

CHEMICAL ENGINEERS AND ENERGY

*“So, I will learn my oxides, Methane, hydrocarbons, too
Then maybe I can help the earth—It’s really overdue!”
Ann Hart, President of Temple University, Philadelphia
From "Greenhouse Effect"*

In the quest for assured energy sources, choices and tradeoffs must be made among the viable alternatives, reconciling the potential downsides of each choice. Such challenges have been with us for all of recorded time.

In 1859, Edwin Drake drilled one of the world’s first commercial oil wells south of Titusville, PA, which produced 25 barrels of petroleum (then called rock oil) on its first day from a geological reservoir located 69 ft below the surface. At the time, people were beginning to recognize the value of petroleum, mostly for its ability to lubricate and illuminate. So, in a sense Drake’s gusher helped usher in the Petroleum Age. Shortly thereafter, in 1888, Nikola Tesla supervised the building of the first large-scale hydroelectric generators in the U.S., at Niagara Falls, NY, which provided electricity to Buffalo via alternating-current power-transmission lines. In 1908, Henry Ford introduced his economical Model T automobile and spearheaded efforts that allowed for its mass production by 1914.

Drake’s oil well, Tesla’s motors and transformers, and Ford’s Model T all helped enhance our country’s modernization and prosperity. The technological developments they inspired also helped give rise to chemical engineering as a profession and solidify the central role that chemical engineers play in the production and use of all forms of energy.

Chemical engineers with diverse technical skills

Because chemical engineers are well versed in chemistry, physics, mathematics, and engineering, they are suited to meet the challenges of all types of energy production and have long contributed to the discovery and commercial-scale exploitation of traditional sources of energy, such as coal, crude oil, natural gas, shale, and tar sands. The widely used fuel sources, called fossil fuels, all derived from the organic remains of prehistoric plants and animals. Because their origins (and the time horizons and conditions required to produce them) cannot be reproduced in our lifetimes, thus they are also called nonrenewable fuel sources. Recently, chemical engineers have also concentrated their efforts on such renewable fuels as those derived from biomass feedstocks, hydroelectric power, geothermal sources, solar radiation, and wind.

Using a vast array of chemical engineering principles, both renewable and nonrenewable feedstocks can be employed to generate electricity, produce various fuels for transportation and for industrial and residential purposes, and produce intermediate chemical products and feedstocks, as well as such high-value finished products as polymers, fertilizers, and paints. In the U.S., fossil fuels account for about 85% of all the energy produced today. Of the remaining 15%, 8% is produced in nuclear reactors and 7% is renewable (with biomass gasification and hydroelectric power being the most widely used renewable).

Energy usage is fairly equally divided among industry and manufacturing applications (33%), transportation (28%), residential use (21%), and commercial use (18%) (Oct. 2006 data, <http://www.eia.doe.gov/neic/brochure/infocard01.htm>). While all known energy sources will likely continue to be used, efforts are under way to help society increase the use of promising new renewable sources of energy to reduce dependence on fossil fuels and the environmental impact associated with burning coal, natural gas, and petroleum-derived fuels. Considerable efforts are also being made to commercialize promising new technologies producing electricity and liquid fuels from coal and natural gas using gasification, instead of combustion.

Several factors are driving chemical engineers' efforts to develop cost-effective strategies to help society reduce its dependence on crude oil, natural gas, and coal.

- Combustion of fossil fuels contributes many pollutants to the atmosphere.
- Domestic supplies and new discoveries of natural gas and crude oil are dwindling.
- Crude oil from foreign sources is subject to persistent geopolitical instability in many of the world's oil-producing regions creating significant volatility in supply and price for imported fossil fuels.

Chemical engineers are also at the forefront of developing the engineering tools and techniques needed to improve the conservation of energy and reduce the routine production of pollutants during the combustion of fossil fuels. Emission of such pollutants as CO₂, SO₂, NO_x, and particulate matter contributes to health problems, urban smog, acid rain, and global climate change.

Producing fuel and power from fossil fuels

The widespread use of coal helped fuel the Industrial Revolution, but it has been gradually surpassed by oil and gas (once the techniques to extract such high-value fossil fuels in commercial-scale quantities were realized). In its raw state, when it is first extracted from deep underground reservoirs, crude oil is of little value, its value (and nowadays that of natural gas) lies in the broad slate of products created by using today's advanced petroleum refining and other chemical conversion processes. Valuable petroleum derivatives include gasoline, diesel and

jet fuel, kerosene, lubricating oils, waxes, asphalt, and intermediate petrochemical feedstocks and finished petrochemical products such as synthetic fibers.

Petroleum refineries use a complex array of chemical conversion processes resulting in physical and chemical changes in crude oil (and natural gas) to produce the end-products that are in demand. Every refinery begins with a distillation step, in which crude oil is separated into different “fractions” (or components) based on the boiling point of each component. Distillation helps isolate crude fractions (such as lighter or lower-boiling fuel gas, propane, butane, gasoline, kerosene, and heavier or higher-boiling constituents, such as fuel oil, gas oil, and residuum), but the process leaves each unchanged on a molecular level. They are then subjected to a series of chemical conversion processes, such as cracking, hydrogenation, reforming, alkylation, polymerization, and isomerization. Each process works differently to break down and rearrange the hydrocarbon molecules for conversion into specific end-products. The mixtures of new compounds created by these chemical conversion processes are later separated into individual products using such methods as distillation and solvent extraction. By combining these chemical engineering processes, modern refineries can convert nearly the entire content of each barrel of crude oil into high-value products that meet different market demands.

There are four main types of hydrocarbons, which are composed of different arrangements of carbon and hydrocarbon atoms and sometimes include other elements, such as oxygen, sulfur, and trace metals. (*Fundamentals of Petroleum*, 3rd ed., edited by Mildred Gerding (Petroleum Extension Service, University of Texas at Austin, 1986).

Paraffins include such compounds as methane, ethane, propane, normal (straight-chain) butane and isobutene (branched-chain), pentane, and octane. Because they have the greatest possible number of hydrogen atoms, they are called saturated hydrocarbons and tend to form very stable chemical compounds.

Olefins include such compounds as ethylene, propylene, butylenes, and butadiene, and contain less than the greatest possible number of hydrogen atoms in their chain structures. Owing to this relative hydrogen deficiency, they are known as unsaturated hydrocarbons. Because carbon atoms within the olefins always seek to attach their “empty” bonds to other atoms, olefins are relatively unstable and thus are easily converted into new chemical compounds during refining.

Naphthenes include such compounds as cyclohexane and dimethyl cyclopentane. Their carbon atoms form rings rather than chains, so they are called ring compounds or cycloparaffins. Because the carbon rings are saturated with hydrogen atoms, they are very stable chemically.

Aromatics include such compounds as benzene, toluene, and xylene, which contain a ring of six carbon atoms with alternating double and single bonds and six attached hydrogen atoms (a structure known as the benzene ring).

Cracking processes

Chemical engineers also continue to develop state-of-the-art advances in machinery and processes to improve energy efficiency and reduce the environmental impact of industrial and petroleum operations in the face of societal pressures and regulatory mandates regarding fuel efficiency. For instance, petroleum refineries have had to pioneer ongoing technological improvements needed to produce lead-free gasoline (to eliminate lead-bearing pollutants in tailpipe emissions, since these compounds are harmful to human health) and diesel fuel with significantly reduced levels of sulfur (to reduce the production of sulfur-bearing pollutants when diesel fuel is burned, since these compounds lead to the formation of acid rain).

Advances in the application of vacuum, heat and catalysts have helped refiners to more effectively convert higher-molecular-weight constituents into lower-molecular-weight products using such processes as thermal cracking relying on heat and pressure alone, catalytic cracking benefiting from the use of a catalyst, and hydrocracking involving the addition of hydrogen in the presence of a catalyst. Important chemical process operations that have been instrumental in the evolution of modern-day refineries include thermal, Houdry catalytic, fluidized-bed catalytic, modern fluidized bed and steam catalytic cracking, as well as advances in modeling, simulation, and control.

Thermal cracking. Early efforts to refine petroleum revealed that heavy hydrocarbon fractions will “crack” at elevated temperatures. In the cracking process, crude-oil molecules break down into smaller molecules and more desirable products, such as gasoline and distillate fuels.

Vladimir Shukhov had invented the first thermal cracking method in Russia in 1891. William Burton of the Standard Oil Co. of Indiana, however, doubled the gasoline yield by the cracking process at elevated pressures. The Burton cracking process spread rapidly after its commercialization in 1913, and by the mid-1920s most refineries had rows of Burton reactors in operation, turning out a high yield of gasoline.

Houdry catalytic cracking. Eugene Houdry revolutionized oil refining by using solid clay catalysts to improve the cracking process under controlled heat and pressure. In 1930, he began working with Sun Oil and Mobil Oil to develop and commercialize the first large-scale catalytic cracking process. It almost doubled the gasoline yield compared with that by conventional thermal cracking techniques. The resulting gasoline also had much higher octane levels, so automobiles and aircraft engines could operate at higher efficiencies without “knocking.” (A gasoline’s octane rating represents the fuel’s combustion efficiency and its antiknock value when burned in an engine. Knock happens when the gasoline-air mixture in an engine leads to microexplosions rather than burning evenly.) This process was called “the new

miracle of gasoline chemistry,” and the gasoline—dyed blue to be readily identifiable—was dubbed “Blue Sunoco.”

The Houdry process, however, formed coke and other unwanted carbon by-products during cracking in certain circumstances. When these solid by-products were allowed to accumulate rapidly on the catalyst, the buildup rendered the catalyst ineffective within minutes. To cope with rapid carbon buildup, each Houdry reactor had to be stopped frequently to burn off the carbon deposits and restore the catalytic activity.

Despite this drawback, 14 Houdry crackers were on stream by 1942 producing much of the aviation fuel used during World War II. This technological breakthrough was well timed, since the newer gasoline gave the Allied planes performance advantages, including a 10-30% superiority in engine power, payload capacity, speed, and altitude.

Fluid catalytic cracking. Eger Murphree of the Standard Oil Co. of New Jersey improved catalytic cracking dramatically. To increase throughput and reduce costs he used buckets and screw feeders to move the catalyst beads continuously between the catalytic reactors and the catalyst regenerators used to burn off any accumulated buildup and thus restore the catalytic activity.

Warren K. Lewis of the Massachusetts Institute of Technology suggested agitating the catalyst beads into motion using the reactant gases, which had been proven to work by the Winkler process. (It had been used in Germany since the 1920s to convert powdered coal into a synthesis gas rich in hydrogen and carbon monoxide, using a process called gasification.)

Murphree, with Don Campbell, Homer Martin, and Wesley Tyson, ultimately invented the fluid catalytic cracking (FCC) process, in which the catalyst is produced as a fine powder (rather than pellets) and is then aerated into a fluidized suspension that flows along, like a liquid, with the crude oil stream. The catalyst particles are later separated from the reaction products and passed through a regeneration process, where the solid deposits are burned off. Then the reactivated catalyst is circulated back to the reactor continuously.

Since the first FCC reactor was commercialized in 1942 by the Standard Oil Co. of New Jersey, 34 more units were put into operation by 1945 and U.S. production of aviation fuel increased 60-fold. FCC processes also aided the rapid buildup of butadiene production, which is the primary feedstock for making synthetic butyl rubber. During World War II, when the Japanese cut off U.S. access to many sources of natural rubber, the ability of the U.S. to quickly ramp up the production of synthetic rubber—thanks to the large-scale butadiene production, which resulted from expanded FCC capacity—proved vital to the Allied war efforts.

Modern fluid catalytic cracking. FCC processes have long been considered one of the most important chemical engineering achievements of the 20th century, and their widespread adoption dramatically changed the capabilities and capacities of the modern petroleum refinery. Today, a large-scale FCC unit is at the heart of most modern refineries.

FCC technology continues to meet society's ongoing demand for cleaner, higher-performance fuels and more diverse downstream petrochemical products. In the 1940s, cracking by FCC processes took 20 minutes or more. By the 1960s, new catalysts and other technological advances had reduced the required cracking times to only a few minutes. By the 1980s, reaction times were even lower (10-20 seconds), and today the complex chemical transformations that occur inside an FCC reactor are nearly instantaneous (often requiring only 1-3 seconds). More importantly, most modern FCC units can convert even the most undesirable "bottom fraction" of the crude-oil barrel (heavy residuum or resid, fraction) into value-added downstream products.

With improved FCC processes, chemical engineers have been able to identify advanced catalyst compositions and structures, devise new techniques to rapidly mix the reactants with the powdered catalyst, minimize catalyst particle segregation, reduce internal recirculation, separate the catalyst from the product, and reduce emissions of powder to the atmosphere. These improvements have worked together to ensure that today's advanced FCC systems provide exceptionally uniform reaction times while preventing unwanted side reactions.

Advances in modeling, simulation, and control

Equally compelling are the advances in computerized modeling programs and process control systems used by chemical engineers. Sophisticated software-based tools have enabled the use of increasingly complex models and simulations. They have also made it possible to correlate, model, simulate, and predict the complex chemical and physical transformations, mass and heat balances, and key operating parameters in the petroleum refinery. Such powerful information and insight are then used to adjust and optimize such things as reaction and flow rates, contact times, and reactor temperatures and pressures. These improvements maximize desired yields, minimize unwanted competing side reactions, evaluate process economics more accurately, and identify process constraints.

Cracking conversion levels inside the early FCC reactor were estimated by analyzing the Watson K factor, which indicates hydrogen content and relates reactivity to boiling temperature and specific gravity. Amazingly, this relatively simple correlation technique worked.

The first major breakthrough came in 1953 when Forest Blanding from the Standard Oil Co. of New Jersey applied a fundamental, kinetic approach to modeling a commercial refinery unit. For simplification, his work on the FCC unit considered all the reactants (at the time, only the gas-oil fraction boiling between 430 and 600°F), as if they were a single “invariant compound pure pseudo-component (later called a ‘lump’) in a second-order reaction.” Blanding determined that for a given lump the conversion rate during FCC cracking was proportional to its concentration squared. This discovery helped chemical engineers explain what they had long observed during refinery operations that the gas-oil fraction became more resistant to cracking as the conversion moved forward. In other words, compounds that are relatively easy to crack disappear quickly during processing. The remaining reactants then became disproportionately enriched in those components that are more resistant to cracking. This bottom-of-the-barrel residuum became harder to crack into valuable downstream compounds.

The lumping technique helps simplify the chemistry by treating structurally similar compounds as though they are kinetically equivalent. This approach is still employed today as a useful predictive tool and has even been extended to other refinery processes such as reforming.

Blanding’s pioneering efforts led to the development of a “two-lump” conversion model. By 1971, Vern Weekman and his colleagues at Mobil (who coined the term lump, which later has become a “term of art” in refinery modeling) extended Blanding’s work on FCC modeling. They first had developed a three-lump model (paraffin, naphthene, and aromatic fractions), and five years later a ten-lump model was in use. Today’s advanced computer models can simulate the complex interactions of as many as 400 lumps.

Hydrocracking. The process of catalytic cracking removes carbon from heavy hydrocarbon molecules and produces increasingly hydrogen-rich products. The catalytic hydrogenation process achieves the same outcome, but it does so by adding hydrogen, instead of removing carbon. In the petroleum-refining technique used widely today called hydrocracking, the petroleum feedstock is first cracked catalytically (to remove carbon) and then hydrogenated (to add hydrogen). The extra hydrogen saturates, or hydrogenates, the chemical bonds of the cracked hydrocarbons and thus creates refined isomers with more desirable characteristics.

The first hydrocracker was installed at Union Oil Co.’s Los Angeles Refinery in 1965, and the process was called Unicracking. The products of hydrocracking are saturated hydrocarbons, mostly paraffins with the greatest possible number of hydrogen atoms. The actual products produced in a refinery depend on the temperature, pressure, and catalytic activity used during hydrocracking. The chief products of hydrocracking are jet fuel, diesel, gasoline, and liquefied petroleum gas, such as ethane and propane.

Steam cracking is a thermal process in which saturated hydrocarbons are broken down into smaller, often unsaturated, hydrocarbons. It is principally used for producing lighter olefins, especially ethylene and propylene. Both of them are highly valued in the modern era, because they are used as the primary materials for producing a broad slate of plastics and petrochemicals. It is used to produce fuels, but most often to produce olefins for plastics manufacturing.

During steam cracking, gaseous or liquid hydrocarbons feeds, especially ethane, are diluted with steam and heated very briefly to an extremely high temperature (1,500-1,600°F). In modern steam-cracking furnaces a residence time of just milliseconds is required for the desired yields of final products. Gas velocities in the reactor can exceed the speed of sound. Once cracking temperatures have been reached, the gas is quenched (rapidly cooled) to stop the reaction quickly. In general, higher cracking temperatures favor the production of ethylene and benzene, while lower temperatures increase the production of propylene, butenes, butadiene, and higher-molecular-weight liquid products. Because over time the effectiveness of the reactor suffers from a slow buildup of by-product coke, the furnaces are usually shut down every several months to remove it.

Safety in the refinery

Many refinery processes are carried out at elevated temperatures, so the risk of thermal runaway is always a major concern, which occurs when an exothermic reaction goes out of control and leads to an uncontrollable increase in both temperature and reaction rates—often with explosive results. They are most often caused by failure of the reactor vessel's cooling system, but human error (for instance, the improper installation of components or inadequate maintenance procedures) is sometimes to blame. The intricate engineered safety systems incorporating emergency venting and shutdown, advanced monitoring, and process control help minimize thermal runaways, and limit injury and property damage.

The use of such safety systems has made today's petroleum-refining industry one of the safest industries. According to the U.S. Occupational Safety and Health Administration (Washington, D.C., www.osha.gov), industry segments that tend to rely less on engineered safety systems were to blame for 48% of all workplace fatalities in 2005. Such segments include construction, transportation, warehousing, agriculture, and forestry.

Catalyst formulation: driving desired reactions

The chemical engineering community is constantly at work to achieve higher conversion rates and yields, improve overall energy efficiency, produce cleaner fuels, reduce refinery emissions, and reduce the capital and operating costs associated with all petroleum-refining

unit operations. Much of this work centers around efforts to find improved catalyst formulations and configurations.

Fluid catalytic cracking (FCC) catalysts. Silica gel, patented in 1919 by Walter Patrick of Johns Hopkins University, was used in gas-mask canisters to adsorb vapors and gases during World War I, but during World War II it was also used widely as a dehydrating agent to protect military equipment from moisture damage.

The first catalysts for FCC, produced in 1942, were based on silica gel. The early crystalline silica-alumina compounds were the catalysts of choice for FCC operations until Mobil's Edward Rosinski and Charles Plank formulated an improved catalyst in 1964. In a radical departure from the prevailing catalyst compositions, zeolitic structures were incorporated into the newer catalysts. Zeolites behave as molecular sieves, segregating the desired molecules as a function of size.

Many researchers had been working to develop catalysts based on three-dimensional, zeolitic molecular sieves to speed up the complex petroleum-cracking reactions. It, however, was not until Rosinski and Plank pioneered a new catalyst (AZM-5) that zeolite-based catalysts made an impact on petroleum refining. The AZM-5 catalyst was the first rare earth metal-stabilized X-zeolite catalyst. The Mobil engineers were able to use new zeolite catalysts to significantly advance FCC processes, once they recognized a key fact that the catalyst's effectiveness in the small reactors of pilot plants could be seen only if the reactors were designed with exceptionally short reaction times.

Today's FCC catalysts are much more complex structures. They are capable of processing polynuclear aromatic compounds, which are multiring aromatic molecules containing iron, nickel, and vanadium. As a result, up to 30% of the "bottom of the barrel"—the viscous fraction of crude petroleum feedstocks requiring temperatures as high as 1,050°F or even higher—can now be refined to produce more desirable end products.

Hydrogenation catalysts. Most hydrogenation processes use metal-based catalysts. The process creates chemical species whose properties are between those of molecular hydrogen and activated hydrogen atoms called free radicals. A hydrogenation reaction may be characterized as either a reduction or an oxidation depending on the particular chemical species involved. Wide ranges of hydrogenation catalysts are available with very different physical properties and levels of activity. Many are based on the platinum-group metals (platinum, palladium, rhodium, and ruthenium), cobalt-molybdenum or nickel-molybdenum, or such nonprecious metals as Raney nickel.

Creating synthetic liquid fuels

Although the ability to achieve energy independence has been a national goal for decades, the U. S. continues to rely heavily on the import of foreign crude oil. Many foreign crude supplies are inherently vulnerable to geopolitical instability and have experienced considerable price and supply volatility in modern times.

Following the Arab oil embargo and crude-oil price spikes of the 1970s and 1980s, chemical engineers throughout academia and industry began working vigorously to develop, scale up, and commercialize promising new processes that could produce synthetic liquid and gaseous fuels and petrochemicals, using coal and oil shale as the primary starting materials.

Because both coal and oil shale are available abundantly in the U. S., their use is preferable to imported crude oil and natural-gas feedstocks. According to recent U.S. Department of Energy data, native coal supplies represent more than 85% of total U.S energy reserves and about 64% of worldwide energy reserves. The U. S. is estimated to have a 300-year supply of indigenous coal and oil shale, earning it the nickname “the Saudi Arabia of coal.” There are essentially two routes for producing synthetic liquid fuels: direct hydrogenation (via the Bergius process) and Fischer-Tropsch synthesis. Not surprisingly, chemical engineers have been instrumental in advancing both.

Bergius process is the grandfather of direct hydrogenation used to convert lignite coal to liquid products. It was pioneered in 1921 by Germany’s Friedrich Bergius. During the process, the lignite is ground to a fine powder and mixed with heavy oil, which is produced during the process, and an iron oxide or nickel catalyst. This mixture is then pumped into a fixed-bed reactor. The first reactions take place at 400°C and 300 to 700 std. atm of hydrogen pressure, and produce mainly heavy oils. The product is then catalytically hydrogenated to produce lighter oils in a second reactor, at the same pressure and temperature as in the first reactor. The second reactor typically uses a vanadium catalyst. The final product of this coal-based process is mainly a high-octane gasoline rich in aromatic compounds.

The capture of German scientists and technical documents at the final stage of World War II raised U.S. interest in coal-to-oil hydrogenation. The collection of the very detailed German documentation of their synthetic fuels R&D was called TOM REELS (technical-oil-mission microfiche records). The TOM group went to Germany in the closing days of World War II and interviewed many of the principal scientists involved in developing the process. The group brought a number of these scientists to the U. S. and collected a great deal of useful technical reports, as well as processing and operating data.

With the passage of the U.S. Synthetic Liquid Fuels Act of 1944 came the first concerted, industry-wide effort to devise more innovative ways to convert coal supplies into valuable

fuels and chemicals. The 1973 Arab oil embargo brought renewed momentum to this effort. Once foreign crude oil was vulnerable and world oil prices skyrocketed, the U.S. government, recognizing Americans could no longer take energy for granted, established the emergency crude-oil reserve in 1975. Meanwhile, the engineering community got to work developing a variety of advanced processes to produce synthetic fuels and chemicals from coal and oil shale. Many of these promising new processes, such as the Exxon donor solvent process, were variations of the direct-hydrogenation Bergius process, in which an aromatic solvent is first hydrogenated and then reacted with slurried coal.

The Fischer-Tropsch synthesis, also known as gas-to-liquids (GTL) technology, is a catalytic process that converts a gaseous feedstock into a variety of cleaner-burning, liquid transportation fuels or intermediate compounds, and can then be further processed to produce lubricating oils and other petrochemicals. Today, Fischer-Tropsch processes can use natural or synthesis gas as the starting material. Synthesis gas (syngas) consists mainly of carbon monoxide and hydrogen, and is produced most often by gasifying coal or biomass material. The facilities using coal as the starting material are often called coal-to-liquids (CTL) or coal-to-chemicals plants.

Inside a Fischer-Tropsch reactor, the natural gas or syngas is catalytically transformed into a mixture of predominantly straight-chain hydrocarbon molecules, such as waxy paraffins. The catalysts used are based most often on iron and cobalt. These molecules are then subjected to a variety of cracking processes and upgraded by a mild hydrotreating step to produce such liquid products as clean diesel fuel, jet fuel, kerosene, chemical-grade naphtha, and waxes. Many process improvements have been made since the invention of the original process by German researchers, Franz Fischer and Hans Tropsch, in the 1920s.

Despite the high capital costs associated with the technology, a handful of companies have commercialized large-scale GTL facilities based on the Fischer-Tropsch synthesis. In general, the use of natural gas as a feed is practical when its source is a conventional gas pipeline, or it can be transported in liquid form, as with liquefied natural gas (LNG). The Shell GTL facility in Bintulu, Malaysia, for example, uses natural gas as a feedstock to produce low-sulfur diesel fuels and food-grade wax. By the mid-2000s, more than a half dozen of the world's largest petroleum refiners have been giving serious attention to building large GTL and CTL plants.

Sasol Ltd. (Johannesburg, South Africa) has been one of the most prominent developers of Fischer-Tropsch processes, aggressively pursuing GTL and CTL technologies to help South Africa (with no indigenous oil reserves) reduce the import of foreign oil and become more energy self-sufficient during the economic isolation in the Apartheid era with international trade embargoes. Today, Sasol's facilities convert both coal-derived syngas and natural gas into a diverse slate of synthetic petroleum products, especially diesel fuel. By late 2006,

Sasol's GTL-CTL facility in Secunda, South Africa, which began commercial operation in 1999, had a total synthetic-fuels capacity of 195,000 bbl/d of crude-oil equivalent. According to the company, synthetic transportation fuels produced at Secunda now satisfy 28% of that country's demand.

The success of the Advanced Slurry-Phase Distillate Fischer-Tropsch process used at Sasol's Secunda facility has aroused keen interest in Europe, Africa, and the Middle East. As a result, Sasol is in the process of developing two large-scale international GTL facilities to convert natural gas into ultra-low-sulfur diesel fuel. The first is a 34,000-bbl/d facility, which will convert 330,000 ft³/d of natural gas into 24,000 bbl of diesel, 9,000 bbl of naphtha, and 1,000 bbl of liquefied petroleum gas. This facility is being developed by Oryx, a joint venture between Sasol and Qatar Petroleum, at Qatar's Ras Laffan industrial city complex. Sasol is also working with Chevron Nigeria Ltd. (Lagos) and the Nigerian National Petroleum Corp. (Abuja) to build a 34,000-bbl/d GTL facility in Escravos, Nigeria, to convert natural gas into clean diesel and naphtha products.

Chemical engineers work hard to improve the overall economy of costly GTL and CTL facilities that use the Fischer-Tropsch synthesis by reducing the enormous energy requirements of these megaplants, and by minimizing the carbon-dioxide emissions and their impact on global warming and climate change.

Using coal gasification for “greener” power. Coal has traditionally been the primary fuel used by power plants to generate electricity. To provide more environment-friendly processes for generating electricity from coal, chemical engineers have made great strides in developing integrated combined-cycle gasification (IGCC) power plants, which can minimize environmental impacts significantly by enabling power generation via coal gasification, rather than traditional coal combustion.

Gasification is carried out by injecting coal, typically in a slurry form, into a gasifier, along with oxygen (of 95 to 99.5% purity) and high-temperature steam. At the elevated temperatures and pressures found inside the gasification reactor, the coal reacts with the steam and oxygen, producing a syngas that consists of carbon monoxide and hydrogen, with lesser amounts of CO₂ and methane.

To generate electricity, the coal-derived syngas is first cleaned to remove unwanted pollutants and is then burned in a gas turbine. The hot exhaust from the primary gas turbine provides energy to a specialized boiler (called a heat-recovery steam generator), which supplies steam to a secondary steam turbine that generates additional electricity (combined-cycle power generation). The combustion of coal and other petroleum-based fuels is known to form various airborne pollutants, such as SO₂, NO_x, particulate emissions (which are blamed for acid rain

and ground-level ozone problems), CO₂ (implicated in long-term climate change and global warming), and mercury emissions (with devastating human-health implications).

Over the last several decades, coal-fired power plants have been the subject of extensive state and Federal regulations requiring the installation of costly, capital-intensive pollution-control systems, such as flue-gas desulfurization (wet scrubber) systems to meet increasingly stringent thresholds on regulated pollutants. By comparison, IGCC power plants, which rely on coal gasification, are inherently less polluting than conventional coal-fired power plants. For instance, with an IGCC system, the unwanted sulfur and mercury are removed from the relatively small-volume, high-pressure (typically 400 to 1,200 psig) syngas stream before it is combusted in the gas turbine.

The syngas stream typically has an overall volume of less than one-tenth that of the flue-gas stream produced by a conventional coal-fired power plant of the same size. The ability to remove pollutants from this small-volume, more concentrated syngas stream helps reduce the capital expenditures and operating costs required for pollution-control systems, compared with those required by typical end-of-pipe pollution-control systems, which are routinely used to capture regulated pollutants from the post-combustion flue gas produced during conventional coal-fired power generation.

In addition, traditional coal-fired power plants typically rely entirely on steam turbines with large water requirements. Typical IGCC facilities, however, use both steam and gas turbines with about 60% of the power coming from the gas turbines. This difference helps an IGCC facility to consume about 30 to 45% less water than a comparably sized coal-fired power plant.

After a ten-year lull, during which only one IGCC plant was built in the U. S., in 2005 and 2006 at least a half dozen new grassroots IGCC facilities were announced. This wave of project announcements validates IGCC technology as a viable “greener” power-generation technology. Each new IGCC facility has a capacity of 600 to 700 MW—more than twice the capacity of the first-generation plants built in the mid-1990s that are still in operation today. Chemical engineers have been working hard to overcome the many technical hurdles arising with the increased size of these novel power plants.

One industry-wide collaborative effort to demonstrate the commercial-scale use of underground sequestration to manage the CO₂ emissions produced during IGCC is the FutureGen Project (www.futuregenalliance.org). Once it begins operation, this plant will showcase the technical and economic feasibility of two noteworthy goals: producing electricity and hydrogen from coal (which remains the lowest cost and most abundant domestic energy resource); capturing and sequestering the carbon dioxide generated in the process.

Hydrogen economy. Hydrogen as a fuel has limitations today, not the least of which is the fact that gaseous hydrogen is difficult to store and distribute. Similarly, no infrastructure exists to deliver hydrogen to households or to allow fuel-cell-powered cars to refuel with hydrogen at local gas stations. Today, electrolysis of water is the cheapest source of hydrogen except as a byproduct of petroleum refining. Water electrolysis, however, is not energy-efficient. Over the last several decades, chemical engineers have been closely involved in developing safe and technically feasible systems that use hydrogen as a cleaner alternative to fossil fuels.

Hydrogen, however, is not a source of energy, only an alternative to electricity as a means of transferring energy from one place to another. Its generation from fossil fuels involves a considerable loss in efficiency and the production of pollutants. Because it readily detonates in air even without a spark, its storage, transmission and combustion pose serious hazards. The need for clean mobile sources of transportation fuel has resulted in the race to develop viable processes to produce safe, energy-efficient and economical sources of hydrogen on a small scale. Chemical engineers are directly involved in this endeavor.

Producing suitable hydrogen sources

On a commercial scale, hydrogen is produced as a by-product of naphtha reforming. Commercial-scale volumes of hydrogen can also be produced from methane in natural gas with a process called steam methane reforming (SMR), which uses metallic catalysts and temperatures in excess of 800°C. While SMR may be efficient for industrial-scale hydrogen production, it is not suitable for serving the smaller-scale hydrogen requirements of fuel cells used in automotive or smaller stationary power plants.

A number of companies and the Federal government are working to develop compact steam reformers and other types of fuel processors that can cost-effectively produce hydrogen on a smaller scale, and at lower pressures and temperatures (hence lower costs) from such hydrocarbon fuels as natural gas, propane, methanol, and naphtha. Chemical engineers have also developed processes to use coal-derived syngas as a source of hydrogen. By using the water-shift gas reaction, the carbon monoxide and hydrogen in syngas are reacted with water in the presence of a catalyst to create a stream that is richer in hydrogen and carbon dioxide. The hydrogen is then removed using membrane-based separation.

Chemical engineers are also working to develop high-temperature ceramic membranes that can efficiently and inexpensively extract hydrogen from fossil fuels. Meanwhile, more imaginative processes—based on biological water splitting, photo-electrochemical water splitting, reforming of biomass and other waste streams, solar thermal water splitting, and renewable electrolysis—are also being pursued as possible options for the small-scale, localized production of hydrogen.

As the engineering community continues to develop viable chemical processes to produce small-scale hydrogen sources at the point of use, key stakeholders continue to debate several larger potential tradeoffs. For instance, there are both costs and technological hurdles associated with developing viable, small-scale, localized reforming systems that could produce hydrogen from widely available liquid fuels near where it is required. Similarly, there are costs and technological hurdles associated with developing an adequate infrastructure that could deliver hydrogen produced in larger, centralized hydrogen plants to end-users who are located further away.

As part of a long-term vision to pursue hydrogen as a fuel of choice for more environment-friendly transportation, the engineering community is also working to develop advanced internal combustion engines that can be fueled directly by hydrogen or hydrogen blends. Such advances, however, cannot gain a meaningful foothold until a complete infrastructure is put in place to allow gas stations everywhere to sell hydrogen as an alternative fuel.

Hydrogen fuel cells. To help reduce society's dependence on fossil fuels, engineering efforts to develop fuel-cell batteries are under way. These innovative devices can extract hydrogen from such fuels as natural gas, propane, methanol, and naphtha. Functioning as minipower plants, fuel cells produce electricity directly from hydrogen and oxygen, and discharge water vapor as the only by-product. Because they rely on electrochemistry, not combustion, fuel cells eliminate the pollutants emitted from cars, trucks, buses, and power plants. Hydrogen-based fuel cells are being pursued to produce power for transportation vehicles and to produce small-scale sources of stationary power.

Hydrogen fuel cells are characterized by their electrolyte. For instance, phosphoric-acid, molten-carbonate and solid-oxide fuel cells can produce power in the range of several hundred kilowatts to several megawatts so that they are being pursued for small-scale, stationary power applications. Long-term, smaller, and more lightweight fuel cells based on proton exchange membranes (sometimes called polymer electrolyte membranes) are being developed for onboard vehicle and specialty uses.

Hydrogen fuel cells use layers of materials with distinct electrochemical properties that are sandwiched together to form a single galvanic cell. Inside the fuel cell, hydrogen gas (H_2) is channeled to a negatively charged anode on one side of the cell, while oxygen gas (O_2 from ambient air) is channeled to a cathode on the other side.

Facilitated by a platinum-catalyst coating inside the fuel cell, the hydrogen is split into positively charged hydrogen protons (H^+) and negatively charged electrons. The electrolyte allows only the positively charged ions to pass through it to the cathode, while the negatively charged electrons are forced to travel along an external circuit to the cathode. This flow of

electrons creates electricity. The electrons eventually return from doing work and react with oxygen and hydrogen protons at the cathode to form water, which flows out of the cell.

An individual fuel cell produces direct-current electricity at a low voltage. To increase power output, multiple fuel cells are often arranged in series to create a fuel-cell stack. Despite design differences among the competing types of hydrogen fuel cells, most share the same basic elements. A negative anode conducts the electrons freed from the hydrogen molecules to be used in an external circuit, while a positive cathode conducts the electrons back from the external circuit to the catalyst, where they can recombine with hydrogen ions and oxygen to form water. A membrane allows only positively charged ions to pass through it, but blocks electrons. A catalyst, most often platinum based, promotes the reaction.

Fuel and power from renewable (nonfossil-fuel) feedstocks

As society has been increasingly recognizing the need to reduce its dependence on fossil fuels, the chemical engineering community has focused on devising methods for using renewable energy sources, which are replenished over time such as forms of biomass, wind energy and solar energy. The term biomass refers to agricultural products including such plant materials as fast-growing trees and grasses, such agricultural residues as grains, corn, sugar cane, and even the woody, cellulose-rich leaves and stalks, and paper-mill and lumber-mill scrap.

Chemical engineers have long been involved in developing and demonstrating cost-effective technologies to convert renewable biomaterials into electricity, transportation fuels, and chemicals, just as they have for the nonrenewable fossil fuels petroleum, natural gas, and coal.

Coal can be transformed into gaseous and liquid fuels for transportation uses via gasification and Fischer-Tropsch synthesis, and biomass can be similarly converted for the same purposes. They have also devised viable engineering systems to convert corn and sugar cane into ethanol (a cleaner-burning alternative to gasoline) and to convert soybeans and other renewable starting materials into biodiesel (a cleaner-burning alternative to conventional petroleum-derived diesel fuel). Today, ethanol and biodiesel use is on the rise, and commercial-scale facilities are in operation worldwide.

Biomass. As with coal gasification, biomass from various sources can be gasified with steam in an oxygen-blown, partial-oxidation reactor at 900-1,400°C. The resulting syngas consists mainly of carbon monoxide and hydrogen. Once the sulfur and other unwanted constituents are removed, the syngas can either be burned in a turbine to generate power or transformed using the catalytic Fischer-Tropsch synthesis process to produce cleaner transportation fuels such as low-sulfur gasoline and diesel fuel.

Although biomass feedstocks will probably not replace fossil-fuel feedstocks entirely, the ability to commercialize technologies that convert “bushels into barrels” promises to increasingly help society pursue more environment-friendly, renewable sources of fuels, electricity and chemical feedstocks, and achieve greater overall energy self-sufficiency.

To generate *electricity from biomass*, such renewable feedstocks as lumber and agriculture industry residues, landfill gases, and municipal wastes are typically used by direct firing, cofiring, gasification, or anaerobic digestion.

In the most widely used direct-fired systems, biomass is burned directly, instead of burning oil or natural gas in a boiler producing steam. The steam is used to power a steam turbine, which then generates electricity. Such systems, however, tend to have low efficiency (20%) owing to the lower heating value of the biomass-based feedstocks than that of traditional fossil fuels.

To attain higher fuel heating values, cofiring systems were invented that mix biomass with coal or other fossil fuels and use it to blend in a conventional power plant.

Biomass gasification systems use a gasification process to convert biomass into syngas consisting mostly of carbon monoxide and hydrogen. Once the syngas is cleaned to remove unwanted pollutants, it is burned (instead of coal, natural gas, or petroleum-derived fuel oils) in a boiler to produce steam for a steam turbine generating electricity or in a gas turbine generating electricity directly. Such power plants achieve efficiency ratings of 60% better.

Anaerobic digestion uses engineered systems designed to promote biomass decay to capture the methane produced as a product during the process. Since methane is the primary constituent of natural gas, methane produced from the anaerobic digestion of biomass can be used to power a conventional power plant generating electricity. This approach requires highly engineered systems to produce and maintain the particular blend of bacteria needed to promote biomass decomposition in the absence of oxygen inside a closed bioreactor. The bioreactor must be designed and operated to maintain the precise balance of nutrients and operating conditions (such as pressure, temperature, and pH) required by this colony of fragile bacteria to sustain the bacteria and maximize the desired, but slow, reactions.

Efforts to scale down all these biomass-to-power technologies are ongoing to provide them in small modular systems that incorporate an internal combustion or small-scale power generator. Such designs could then be used in remote locations removed from the electricity power grid to convert cheap, available waste crops and other biomass sources directly into electricity. There are also efforts to provide new catalytic processes to convert biomass to green fuels.

Ethanol is an alcohol made by fermenting any biomass that is rich in carbohydrates, such as starches and sugars. Chemical engineers have designed large-scale reactors that allow enzymes and yeasts to convert grains into fuel-grade ethanol in a fermentation process similar to that used to brew beer. Efficient distillation techniques separate the alcohol from the unwanted by-products. The use of ethanol as a gasoline additive has been increasing, since it helps engines run more efficiently by raising octane and reducing carbon monoxide and other smog-causing pollutants. Its use as a direct gasoline substitute is also being investigated, although engine modification will be required for it. Current technologies and those under investigation allow us to convert plentiful, naturally occurring biomaterials into clean fuels, alcohols, and other valuable products.

While corn reigns supreme as the choice of farmers for the source of ethanol in the U. S., Brazil has emerged as a leader in producing ethanol from sugar cane. Ethanol derived from sugar cane is reported to get about 70% of the mileage of gasoline, so it is often blended into the gasoline pool, rather than being used as a direct gasoline substitute. By 2006, Brazil's enormous indigenous sugar-cane crop made it possible to develop a thriving ethanol industry that can sufficiently replace about 40% of the country's gasoline consumption with sugar-derived ethanol. The primary process used in Brazil produces ethanol from the juice extracted from sugar cane, although intensive efforts are under way to develop cost-effective chemical-conversion processes producing ethanol from the leafy, cellulose-rich waste that comes from the sugar-cane harvests (bagasse and straw).

A promising process was demonstrated in a 5,000-L/d facility by Dedini S/A Industrias de Base (Piracicaba, Brazil) using hydrolysis to convert the cellulosic materials into sugars, which are then fermented and distilled to produce ethanol. If this new process can be scaled up successfully, it will offer a chance to increase significantly the current production of ethanol per hectare of harvested sugar cane and bring down its overall costs. As with many promising new technologies, greater operating efficiencies and lower costs come from additional operating experience, ongoing technical advances, and economies of scale associated with increasingly larger facilities. Over time, these factors are expected to improve for use as valuable transportation fuels, electricity, and petrochemicals.

In the U. S., as of mid-2007, there were 119 ethanol plants in operation with a combined production capacity of more than 6.2 billion gal/yr, according to the Renewable Fuels Association (Washington, D.C., www.ethanolrfa.org), the trade association for the U.S. ethanol industry. An additional 86 ethanol refineries or expansions are under construction, with another 6.4 billion gal/yr of new capacity anticipated to come online by 2009.

Biodiesel is a cleaner-burning alternative to conventional diesel produced in a petroleum refinery. It consists of fatty-acid methyl esters that can be produced from starting materials

including vegetable oils (such as those derived from soybeans or rapeseed), animal fat, and even recycled cooking grease. These esters are reacted with ethanol or methanol in the presence of a catalyst. Today, numerous catalysts and competing reactor designs are available, and others are being investigated to allow biodiesel producers to manufacture the environment-friendly fuel at increasingly mild operating conditions (at lower pressures and temperatures), with the hope of increasing biodiesel yield and reducing costs.

Biodiesel can be blended in any amount with traditional diesel fuel or used on its own. Today, many diesel engines are available that can use this renewable fuel with no change in performance. It is currently produced and used on a far smaller scale than ethanol worldwide, but its U.S. production capacity has grown rapidly. For example, in 2004 there were only 22 plants producing about 157 million gal/yr of biodiesel, but by mid-2007 105 plants has brought nameplate capacity to 1.4 billion gal/yr, according to the U.S. industry's trade group, the National Biodiesel Board (Jefferson City, Mo.; www.biodiesel.org). According to the Biodiesel Board, an additional 97 facilities were under construction by June 2007. Should they all come online, they will add another 1.9 billion gal/yr of U.S. biodiesel capacity by 2009.

In addition to being produced from renewable feedstocks (some of which like restaurant grease are considered to be a waste product), biodiesel also produces considerably fewer environmental pollutants when burned in a diesel engine than does conventional diesel. In particular, biodiesel produces substantially lower levels of particulate matter, carbon monoxide, carbon dioxide, SO₂, and NO_x than does petroleum-derived diesel.

Turning solar energy into electricity

History. The desire to harness the sun's energy cost-effectively is not new. Early civilizations routinely relied on the sun for heating and drying. In the second century BCE, Archimedes allegedly used solar energy to "reduce the Roman navy to ashes" by having soldiers reflect sunlight off their shields and set fire to the Roman ships encroaching on its shores.

The Romans in the first century CE installed glass windows in buildings to let in the sun and designed greenhouses that would allow fruits and vegetables to grow more effectively. Meanwhile, the Romans, recognizing the value of solar energy, began regulating domestic solar rights in the second century.

In 1515, Leonardo da Vinci envisioned using parabolic-mirror concentrators to improve cloth dyeing. Antoine Lavoisier built a solar furnace to melt platinum and reportedly achieved temperatures of 3,236°F. In 1767, Horace de Saussure invented the flat-plate solar collector; in the 1880s, John Ericsson, who designed the ironclad ship Monitor, demonstrated the first solar heat engine.

Engineered approaches to capturing solar energy. In 1939, Professor Hoyt Hottel built at the Massachusetts Institute of Technology a fully functioning active solar-energy house, using three independent roof sections with three different flow systems. Its practical flat-plate collector design has remained virtually unchanged and is still in use today. During World War II, small-scale, solar-based systems were used to make water potable for aviators lost at sea. By the 1950s, the abundance of fossil fuels and cheap electricity had been partly responsible for moving solar products to the sidelines, but the OPEC energy crisis of the 1970s caused the engineering community to reexamine the use of renewable energy sources.

Coupled with a variety of Federal and state government subsidies and tax incentives, efforts to harness solar energy became hot once again. Various solar electric systems are under development today. Parabolic-trough collectors track the sun throughout the day. Reflectors shaped like a parabola concentrate the sun's radiation thirty- to a hundredfold. Parallel rows of solar collectors aligned can capture the sun's energy and heat water to temperatures over 400°C, which is sufficient for use in conventional steam turbines. Nine parabolic-trough plants, with a total capacity of 354 MWe, have been operating in California since the 1980s, producing electricity at a cost of about 12 to 14 cent/ kWh.

Another promising design is the sun-tracking "power tower," which can produce working fluids with temperatures of 400 to 800°C. The resulting heat can be used in conventional steam or gas turbines to produce electricity with solar-to-electric efficiencies up to 30%. Plant size can range from 30 to 200 MWe. Power towers must be large to be economical, so their use is envisioned as part of large-scale power plants connected to the power grid.

Although power towers are in the early stages of development compared with the more well-established parabolic-trough technology, a number of test facilities have been constructed around the world. A 10-MW power-tower plant built by Concentrating Solar Power has been operating successfully near Barstow, CA. Dish-shaped reflectors can produce 2 to 25 kW, which is sufficient to power small engine-generators or, when arranged in clusters, to supply power to remote locations or for use in utility-scale applications.

Milestones achieved in solar energy during the last two decades (courtesy of the U.S. Dept. of Energy's Energy Efficiency and Renewable Energy Center) illustrate engineers' contributions in advancing the use of solar energy.

1992. The University of South Florida demonstrated a 15.9%-efficient thin-film photovoltaic cell made of cadmium telluride (which broke the 15% barrier for the first time). Thin-film modules made from amorphous silicon can be deposited on a variety of low-cost substrates, including glass and flexible plastic sheets.

1993. California's Pacific Gas & Electric installed the first grid-supports photovoltaic system at one of its substations in California. This 500-kW system was the first "distributed power" effort based on solar energy.

1994. The U.S. Dept. of Energy's (DOE) National Renewable Energy Laboratory (Golden, CO) developed a solar cell made from gallium indium phosphide and gallium arsenide that became the first to exceed 30% conversion efficiency.

1996–1999. The U.S. DOE, with industry partners, operated its Solar Two "power tower" to demonstrate how solar energy could be stored efficiently and economically so that power could be produced even when the sun was not shining. In the ingenious setup, a field of mirrored heliostats focuses sunlight on a 300-ft tower, which is filled with molten nitrate salt. The salt flows like water and can be heated to 1,050°F. The molten salt is pumped through a steam generator to produce steam to power a conventional steam turbine producing electricity.

1999. Spectrolab, Inc. (Sylmar, Calif.) and the National Renewable Energy Laboratory (NREL) developed a photovoltaic solar cell with 32.3% conversion efficiency. The NREL achieved a new record for thin-film photovoltaic solar cells when it developed a prototype solar cell that demonstrated 18.8% efficiency.

2000. BP Solarex (now called BP Solar, Frederick, MD) developed two new thin-film solar modules breaking previous performance: its 0.5-m² thin-film module achieved 10.8% conversion efficiency and its 0.9-m² module achieved 10.6%, and delivered a power output of 91.5 W (the highest power output of any thin-film module at that time).

Since chemical engineers are well trained in both material science and heat transfer, and have perfected many of the semiconductor-manufacturing techniques for producing photovoltaic cells, their efforts have been instrumental in designing the most efficient systems for the collection of solar energy and its conversion to electricity.

The sun produces a lot of energy across a wide light spectrum, but so far we have learned to capture only small portions of that spectrum and convert the light into electricity using photovoltaic cells. The development of photovoltaic cells that convert sunlight to electricity represented an enormous breakthrough in the engineering community's ability to harness the sun's energy.

The successful manufacture of efficient silicon solar cells, including those based on silicon with a crystalline morphology and those based on silicon with a noncrystalline (amorphous) morphology, requires many of the same chemical engineering techniques used during

semiconductor manufacturing. They include crystal growth techniques, plasma spraying processes, and methods for diffusing or implanting critical elements into the photovoltaic cells.

According to the U.S. Dept. of Energy, today's commercial photovoltaic systems have an efficiency of about 7 to 17%, although some experimental systems have been able to convert nearly 40% of the energy in sunlight to electricity, compared to about 28% by a typical fossil-fuel generator. To improve the efficiency of solar cells, they are often paired with complex mirror arrays, specialized Fresnel lenses and even holographic films, which maximize energy capture by focusing sunlight more efficiently on these cells. Ingeniously, such concentrator systems are often mounted on tracking systems that keep them pointed toward the sun throughout the course of the day.

Chemical engineers have been able to improve photovoltaic cells and concentrator systems by overcoming the prevailing threshold for maximum conversion efficiency and helping make solar-based power a more reliable and cost-competitive alternative to fossil-fuel-based power generation. These gains have also enabled the construction of such larger-scale systems as those producing enough electricity not only to power a building but to supply electricity to a nearby power grid.

As the wind blows

Wind-based power generation also offers inherently environment-friendly alternative to traditional electricity generation. Today, the term wind farm is used to describe the use of a single or several hundred wind turbines. Ongoing increases in installed capacity help wind-based power generation become an increasingly important component of the world's electricity pool. Efforts to improve modern windmill designs tend to be the domain of mechanical engineers, but chemical engineers lend their own expertise by developing improved materials, control systems, and sensors, and assisting with environmental issues.

According to mid-2006 data by the American Wind Energy Association (AWEA, Washington, D.C.; www.awea.org), the total installed capacity for U.S. wind-based energy was 9,150 MW (enough to serve the annual electricity needs of 2.3 million homes), and an additional 3,000 MW of new capacity (with an investment of over \$4 billion) was slated to come online during 2006. The report also indicates that, in 2005, the new 2,431-MW capacity installed in 22 states made wind-based power generation the second-largest source of new power generation capacity in the U. S. after natural-gas-fired power plants.

Europe, however, has been more active in this sector than the U.S. with the total installed capacity of 40,504 MW for wind-based power generation across the European Union by the end of 2005, according to the European Wind Energy Association (Brussels, Belgium,

www.ewea.org). Cumulative wind-power capacity in the European Union grew by an average 32% per year between 1995 and 2005, from a base of 1,638 MW in 1994. By 2010, wind power is expected to deliver 33% of all new electricity generation capacity and provide electricity for 86 million Europeans, according to a 2004 estimate by the EWEA.

Engineered systems to capture wind energy. It is difficult to harness wind energy, because wind is by its very nature unpredictable, and its strength and reliability depend on location. It sometimes does not blow and often blows in unpredictable gusts. To cope with such variations in wind energy, developers of commercial-scale wind farms tend to install hundreds or even thousands of wind turbines. Due to its inherent variability, however, wind-based energy is not typically used as the sole source of power for a residential or industrial application (as is often the case for solar-energy-based solutions), and wind farms are more commonly used to produce electricity, which is then blended into the power grid.

Wind technology has progressed mightily over the past quarter century. Chemical engineers have been involved in fundamental and applied research of the effects of wind gusts and turbulence. These two phenomena create significant wear and tear on wind-turbine components and can significantly reduce the life expectancy of turbine blades and airfoils. As a result, efforts to make wind-turbine components more robust and reliable are ongoing to cost-effectively convert wind energy into electricity.

To design rotating wind-turbine blades with the greatest span or sweep area to maximize the amount of electricity generated by the captured wind energy, the rotating blades must combine strength and structural integrity (to maximize reach and minimize fatigue-related failures) with flexibility (to adapt to varying wind loads). To develop rotating turbine blades with more strength, more lightweight, and less cost, chemical engineers use advanced modeling, simulation and fabrication techniques. Advanced materials, such as carbon fiber, advanced resins, and carbon-glass hybrid composites, are constantly evaluated to make them better withstand the rigorous operating conditions experienced by a wind turbine.

Efforts are also under way to apply modern, fast-acting sensors and control systems and nondestructive testing methods, such as ultrasonic testing and vibration monitoring, to evaluate the performance of existing blades and allow diagnostic analyses. Such insight allows operators to adjust the operation of a system quickly. It also allows them to carry out maintenance procedures and repairs most cost-effectively by addressing the potential damage from high loads that periodic wind gusts and turbulence impose on wind-turbine blades.

Proven condition-monitoring sensors and systems are now widely used in wind turbines to track such critical operational parameters as vibration signatures, temperature, shaft speed, torque, wind velocity, and other machinery parameters. They track the ongoing condition of all

rotating parts to undertake preventive (and even predictive) maintenance before system failure, improve efficiency, and reduce operational performance. Most state-of-the-art wind turbines also include monitoring devices to track the performance of gears and bearings, which are most often to blame for extended outages related to wind turbines.

Nuclear power

By design, nuclear power plants create less air pollution than conventional power plants, because they do not involve the combustion of fossil fuels. Because these facilities produce radioactive products requiring long-term confinement storage, however, they are subject to lengthy site reviews and regulation, and generate considerable public fear related to potentially catastrophic accidents and, more recently, terrorist attacks. Public opposition has limited the more widespread use of this power-generation option in the U.S.

America's first large-scale nuclear power plant began commercial operation in 1957, in Shippingsport, PA. Today, 104 nuclear plants are licensed to operate in the U. S., but one is not operational. All were designed before the 1970s, after decades of R&D efforts in uranium enrichment and reactor design. The technologies used for nuclear-power production have continued to progress since then.

Although several U.S. nuclear power plants have been built in recent decades, most existing ones have been retrofitted periodically to incorporate state-of-the-art advances related to uranium enrichment, cooling and heat exchange, management of spent nuclear fuel, monitoring and process control, overall reactor design, and safety from terrorists. Such advances, many spearheaded by chemical engineers, have helped operational these plants to improve safety, increase power output, and maximize operating life. Chemical engineers work closely with nuclear engineers to design, develop, monitor, and operate nuclear power plants in the safest and most efficient manner and to safely produce, handle, use, and dispose nuclear fuels.

Despite ongoing political and environmental opposition, nuclear power is expected to play an increasingly larger part in our overall energy mix in light of dwindling fossil-fuel supplies, price and supply volatility, and efforts to curtail the production of carbon-dioxide emissions and other greenhouse gases.

Most naturally occurring uranium appears as the nonfissionable uranium-238 isotope, which is found in much greater abundance than the fissionable uranium-235 isotope. Uranium-238, however, cannot be used directly as a reactor fuel. In general, as a source material, unprocessed uranium ore contains only about 0.7% fissionable uranium molecules. During the reactor operation, a portion of the uranium-238 (providing a large portion of the energy used in today's nuclear power plant) in the fuel is converted to plutonium, primarily the desirable plutonium-

239 isotope. To provide fuel for conventional nuclear reactors, the source materials must be processed to extract and concentrate these fissionable atoms by almost a factor of ten. Chemical engineers, with their extensive knowledge of the many available chemical and mechanical methods for complex separations, have been instrumental in designing and building the separation units for the process called ore beneficiation. Because nuclear reactors generate a tremendous amount of by-product heat, there have been efforts to design systems for the safe, controlled removal of heat buildup. Chemical engineers also have been closely involved in designing safe, effective heat-removal systems for nuclear facilities.

According to the U.S. Nuclear Regulatory Commission (NRC), which oversees commercial nuclear power plants generating electricity, existing operational U.S. nuclear reactors fall into two broad categories: pressurized water reactors (PWRs) and boiling water reactors (BWRs). Both types are called light-water reactors (LWRs), because both are cooled and moderated using ordinary water. (Light water means ordinary water used to distinguish it from “heavy water,” which contains more than the natural proportion of heavy hydrogen atoms called deuterium, compared with ordinary hydrogen atoms. Heavy water is used by some nuclear reactor designs, because it slows down neutrons effectively and the probability for the absorption of neutrons is low. LWRs generate power through steam turbines similar to those used by most coal- or oil-fired power plants.) According to the NRC, the 69 PWR and 35 BWR nuclear power plants in operation today in the U. S. generate enough power to meet about 20% of our nation’s overall electrical use.

PWR reactors use nuclear fission to heat water under pressure within the reactor. This water is then circulated through a heat exchanger, which vaporizes the water to create steam used to drive a turbine generating electricity. The water used as a coolant in the reactor and the water used to provide steam to the turbines exist in separate closed loops that involve no substantial discharges to the environment. In a typical BWR, however, fission-based heat from the reactor core creates heat. A single loop is used to deliver steam to the turbine and returns the water to the reactor to cool it. The cooling water is force-circulated by electrically powered pumps. Emergency cooling water is supplied by other pumps powered by on-site diesel generators.

Several other designs available have not been built in the U.S. yet, but have been operating in other countries. One newer reactor design is the fast breeder reactor (FBR), in which the chain nuclear reaction uses the energetic “fast” neutrons without being slowed down by a moderator (e.g., water or carbon) and produces more fuel than is consumed. Excess, unused fuel is then “reprocessed” by various chemical engineering unit operations so that some of the plutonium and the remaining uranium-235 and -238 might be usable as a reactor fuel. Critics of this design, however, note that operating with fast neutrons is risky, because any chain-reaction runaway could have catastrophic results. Early FBRs have proven expensive to build and operate, and the production of plutonium raises concerns over potential nuclear-weapons

proliferation. Today, a commercial-scale FBR operates in Russia, its prototypes exist in France, Japan, and India, and China and India are building commercial-scale FBRs.

Another design called pressurized heavy-water reactors, which use heavy water as moderators and coolants, have been promoted primarily in Canada and India, with additional commercial reactors operating elsewhere. This design has gained some popularity in recent years, because it uses natural uranium as the fuel and can be built and operated at competitive costs for electricity, but there are concerns over the possibility of nuclear-weapons proliferation because of the high levels of plutonium-239 in the spent fuel produced by these reactors.

Some other designs, the gas-cooled reactor and its derivative, the advanced gas-cooled reactor, are in operation in the U.K., France, Sweden, and Japan. Like pressurized heavy-water reactors, the original gas-cooled reactor designs use natural uranium fuels, though the newer advanced designs use slightly enriched fuels and fuels other than uranium.

For safer, more cost-effective nuclear power generation, the U.S. DOE participates in the Generation IV International Forum, an association of 13 nations seeking to develop a new generation of commercial nuclear-reactor designs before 2030. The group is pursuing the development of advanced nuclear reactors with significant improvements in fuel availability, environmental impact, costs, construction times, safety features, and resistance to weapons proliferation (i.e., designs that do not add unduly to the production of unsecured nuclear materials) and protection against terrorist attacks.

Managing nuclear waste

The volume of nuclear waste produced by the world's nuclear-power industries is relatively small compared with other forms of industrial waste. For example, in countries with nuclear power, radioactive wastes make up less than 1% of total industrial toxic wastes. These waste volumes, however, are deadly and must be managed properly, using the best engineering control technologies available to ensure the safety of workers and the general public. Nuclear wastes are generally handled using interim storage on site or in decommissioned nuclear-reactor facilities. Such wastes will require reprocessing or direct disposal (burial) for thousands of years.

Reprocessing now is controversial and requires huge improvements using chemical engineering technology. It involves dissolving small pieces of spent uranium fuel rods in massive quantities of boiling nitric acid. Unused uranium and produced plutonium are individually separated from the acid solution using a series of processing steps, leaving large quantities of high-level radioactive liquid waste and sludge behind. After being cooled for several years, this liquid waste must be solidified for ultimate disposal, while the recovered uranium and plutonium become available as recycled nuclear fuel or nuclear weaponry.

Direct disposal means permanent storage underground, in the ocean, beneath the ocean floor, or above ground in secure storage vessels. Ensuring safe storage for millennia requires careful consideration of material stability, heat generation, complex separations, vapor generation, and the like—all within chemical engineers' expertise. Canada is considering placing a vault 500 to 1,000 m below ground inside geological formations known as batholiths. Finland is building a vault at similar depths, not far from its Olkiluoto nuclear plant. The U.S. decided to use the Yucca Mountain site in Nevada, although the project had been widely opposed. In the late 1970s, the U.S. planned to use reprocessing, which was rejected because of concerns for safeguarding the plutonium (to set an example to the world for not producing and using plutonium) and the belief that direct disposal poses fewer risks. Many countries have long-term nuclear-waste disposal policies (<http://www.uic.com.au/nip09.htm>).

- Countries committed to direct disposal: Canada, Finland, Germany (currently committed to reprocessing, but moving toward direct disposal), South Korea, Spain, Sweden, and the U.S. (reconsidering reprocessing)
- Countries committed to reprocessing: Belgium, China, France, India, Japan, Russia, Switzerland, and the U.K.

Greenhouse-gas emissions and global climate change

The greenhouse-gas emissions produced by the combustion of coal, crude oil, and natural gas, as well as their impact on global climate change, in the earth's atmosphere were once hotly debated, but have gained general acceptance by a growing number of international scientists, engineers, and business leaders, according to the U.S. Environmental Protection Agency (EPA, Washington, D.C., epa.gov). Greenhouse gases covered in the Kyoto Protocol are carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), and greenhouse-gas families are hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆).

By mid-2006, 164 countries, representing nearly half the world's economy (48% of the world gross domestic product), had ratified the Kyoto Protocol, an international agreement that mandates specific reductions in greenhouse-gas emissions. Under the Kyoto Protocol, 30 industrialized countries are now legally bound to reduce emissions by an average of 5.2% by 2012 (using their 1990 emissions as a baseline value).

In addition, a growing number of oil companies, electric utilities, and industrial companies that are large consumers of fossil fuels are undertaking aggressive, voluntary programs to reduce their greenhouse-gas emissions. Such efforts typically involve engineering upgrades related to

the use of cleaner combustion technologies, increased reliance on renewable fuels, and energy conservation measures. All such efforts are within the domain of chemical engineers, particularly engineering upgrades allowing for the use of cleaner fuels and improving energy efficiency not only benefit the environment, but also reduce fuel and downstream costs associated with pollution abatement.