Changing Biomass, Fossil, and Nuclear Fuel Cycles for Sustainability

Charles W. Forsberg

Oak Ridge National Laboratory[*]
P.O. Box 2008
Oak Ridge, TN 37831-6165
Tel: (865) 574-6783
Fax: (865) 574-0382
E-mail: **forsbergcw@ornl.gov**

―――――――――――――――――

[*]Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Department of Energy
under contract DE-AC05-00OR22725

Changing Biomass, Fossil, and Nuclear Fuel Cycles for Sustainability

Charles W. Forsberg
Oak Ridge National Laboratory; P.O. Box 2008; Oak Ridge, TN 37831-6165
*Tel: (865) 574-6783; Fax: (865) 574-0382; E-mail: **forsbergcw@ornl.gov***

Abstract

The energy and chemical industries face two great sustainability challenges: the need to avoid climate change and the need to replace crude oil as the basis of our transport and chemical industries. These challenges can be met by changing and synergistically combining the fossil, biomass, and nuclear fuel cycles.

- *Fossil fuel cycles*. Fossil fuel cycles must be changed to reduce greenhouse impacts and will require options beyond carbon-dioxide sequestration. In situ thermal cracking of heavy oils, oil shale, and coal may enable the production of high-quality transport fuels while sequestering the byproduct carbon without moving it from the original underground deposits. Nuclear-fossil combined-cycle power plants may enable the large scale use of renewable electricity by matching electricity production to demand. However, these and other options require integration of high-temperature heat from nuclear and other sources with fossil systems.

- *Biomass fuel cycles*. The use of biomass for production of liquid fuels and chemicals avoids the release of greenhouse gases. However, U.S. biomass resources are insufficient to (1) meet liquid fuel demands and (2) provide the energy required to process biomass into liquid fuels and chemicals. For biomass to ultimately meet our needs for liquid fuels and chemicals, outside sources of heat and hydrogen are required for the production facilities with biomass limited to use as a feedstock.

- *Nuclear fuel cycles*. Nuclear energy can provide the stationary greenhouse-neutral heat and hydrogen for alternative biomass and fossil fuel cycles. However, in many cases this will require high-temperature reactors, a change in reactor safety philosophy, and nuclear fuels that are nearly indestructible. Such difficult-to-process nuclear fuels may require rethinking of nuclear fuel cycles.

1. Introduction

The two major energy challenges for the United States are replacing crude oil and eliminating net greenhouse gas emissions. Oil provides 39% of the total U.S. energy demand, with two-thirds of that oil used for transportation. The other challenge is the increasing concentration of greenhouse gases in the atmosphere, particularly carbon dioxide. Carbon dioxide is the primary greenhouse gas that affects climatic change. After atmospheric carbon dioxide levels have increased, it takes millennia for these levels to return to normal. Equally important, carbon dioxide levels strongly impact the characteristics of the biosphere and geochemistry because atmospheric carbon dioxide controls the planet's average pH (acid–base concentrations).

The world has three major fuel cycles: fossil fuels, biomass, and nuclear energy. Changes in these fuel cycles to replace the use of crude oil and stop increases in atmospheric carbon dioxide levels are identified and described.

2. Fossil Fuel Cycles

The primary energy source for man today is the burning of fossil fuels. If major changes in climate are to be avoided, significant reductions in fossil carbon dioxide releases to the atmosphere are required. The fossil fuel cycle must become a closed fuel cycle, with geological disposal of carbon where possible. Where geological disposal is not possible, carbon dioxide releases to the atmosphere must be minimized.

2.1 Energy Production with Sequestration

To minimize atmospheric carbon dioxide releases from stationary burning of fossil fuels, carbon dioxide can be sequestered underground. Major programs are under way to develop methods to sequester carbon dioxide in geological structures. Recent assessments[1] indicate that sequestration may increase bus-bar electrical costs by up to 40% for base-load power production systems. However, these and other studies indicate that burning fossil fuels with carbon dioxide sequestration will likely be competitive in much of the world with other energy sources for large energy facilities such as central electric power plants that operate at constant power levels. In contrast, the costs of carbon dioxide sequestration for small systems or systems that are use only a limited number of hours are likely to be very high and not competitive. Other energy systems may be required to meet those energy needs.

2.2 Transportation Fuels

The most important uses of fossil fuels are as liquid fuels for transport. The fuel cycle for liquid fuels includes obtaining the feedstocks; conversion of those feedstocks to liquid fuels; transport of the liquid fuels to the user; and burning the liquid fuel in a car, truck, or airplane. Each step consumes energy and releases carbon dioxide. Figure 1 shows the greenhouse gas releases per vehicle mile from a diesel-powered SUV for each step in this fuel cycle.[2] Carbon dioxide is the primary greenhouse gas. With the production of liquid fuels, the total fuel-cycle energy consumption and carbon dioxide releases to the atmosphere are 130 to 200% of those of the vehicle. If carbon dioxide releases to the atmosphere are to be minimized, the avoidable releases from the production of liquid fuels must be reduced.

The process of extracting high-quality sweet (low-sulfur) crude oil, converting it to diesel fuel, and transporting the diesel fuel to the fuel pump consumes relatively little energy and releases relatively small quantities of carbon dioxide. In contrast, if liquid fuels are made from coal, more energy is used and more carbon dioxide is released in the production process than is present in the final fuel. As the stocks of high-grade crude oil are exhausted and liquid fuel is made from lower-grade resources, much more energy will be used and much more carbon dioxide will be released to the atmosphere to make a gallon of liquid fuel.
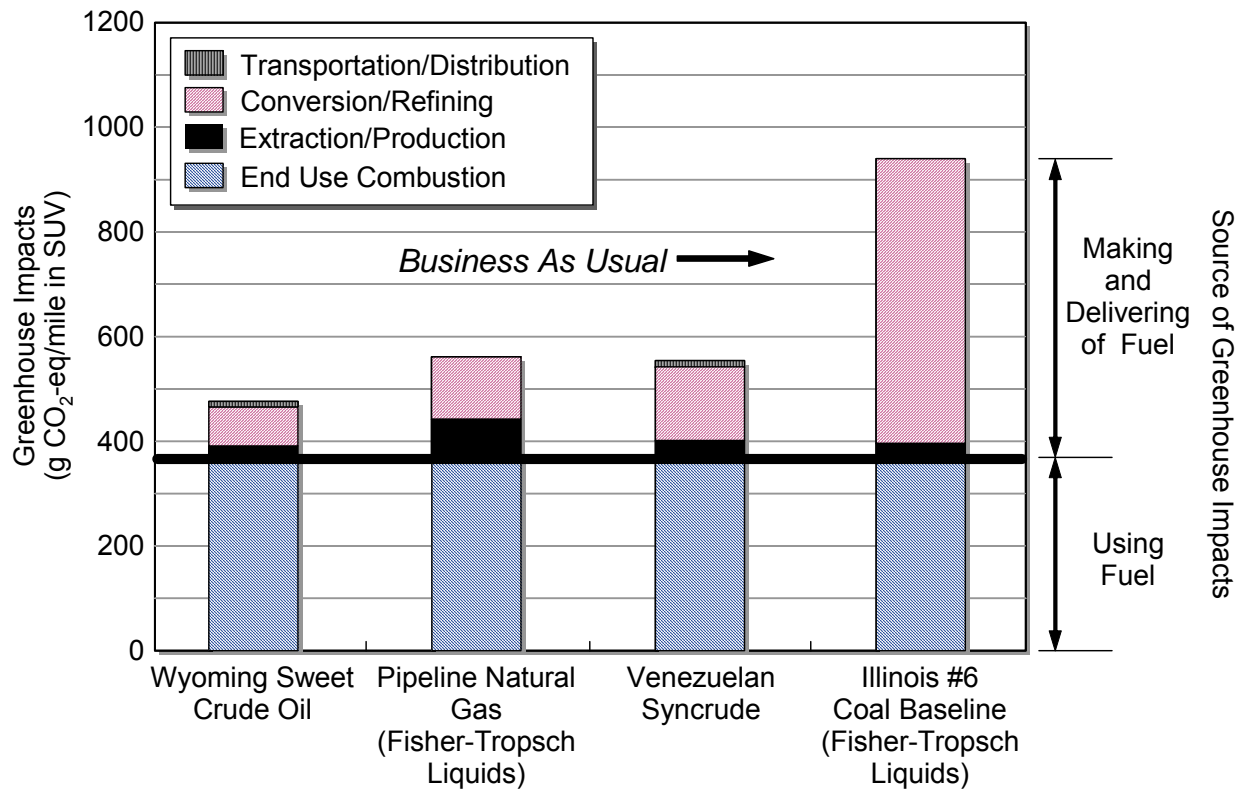
Fig. 1. Greenhouse gas releases per vehicle mile for diesel fuel produced from different sources.

Liquid fuels have a roughly two-hydrogen-to-one-carbon ratio. Heavier feedstocks such as heavy oil and coal have less hydrogen. To convert these feedstocks into liquid fuels, there are two choices: (1) produce hydrogen and add it to the feedstock or (2) subtract carbon from the feedstock. Both processes are used in modern refineries and coal liquefaction plants. The refinery operation for removing excess carbon to make transport fuels is thermal cracking and involves heating heavy oils to between 500 and 700°C to break large molecules into transport fuels and petrocoke. The high-carbon petrocoke is then burned for energy. Significant energy consumption is also associated with removal of various impurities, including heavy metals and sulfur.

If greenhouse gases are to be minimized, the carbon dioxide releases from the production facilities must be minimized. There are three strategies.

- Fossil fuels can supply the energy and hydrogen needed to produce liquid fuels from heavy feedstocks, with sequestration of the resultant carbon dioxide from these process operations.

- Nuclear and other energy sources can be used to supply the energy and hydrogen for liquid-fuel production facilities such as refineries and coal liquefaction plants.

- High-quality crude oils that require little processing can be produced by in situ thermal cracking of oil, shale oil, and coal deposits. By conducting the thermal cracking operations underground in the original hydrocarbon deposit, the resultant carbon-rich by-product is geologically sequestered in place.

In situ refining of carbon feedstocks thousands of feet underground is a new technology to create and recover light oils from heavy oil, shale oil, coal, and other fossil deposits.[3] The feedstocks are processed in-place where they were originally found. The slow heating of oil, oil shale, or coal to 500 to 700°C produces a light crude oil and a carbon residue. As the hydrocarbon deposit is heated, the hydrocarbon molecules are cracked, with the lighter transport fuels distilled (boiled) from the solid in its original geological deposit. The distillation is a purification process that leaves many of the impurities with the solid. The engineering is complex and involves wells with heaters to heat the geology and other wells some distance away to collect the distilled fuel as a liquid, a hot gas, or a mixture of liquids and gases. The requirements for this process are large quantities of high-temperature heat and the appropriate geology.

Conducting this refining operation in an oil field, shale oil deposit, or coal field has one major advantage. The resultant carbon becomes petrocoke, expended shale, or char that is geologically buried underground. Furthermore, this carbon is in the chemically stable form of solid carbon whereas sequestered carbon dioxide is initially a liquid at high pressure. Only the light crude oil and hydrocarbon gases are removed. In situ refining is in an early stage of development with a small number of pilot plants. However, it may become a preferred strategy for production of liquid fuels because carbon from the production process is sequestered in place in a chemically stable form.

2.3 Peak Electricity

The storability of fossil fuels and the relatively low-cost equipment to convert this energy into useful heat and electricity are key reasons for widespread fossil fuel use. If greenhouse gas releases to the atmosphere are to be limited, technologies must be developed to restrict their release to the atmosphere to only premium applications. This process will require much innovation. One potential example of this type of technology is described in this paper—the production of peak electricity.[4]

The demand for electricity varies with the time of day, week, and season. Base-load plants provide constant power output. Renewable energy sources such as wind and solar will increasingly provide electricity when those renewable sources are available. However, a source of electricity with highly variable output is needed to match these production systems with demand. Today, natural gas and jet fuel combined-cycle systems provide this variable output. Methods to produce premium-price peak electricity with lower greenhouse gas releases are needed.

One option is a nuclear combustion combined-cycle (NCCC) power plant (Fig. 2) that uses heat from a high-temperature nuclear reactor and fuel (natural gas or jet fuel) to meet base- and peak-load electrical demands. For base-load electricity production, air is first compressed; then flows through a heat exchanger, where it is heated to between 700 and 900°C; and finally exits through a high-temperature gas turbine to produce electricity. The heat, via an intermediate heat-transport loop, is provided by a high-temperature reactor. The hot exhaust gases from the Brayton-cycle turbine are then fed to a heat recovery steam generator that provides steam to a steam turbine for added electrical power production.

Gas Turbine Cycle
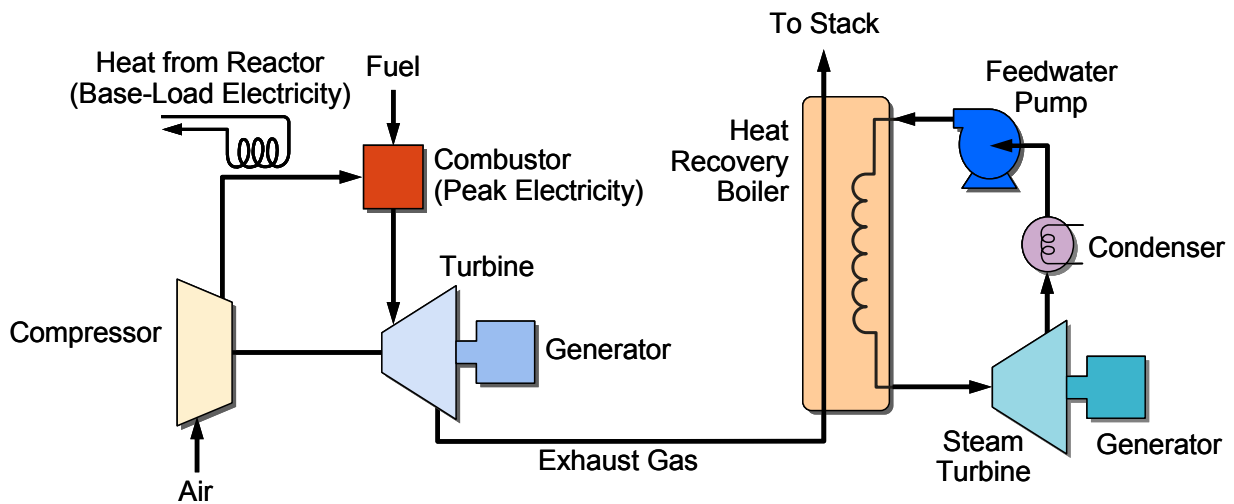
Steam Turbine Cycle

Fig. 2. Nuclear-combustion combined-cycle electric plant.

To meet peak electrical demand, after the nuclear heating of the compressed air, natural gas or jet fuel is injected into the hot air and burned to increase power levels. This process raises the peak inlet temperatures to both the gas turbine and the steam turbine. In this mode of operation, the peak gas-turbine inlet temperature is ~1300°C—about the same temperature and operating conditions as those of a standard utility natural-gas-fired combined-cycle gas turbine that exhausts its heat to a bottoming Rankine steam cycle.

The nuclear heat raises the temperature of the incoming air above the auto-ignition temperature of the fuel—the temperature at which the fuel will spontaneously burn; thus, the fuel-to-air ratio does not need to be controlled to ensure flame stability and plant operation. Consequently, the combined-cycle plant can operate at any power level between base-load nuclear and the maximum peak power output. The response time to changes in power demand is much faster in an NCCC plant than in a plant that uses traditional fossil-fueled combustion turbines. This capability for rapid changes in power production is a result of the difference between operation of a conventional combustion turbine and that of an NCCC plant.

- *Traditional Brayton power cycle*. In a traditional combustion turbine, the fuel-to-air ratio must be controlled to ensure flame stability. To increase the power demand, the airflow and fuel injection rate are increased simultaneously. As more fuel is added, the extra power is first used to increase the airflow. Consequently, a significant lag time between the signal for more power and the delivery of that power exists.

- *NCCC power cycle*. With nuclear base-load heat, the compressor operates at a constant speed with a constant airflow through the system. When additional electricity is required, fuel is injected into the system. The time between fuel injection into the burner and an increase in power level is determined by the flight time between the fuel injectors and the turbine—a fraction of a second. The air compressor does not change speed or require more energy.

The nuclear preheating avoids the use of the premium fossil fuel to heat air to 700+°C. The fossil fuel is thus used for a premium application—providing peak power to the electric grid when required. This capability may enable larger-scale use of renewables for electricity because it can provide the rapid response to power demand with highly variable levels of renewable electricity input into the electrical grid.

3. Biomass Fuel Cycles

Today biomass is used on a relatively small scale for the production of liquid fuels and as a chemical feedstock. Each year the United States could produce about 1.3 billion dry tons of biomass feedstock[5] for conversion to liquid fuels without major cost or availability impacts on the production of food or fiber. Liquid fuels from biomass are greenhouse neutral. Biomass is produced by sunlight, carbon dioxide from the atmosphere, and water. The carbon dioxide from burning biomass fuels recycles the carbon dioxide back to the atmosphere.

As a source of energy and liquid fuels, biomass presents one major limitation.[5-6] The available quantity is insufficient to meet our liquid fuel and energy needs. The actual energy value of the 1.3 billion tons of dry biomass per year depends upon the form in which it is used.

- *Burnt biomass*. The energy content of the biomass, if burned, would be equal to burning 9.8 million barrels of diesel fuel per day; however, additional energy would be required to grow, collect, and transport the biomass to furnaces.

- *Fuel ethanol.* If the biomass were converted to fuel ethanol, the energy value of the ethanol would be equal to about 4.7 million barrels of diesel fuel per day. This scenario assumes that some of the biomass is converted into ethanol and that the remainder of the biomass provides the energy for the biomass-to-ethanol conversion processes. The energy value of the product ethanol is only half that of the original biomass. Like the conversion of heavy oils and coal to liquid fuels (Fig. 1), biomass requires significant energy inputs for production of high-quality liquid fuels.

- *Diesel fuel.* If all of the carbon in the biomass were converted to diesel fuel, 12.4 million barrels of diesel fuel could be produced per day. This assumes that non-biomass energy sources provide the needed energy for operation of the biomass-to-fuel plants and to produce the hydrogen needed for the conversion process. The energy value of this diesel fuel exceeds the energy value of the burnt biomass because of the non-biomass energy and hydrogen inputs in the biomass-to-fuel plant. This quantity of diesel fuel would meet the nation's demand for liquid fuels.

Biomass is unique as a carbon-neutral fuel and chemical feedstock. Although the available biomass is sufficient for use as a feedstock for liquid fuels, there is insufficient biomass for use as both a feedstock and an energy source. Therefore, if biomass is to be the long-term source of fuel and chemicals, the biomass fuel cycle must ultimately evolve to the point at which biomass is primarily a feedstock, not a general energy source for the production of liquid fuels.

A noteworthy characteristic of biomass processing is that in most cases much of the energy input is in the form of relatively low-temperature heat. Consider the conversion of corn into ethanol. The nonsolar energy inputs from growing the corn to its conversion to ethanol are about 70% of the energy value of the ethanol. One half of the nonsolar energy input is in the form of 150-psi steam, which is used to distill the ethanol from the fermentation broth and to dry fermentation by-products. Such low-temperature steam can be provided at relatively low costs by cogeneration of electricity and steam from nuclear plants.

The use of biotechnology to increase the biomass yields of plants for fuels is at an early stage of development. Much work is under way to develop plants with (1) higher biomass yields and (2) selected biomass constituents. Over a period of decades, dramatic increases in biomass production may be possible with plants optimized for fuel production. For example, the corn yield per acre in the United States has increased by a factor of 6 over an 80-year period.[7] There is the potential for major increases in biomass availability. In addition, there are non-traditional biomass plants such as algae that could be grown in locations unsuitable for traditional biomass.

The per capita biomass resources of the United States are much larger than those of most countries; consequently, the United States is one of the leading exporters of agricultural goods. If the biotech revolution can dramatically increase yields of biomass to produce fuels, the United States in the long-term may become an exporter of liquid fuels.

4. Nuclear Fuel Cycles

Changing the biomass and fossil fuel cycles has major impacts on associated nuclear fuel cycles. Many of the options considered require large quantities of high-temperature heat—and, thus, nuclear reactors that can provide that heat. Furthermore, many of the options require relatively distributed sources of heat, which imply smaller, more-dispersed reactors. The economics of such reactors depend upon developing reactor technologies that can be economically deployed in smaller sizes. Associated with traditional nuclear technologies, are large economics of scale because many of the costs (operations, security, etc.) are relatively independent of reactor size.

The likely solutions[8] are high-temperature reactors with coated-particle and other advanced fuels that are designed so that the fuel, not the reactor system itself, is the primary line of defense against release of radionuclides from an accident or act of terrorism. With existing reactors, the reactor systems protect the public against releases of radioactivity. These systems include the fuel, complex systems to maintain the fuel below conditions at which it can fail, and multiple barriers (pressure vessel, containment dome, etc.). An alternative strategy is to create a fuel that is the primary barrier against releases of radioactivity and that functions as a barrier even if the reactor vessel and containment structure are compromised. This strategy may reduce both the capital and nonfuel operating costs of the plant. However, this change in design and safety strategy places extreme demands on the fuel design and fabrication.

Such design approaches have major implications for nuclear fuel cycles. The ease and cost of reprocessing spent nuclear fuel (SNF) depend upon its physical and chemical form. Nuclear fuels that were developed for production of plutonium for weapons purposes were designed to simplify the chemical recovery of the plutonium. In contrast, a fuel designed to survive most accidents and acts of terrorism is a fuel that by definition is going to be difficult to process for recovery of fissile materials and subsequent recycle into other reactors. The closest existing example of this is navy submarine fuel. Submarine fuel is designed to withstand very severe conditions such as (1) extremely rapid transients to full power to evade an enemy torpedo or (2) extreme shaking caused by the detonation of a torpedo somewhere near the submarine. Nuclear fuels designed to meet extreme conditions are difficult and expensive to reprocess.

If such fuels and reactors are developed to enable small economic reactors with reduced operational and security forces, significant time will be required to develop processes to recover fissile materials from these SNFs. Alternatively, for some of these fuels, direct disposal of SNF may become the preferred choice. The same properties that make such fuels so difficult to process potentially imply superior waste forms for direct disposal as SNF. The availability of uranium resources makes it unlikely that such SNF will need to be reprocessed for fissile material recovery.[9] Last, such fuels tend to have very high fuel burnups that reduce (1) the value of the fissile material in the SNF for recovery and recycle into other reactors and (2) the potential concerns about possible use of these fissile materials in nuclear weapons. The optimum global fuel cycle may be a split fuel cycle, with an open fuel cycle (direct disposal) for high-integrity SNF and a closed fuel cycle for other SNF. This issue has not yet been explored.

5. Conclusions

Major changes are required in fossil, biomass, and nuclear fuel cycles for an energy-sustainable world. Fossil fuels must make the transition to a mostly closed fuel cycle, with carbon dioxide sequestration or in situ carbon sequestration with in situ processing for liquid fuel recovery. Fossil fuel applications that release carbon dioxide to the atmosphere will ultimately be reserved for premium services such as transport fuel and peak electric power. Biomass can be the long-term feedstock for liquid fuel production and the chemical industry; however, the limited worldwide biomass availability will ultimately require outside energy sources to operate the production facilities. Although the nuclear fuel cycle will be greatly expanded, the potential need for more-indestructible fuels may result in split fuel cycles in which some SNF is processed for recovery of fissile materials and other SNF is subject to direct disposal.

6. References

1. Massachusetts Institute of Technology, *The Future of Coal: Options for a Carbon-Constrained World*, Cambridge, Massachusetts, 2007.

2. Marano, J. J., Ciferno, J. P., *Life-Cycle Greenhouse-Gas Emissions Inventory for Fischer-Tropsch Fuels,* Energy and Environmental Solutions, LLC, for the U.S. Department of Energy National Energy Technology Laboratory, Pittsburgh, Pennsylvania, 2001.

3. Forsberg, C. W., "High-Temperature Nuclear Reactors for In-Situ Recovery of Oil from Oil Shale," *Proc. 2006 International Congress on Advances in Nuclear Power Plants (ICAPP'06)*, Reno, Nevada, June 4–8, 2006, American Nuclear Society, La Grange Park, Illinois, 2006.

4. Forsberg, C. W., Conklin, J. C., *Hydrogen-or-Fossil-Combustion Nuclear Combined-Cycle Systems for Base- and Peak-Load Electricity Production*, ORNL-6980, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 2007.

5. Perlack, R. D., Wright, L. L., Turhollow, A. F., Grahan, R. L., Stocks, B. J., Erbach, D. C., *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*, DOE/GO-102995-2135, ORNL/TM-2005/66, U.S. Department of Energy, Washington, D.C., April 2005.

6. Forsberg, C.W., "Meeting U.S. Liquid Transport Fuel Needs with a Nuclear Hydrogen Biomass System," *Proc. of the American Institute of Chemical Engineers Annual Meeting, Salt Lake City, Utah*, November 4–9, 2007.

7. U.S. Department of Agriculture, National Agricultural Statistics Service," Trends in U.S. Agriculture," 2003, www.usda.gov/nass/pubs/trends/.

8. U.S. Nuclear Regulatory Commission, Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs), NUREG/CR-6944, Washington, D.C.

9. E. Schneider and W. Sailor, "Long Term Uranium Supply Estimates," Nuclear Technology, LA-UR-05-8879, January 2008.