

# Nuclear Power: Energy to Produce Liquid Fuels and Chemicals

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Using nuclear energy to operate refineries and chemical plants would allow more fossil and biomass resources to be converted to fuel and chemical products.

The U.S. faces two energy challenges: dependency on foreign oil and gas, and the risk of climate change from burning fossil fuels. Meeting these challenges will require the most sweeping changes in energy systems since the beginning of the industrial revolution and the large-scale use of fossil fuels.

## The energy challenge

The global oil market is being driven by rising demand for oil in China, which now equals 40% of U.S. oil consumption. As liquefied natural gas becomes a commodity, the natural gas market is transitioning from isolated regional markets (North America, Europe, and Japan) to a global market, and the differences in natural gas prices between major markets will narrow. However, most of the world's oil and gas reserves are owned by state-owned oil companies (Table 1), and pricing decisions are ultimately political decisions. Most of those reserves are near the Persian Gulf — an area of political instability. U.S. trade deficits and a significant fraction of national security costs are driven by dependence on oil and gas imports.

The burning of fossil fuels is raising the concentration of CO<sub>2</sub> in the atmosphere, from 280 ppm in pre-industrial times to 387 ppm today (1). This has lowered the pH in parts of the world's oceans from 8.2 to 8.0. And although there are uncertainties about the rate of climate change, altering the composition of the atmosphere — a large chemical system — will ultimately change the biosphere and its climate.

Legal restrictions and taxes on greenhouse gas (GHG) releases exist in some countries today and will likely be adopted by many other nations. This will have major impacts on how liquid fuels and chemicals are produced (2).

Table 1. Of the 20 companies with the largest oil and gas reserves, 17 are government-owned or controlled.

Rank	Company	Oil/Gas Reserves, 10 <sup>9</sup> bbl oil equivalent
1	Saudi Arabian Oil Co.	303
2	National Iranian Oil Co.	300
3	Qatar General Petroleum	170
4	Iraq National Oil Co.	134
5	Petroleos de Venezuela S.A.	129
6	Abu Dhabi National Oil Co.	126
7	Kuwait Petroleum Corp.	111
8	Nigerian National Petroleum Corp.	68
9	National Oil Co. (Libya)	50
10	Sonatrach (Algeria)	39
11	OAO Gazprom (Russia)	29
12	OAO Rosneft (Russia)	22
13	PetroChina Co.	21
14	Petronas (Malaysia)	20
15	Lukoil*	16
16	Egyptian General Petroleum Corp.	14
17	ExxonMobil Corp.*	13
18	Petroleos Mexicanos	13
19	BP Corp.*	13
20	Petroleo Brasileiro S.A.	12

\* Public corporations

Source: [www.petrostrategies.org/Links/worlds\\_largest\\_oil\\_and\\_gas\\_companies.htm](http://www.petrostrategies.org/Links/worlds_largest_oil_and_gas_companies.htm).



Historically, fossil fuels and biomass have been used as both chemical feedstocks and energy sources. Altering the carbon content of a particular fuel or chemical is not desirable, because the properties of the product would also change. However, there are choices for carbon-containing feedstocks and the energy sources of refineries and chemical plants. Climate risk, dependence on foreign resources, and economics (including carbon taxes) require that the process industries consider alternative energy sources.

Figure 1 compares the GHG emissions from each step in the production of diesel fuel from four different feedstocks (3). The GHG releases are roughly proportional to the energy consumed in each step. More energy is required to convert low-grade feedstocks into diesel fuel than higher-grade feedstocks. In the case of coal, more energy is consumed at the coal liquefaction plant than is released in burning the diesel fuel. As the world depletes light crude oil resources and switches to heavier feedstocks, the energy consumption and GHG releases from fuel processing facilities are expected to increase. Currently, petroleum refineries consume 7% of the total energy used in the U.S.

The U.S. could replace imported oil with domestic feedstocks, but the most-abundant feedstocks require massive amounts of energy for their recovery. For example, the steam energy input needed to recover heavy oil, such as that found in California, is 25–40% of the energy value of the recovered oil. The U.S. has the world's largest reserves of shale oil, but the extraction process consumes one-third of the energy value of the recovered gases and liquids.

Biofuels have been proposed to reduce dependence on foreign oil and address climate change. Biofuels are low-

carbon fuels because they recycle  $\text{CO}_2$  from the air through the growing of biomass and thus do not increase the carbon dioxide content of the atmosphere. However, converting biomass into liquid fuels requires energy — the energy needed to grow and convert corn to ethanol is 80% of the energy content of the product ethanol.

The ultimate potential of biofuels to replace oil as a low-carbon fuel depends on the energy sources for the biorefineries. It has been estimated that the U.S. could produce 1.3 billion ton/yr of renewable biomass without major impacts on food and fiber production. If that biomass were burned, the energy output would be equivalent to burning 10 million bbl/d of diesel fuel. If it were converted to ethanol, the energy value of the ethanol would be equivalent to 5 million bbl/d of diesel, with most of the remaining energy used in the biomass-to-fuels production process. If external heat and/or hydrogen were available to supply energy to operate the biorefinery, the same biomass could produce about 12 million bbl/d of diesel fuel — about equal to the amount of oil consumed by the transportation sector (Figure 2).

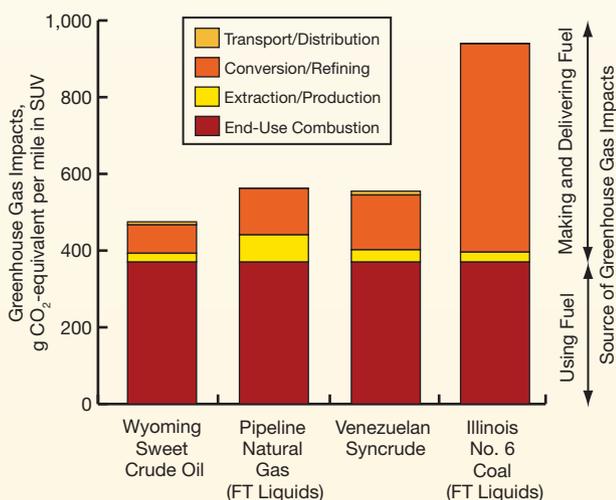
### Nuclear energy

Nuclear reactors provide 20% of the electricity and 70% of the zero-carbon electricity in the U.S. The output of those reactors is approximately equal to the energy consumption of the nation's refineries. Their numbers are similar, too: 104 nuclear power reactors and 141 refineries. Nuclear energy is a centralized method of producing heat that can match the energy needs of the process industries.

All power reactors in the U.S. are light-water reactors (LWRs) that use water as a coolant and have peak temperatures near 300°C. Current reactor sizes vary from 500 to 1,300 MWe, but smaller reactors (50–150 MWe) are in development. The typical efficiency is about 33%; thus, the thermal output is three times the electrical output. These reactor characteristics define the near-term applications of nuclear energy.

High-temperature reactors (HTRs) are under development (4) for use in the process industries and may become available within a decade. They operate at peak temperatures of 700–850°C and have thermal outputs in the range of 250–600 MWt. China and Japan have built test reactors, and China is building a full-scale demonstration plant. In the U.S., the Dept. of Energy (DOE) recently awarded design contracts to General Atomics for the design of an HTR. U.S. progress will partly depend on industrial commitments to fund the initial demonstration plant.

Nuclear reactors are capital-intensive, long-lived assets. Current nuclear reactors are expected to operate for 60 years. Their operating and fuel costs represent less than 20% of the total cost of electricity or steam. Consequently, there are large economic incentives to operate such plants at full



▲ **Figure 1.** Lifecycle greenhouse gas releases per vehicle mile for a diesel sport-utility vehicle. Although the emissions associated with driving are comparable, total lifecycle emissions vary for different feedstocks. Source: Based on data in Ref. 3.

capacity all the time. This creates incentives for cogeneration plants to produce electricity for the grid and heat for industry — when the refinery or chemical plant is not fully utilizing the heat, electricity can be produced for the grid.

Large parts of the world, including much of the U.S., have a deregulated electricity market, where the price paid to the electricity generator depends on demand and may vary by a factor of four over the course of a day. Electricity prices are low at night and high in the late afternoon. In this environment, the price of electricity or heat is extremely low for approximately 1,500 h/yr — in the middle of the night. For process industries that can control their time-of-day energy demand, extremely low-cost heat is available.

### Near-term applications

Outside the U.S., steam from nuclear plants has been used for district heating (45 reactors), desalting of seawater (10 reactors), and industrial purposes (25 reactors) — including the production of ethanol (5). Most of these are cogeneration plants that produce electricity and steam.

There is industrial experience with nuclear cogeneration in Canada, Switzerland, Russia, Japan, and other countries, but not in the U.S. Historically low natural gas prices, the rural siting of reactors, and the structure of utilities have inhibited both fossil-fuel and nuclear cogeneration plants in the U.S. There have been recent discussions between U.S. utilities and industrial users of steam, but no agreements for the sale of steam from nuclear plants have yet been reached.

Because steam can be transported long distances, the nuclear plant need not be located next to the industrial user. The primary market for the low-pressure steam is for bioprocessing, including ethanol production. Today, ethanol is made primarily from corn, and the total energy inputs are about 80% of the energy value of the product ethanol. Half of the energy input is in the form of low-pressure (150 psi) steam for ethanol distillation and other process operations. Nuclear power could be an economic replacement for natural gas for the production of this steam.

Next-generation ethanol plants will convert lower-cost cellulosic feedstocks into ethanol (6, 7). These plants separate biomass into a cellulose-rich stream and a stream rich in lignin. The cellulosic components are converted to ethanol, and the lignin is burned to produce the required steam. Alternatively, a nuclear plant could provide the low-pressure steam and the lignin converted into a liquid fuel. Lignin makes up 20–30% of the original biomass. Biomass accounts for 50–75% of the costs associated with a biorefinery. Thus, there are economic incentives to not burn lignin as boiler fuel.

The use of external energy sources for the process industries will create new options, but this also implies major changes in plant flowsheets and commercialization of new processes.



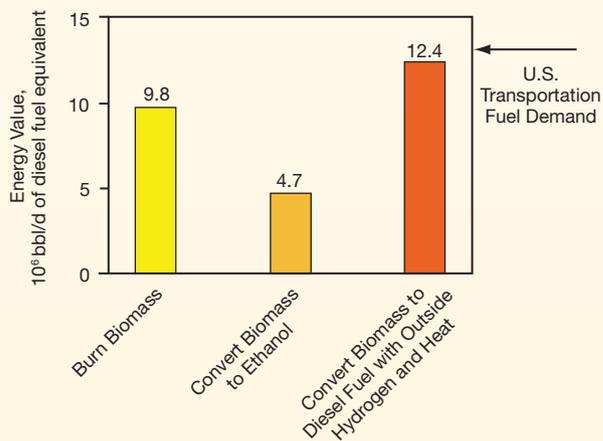
▲ Nuclear reactors could supply the heat to extract bitumen from oil sands and process it into synthetic crude oil.

### Nuclear geothermal

Nuclear geothermal refers to using nuclear reactors to heat rock. North America has some of the largest reserves of heavy oil, tar sands, and oil shale. Massive quantities of heat are required to recover these resources. Heat from nuclear reactors could replace the burning of fossil fuels as the heat source.

*Heavy oil.* The U.S. is a leader in heavy oil production, primarily from California oil fields. Steam is injected underground to heat the oil field, lower the viscosity of the oil, and enable the oil to be pumped out of the ground (8). In this process, 25–40% of the energy value of the oil is required to provide the heat.

*Oil sands.* Oil sands may account for up to two-thirds of the world's petroleum reserves. Canada has the largest deposits, with current production above 1.5 million bbl/d. Open-pit mining is used to recover oil from deposits near the surface. The oil sands are slurried in large hot-water



▲ **Figure 2.** The availability of liquid fuels from sustainable U.S. biomass (1.3 billion ton/yr) depends on the amount of energy consumed in the conversion process and where that energy comes from. Source: (2).



tanks, where the oil floats and the sand sinks.

The preferred recovery method for deeper deposits is steam-assisted gravity drainage (SAGD). Steam is injected underground to heat the oil sands and reduce the viscosity of the oil, which flows to wells and is pumped out. The heavy oil is then upgraded for transportation in unheated pipelines.

Up to 20% of the energy (primarily heat) is consumed by the production process. SAGD will dominate future production because of its lower cost and because most oil sands reserves are too deep for surface mining.

*Oil shale.* The U.S. has the world's largest reserves of oil shale, but no commercial operations. Pilot plants are testing new underground thermal-cracking processes that heat the shale oil and crack it into a carbon residue that remains in place and a light crude oil. In effect, the thermal-cracking process is moved out of the refinery and carbon is sequestered as a solid underground. The process is applicable to some types of heavy oil, oil sands, and soft coals. Although the production process requires one-third of the energy value of the oil, it produces high-quality light crude oil that reduces refinery energy consumption.

All of these processes require massive quantities of thermal energy. Any restrictions on the release of CO<sub>2</sub> to the atmosphere would significantly alter their economics. In many cases, the temperature of the heat is low enough that it can be provided by LWRs. However, HTRs are required for thermal cracking of shale oil. Nuclear reactors are now being considered to provide process heat for Canadian oil sands.

The economics of using heat from nuclear reactors for these applications may partly depend on the price of electricity. In states such as California, the price of electricity in the middle of the night and the price in the middle of the day differ by a factor of four. At night, electricity prices, and hence the price of heat from a nuclear power plant, are extremely low. Because the thermal response of heavy oil, oil sands, and oil shale deposits are measured in weeks, it would be possible to use very-low-price nuclear heat at night, and during the day the high-priced electricity would be sold to the grid. This different mode of operation reflects the fact that nuclear plants have high capital costs and low operating costs, whereas fossil-fuel plants have low capital costs and high operating costs. Several companies are commercializing smaller LWRs that may be well-suited for this market.

An area of active research is nuclear gigawatt-year geothermal heat storage (9). When electricity demand is low, a 500-m cube of rock located a kilometer or more underground is heated to high temperatures. This creates a manmade geothermal heat source to supply heat for peak electricity production or industrial markets. The technology is based on decades of steam injection into heavy oil and tar sands deposits and a century of experience in geothermal power production. The technology is only viable on a large

scale. The thermal storage capacity increases as a function of the cube of the system size (volume), whereas the heat losses increase with the square of the size (surface area). In a large system, the fractional heat losses are very low, but in small systems they are unacceptably high.

Nuclear-geothermal heat storage, if it can be successfully developed, has major implications for coupling cogeneration nuclear reactors with the process industries:

- *economics.* Heat for storage is purchased at night when prices are low but can be delivered at any time over a period of many months. The reactor owner/operator sells electricity when the price of electricity is high.
- *reliability.* Heat storage decouples the operating schedule of the reactor and the chemical plants.
- *scale of operation.* Stored heat can be used either for process heating or to generate peak electricity. The storage system can be shared, and it is not necessary to match nuclear plant size and chemical plant size.

### Hybrid energy systems

Changing energy sources for liquid fuels and chemical production involves more than switching heat production from a burning flame of natural gas to a nuclear reactor. In many cases, energy consumption is embedded within the chemistry of the process, not just in the heating of fluids in heat exchangers. Hybrid systems combine nuclear energy with feedstocks for producing liquid fuels and chemicals.

A classic example is the traditional coal liquefaction process where coal is gasified and the product syngas (a mixture of CO and H<sub>2</sub>) is converted to liquid fuels using the Fischer-Tropsch process. Although high-quality liquid fuel is produced, more energy is consumed in the production process than is obtained from burning the liquid fuels. Some of the largest single-point sources of CO<sub>2</sub> emissions are coal liquefaction plants.

Recent work at Idaho National Laboratory (10) has examined how the process can be changed so that all the carbon in the coal exits the plant as liquid fuel and nuclear energy provides the energy to operate the plant. In this specific case, the primary energy input is in the form of hydrogen to raise the hydrogen-to-carbon ratio from approximately 1 for coal to about 2 for liquid fuels — internal chemical reactions provide the necessary heat.

Such hybrid systems enable nuclear energy to be the replacement energy source for liquid fuels and chemical production. However, it does imply major changes in process flowsheets. Chemical engineers have only begun to understand the implications of using fossil fuels and biomass as feedstocks and other energy sources to operate the plant.

Major efforts are underway to develop nuclear hydrogen production technologies. Hydrogen is used today primarily for fertilizer production and liquid fuels production (hydro-

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cracking and desulfurization). Demand is expected to increase rapidly with increased production of liquid fuels from lower-quality feedstocks (e.g., oil sands, biomass, etc.) that require more hydrogen per gallon of fuel produced. If there are severe restrictions or high taxes on greenhouse gas emissions, hydrogen may replace carbon as the preferred reducing agent for converting metal ores to metals. It is also possible that hydrogen itself may become a transportation fuel.

### Closing thoughts

Historically, fossil fuels and biomass have been used by the process industries as feedstocks and energy sources. Cost, national security considerations, and risks of climate change may restrict the use of fossil feedstocks as energy sources. Biomass resources are limited — there is insufficient biomass for biofuels to have a major impact if biomass is both the feedstock and energy source for biorefineries.

This suggests that we consider processes where the fossil or biomass feedstock is used only as a feedstock and external energy sources power the process. In some cases, no changes in the process will be needed, but in other cases, major process changes will be required. Nuclear energy is a viable alternative energy source for the production of liquid fuels and chemicals.

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