drive the reaction is produced by burning part of the natural gas feedstock with the consequent by-product generation of additional carbon dioxide. Thus, from a greenhouse gas perspective, there is not much to be gained should this means of generating hydrogen be used in the long term to supply hydrogen for the transportation sector. None-the-less hydrogen, generated from natural gas, is economically important for the world and should not be minimized just because the process generates carbon. Greater than half of the hydrogen produced is used today to manufacture ammonia-based fertilizers. These fertilizers help feed the world. Most of the rest is used to reduce sulfur emissions from high sulfur oil products**.** Further this hydrogen, when added to heavy crude oil enhances the yield of high hydrogen products such as gasoline from low-grade crude and extends the reserves.

Heat necessary to drive the reforming reactions could be supplied from nuclear energy rather than from burning part of the fossil feedstock. Advanced reforming techniques are under development that reduce the reaction temperature for steam reforming with the application of ceramic membrane science – thus opening up this possibility for nuclear-assisted steam methane reforming to several proposed classes of reactor types. Should this be the case, then while not all the carbon dioxide generated from steam methane reforming would be mitigated, at least that portion produced from the combustion of natural gas for process heat would vanish. The problem with the application of nuclear energy for this purpose is that the high outlet temperature nuclear reactors are not currently available commercially. How can we get started?

The hydrogen generation technology available for more than a century but never deployed in large scale is electrolysis of water. This technology is mature. Several manufactures offer electrolyzer units in a range of outputs. Soon to be on the market are units with a hydrogen generation rate suitable for the fueling of a personal automobile. Units are already operating around the world, in prototype demonstrations, for the provision of central fueling for public transportation and auxiliary energy for large buildings. An argument commonly associated with the transition to a hydrogen based transportation system is the lack of a hydrogen delivery infrastructure comparable to the current deployment of fueling stations for internal combustion gasoline and diesel vehicles. But with electrolysis an even more ubiquitous deliver infrastructure is already in place, – the electrical transmission system, as near as the receptacle on the wall. Another common observation is that electrolysis is inefficient. Electrolysis itself is highly efficient, approaching 85% or better.

The power plant that generates the electricity for the electrolysis may have an efficiency of perhaps 30%, such as that for a nuclear reactor. The combined efficiency is the product of the efficiencies, which is about 25%. Even so, several studies have shown that when electricity is cheap enough, for example at off-peak rates of 2 to 3 cents per kilowatt-hour, that hydrogen can be produced at a price competitive with the price of gasoline or diesel fuel [6,7]. An electricity load-leveling advantage, based on storing hydrogen during off peak periods, may become commercially viable in the future.

The third means of producing hydrogen is the direct "splitting" of water in a high temperature thermo chemical process. These processes have been under investigation for almost four decades. Each of the processes requires heat energy input to achieve the reaction $2H_2O + heat \leftrightarrow 2H_2 + O_2$. Temperatures, in the range of 700 to 900ºC and recyclable chemical reagents can provide the chemical reactions that result in the dissociation of the water into hydrogen and oxygen. The chemical reagents never leave the cycle, with only water as input and hydrogen and oxygen as products. The efficiencies of these processes are expected to be in the range of 40 to 50 %. The most promising of these cycles are the calcium- bromine process and the sulfur-iodine process. None of the thermo chemical processes have progressed to the point of commercial viability, mainly because there has not been the economic incentive to do so. But within the past few years' incentives related to environmental benefits and energy independence have given rise to a resurgence of interest in these high temperature thermochemical cycles. A pilot-scale demonstration of the sulphur-iodine system with a high temperature helium-cooled nuclear reactor as the heat source is being planned in Japan [8].

Feasible Growth of Nuclear Energy

Electricity constitutes about 33% of total energy use with the other 67% of the energy being used for transportation and process heat. Today there are 435 nuclear reactors in the world producing electricity for 17% of the world's electrical needs. Nuclear energy does not currently contribute to the 67% for transportation and process heat, and thus contributes only 6% of the world's total energy. If nuclear energy continues to supply electricity only, then the maximum contribution of nuclear energy to the world's future energy needs is capped at 33% to 50%. By only supplying electricity, nuclear energy cannot provide an ultimate solution for independence from foreign oil and gas nor can it be the final answer to the elimination of the enhanced greenhouse effect. Nuclear production of hydrogen provides the avenue for entry into the other two thirds of the energy market because hydrogen can substitute for any and all fossil energy applications. But what advances in nuclear technologies would be required?

In terms of technology maturity the nuclear reactor variations fall into three categories. The first category constitutes nearly all the 435 reactors that are commercially producing electricity today. For the most part these reactors are water-cooled, thermal reactors that are initially fueled with either natural uranium or low enriched uranium. The capacity factors for these reactors are high, the accumulated safety record excellent, and within the past few years they have been economically competitive throughout the world. The coolant outlet temperatures are a maximum of 400ºC, and thus too low for use in thermo chemical cycles for the direct splitting of water or even for nuclear assisted steam methane reforming. However, they can couple to electrolysis as soon as a market for hydrogen exists at a scale to induce producers to enter. Near the end of fuel life about 40% of the energy from an LWR originates from plutonium that is bred into the fuel from the conversion of the fertile ^{238}U. However, these reactors are overall net consumers of fissionable uranium from virgin ore, so in the long run the LWR once-through fuel cycle technology is not sustainable once the uranium resources are exhausted.

The second category of reactors is the sodium cooled fast reactors that were designed not only to generate electricity but also to breed net fissile from ^{238}U and extend the uranium resources from decades to thousands of years. Several countries have brought these to the brink of commercialization. Operating experience with these reactors has been excellent. The main reason they have not been commercially deployed is that their capital cost has been substantially greater than the current water-cooled reactors. The issues surrounding the proliferation of nuclear weapons are also of concern because reprocessing of the fuel containing the bred plutonium is necessary. Additionally, since there is no near term shortage of uranium, a near-term need to breed additional fissile material does not exist. The peak coolant outlet temperature for the sodium-cooled fast reactors is 600ºC. This temperature is still too low for direct use of the heat for the thermo chemical splitting of water but could couple with steam reforming of methane and/or electrolysis. The Russia nuclear program has been developing a lead cooled fast reactor. Lead coolant holds the potential of coolant outlet temperatures in the range of 850-900ºC – high enough for thermochemical water cracking.

The final category of nuclear reactor is the gas cooled high temperature reactors. An early (Magnox) design was commercialized and with the Advanced Gas Reactor (AGR) successor design, has had successful commercial operation in Great Britain and France. These older gas cooled reactors are now being phased out because they are not economically competitive. A second class of gas cooled reactor based on coated particle fuels, was developed in the U.S. and Germany. While commercialization was never reached, many variations are in the conceptual stage and a few small experimental reactors have been built and operated. South Africa is revisiting the pebble bed gas cooled reactor, successfully demonstrated by Germany. They believe they will have a commercial prototype ready for the market within a decade. The peak coolant outlet temperatures for these reactors will be in the range of 900ºC and one of their principal purposes is hydrogen production by thermochemical water splitting.

Figure 1 illustrates a time evolution of increasing reactor temperatures able to support various hydrogen manufacturing technologies.

Transition to a Nuclear/Hydrogen Economy

Criteria for a commercially viable nuclear/hydrogen system

A transportation system based upon nuclear generated hydrogen will not begin to emerge until nuclear energy is accepted on its own virtues. First and foremost nuclear energy must compete favorably with all other major forms of energy production from an economic viewpoint. It has begun to do so now even without the advantage of external costs being factored into the total cost. Public concern with safety issues associated with nuclear power seem to be diminishing as the lessons learned from past events are implemented and the safety record remains unblemished from further events. The safety trust is still fragile, such that an additional event, even with no casualties, would have a large unfavorable impact on the future of nuclear energy. Waste and nonproliferation issues although technically under control now, with a number of plausible paths, remain a major concern in the minds of much of the public. These issues must simply diminish in importance, as benefits of nuclear power are perceived to outweigh the perceived risks: benefits of economy, reduction of the insult to the environment by avoidance of carbon dioxide and other pollutants, and the possibility of energy independence. When these benefits are understood by a large fraction of society, nuclear energy will be able to move out of its small niche of 17% of the electricity for the grid to the huge market in the transportation sector. It may well be that the vision of an essentially inexhaustible nuclear resource, when coupled with the production of environmentally friendly hydrogen, is the catalyst that will lead to a new wave of rapid deployment of nuclear energy.

All automobile companies hold an intense interest in hydrogen-fueled transportation. A hydrogen internal combustion engine now compares well with gasoline and diesel engines. Within a few years fuel cell cars will achieve the same level. To be a contender in the market these hydrogen-propelled vehicles will have to have a cost, convenience, or safety advantage. Assuming they will be a contender on that basis, then a convenient and economic fueling system must emerge. A disconnect exists here. Currently all the hydrogen is produced from centralized methane reforming but a national hydrogen pipeline system does not exist. The capital needed to emplace a hydrogen pipeline system will not appear until a market for the hydrogen exists. This market will not exist until the use of hydrogen vehicles is widespread and fuel is conveniently available. This "chicken and egg" dilemma can be solved by the introduction of a dispersed system of electrolyzers for the production of hydrogen that depends upon the convenient electrical distribution system already in place coupled to inexpensive off peak electricity.

The cost of driving a mile by the use of hydrogen produced by electrolysis must be close to that for gasoline for this to happen. It was pointed out earlier that the cost differential is small without invoking any special considerations for hydrogen fuel not being a carbon dioxide producer [6,7]. These considerations were based on the assumption of the availability of cheap electricity such is now available from hydro or the off peak operation of nuclear power plants. Substitution of hydrogen for gasoline, in the transportation sector, will require much more new electricity than renewables could reasonably produce.

Transition to sustainability

The transition to a complete nuclear/hydrogen economy could take three or more decades. Figure 1 summarizes the time evolution of possible nuclear hydrogen options. The 435 reactors currently deployed could be producing hydrogen today with their off-peak power by electrolysis. Within two decades, should a national will exist to do so, hydrogen could be produced with sodium cooled fast reactors by electrolysis or by use of nuclear heat to assist traditional methane cracking. Potentially, hydrogen could be produced even by the use of nuclear heat to assist in the thermo chemical cracking of water. This latter application would require the combustion of a fraction of the product hydrogen to reach the required temperature for the thermo chemical reactions. Finally, within 3 to 4 decades reactors may be available whose outlet temperatures are high enough that any of the hydrogen production schemes are options. These would couple symbiotically with Na fast reactors to extend the uranium resource to many countries.

Ultimately, the vision is that nuclear energy would become the vital link in the energy supply chain. This vision has emerged as one element in the U.S. Department of Energy's Generation-IV deliberations. In collaboration with the Generation-IV International Forum of ten nations, this initiative is considering the R&D required for the next phase of nuclear energy. In Generation-IV planning, nuclear power is no longer being thought of as simply a source of electricity for the grid, but as suitable for other energy services as well. Figure 2 reflects this vision. This figure reflects the fact that a huge market may very well develop for the non-electric products of nuclear power.

Should this new market develop for nuclear power then what can be said of the current projection for the longevity of the uranium resource? Currently, the most optimistic growth rate for nuclear power is about 2.5% per year. This translates to nuclear power holding on to 17% of the electricity produced for the grid. At this growth rate the uranium resource recoverable at ≤ 130$/KgU would last for fifty years or more and there is no immediate economic incentive to change the inefficient once through use of uranium [9]. Thus, though there may be an incentive for waste management purposes, there is no resource shortage incentive to rekindle the interest in fast reactors for the breeding of fissile material from ^{238}U. However, should this vision of nuclear power moving into the non-electric market materialize, then projections for growth rates of nuclear power may double or triple. Should this happen then the sustainability of the nuclear/hydrogen option would immediately be questioned on the basis of ore availability. Fast breeder reactors should receive a great deal of renewed attention in that case.

Figure 3 reflects the coupling of the nuclear and hydrogen technologies in a manner that stresses their role in sustainability; it emphasizes many of the points made previously. The figure shows the coupling of the particular reactor type to the method of hydrogen generation and the time line for doing so. Of special significance in regard to sustainability is the vision, displayed on the figure, that when these two technologies are coupled properly the net impact to the environment is essentially neutral. Uranium moves into the system from the geosphere, is recycled until completely fissioned to produce energy and fission products. Only the fission products flow out of the system as waste and back into the geosphere, where they decay back to the level of the original uranium ore within a few hundred years. Water moves into the system from the atmosphere, hydrogen and oxygen are produced, transported to the point of utilization, recombined for energy extraction, and returned to the atmosphere as water vapor. This ecologically neutral energy supply architecture is what humankind must achieve if our way of life is to be sustained in the long-term.

Conclusions

Although interest in hydrogen as an energy carrier has emerged repeatedly as an option for more than a century, it has never succeeded to become a major player in the energy market. There simply have never been the incentives to seriously develop the option. At the dawn of the 21st century the incentives do exist. They are driven by widespread social sensitivity to protecting the environment. Most importantly, many nations see an urgency to grow their economies independent of foreign oil supplies and free of energy sources of limited duration. A key enabling break through is the recent success in the development of the fuel cell energy converter.

Hydrogen, when produced from fossil fuels, is not the long-term answer to these concerns because environmental compatibility or energy independence would not be achieved. Wind, solar, and geothermal can contribute to carbon-free hydrogen manufacture more easily than to electricity production (which can't be stored), but they simply do not possess the energy density required to generate the copious quantities of hydrogen required for fully industrialized societies. Thus, nuclear fission becomes the only primary energy source that can generate enough hydrogen to fuel the world's economies in a carbon dioxide free manner.

The transition to a nuclear/hydrogen economy can begin today with the current generation of nuclear reactors and the mature electrolysis technology. Nuclear energy can support a cleaner use of fossil fuel through nuclear assisted steam methane reforming for heavy oil enhancement. Finally, highly efficient carbon-free means of producing hydrogen by coupling advanced high temperature nuclear reactors with thermo chemical processes is on the horizon.

The modest growth rate predicted for nuclear power would greatly increase should this vision of a nuclear/hydrogen economy materialize. Uranium resources would be depleted within a few decades without the deployment of fast breeder reactors in symbiosis with the existing and new reactor types. Thus, for a transition to a nuclear driven hydrogen economy to be sustainable, the nuclear side of the equation must include not only the tie to hydrogen generation but also to the breeding of fissile from fertile uranium.

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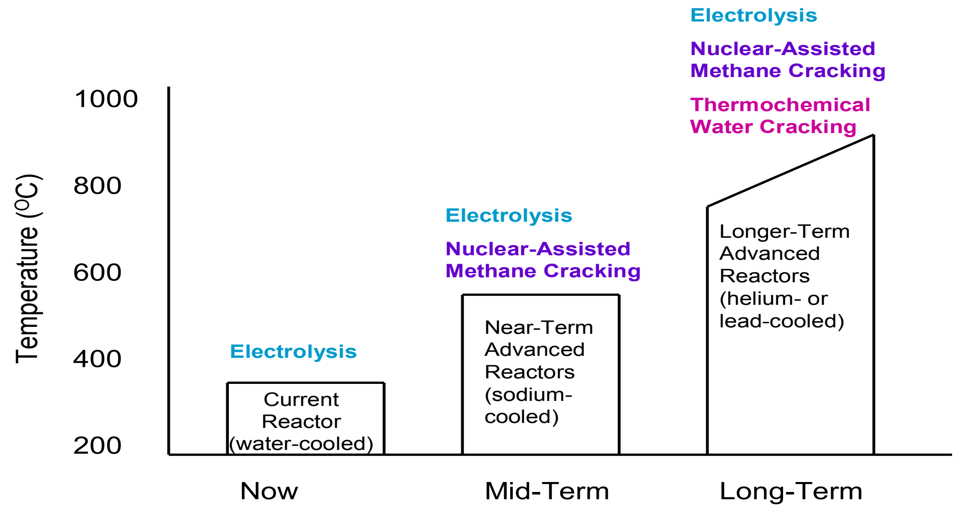

Fig. 1 Deployment of Nuclear-Generated Hydrogen

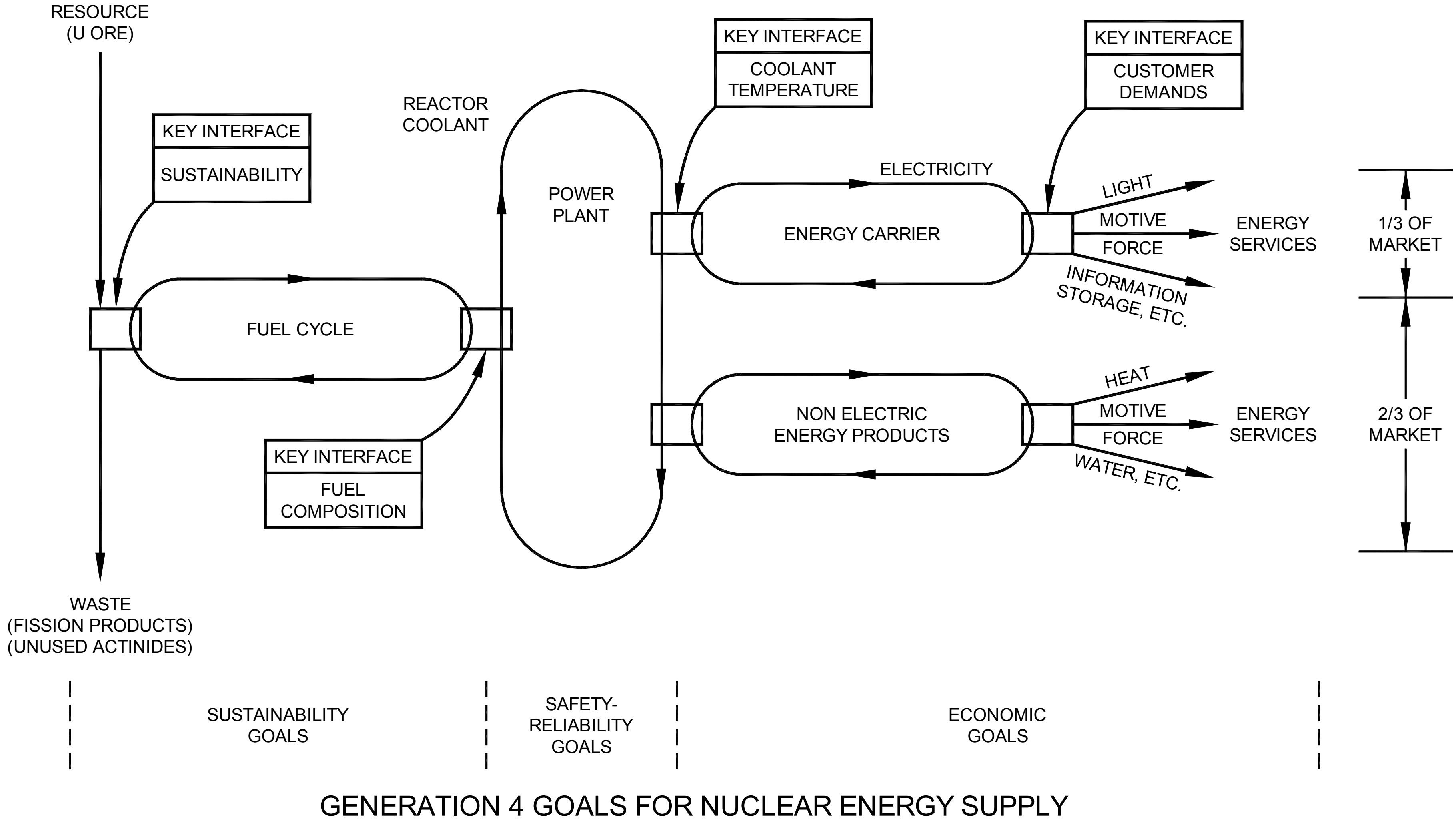

Fig. 2 Nuclear as a Link in the Energy Supply Chain

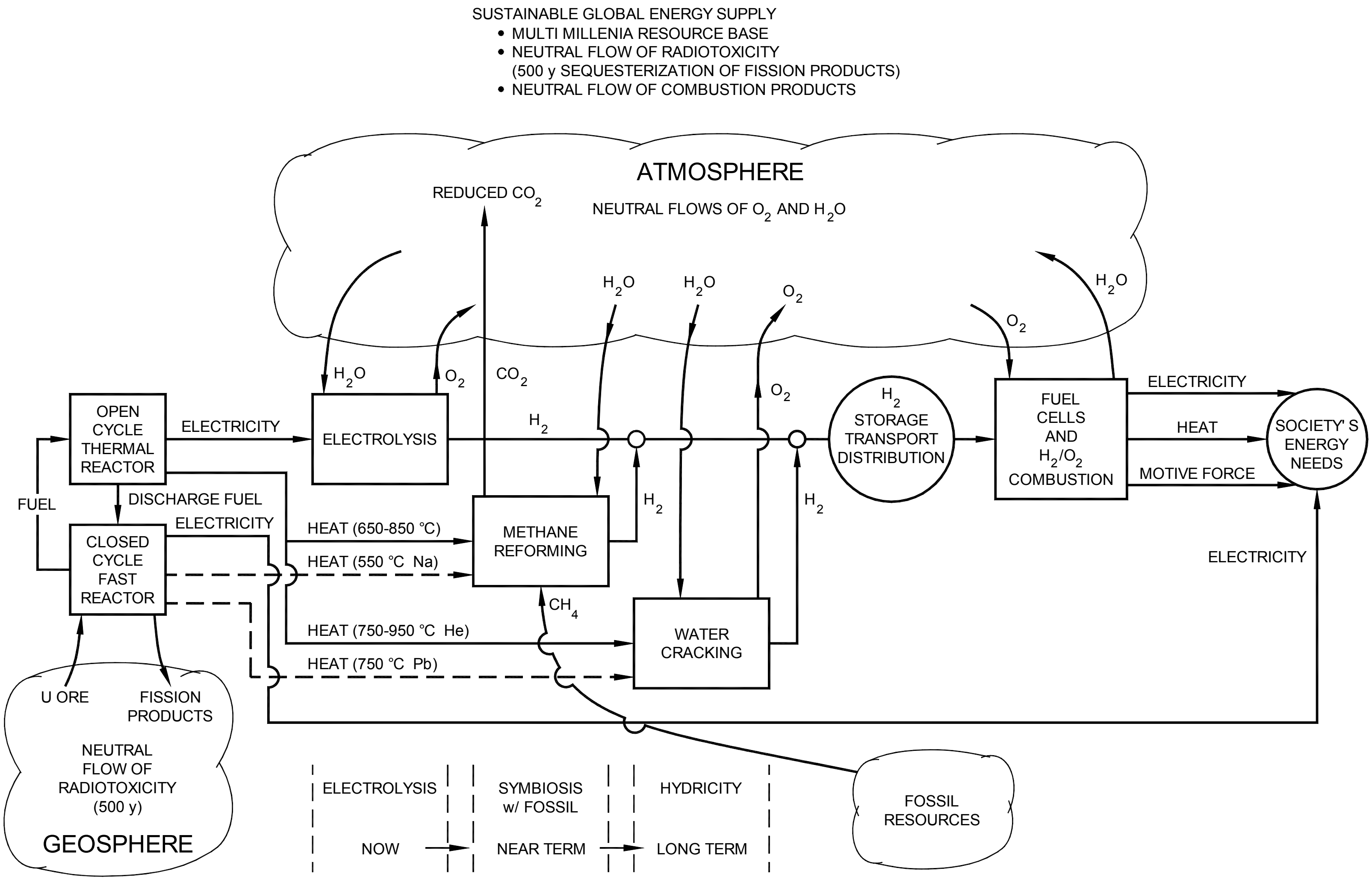

Fig. 3 Transition to Sustainability