A Low-Greenhouse-Impact Hydrogen-Based Liquid-Fuels Future

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Abstract

The world faces two interconnected energy challenges: higher cost crude oil and potential greenhouse impacts from the burning of fossil fuels. The fundamental challenges are primarily associated with transportation because stationary energy demands can be met using electricity and heat from multiple non-greenhouse-emitting sources.

The high volumetric and energy density of liquid fuels make it technically difficult to replace liquid fuels in the transport sector. The key to success for starting down the path toward a hydrogen economy is to provide a means for gradually integrating hydrogen generating technologies into the highly integrated, huge liquid fossil fuel based economy. A two part strategy to reduce greenhouse emissions in the transport sector by ~80% while retaining the use of hydrocarbon liquid fuels for transportation purposes is proposed.

- *Liquid fuels production*. An economic source of hydrogen from a non-greenhouse-emitting source is used to generate liquid fuels from a variety of carbon sources other than crude oil, such as tar sands, coal, biomass, and garbage. Depending upon the feedstock, the carbon dioxide released from all the steps required to make the fuel varies from 20 to 200% of the amount of carbon dioxide released from burning the fuel. With nuclear generated hydrogen, all of the carbon in the fuel feedstock can be converted to liquid fuels drastically reducing the total carbon dioxide released per liter of fuel.

- *Hybrid vehicles*. The full deployment of plug-in hybrid vehicles (electric batteries with liquid-fuel engines) can double the vehicle mileage per liter of liquid fuel for cars and light trucks. A plug-in hybrid uses night-time electricity to recharge vehicle batteries and uses a combination of electricity and liquid fuels to minimize liquid fuel use without compromising vehicle range or performance. Plug-in vehicle prototypes are now being tested and hybrid vehicles are in production.

Alternative scenarios and the potential reductions in greenhouse gas emissions and costs are evaluated. The use of a PBMR reactor to generate hydrogen is used as the economic basis.

Introduction

The existing transportation and electric power generating industries are the result of over 100 years of evolutionary change. The availability of inexpensive hydrocarbon fuels with very high energy densities has been the driving force that has made the internal combustion engine the basis of the current transportation system. On the opposite side of mobility has been the electric industry. Except for a brief time at the beginning of the last century when the performance of the battery-powered electric cars could rival that of the internal-combustion engine powered cars, electricity has not been a significant factor in the transportation industry. Even where electricity was a factor (as in interurban and city street cars), electricity was largely replaced by either the automobile or by buses by the 1930's.

However, the very success of the internal combustion engine has sown the seeds of its own destruction. The hydrocarbon fuel which makes the internal combustion engine possible is now much more expensive than it has ever been before, with the prospect that future increases in demand by developing countries such as China and India will continue to drive the cost even higher. On the other hand, electricity supplied by more environmentally friendly and available means such as nuclear energy, promises to be available at reasonable prices for the foreseeable future. In addition to electricity, high temperature (~900°C) thermal energy is now available from nuclear sources such as the Pebble Bed Modular Reactor (PBMR). The high temperature energy can potentially be used in chemical process plants to efficiently and economically produce hydrogen from processes such as the Hybrid Sulfur Process (HyS) without the use of hydrocarbon fuel (methane) that is currently used or the capital intensive and relatively inefficient water electrolysis process.

The current hydrocarbon fuel generation and distribution system is highly integrated with the current internal-combustion-engine-based transportation system. Change of the current system is therefore very difficult due to the massive infrastructure changes that would have to be wrought to achieve a system that can use lower cost energy from more stable nuclear power sources in forms such as electricity and hydrogen.

This paper examines the consequences of a transition strategy that utilizes nuclear energy to make electricity and hydrogen that are used to reduce the demand for liquid and gaseous hydrocarbons as transportation fuels. Among the consequences considered are the expected cost for transportation fuel, the level of CO_2 that is emitted, and the timeline for achieving this change.

Challenges

The era of producing liquid fuels from crude oil is ending. The rate of discoveries of crude oil is far lower than the rate of consumption. This does not imply that we will run out of liquid fuels. Liquid fuels can be and are made from other feedstocks such as coal. However, these business-as-usual methods for liquid-fuel production imply massive increases in carbon dioxide emissions per vehicle mile traveled relative to that for liquid fuels made from crude oil (Fig. 1). In conversion of coal and other low-cost abundant fossil fuels to liquid fuels, half the coal is used to make hydrogen, produce oxygen (a required input to coal liquefaction), and provide heat to the fuel processing plants. Research is under way to sequester carbon dioxide from power plants and industrial facilities and thus minimize the environmental impacts from using coal. However, sequestration of carbon dioxide requires very special geological conditions that may or may not be located where the fossil fuels and coal liquefaction plants would be built. Producing liquid fuels from coal and other low-grade fossil sources without large carbon dioxide emissions from the production process is challenging.

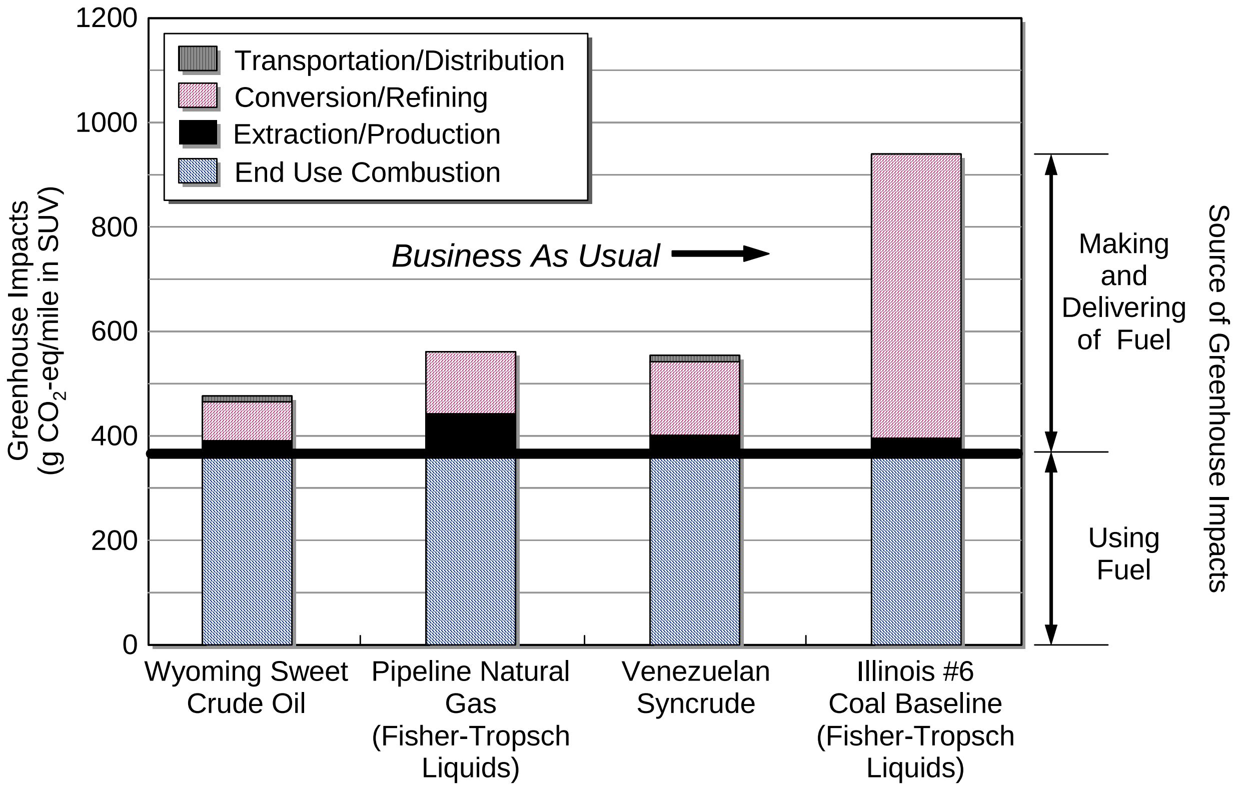


Fig. 1. Equivalent Carbon Dioxide Releases per SUV Vehicle Mile for Diesel Fuel Produced from Different Feedstocks (Ref. 1).

There are alternatives to traditional liquid fuels; however, the transport area is a particularly difficult technical challenge since all facets of the technology must be conveniently usable by a wide range of users with various skill levels (i.e., it must be user friendly). The hydrogen containing fuel must have a high energy density, be easily stored, transferred between storage and a vehicle, and then efficiently used by the vehicle in an energy conversion device that has a reasonably high energy density. Ideally, the system of choice should be the safest, most environmentally friendly, achieve the longest range, and be the most efficient. However, since the optimums of all these factors rarely coincide, overall cost and usability are usually the deciding factors.

Since the choice of fuel to a large extent determines the system, several fuels are considered and evaluated. All are hydrogen-based fuels.

1. Gaseous or liquefied hydrogen;
2. Absorbents such as metal hydrides;
3. Hydrogen containing compounds such as $LiBH_4$, NH_3 and CH_4;
4. Beneficially used hydrogen in current fuels where the hydrogen is generated by a process that does not generate CO_2. Examples of such fuels are diesel, methanol and ethanol.

The volumetric and gravimetric energy densities of the various candidates are shown in Table 1 and compared with current diesel hybrid engine technology. Note that one big usability standard is the vehicle range. No matter how efficient the vehicle, if it only goes a short distance before it needs refueling, the technology will not be accepted by consumers. On this basis, Table 1 (last column on the right) shows that it is difficult to beat a hybrid diesel engine operating with diesel fuel. Methane, both liquefied and pressurized, are also reasonable. Almost all of the other options give ranges that are too low. The metal hydride, ammonia and $LiBH_4$ systems are all limited by weight whereas all of the other systems are limited by volume.

Another attribute of the system to consider is safety. There are four main safety considerations: toxicity, flammability, temperature and pressure. These items are compared in Table 2. Of the options considered, three have a combination of low toxicity, pressure and room temperature: metal hydrides, diesel and $LiBH_4$. Two of these options involve hydrogen which has the widest flammability limits. Again, diesel fuel is the most benign approach followed by compressed or liquefied methane.

Table 1. Comparison of Various Hydrogen Based Fuels with Ultimate Performance Goals

H_2 Storage Method	Engine Type	Engine Thermal Efficiency	Gravimetric Energy Density (btu/lb)	Volumetric Energy Density (btu/ft^3)	Specific Gravity	Est. Milage for Max. 20 gallon Tank of Fuel	Est. Milage for Max. 120 lb Tank of Fuel	Est. Miles for Tank of Fuel
Compressed H_2 @ 700 bar	Fuel Cell	70%	51,623	186,798	0.058	192	2645	192
Liquefied H_2 @ 4°K	Fuel Cell	70%	30,476	133,119	0.070	137	1562	137
Metal Hydrides (5% H_2/lb metal @8 lb/ft^3)	Fuel Cell	70%	2,581	1,288,510	8.000	1323	132	132
Liquefied NH_3 @ 300°K @10 bar	Hybrid	40%	8,001	664,019	1.330	389	234	234
Compressed CH_4 @ 300°K @700 bar	Hybrid	40%	21,520	622,962	0.464	365	630	365
Liquefied CH_4 @ 109°K	Hybrid	40%	21,520	625,767	0.466	367	630	367
Methanol	Hybrid	40%	9,735	480,747	0.791	282	285	282
Ethanol	Hybrid	40%	9,735	479,289	0.789	281	285	281
$LiBH_4$ (50% slurry in water)	Fuel Cell	70%	4,777	327,908	1.100	337	245	245
Diesel Hybride (Made with H_2 from hydrogen generation process)	Hybrid	40%	27,321	1,363,864	0.800	800	800	800

Table 2 Comparison of the Flammability Limits for Ammonia, Hydrogen and Gasoline Compounds

H_2 Storage Method	Est. Milage for Max. 120 lb Tank of Fuel	Est. Miles for Tank of Fuel	Flammability Lower Limit (Volume%)	Flammability Upper Limit (Volume %)	Toxicity	Storage Pressure	Storage Temperature
Compressed H_2 @ 700 bar	2645	219	4	74.2	Minor Asphixiation Hazard	700 bar	Room Temperature
Liquefied H_2 @ 4°K	2645	264	4	74.2	Minor Asphixiation Hazard	Atmospheric	4°K
Metal Hydrides (5% H_2/lb metal @8 lb/ft^3)	132	132	4	74.2	Minor Asphixiation Hazard	Atmospheric	Room Temperature
Liquefied NH_3 @ 300°K @10 bar	234	234	15.5	27	IDLH 500 ppm	10 bar	Room Temperature
Compressed CH_4 @ 300°K @700 bar	630	416	5	15	Asphixiation Hazard	700 bar	Room Temperature
Liquefied CH_4 @ 109°K	630	418	5	15	Asphixiation Hazard	Atmospheric	109°K
Methanol	285	285	6	36	200 ppm TWA; 6000 ppm IDLH	Atmospheric	Room Temperature
Ethanol	285	285	3.3	19	1000 ppm TWA; 3300 ppm IDLH	Atmospheric	Room Temperature
$LiBH_4$ (50% slurry in water)	245	245	4	74.2	Minor Asphixiation Hazard	Atmospheric	Room Temperature
Diesel Hybride (Made with H_2 from hydrogen generation process)	800	800	0.77	5.35	Low (>1369 ppm for 8 hours)	Atmospheric	Room Temperature

A Transport Strategy Using Nuclear Energy Products

The increasing cost of crude oil, the national security implications of importing oil, the need to reduce greenhouse impacts, and the characteristics of alternative transport fuels leads to a need for a new transport fuel strategy.

The most straightforward option is to go back to the beginning of the 20th century and utilize all electric vehicles. While attractive from the point of view that the electrical production and distribution system is already well established, this option is not yet feasible due to the very low energy density of battery storage as compared to hydrocarbon fuel storage. The other option that is referred to as the hydrogen economy is at the other end of the practicality spectrum; a widespread production and distribution system does not exist, the storage technology is not that much better than current battery systems, and the use of hydrogen in current internal combustion engines would be relatively inefficient.

A transitional strategy (Fig. 2) to a new hydrogen-fuel economy is proposed herein that is based on the use of hydrogen and electricity that has three components.

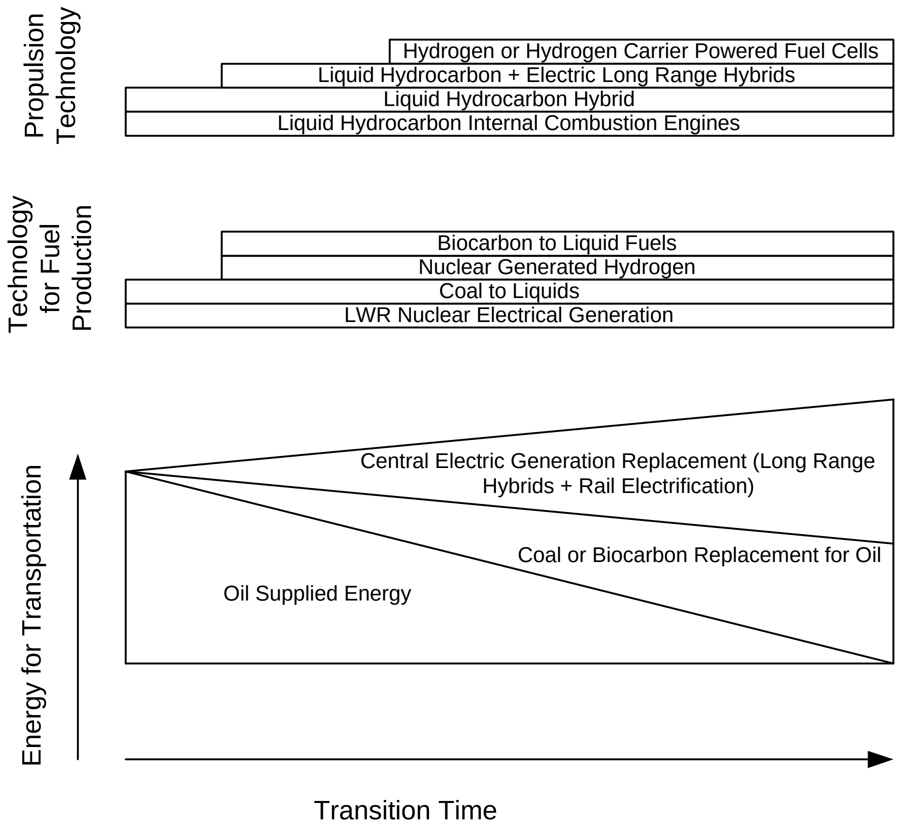


Fig. 2. Proposed Transition Strategy

Hydrogen Fuel Production

Nuclear reactors, such as the PBMR high temperature gas cooled reactors that are coupled to the HyS hydrogen generation process to make hydrogen, would produce hydrogen. At first, petroleum-based fuels could be upgraded. As the availability of petroleum decreased, the hydrogen could be used to upgrade other hydrocarbons. The first might be coal and tar sands. Future sources could be biomass materials such as garbage, wood, plants and other carbon sources derived from wastes. As an infrastructure for hydrogen distribution is developed and dedicated supplies of hydrogen for transportation fuels became available, the hydrogen could then be used directly in fuel cells or other transportation power devices. During this time period, it is assumed that practical means for storing hydrogen will have been developed.

Modern refineries use large quantities of hydrogen to remove sulfur and convert heavy oils into liquid fuels. That hydrogen is currently made from fossil fuels with the release of large quantities of carbon dioxide to the atmosphere. With nuclear hydrogen, the hydrogen production process would not generate carbon dioxide and the carbon dioxide releases from the atmosphere (Fig. 1) would decrease per unit of liquid fuel produced.

For feedstocks such as coal, there are large carbon dioxide releases per unit of fuel produced with traditional technologies. For example, the traditional process for liquid fuels production from coal is the Fischer-Tropsch process where reaction used to produce hydrocarbon liquids is:

$$CO + 2\ H_2 \Rightarrow -CH_2- + H_2O$$

It requires a feed with H_2/CO in a ratio of 2. If coal is used as the sole source of the process heat as well as the hydrogen, then a significant amount of carbon dioxide is produced just to manufacture synthesis gas feed to the Fischer-Tropsch process:

$$C + 0.5\ O_2 \Rightarrow CO$$
$$C + H_2O \Rightarrow CO + H_2$$
$$CO + H_2O \Rightarrow CO_2 + H_2$$
$$CO + 2H_2 \Rightarrow -CH_2- + H_2O$$

or overall

$$2C + 0.5\ O_2 + 2\ H_2O \Rightarrow CO_2 + -CH_2- + H_2O$$

This reaction therefore produces a mole of CO_2 per mole of carbon that is liquefied fuel, resulting in almost doubling the amount of CO_2 produced per vehicle mile. However, if nuclear generated hydrogen is used instead of a totally hydrocarbon based process, than a minimum of CO_2 is produced as almost all of the carbon in the feedstock is turned into liquid fuel.

$$C + 0.5\ O_2 + 2H_2 \Rightarrow -CH_2 - + H_2O$$

If the feedstock for liquid fuels production is a biological source of carbon, such as wood and plant wastes from agriculture and manufacture, or crops are specifically grown for feedstock for transportation fuel manufacture, the net generation of CO_2 becomes zero. The plants collect carbon dioxide from the atmosphere, the carbon is converted to liquid fuels, and the fuels are burnt with return of the carbon dioxide to the atmosphere. The use of an outside source of hydrogen (such as nuclear hydrogen) in the biomass-to-liquid-fuel production process can increase the liquid-fuels production per unit biomass by a factor of two or more. All the carbon is converted to high-quality fuel rather than much of the carbon being used as an energy source in the production process of making the liquid fuel.

Hybrid electric vehicles

A revolution in vehicle engine design is occurring with the commercial manufacture of hybrid cars and trucks today and the announced introduction of plug-in hybrid electric vehicles in several years. A hybrid car or truck has a gasoline or diesel engine, generator-motor, and storage batteries. The engine is operated at the power level and speed that maximized fuel economy. At times of low power demand (such as at stop lights), the batteries are charged. At times of high power demand, the batteries provide additional energy. Because the internal combustion engine is efficient over only a narrow range of operating conditions, hybrid vehicles have higher efficiencies because the engine speed is optimized for fuel economy.

The plug-in hybrid has a larger battery system and is an electric vehicle for short trips and a hybrid vehicle on long trips. Because most vehicle trips are short trips, high performance plug-in hybrids could reduce liquid fuel consumption in half (Ref. 2). The deployment of plug-in hybrid vehicles that have extended battery life (30 to 50 mile range) built into the vehicle offer major advantages

1. *Economics*. Plug-in hybrids have the potential to greatly reduce the liquid fuel demand within a relatively short time period and slow price increases in liquid fuels. Electricity per vehicle mile is less expensive than liquid fuel.

2. *National security*. Plug-in hybrids offer protection against supply disruptions because they are multifuel: liquid/hydrogen fuel or electricity. While operating such vehicles as electric vehicles on longer trips would be highly inconvenient due to the need for battery recharge, it is a viable contingency option.

3. *Electrical grid*. Plug-in hybrids allow nuclear electricity to directly meet the transport needs of the country. Equally important, the option for use of nighttime electricity levels the electrical load and increases the base load, that part of the electrical power demand most suitable for the use of nuclear power.

4. *Environment*. Plug-in hybrids reduce carbon dioxide emissions by the use of electricity from non-carbon-dioxide emitting electricity production. The technology also drastically reduces the health effects from local air pollution. Vehicle air pollution in the morning has far higher health effects than air pollution latter in the day because of photochemical conversion of pollutants by sunlight. With nighttime recharge of batteries, pollution generation rates are the smallest in the morning.

5. *Transition to hydrogen fuel cells*. In the long-term, there are strong incentives to use hydrogen fuel cells for vehicles because of their very high efficiency. Fuel cells produce electricity. Hybrids offer a chance for automobile manufacturers to learn how to build low-cost reliable, all-electric drive systems. It would be extraordinarily difficult to jump to a hydrogen fuel cell without an existing hybrid vehicle industry.

6. *Development time*. This approach provides years of development time that will be necessary to develop reliable hydrogen storage systems. These storage systems may store hydrogen directly (for example, metal hydrides) or use an alternate hydrogen carrier like liquid ammonia or metal borohydrides. At the same time it is a pathway to a low-CO_2-emissions non-imported-crude-oil system even if the ultimate hydrogen economy does not occur

Electricity for transport

The freight transportation sector is a unique case. In this sector, it will be very difficult to integrate hydrogen as a fuel because of the very high power levels that are required (~4 MW per locomotive). In this case, the electrification of the railroads and the substitution of rail transportation for truck transportation for long distance freight hauling are proposed. Such a scenario is outlined in Table 3. Currently, about 14% of all freight is shipped on railroads while 86% is shipped by truck. Assuming that this could be reversed with a well planned investment in railroads and their electrification, 52 LWR-type nuclear plants would be required for electrical generation for rail transit.

Table 3. Effect of Nuclear Electrical Generation for Freight Hauling on CO_2 Emissions

	Truck	Rail	Total	
Freight Carriers Before Elecrification	86%	14%		
Freight Energy Usage	5.32	0.84	6.16	Quads
Freight CO_2 Emmisions	553	87	640	millions of tons CO_2
Freight Carriers After Elecrification	14%	86%		
Freight Energy Usage	0.84	5.32	6.16	Quads
Freight CO_2 Emmisions	87	0	87	millions of tons CO_2
LWR Availability	NA	95%		
LWR Rating	NA	3,600		MWt
LWR Nuclear Plants	NA	52		

Transition Strategy

An example transition strategy has been developed based on the following assumptions considerations.

1. An ultimate hydrogen transport sector that uses hydrogen-powered fuel cells (assumed to operate at ~70% efficiency);

2. A near-term transition to Diesel based hybrid engines (diesel with electric power/battery storage - assumed to operate at ~40% efficiency) with the phased in use of hybrids to counterbalance the growth in the number of vehicles.

3. Straight line reduction in gasoline used as hydrogen or hydrogen carriers or biofuels are substituted for liquid hydrocarbon fuels;

4. Direct carbon substitution of coal for liquid hydrocarbons;

5. Automobiles account for 35% and light trucks 26% of transportation energy use in the base year of 2005 (Ref. 3).

Figure 3 shows the implications in terms of carbon dioxide releases.

One important factor to note is that as biological sources of carbon such as wood and plant wastes from agriculture and manufacture, and crops are specifically grown for feedstock for transportation fuel manufacture are substituted for oil or coal feeds, the net generation of CO_2 will decrease to zero. In this case, the use of nuclear hydrogen will allow this relatively expensive source of carbon to be efficiently used. Half or less of the biomass carbon will be required for the nuclear option as compared to the non-nuclear option for H_2 (Ref. 4).

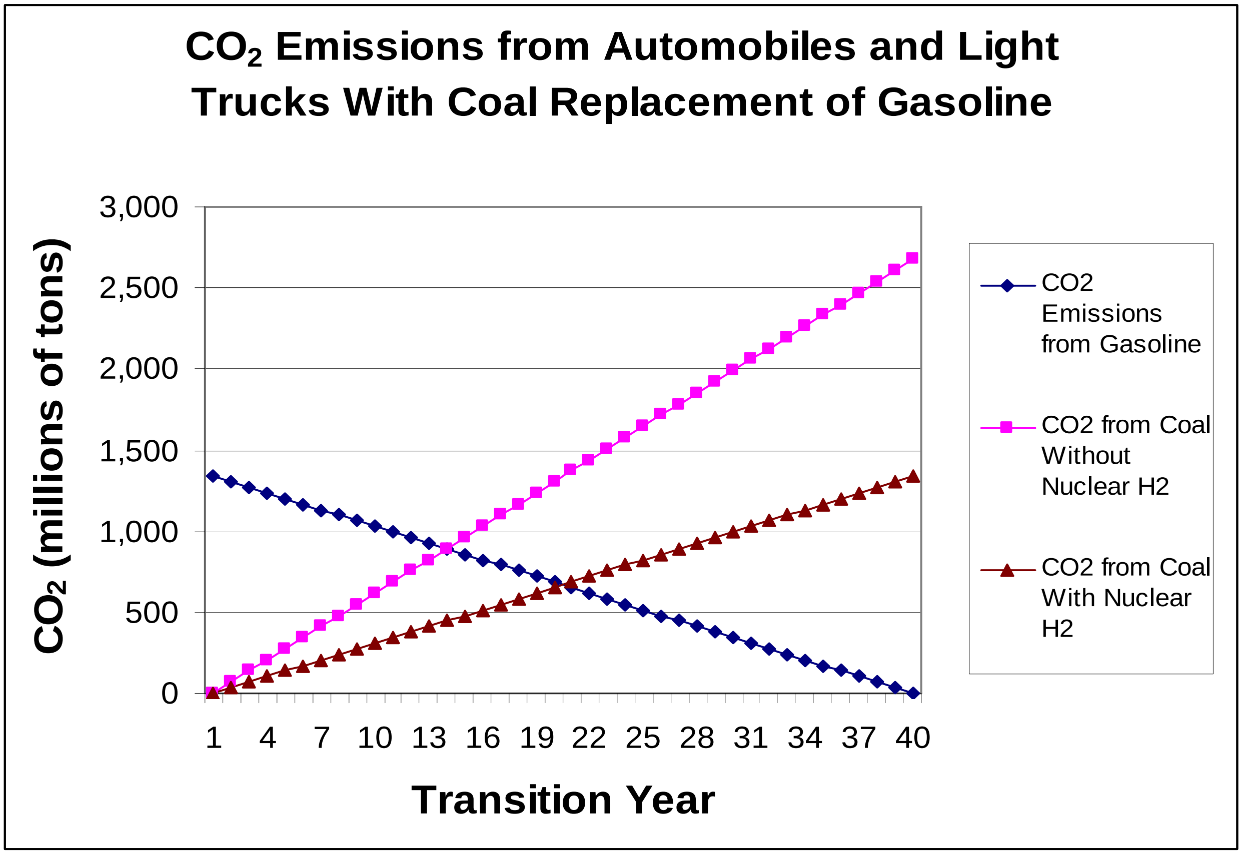
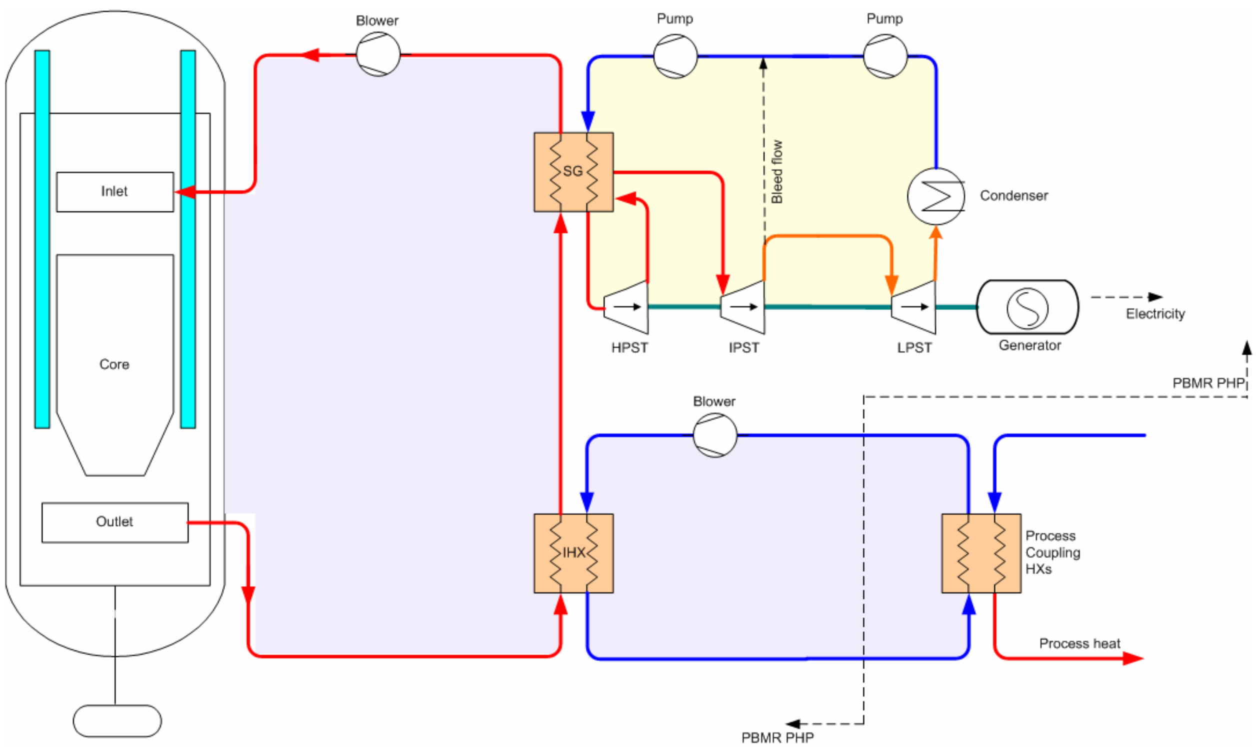


Fig. 3 Effect of Using Nuclear Generated Hydrogen on CO_2 Emissions

Nuclear Energy Requirements to Replace Traditional Liquid Fuels

Nuclear energy produces heat that can be used for a variety of purposes. The major use to date is for the generation of electricity form light water reactors. Due to the relatively low production temperature (~300°C), electrical production is the only large scale feasible use. Other types of reactors such as the gas-cooled PBMR (Fig. 4, Refs. 5, 6) and liquid-salt-cooled high temperature reactors such as the Advanced High-Temperature Reactor (Ref. 7) are being developed to produce high-temperature heat. The modular high-temperature gas cooled reactors are the near-option and in the case of the PBMR, are being commercially deployed. The more advanced reactors have potentially superior economics but require more development.

The PBMR produces high temperature thermal energy at about 900°C. These higher temperatures provide the capability of powering high temperature chemical reactions that produce hydrogen Ref. 8). An example of these thermochemcial reactions is the HyS process that produces hydrogen (Fig. 5, Ref. 9). Both electricity and hydrogen could be used as transportation fuels that could replace hydrocarbons. Both products would have the very positive benefit of producing no CO_2 during either the production or use phase if nuclear were used to generate them. There are, however, questions about the practicality of using these two products directly in the transportation area and about the time required to build the capability to supply the required quantities of energy.



- **Reactor Thermal Power – 400 to 500MWt**
- **Allowable Reactor Inlet Temperature – 300 to 500°C**
- **Maximum Operating Helium Pressure in Reactor – 9MPa**
- **Maximum Helium Pressure in Process Coupling Heat Exchanger- 9MPa**
- **Maximum Reactor Outlet Temperature – 950°C**
- **Maximum Temperature available for process – 900°C**

Fig. 4. PBMR Process Heat Reactor and Power Generation Configuration

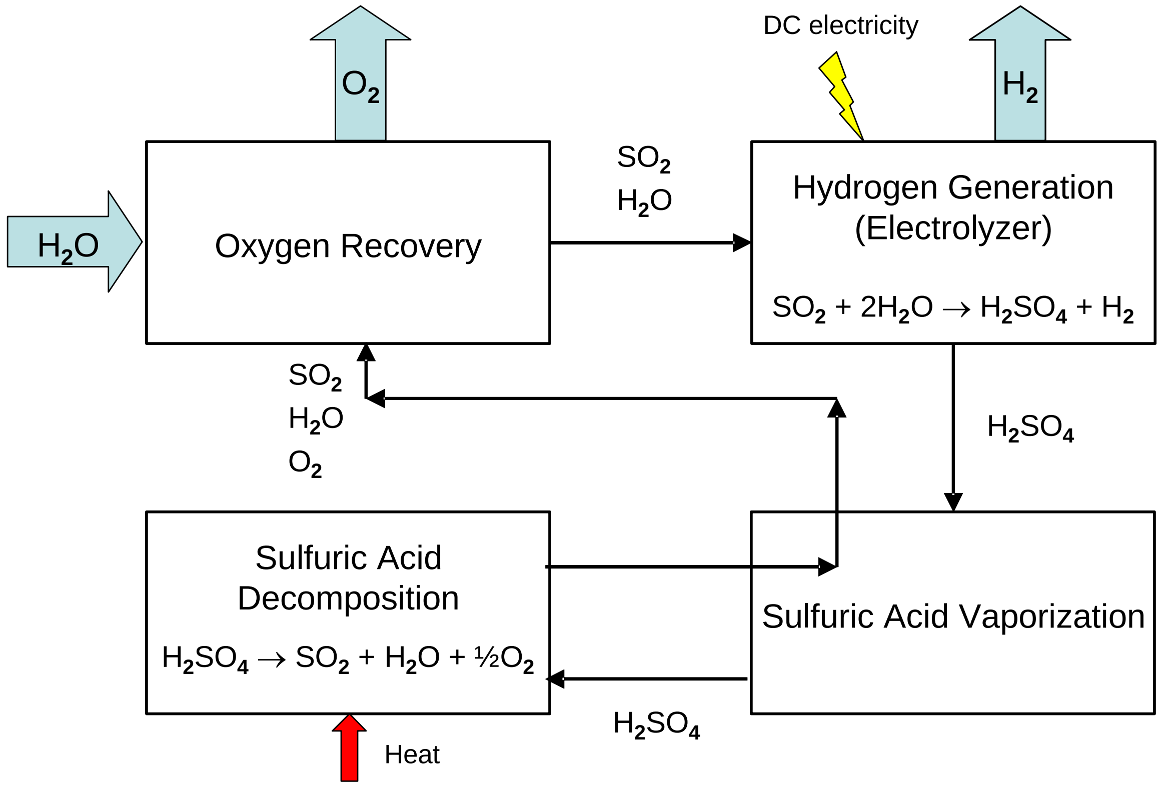


Fig. 5. Hybrid Sulfur Process

We will first address the capability question. Based on recent EIA data from 2005 (Ref. 10), the amount of fuel used in the land-based transportation sector amounted to 22.1 Quads (heat equivalent). Note that the land-based transportation system includes automobiles, trucks and locomotives. If one assumes that newer technologies such as fuel cells and long range hybrids will effectively cut by one third the energy use of the current transportation system, then about 7.4 Quads of high-quality hydrogen and electricity will be required. Further assuming that about half of the land transportation will be fueled by hydrogen and half by electricity produced at an efficiency of 45% from PBMR type reactors and 33% from light water reactors (LWRs) respectively, then the total nuclear output will be 8.2 Quads from PBMRs and 11.2 Quads from LWRs. This is the equivalent of 577 PBMRs at 500 MWt each and 109 LWRs at 3600 MWt each. These calculations are summarized in Table 4.

If PBMRs can be brought on line in 2 years and LWRs in 3 years and 30 of each type can be under construction in any year, then it will take at least 40 years to build the required PBMR fleet and 14 years to build the LWR fleet for transportation applications even with this very aggressive schedule. Note that this calculation also assumes no net growth in the transportation field over the transition period. Any growth would simply extend the transition time. This simple calculation indicates the scale of the challenge to replace the current internal combustion engine based transportation with a whole new system. The other challenge is to generate the required capital investment. Assuming a cost of about $400/KWt for LWRs and $700/KWt for PBMRs, the total investment required is $360 billion dollars!

Clearly, wholesale and immediate replacement is not a practical expectation. Therefore, a method that recognizes a timeframe of about 40 years will be proposed that provide a relatively continuous transition path between our current transportation system and a future system that can use nuclear power as a basis.

Table 4. Time Frame and Cost for Producing Transportation Fuels from Nuclear

Land Transportation Energy Use	22.12	Quads	(2005, EIA)
H_2 and Electrical Efficiency			
Current Internal Combustion Engine Efficiency	3		
H_2 and Electrical Energy Use	7.4	Quads	
Energy Source	H_2	Electricity	
Fraction Supplied	50%	50%	
Energy Required	3.7	3.7	Quads
Efficiency of Production	45%	33%	
Nuclear Thermal Energy	8.2	11.2	Quads
Availability	95%	95%	
Reactor Size	500	3600	MWt
Number of Reactors	577	109	
Reactors Under Construction	30	30	/yr
Years to Complete Each Reactor	2	3	yr
Transition Period Years	40	14	yr
Specific Cost for Reactors	$700	$400	/KWt
Total Cost for Reactors	$202	$157	(billions)

Conclusions

Nuclear generated hydrogen can play a decisive role in both the transition from the current oil driven transportation economy to the future hydrogen/electric or bio-carbon/electric transportation economy as well as in the future transportation economy. Nuclear hydrogen increases the usefulness of the bio-carbon fuels by reducing by half the bio-carbon that must be produced in order to meet the needs of liquid transportation fuels.

Given that nuclear energy plays a major role in this future economy, then our nation must be willing to make major investments (~$400 billion) on a sustained basis (~40 years) in order to achieve the goals of both net zero CO_2 emissions and energy independence. The major role that nuclear plays also means that the whole nuclear fuel cycle must be developed to ensure long term supplies of nuclear fuel as well as to safely treat spent nuclear fuel and to provide for the safe ultimate disposal of nuclear waste.

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