The Hydrogen Economy is Coming
The Question is Where?

The end of the oil age is coming. While the replacements for oil are uncertain, the leading candidates have one thing in common — the need for massive quantities of hydrogen in the production process.

CHARLES W. FORSBERG
OAK RIDGE NATIONAL LABORATORY

About 40% of the U.S. energy demand is met by petroleum that is converted primarily to liquid fuels: gasoline, diesel and jet fuel. Today's transportation system depends on liquid fuels because of their high energy density by weight and volume and their ease of use. However, the world is quickly exhausting its resources of the light crude oils used to make liquid fuels (Figure 1). The rate of use is increasing rapidly as China and India begin to enter the world oil market. To meet our transportation needs, a replacement for crude oil is required.

Hydrogen has been proposed as the replacement for crude oil. However, the viability of a hydrogen economy is the subject of debate. An assessment of transport fuel options strongly supports the perspective that a hydrogen economy is coming, but not necessarily in the form discussed in the popular press. Transport fuel futures include: conversion of tar sands, shale oil and coal to liquid fuels; greenhouse-gas-free fuels; and hydrogen. While each of these futures is very different, they share the common characteristic that the primary ingredient to produce these fuels is hydrogen. Hydrogen production options include solar, nuclear, and traditional fossil-fuel steam reforming with underground sequestration of the carbon dioxide. The real question is not whether there will be a hydrogen economy, but instead where — at the refinery, at the fuel factory, or onboard a car or truck?

Electric cars

Any consideration of transport futures must take into account the role of electric vehicles. If these vehicles are successful, then there is no need for liquid fuels for cars and light trucks. However, electric vehicles have two key limitations:

• Vehicle range — Because of battery limitations, electric vehicles have restricted range.

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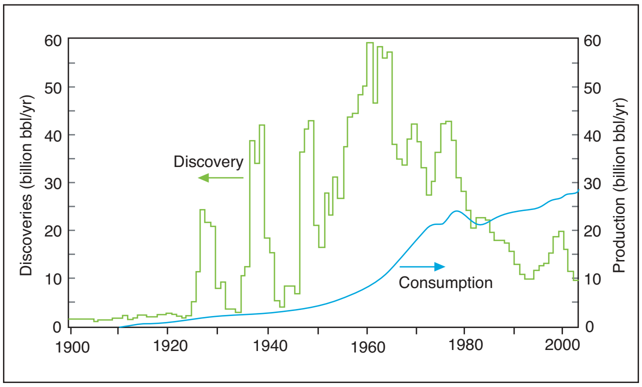

Figure. 1. Rate of discovery and consumption of conventional crude oils vs. time (*1*).

• Battery recharging — In a gasoline refueling station, the rate of energy transport from the pump to the automobile tank is ~10 MW, a rate that enables an automobile to be refueled in minutes. If batteries replace gasoline and the battery recharge process is 90% efficient, the batteries would have to reject 1 MW of heat during recharging for the same rate of energy transfer as in refueling a gasoline vehicle. This is not practical.

While electric vehicles were not credible a decade ago, the development of solid-state electronics has made possible the hybrid automobile, a technological advance that can seriously impact the demand for fuel. A hybrid car contains an engine, batteries and an electric motor-generator. The electric battery and motor provide the power to rapidly accelerate the car and provide power at low speeds. The battery is charged by recuperative braking (*i.e.*, recovering the energy of forward motion when the car brakes) and by the internal combustion engine. The internal combustion engine operates at a constant speed and load under conditions to maximize the energy output per liter of fuel. When the batteries are charged and the power demand is low, the internal-combustion engine is shut down until needed. When the batteries are low or are rapidly being drained, the internal-combustion engine is turned on to

Table. Near-term and long-term transport fuel options.

Product	Feedstock	Greenhouse CO_2
Liquid fuels	Crude oil	Yes
	Heavy oil	Yes
	Tar sands	Yes
	Oil shale	Yes
	Coal	Yes
CO_2-Neutral Fuels	Air	No
	Biomass	No
	H_2 Carrier	No
Hydrogen	H_2O	No

recharge the batteries and provide motive power. Because the efficiency of internal combustion engines is a very strong function of engine speed and load, operating the engine under efficient "base-load" conditions and using the battery as an energy storage device to meet peak energy demands allows the total fuel consumption per kilometer traveled to be greatly reduced.

Advanced hybrid vehicles now being tested allow the battery to be recharged by connection to the electrical grid when the car is parked, particularly overnight, at a low charging rate that avoids the cooling challenges of fast recharging, and allows household electrical circuits to be used for the process. For shorter trips, the batteries would provide the energy. For longer trips, after the battery is partly exhausted, the engine provides the energy. It has been estimated that if the battery can provide power for 20 miles (current technology), the fuel consumption in cars and light trucks would be reduced by half compared with that of conventional vehicles. Large-scale implementation of plug-in hybrids could occur in less than two decades.

Transport fuel options

There are many ways to make transport fuels. Economics and environmental constraints will determine which options are chosen. Some of the major options are listed in the table above.

Traditional liquid fuels — Liquid fuels can be made from hydrogen and any source of carbon (crude oil, heavy crude oil, tar sands, oil shale, coal, etc.). They have traditionally been made from light crude oils, a process that does not require hydrogen. In the future, however, they will increasingly be produced from heavier, higher-carbon feedstocks with lower hydrogen-to-carbon ratios. Liquid fuels today are made from heavy oils (many countries), tar sands (Canada) and coal (South Africa). In a refinery, these lower-grade feeds are converted to liquid fuels by increasing the hydrogen-to-carbon ratio of the feedstock to that of liquid fuels (hydrogen-to-carbon ratio of 1.5 to 2). This requires either thermal cracking to remove carbon or hydrogenation to add hydrogen. The carbon from thermal cracking is ultimately released as carbon dioxide to the atmosphere. Traditionally, hydrogen is produced by steam reforming of fossil fuels, a process that produces hydrogen and carbon dioxide, with the

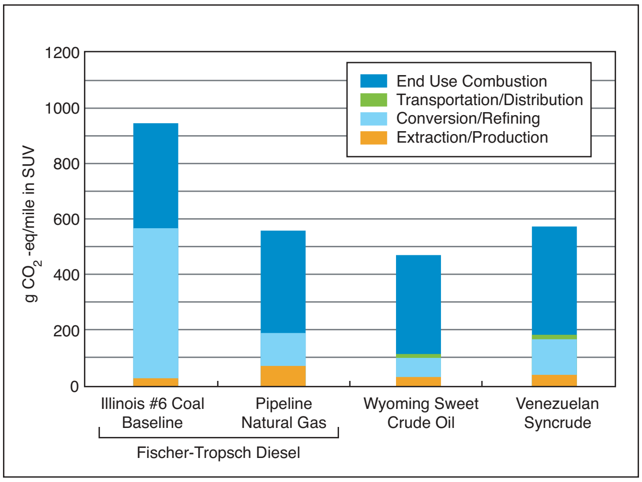

Figure 2. Equivalent carbon dioxide releases per SUV vehicle mile for diesel fuel produced from different feedstocks (*2*).

latter being released to the atmosphere.

If we switch from light crude oils to alternative hydrocarbon feedstocks to produce liquid fuels, the carbon dioxide emissions per vehicle mile traveled will increase significantly, as shown in Figure 2. In this figure it is assumed that the natural gas and coal are converted to diesel fuel by the classical three-step gasification, water-gas shift and Fischer-Tropsch synthesis processes. Traditional refining is used to produce diesel fuel from the various crude oils.

Because of the expected impacts of greenhouse gases on climate, there are serious questions as to whether traditional technologies should be used to produce liquid fuels from alternative feedstocks. Alternatively, if economic hydrogen is available from non-greenhouse-gas-emitting sources (solar, nuclear, or steam reforming of fossil fuels with carbon dioxide sequestration), and the energy for the fuel processing does not release greenhouse gases to the atmosphere, the atmospheric carbon dioxide emissions from liquid-fuel production per vehicle mile (unit of liquid fuel) can be the same as or lower than that available today from light crude oil.

Carbon dioxide-neutral liquid fuels — Traditional liquid fuels are made from fossil fuels. However, there are hydrocarbon liquid fuels that do not require fossil-fuel feedstocks and do not result in net emissions of carbon dioxide to the atmosphere — provided that the hydrogen production techniques used do not release additional carbon dioxide to the environment

Liquid fuels from air. Liquid fuels can be made from hydrogen and carbon dioxide extracted from the atmosphere or the ocean. A modified Fisher-Tropsch synthesis process is used. The hydrogen is used as a feedstock to make the liquid fuels and as an internal energy source to drive the production of the fuel. Because the carbon dioxide is recycled from the atmosphere or seawater, no greenhouse impacts occur. About 80% of the total energy input required to make the liquid fuel is used to produce the hydrogen. This technology has several implications:

• Liquid-fuel impacts — This option provides unlimited liquid fuels with no greenhouse impacts as long as the hydrogen and energy come from non-greenhouse-gas-emitting energy sources.

• Ultraclean liquid fuel — The feedstocks contain no sulfur or heavy metals; thus, ultraclean liquid fuels are produced.

• Hydrogen economy — From an economic perspective, this technology places an upper economic limit on the allowable costs for using hydrogen directly as a transport fuel compared with those for using liquid fuels. The production costs of liquid fuels using hydrogen and carbon dioxide from the atmosphere are significantly higher than the production costs of hydrogen. However, the costs of distributing and storing liquid fuels are much lower than the cost of distributing and storing hydrogen. Either approach can provide the fuel for the transport system without increasing atmospheric greenhouse gas concentrations. Economics will likely determine the preferred option.

Liquid fuels from biomass. Biomass is used today to produce liquid fuels such as alcohol by fermentation. In this process, there are no greenhouse gas impacts, because the carbon dioxide used to make the biomass comes from the atmosphere. However, only a fraction of the biomass becomes a liquid fuel. For example, the conversion of corn to ethanol results in roughly one-third of the carbon from the original corn in the ethanol, one-third in the byproduct animal feed, and one-third in the form of carbon dioxide released to the atmosphere from respiration of the yeast.

The quantities of liquid fuels from biomass can be dramatically increased if hydrogen is available. An alternative to producing alcohol from biomass (primarily cellulose, $C_6H_{10}O_5$) is to convert all of the biomass into a hydrocarbon fuel. This process triples the liquid fuel production per unit of biomass and also produces a higher-quality fuel. Biomass contains significant quantities of oxygen and can be thought of as a partially oxidized hydrocarbon. The energy value per unit of carbon in a liquid fuel can be significantly increased by hydrogenation processes that remove that oxygen while producing a liquid fuel.

Hydrogen carriers. Hydrogen is proposed as the ultimate transport fuel because it enables the use of highly efficient fuel cells in cars, trucks and buses. Multiple systems are in development that deliver hydrogen to the vehicle engine, but that do not require hydrogen distribution systems to the vehicle refueling station (gasoline station) or onboard vehicle hydrogen storage. These systems use some type of chemical hydrogen carrier. The production of that hydrogen carrier requires large quantities of hydrogen, but the hydrogen is used only at centralized fuel-production facilities — a non-oil version of a refinery. Each of these systems uses a different method to carry hydrogen: ammonia, iron, organics, etc.

One example is a liquid and solid fuel system that is being investigated in Japan. Current estimates indicate that the volume and mass of this hydrogen fuel delivery system onboard the vehicle are less than those for onboard storage of hydrogen. The vehicle is fueled with a hydrocarbon fuel and a calcium oxide (CaO) bed. The system contains the following components:

• Vehicle steam reformer — The CaO bed on the vehicle is used as a steam reformer where the liquid fuel is converted to hydrogen and carbon dioxide. The carbon dioxide then reacts with the CaO to form solid calcium carbonate ($CaCO_3$). The reaction of the CaO and the CO_2 is highly exothermic and provides the energy necessary to drive the highly endothermic stream-reforming reaction that produces hydrogen. It also removes all of the CO_2 and, thus, drives the equilibrium reactions to produce hydrogen rather than a mixture of H_2, CO and CO_2.

• Vehicle engine — Fuel cells or an internal combustion engine powers the vehicle with hydrogen.

• Fuel factory — The $CaCO_3$ bed is returned to a fuel factory, where hydrogen chemically reduces the $CaCO_3$ to CaO for recycle to vehicles, and the recovered carbon dioxide is combined with hydrogen to produce a new carbon-based liquid fuel.

In this system, carbon is an integral part of a recyclable hydrogen storage mechanism between the fuel factory and the vehicle. Hydrogen enters the fuel factory and reappears inside the vehicle. The low volume and mass of the fuel system aboard the vehicle are possible because energy is stored in two high-energy-density forms— the solid CaO reformer beds and the liquid fuel.

Hydrogen as a fuel

Hydrogen is proposed as the ultimate transport fuel for cars, trucks and buses. Numerous articles and letters in *CEP* (Nov. 2004, pp. 4-6) have detailed the advantages and disadvantages of this technology. The direct use of hydrogen as a transport fuel can be considered the ultimate end state of hydrogen development, only if the various technical barriers are eliminated. CEP

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CHARLES W. FORSBERG is a principal investigator for the Advanced High-Temperature Reactor, a new nuclear power reactor concept being developed for the production of hydrogen and electricity at Oak Ridge National Laboratory (ORNL; P.O. Box 2008, Oak Ridge, TN 37831-6165; Phone: (865) 574-6783; Fax: (865) 574-0382; E-mail: forsbergcw@ornl.gov). He holds 10 patents and has published more than 200 papers on subjects including improved methods for hydrogen production. Forsberg earned a BS in chemical engineering from the Univ. of Minnesota, and an MS and a PhD in nuclear engineering from the Massachusetts Institute of Technology. He is a Fellow of the American Nuclear Society and topical chair for hydrogen production for AIChE.