Nuclear Energy for Transportation: Electricity, Hydrogen, and Liquid Fuels

by Masao Hori

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The transportation sector consumes about a quarter of final energy in Japan and worldwide, and presently most of this energy is supplied by petroleum. For the sake of the global environment and resources, it is important to seek possibilities of replacing a substantial part of this transportation energy by nuclear energy. There are several ways to do this, using energy carriers like electricity, hydrogen, and synthetic liquid fuels to fuel transportation vehicles. These energy carriers can be produced from nuclear energy alone, or synergistically with other primary energies like fossil fuels or biomass.

In this paper, we review the possibilities and impacts of these energy carriers, and examine the measures and tasks for using nuclear to supply the energy carriers. In converting the primary energies into the energy carriers, synergistic processes may be more advantageous than the individual process. Some of the exploratory processes to produce synthetic liquid fuels from fossil fuels and nuclear energy are presented.

About one-third of the world's primary energy is converted to electricity at present. The remaining two-thirds is consumed in such non-electric applications as process-heat for industry, space heating, and transportation. Although the ratio of electricity will likely increase to about one-half by the end of the 21st Century, that still leaves one-half of the world's primary energy being used for non-electric purposes. As it is essential to reduce the global use of fossil fuels, it is important to explore the feasibility of nuclear energy replacing fossil fuels as the power source for non-electric applications.

1. Introduction

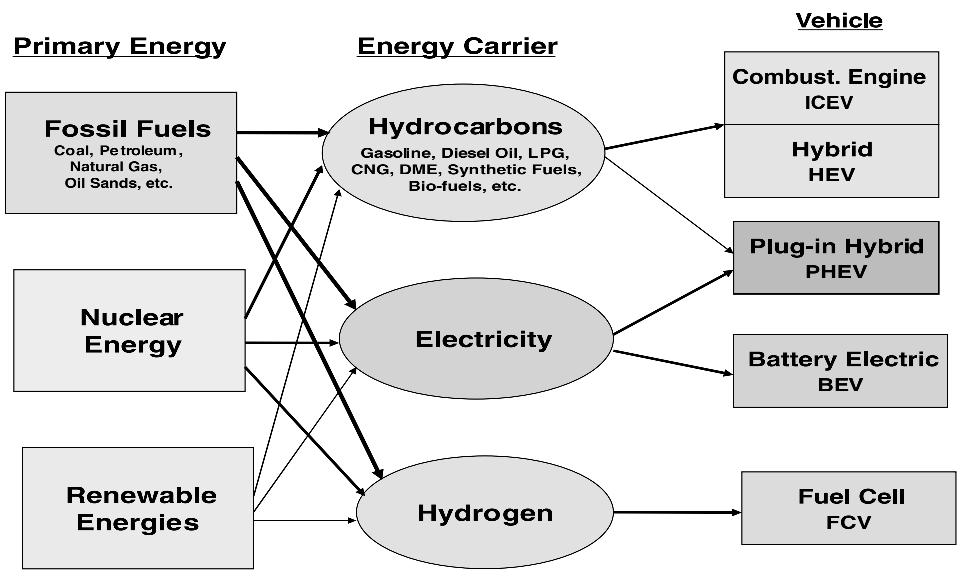
The transportation sector consumes about a quarter of all energy used in Japan, which is similar to the global average. Most of this consumption is in the form of petroleum fuels, such as gasoline or diesel oils, used in automobiles. Japan's electricity, which also makes up a quarter of the nation's final energy, is generated from nuclear (32%), coal (25%), natural gas (24%), petroleum (10%), and hydro (8%) (2005 figures). Thus, in the power-generation sector, the dependence on fossil fuels is now below 60%, and the security of energy supply and the reduction of CO_2 emissions are progressing by decreasing the petroleum and carbon consumption.

There would be significant advantages for energy security and the global environment, if the energies for the transportation sector were to be supplied by nuclear energy. At present, the energy carriers to power the vehicles are such hydrocarbons as gasoline or diesel oil. Promising energy carriers capable of replacing these hydrocarbons are, as shown in **Table 1**, hydro-

TABLE 1
Nuclear-Derived Energy Carriers for Transportation

Primary Energy	Energy Carrier	Transportation Application
Nuclear Energy (Synergistically with Fossil Fuels or Biomass)	Hydrogen	Automobiles
	Electricity	Airplane
	Synthetic Fuels Biofuels	Railway
		Ship

FIGURE 1
Energy Flows to Vehicles with Various Power Trains



gen, electricity, synthetic liquid fuels such as DME (dimethyl ether), methanol, or Fischer-Tropsch (FT) oils, and biofuels such as ethanol or ETBE from biomass. These energy carriers can be produced from nuclear energy by itself, or by a synergistic process using both fossil fuels (or biomass) and nuclear energy. The merits of using nuclear energy for production of these energy carriers are that there is no CO_2 emission, a sustainable bulk supply capability, and a high energy density, facilitating energy security.

For the case of automobiles, the energy flow to different types of power trains is shown in **Figure 1**. These include internal combustion engine vehicles (ICEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV), and hydrogen fuel cell vehicles (FCV). Thus, through the paths of synthetic fuels, electricity, and hydrogen, nuclear energy could power these vehicles.

In this paper, we review the possibilities and impacts of these energy carriers for powering transportation means, and we examine the measures and tasks required to supply these energy carriers by nuclear energy.

2. Hydrogen

Application to Transportation

The term Hydrogen Economy means a society which uses electricity and hydrogen predominantly as its energy carriers, replacing the now-dominant hydrocarbons in the transportation sector with hydrogen.

The energy sources we use for industrial and consumer purposes are called energy carriers. These are sources of energy which are derived from primary energy sources. Gasoline and electricity are familiar examples of energy carriers. After electricity, hydrogen is one of the most promising energy carriers for the future, because hydrogen is not only clean and efficient, but also can be stored. Essentially, water is the only emission when hydrogen is used.

The chemical energy of hydrogen can be converted to power most efficiently by a device known as a fuel cell. Combustion of hydrogen, as in an engine, could also be used for obtaining power. Hydrogen is easier to store than electricity, but hydrocarbons, especially liquid fuels, are much easier to store than hydrogen.

Hydrogen is the most abundant element in the universe. However it does not normally exist on Earth as a gas (H_2), but is rather found in the form of chemical compounds. It is most often found combined with oxygen in water (H_2O). It is also found combined with carbon in the various hydrocarbons. To produce hydrogen gas from compounds, it is necessary to use energy to break the chemical bonds which hold the hydrogen. Nuclear energy and renewable energies are ideal to do this, because they do not emit CO_2 or are carbon neutral. Renewable energies like wind and solar are inherently dilute, so their hydrogen production capacity is naturally limited.

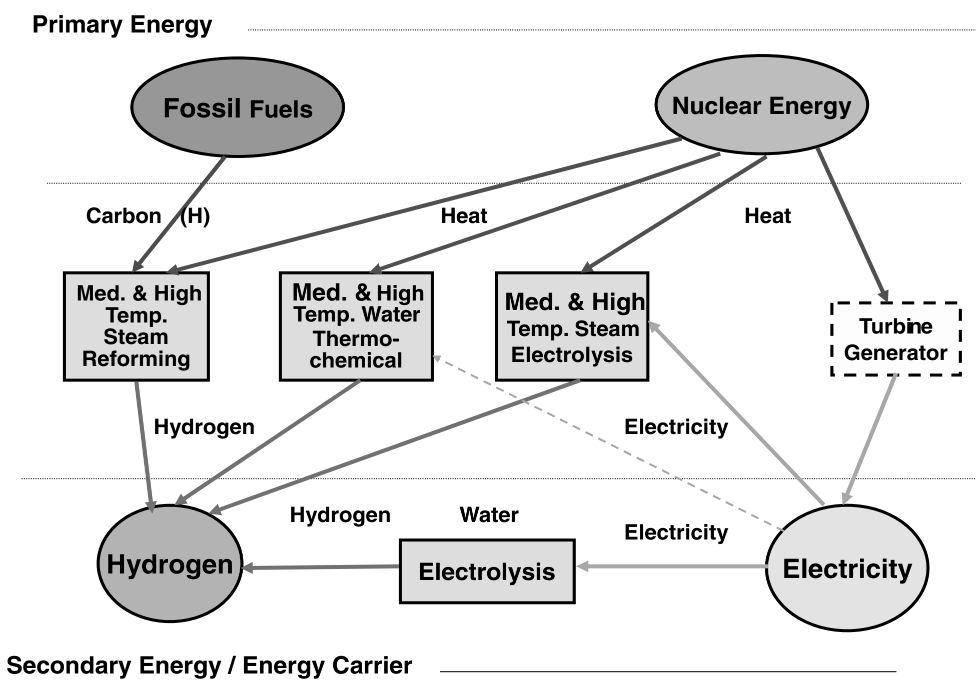
Utilization of hydrogen in automobiles, through fuel cell technology, is one of the primary goals of the Hydrogen Economy. There are still major problems to be solved before the commercialization of hydrogen fuel cell vehicles can be realized. The biggest challenge we face is the cost of the fuel cell.

Other challenges are the method of storing hydrogen on board the vehicle to ensure an adequate cruising range, the creation of hydrogen distribution infrastructure, and so on. Because hydrogen is the most promising energy carrier, it is expected that application technologies will evolve by breaking through the various problems we encounter now, although it might take a few decades.

There are other transportation applications of hydrogen fuel: for fuel cells to supply electricity to railway trains, marine vessels, and aircraft, and for jet engines to propel aircraft. If the application of hydrogen to jet engine aircraft is actualized in the future, nuclear-produced hydrogen is the best suited to the supply at hub airports for its features of no CO_2 emission and bulk supply capability.

It is expected that we will ultimately achieve the Hydrogen Economy. In the course of evolution, nuclear hydrogen may be employed for broader uses, such as a material for producing synthetic liquid fuels from heavy oils and coal, as discussed in later sections.

FIGURE 2
Methods for Hydrogen Production by Nuclear Energy



Supply by Nuclear Energy

Hydrogen can be produced from any of the primary energy sources (fossil fuels, nuclear energy, and renewable energies). Nuclear hydrogen will be expected to supply the base load, because of its characteristics. Many processes have been proposed for production of hydrogen using nuclear energy (**Figure 2**). The leading processes presently under research and development are:

- Electrolysis of water by nuclear electricity;
- High-temperature electrolysis of steam by nuclear electricity and heat;
- Thermo-chemical splitting of water by nuclear heat, or by both nuclear heat and electricity; and
- Nuclear-heated steam reforming of natural gas, or other hydrocarbons.

Although it is not certain what course the commercialization of nuclear hydrogen production will take, a typical prospect based on the current state of knowledge (Hori and Spitalnik, 2004) could be as follows:

1. In the near term, electricity generated by light water reactors (LWR) can be used to produce hydrogen from water by electrolysis. This process can be commercialized, in some cases by using off-peak power, because the relevant technologies are already proven.

2. In the intermediate term, nuclear-heated steam reforming of natural gas, using medium-temperature reactors, could be utilized, in spite of some carbon dioxide emissions, because of its advantages in economic competitiveness and in technical feasibility. Also, high-temperature reactors could be used to carry out high-temperature steam electrolysis, with higher conversion efficiency and fewer materials problems.

3. In the long term, high-temperature reactors would be coupled to thermochemical water splitting. These bulk chemical processes benefit from economy of scale, and may turn out to be the best for very-large-scale nuclear production of hydrogen for a mature global hydrogen energy economy.

3. Electricity

Application to Transportation

Introduction of electric automobiles, such as a battery electric vehicle, into the market enables the supply of nuclear energy to transportation sector. However, the battery electric vehicle is still high in cost, because the battery capable of propelling an ordinary cruising distance is pricey, so it is still in a niche application.

A plug-in hybrid electric vehicle is a hybrid electric vehicle with increased battery capacity, capable of being recharged from an external electrical plug. Up to a certain distance, which depends upon the battery capacity, the plug-in hybrid electric vehicle is powered solely (or mostly) by the battery, like a battery electric vehicle. Only after

TABLE 2
Energy Utilization Efficiency for Electric and Fuel Cell Vehicles

Nuclear Reactor	Electricity / Hydrogen Vehicle Power Train	Efficiency Reactor → Battery/Tank	Efficiency Battery/Tank →Wheel	Overall Efficiency Reactor →Wheel
LWR	Steam Turbine BEV	30%	70%	21%
	Electrolysis FCV	23%	50~60%	12~14%
SFR	Steam Turbine BEV	39%	70%	27%
	Nuclear-Heated Steam Methane Reforming FCV	77%*	50~60%	38~46%*
VHTR	Gas Turbine BEV	45%	70%	31%
	Thermochemical FCV	45%	50~60%	23~27%

➢ Thermal efficiency: LWR steam turbine 32%, SFR steam turbine 41%, VHTR gas turbine 47%
➢ Efficiency of H_2 production: Electrolysis 80% from electricity and Thermochemical from heat 50% (LHV) Reforming 85% (* Based on the sum of both primary energies)
➢ Transmission & distribution loss for electricity: 5%, Compression & transportation loss for H_2: 10%

that certain distance, does the plug-in hybrid electric vehicle rely on an internal combustion engine, like a hybrid electric vehicle.

By this means, the plug-in hybrid electric vehicle can save on fuel consumption as compared to an ordinary hybrid. All of the energy powering a hybrid electric vehicle comes from petroleum (gasoline or diesel), while the energy powering a plug-in hybrid electric vehicle comes from both petroleum and the primary energies which generate the electricity used to charge the battery when plugged in.

According to Robert E. Uhrig, Professor Emeritus of the University of Tennessee, who analyzed the effect of introducing plug-in hybrid electric vehicles into the United States, transportation petroleum use could be reduced by about 74% by powering the plug-in hybrid electric vehicle with electricity from a battery of 35-mile cruising capability.

Assuming that all of the 225 million light transportation vehicles (automobiles, SUVs, pickups, vans, etc.) are plug-in hybrid electric vehicles, then 422 GWe would be required to charge the batteries during eight hours at night. Uhrig concluded that, considering spare generating capacity at night, perhaps 200 new 1,000-MWe nuclear power plants are needed.

From my research in Japan, the estimate is that on any given day, on average, 50% of Japanese vehicles are driven less than about 20 kilometers. Thus, a battery capable of powering a plug-in hybrid electric vehicle for a certain distance, say 35-60 kilometers, depending on the categories of vehicles—which is far less than the capacity required for an ordinary battery electric vehicle—could power for about 70% by distance, on average, by electricity alone, and thus save a substantial amount of gasoline.

With the recent rapid evolution in battery technology, especially in lithium ion batteries, there is a possibility that plug-in hybrid electric vehicles (more so than battery electric vehicles) can be commercialized within several years. Now the Japanese government, as well as the U.S. and other governments, are pushing the development of advanced battery technology to be applied to plug-in hybrid electric vehicles.

There were about 77 million vehicles altogether in Japan as of 2003. From the size and the driving pattern of vehicles, the categories suitable for the plug-in hybrid electric vehicles are the personal-use, passenger vehicles, which number 54 million. They are classified into the registered vehicle and the light vehicle, depending on the size of body and engine.

The average daily travel distances of these categories of vehicle are estimated from the statistical survey data by the Ministry of Land Infrastructure and Transport (MLIT), on the relationship of passengers carried with a distance band. From the estimated driving pattern of Japanese passenger vehicles, it is presumed that 50% of Japanese vehicles are driven less than about 20 km (18 km for the light vehicles and 22 km for the registered vehicles).

Also estimated is the relation between given capacities of equipped battery and the average fraction, by distance, of travelling in the electric vehicle mode (Hori, 2006-2). Assuming that plug-in hybrid electric vehicles are introduced in the category of private passenger vehicles, about a 70% savings in gasoline, and consequently a 70% reduction in CO_2 emission, would be realized by using batteries with a range of 35 kilometers for the light vehicles and 60 kilometers for registered vehicles. For powering all of the 54 million private passenger vehicles in Japan, the electric power needed for charging the batteries in eight hours at night would be 35 GWe.

Supply by Nuclear Energy

Since there is about a 50 GWe difference between the peak hours and the nighttime usage in the power supply currently in Japan, the 35 GWe power for plug-in hybrid electric vehicles could be supplied by the existing spare generating capacity.

Because nuclear power is presently used as the base load in Japan, additional power requirements would have to be supplied by increasing the operation of fossil-fuel-powered plants. For energy security and the global environment, it were better to shift the power supply structure to more nuclear electricity, replacing fossil fuel electricity, while converting vehicles to plug-in hybrid electric.

4. Efficiency of Hydrogen and Electric Paths

It is essential to utilize available primary energies as efficiently as possible for the global environment, resources, and the economy. Therefore, it is important to choose efficient paths, both in the conversion process of primary energies to energy carriers, and in the utilization method of energy carriers to final applications.

The energy utilization efficiencies of a nuclear energy base by the battery electric vehicle and the fuel cell vehicle are compared in **Table 2** (Hori 2006-1). Here, the efficiencies from three kinds of nuclear reactors are examined, namely LWR (the Light Water Reactor, typical of low-temperature reactors), the SFR (Sodium-Cooled Fast Reactor, typical of medium-temperature reactors), and the VHTR (Very High-Temperature Gas-Cooled Reactor, typical of high-temperature reactors).

As for the LWR-based energy flow paths to vehicles, one path is the electricity from the steam turbine generator of the LWR being supplied to battery electric vehicles, and the other is hydrogen from water electrolysis by the LWR electricity being supplied to fuel cell vehicles.

As for the SFR-based energy flow paths to vehicles, one path is electricity from the steam turbine generator of the SFR being supplied to battery electric vehicle, and the other path is hydrogen from the SFR heated steam reforming of natural gas being supplied to fuel cell vehicle. As for the VHTR-based energy flow paths to vehicles, one path is electricity from the gas turbine generator of VHTR being supplied to the battery electric vehicle, and the other path is hydrogen from the thermochemical splitting of water by VHTR heat being supplied to the fuel cell vehicle.

As shown in Table 2, in either the LWR or the VHTR case, the path to a battery electric vehicle is more efficient than the path to a fuel cell vehicle. This is due to the following two reasons:

1. Both electricity generation by turbine generator and hydrogen production by electrolysis or thermochemical splitting of water, have to go through the heat engine cycle, where conversion efficiency is limited by thermodynamic law (the Carnot-cycle efficiency is at the highest for the case of the steam turbine).

2. The power train efficiency is higher in the battery electric vehicle (70%) than in the fuel cell vehicle (50-60%).

Contrary to the above, in the SFR case, the path to the fuel cell vehicle becomes more highly efficient than the path to battery electric vehicle, where hydrogen is produced by the process of nuclear-heated steam reforming of natural gas (methane). In this hydrogen-production process, the chemical energy of methane and nuclear heat is converted to chemical energy of hydrogen, regardless of the limitation of thermodynamic cycle efficiency.

In the case of nuclear-heated steam reforming of methane, although it is inevitable that the process produces CO_2, the amount is reduced about 30% as compared to the case of conventional methane-combusted steam reforming of methane.

A medium-temperature reactor with outlet temperature 500-600°C, such as the SFR, is the best suited for the membrane reformer hydrogen production method using palladium (Pd) as a membrane material (Tashimo 2003 and Uchida 2004).

It can be concluded that, in the nuclear-based energy flow to vehicles, the path to electric vehicles is more efficient than the path to hydrogen fuel cell vehicles, except in the case of using hydrogen produced by nuclear-heated steam reforming of methane.

5. Synthetic Liquid Fuels

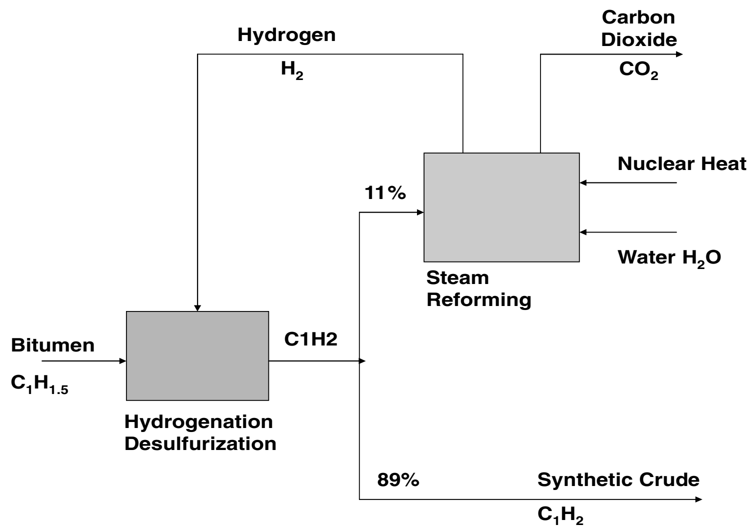
Application to Transportation

Liquid fuels containing carbon, such as gasoline and diesel oil, are far higher in energy density than compressed gaseous hydrogen and battery-stored electricity, and are more easily delivered and stored onboard for transportation purposes.

Therefore, these liquid fuels will remain useful for decades as energy for vehicles. These liquid fuels have been produced from petroleum by refining the crude oil. Now, because of concerns such as the forecast of "peak oil" and price hikes, there are alternate solutions under development to produce synthesized crude oil from oil sands and other unconventional oils.

For example, to produce dimethyl ether (DME) and Fischer-Tropsch oils, from natural gas by gas-to-liquid (G-to-L) and coal by coal-to-liquid (C-to-L) processes, and to produce

FIGURE 3
Nuclear-Heated Steam Reforming for Upgrading Bitumen to Synthetic



ethanol and ETBE from biomass by biomass-to-liquid (B-to-L) processes.

These liquid fuels emit CO_2 from the tail-pipe when they burn in the engine. So far, the emission of CO_2 in the production process of gasoline and diesel oil from crude oil has been small, as light (low carbon/hydrogen ratio) crude oil has been used. When the liquid fuels are produced from heavy (high carbon/hydrogen ratio) crude oil, oil sands, and other ultra-heavy oils, the emission of CO_2 in the production process increases, because energy/fuel is necessary for hydrogenation and heating in the production process.

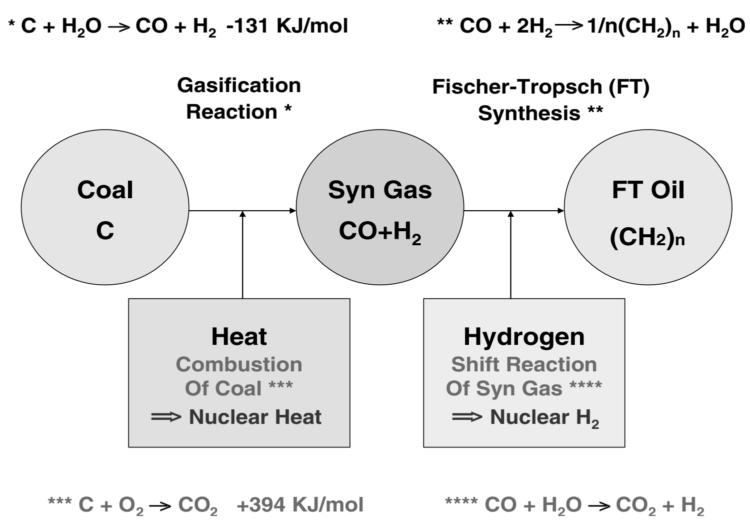
When the FT oils are produced from coal, emission of CO_2 in the production process increases, because energy/fuel is necessary for heating in the gasification process and for hydrogen in the Fischer-Tropsch synthesis. In the case of FT oil produced from coal, the CO_2 emission in the production process would be as large as 1.5 times that from the tail-pipe by combustion in engine (Marano, 2001).

To reduce the total life-cycle CO_2 emission per kilometer, it is necessary to supply heat and hydrogen produced from a non-carbon-emitting energy source. Nuclear heat supply and/or nuclear hydrogen supply can be adopted for this purpose if their costs are reasonable.

Supply by Nuclear Energy

Figure 3 shows a schematic flow of the upgrading process of the bitumen extracted from oil sands into the synthetic crude oil using nuclear energy (Hori, 2005). In this setup, the hydrogen used for upgrading is produced by nuclear-heated steam reforming of a part of the synthetic crude product. Together with the nuclear supply of electricity and steam (heat) to the whole process, the nuclear supply could eliminate the combustion of fossil fuels in the extraction and upgrading process.

FIGURE 4
Supply of Nuclear Heat and Hydrogen to the Gasification and FT Synthesis Processes



In the process of C-to-L, which is gasification of coal to produce the synthetic gas (carbon monoxide, hydrogen gas), and the subsequent conversion of the synthetic gas into an FT oil by Fischer-Tropsch synthesis, the contribution of nuclear energy is the supply of heat and hydrogen, as shown in **Figure 4**.

In these processes, nuclear heat replaces the heat necessary for the gasification process, which is usually produced by the partial oxidation of feed coal, and nuclear hydrogen replaces the hydrogen necessary for the Fischer-Tropsch synthesis, which is usually produced by the shift reaction of carbon monoxide in the synthetic gas, thus eliminating the combustion process of coal and the CO_2 formation process from carbon monoxide.

High-temperature reactors like the VHTR hold the promise of application for various chemical processes that need high temperature, especially for coal processes, to produce hydrocarbons and hydrogen. However, in high-temperature reactors, because of the cur-

TABLE 3
Status and Prospect of Three Paths

Primary Energy	Path / Energy Carrier	Status		Prospect
		Nuclear Conversion Process	Automobile Application	
Nuclear Energy (Synergistically with Fossil Fuels and Biomass)	Hydrogen	R&D In progress	FCV; A few decades more	Long Term Broader uses
	Electricity	Commercia-lized	PHEV; In several years	Early Impact; Continue in effect
	Liquid Fuels Synthetic Fuels Biofuels	Proposals / Research Started	Engines; Almost ready	Intermediate; Environmental Compatibility

rent materials limitations, the pressure of the chemical process should be in the same range as the primary coolant pressure, which may be a hindrance factor in some applications.

In the medium-temperature reactors like the SFR, the pressure of the chemical process can be different from the primary pressure. Usually, chemical equilibrium may be not favorable, in the medium-temperature range, for processing fossil fuels, but such technology as membrane separation could be used to alleviate this disadvantage.

The role of nuclear energy in the production of synthetic liquid fuels is mainly for the supply of hydrogen and/or heat. The contribution of nuclear energy in these synergistic processes is usually subsidiary in the energy quantity. However, the following features are noteworthy:

• Reducing CO_2 emission by eliminating the combustion of fossil fuels in a production process;

• Saving resources of both fossil fuels and nuclear energy by processes of higher energy utilization efficiency;

• Lowering production costs by the lower heat costs of nuclear energy.

6. Concluding Remarks

I have reviewed the three paths to supply nuclear energy to the transportation sector by way of hydrogen, electricity, and liquid fuels as the energy carrier. The status and prospect of these paths are summarized in **Table 3**.

Hydrogen: As a breakthrough is indispensable in onboard hydrogen fuel cell and storage technologies, we would expect a long-term or ultimate deployment of FCVs, while seeking broader uses of nuclear hydrogen, such as in jet engine fuel in airplane and synthetic fuel production.

Electricity: As nuclear power generation by light water reactors is already commercialized, and PHEVs are expected to be introduced by about 2015, the electricity path has an early impact, while the plug-in hybrid technology will continue in effect for decades, by combining the battery with a biofuel or synthetic fuel engine, or with a fuel cell.

Liquid Fuels: While the technologies for nuclear-assisted synthetic fuel production are at the stage of proposals or the early stages of research, the use of synthetic fuels in engines is almost ready. So the nuclear synthetic fuels path may be realized in an intermediate term, and will continue to be practical, as long as compatible with the environment.

By supplying nuclear energy to the production processes of transportation energy carriers, nuclear energy can expand its contribution to the energy security and global environment by far beyond the current level.

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