The chemical industry is finding creative ways to reduce energy usage and reshape product life cycles.

Improving Energy Efficiency in the Chemical Industry

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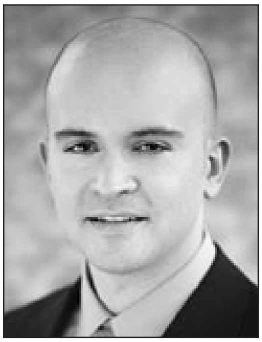

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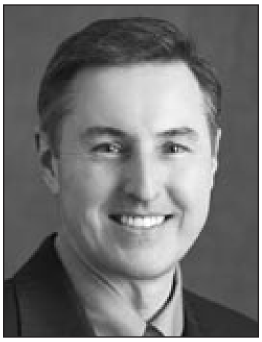

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The chemical industry accounts for 6 percent of energy usage in the United States (Wells, 2008). Approximately half of this energy is contained in hydrocarbon raw materials—primarily from oil and natural gas. The other half is used to transform raw materials into useful chemical products through reaction and purification steps (Neelis et al., 2007).

The key difference between the chemical industry and the fuels sector is that, in the production of chemicals, most of the enthalpy of the starting materials is preserved in the final products. In the fuels sector, the enthalpy is completely consumed to generate energy. Since both sectors rely on the same hydrocarbon resources, conservation in the chemical sector also benefits the fuels sector.

Because of the magnitude of its energy consumption, the chemical industry is motivated to conserve, and U.S. producers have reduced their fuel and power usage per unit output by nearly half since 1974 (ACC, 2009). But opportunities for energy savings go beyond internal consumption. Because more than 96 percent of manufactured goods involve chemistry (Durbin, 2008), the industry can also improve energy usage by consumers through the careful shaping of the product life cycle.

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In this article, we describe how the industry is improving energy efficiency in five areas: improving existing processes, commercializing new processes, recycling waste, investing in renewable raw materials, and creating products that enable energy savings. Specific examples from Dow Chemical Company, the largest U.S. chemical company, are used as a proxy for the industry.

Improving Existing Production Processes

In 2008, Dow's total energy bill was $27 billion, by far the largest component of production costs and equal to about half of total revenues. In its global operations, Dow uses the energy equivalent of 850,000 barrels of oil per day—more than the oil consumption of some countries, such as the Netherlands and Australia.

Dow publishes the energy used per pound of product on its sustainability web page (*http://www.dow.com/commitments/index.htm*). Since 1994, Dow has reduced its energy intensity by 22 percent through a structured program targeting process improvements. This has saved 1.6 quadrillion BTUs, equivalent to the energy required to generate all of the residential electricity used in California for one year. The savings have totaled $8.6 billion on an investment of $1 billion.

Substantial improvements in energy efficiency have been made by improving existing processes and commercializing new processes.

Advanced Control and Optimization

One improvement that is a major change throughout the chemical industry is the recent and ongoing implementation of advanced control and optimization (AC&O). Traditional process control involves monitoring and manipulating parts of the chemical plant, for example setting reactor temperature and pressure to control product yield. With implementation of AC&O, engineers create a predictive model for the entire process based on either matrix algebra or a set of first-principle equations. This is considered a closed-loop application, meaning the model reads in values from the plant, evaluates the operating conditions, calculates the conditions under which the plant will make the most money, then moves the plant to the new target conditions. Typically there are hundreds of measured inputs—such as temperatures, pressures, flow rates, and compositions. Additional inputs include changing economic values, such as current prices and supply/demand constraints for raw materials, utilities, and products. The model manages hundreds of outputs for adjusting conditions of the process and includes built-in constraints to ensure the safety and operability of the target conditions.

Because a typical plant is very complex, with nonlinear and multivariate interactions, it is impossible for a human operator to select the best operating conditions. For example, restarting a complicated plant with many recycle streams can take several days to reach full production rates. AC&O can press the limits of stability and cut this time in half. Dow has found that adding AC&O applications improves production capacity by 3 to 5 percent and decreases energy intensity by 4 to 6 percent. Dow's cumulative savings from AC&O are projected to be more than $1 billion in 2009.

Reducing Gas Flaring

Another area of close attention in the chemical industry is the reduction of flaring, the intermittent burning of flammable gases or liquids. Flaring does not occur during normal steady-state operations, but does occur in episodes when a plant is operating outside its intended design conditions, such as unplanned overpressure of plant equipment during a process upset. The relief valves that protect equipment are tied into the flare system. Usually the flared material is combusted at the tip of a tall tower called a flare stack.

Another reason for gas flaring is the production of unusable "off-spec" material that has no other place to go and cannot be stored or purified. This usually occurs during process upsets or when a plant is restarting after a shutdown. There are two ways to reduce flaring—by maximizing the stability of plant operations to avoid upset conditions and by finding practical opportunities for storing, purifying, or reusing unwanted materials.

A typical world-scale olefins plant may flare several thousand metric tons of hydrocarbons per year. Olefins are the basic building blocks of many important chemical derivatives, including plastics, and Dow operates more than a dozen olefins plants around the world. For several decades, there has been an intense focus on reducing the amount of flaring at these sites.

One successful initiative was replacing gas turbines to improve the reliability of a plant. Gas turbines, although they are highly efficient, are more complicated than steam turbines. They also cause more plant outages, which can result in large flaring events. A single large flaring event can wipe out marginal savings from better turbine efficiency. After installing steam turbines at a plant in Plaquemine, Louisiana, the time between plant outages increased from approximately 250 days to several years.

A second major initiative to reduce flaring has been gas recycling. At olefins plants in Canada, Argentina, and the United States, Dow has found ways to recycle gas back into the system rather than sending it to the flare. As a result of these initiatives and other targeted projects, Dow has reduced the rate of flaring at its olefins facilities by 20 percent since 1998.

Improving the Yield of Raw Materials

There are many ways to improve the efficiency of a plant, and often the most significant benefits are realized by improving the yield of raw materials to desired products. Throughout the chemical industry, companies are developing better catalysts that can increase yields for existing plants. One recent innovation relates to the hydroformylation process, the reaction of propylene with syngas (a mixture of hydrogen and carbon monoxide) to produce butyraldehyde isomers. The highest value isomer is normal-butyraldehyde, which is converted to 2-ethylhexanol (2EH) for use in the production of plasticizers that add flexibility to PVC plastics.

A new hydroformylation catalyst was recently introduced and is cooperatively offered by Dow Technology Licensing and Davy Process Technology. This catalyst is based on rhodium modified with a biphosphite ligand with a unique geometry that selectively hinders molecular movement around the rhodium center. This improves yield to normal-butyraldehyde over iso-butyraldehyde based on the different geometries of the two isomers.

NanYa Plastics has selected the new catalyst technology to retrofit and expand its existing plant in Taiwan. With startup targeted for early 2010, the new catalyst will more than double the production ratio of normal- to iso-butyraldehyde, providing a selectivity of 30:1. This will reduce the amount of propylene required for making 2EH by more than 6 percent compared to the current operation. Considering the annual 2EH production capacity of 200,000 metric tons, this retrofit will provide a significant reduction in propylene consumption.

Commercializing New Processes

The chemical industry has achieved tremendous efficiency gains by introducing new breakthrough processes. One very recent production technology was developed jointly by BASF and Dow. The development program began in 2003, construction broke ground in 2006, and the startup phase for the production plant was completed in 2009. The plant, located at the BASF site in Antwerp, Belgium, produces propylene oxide (PO) with an annual capacity of 300,000 metric tons (Figure 1).

PO, one of the top 50 largest-volume chemical intermediates produced in the world, is a key raw material for the production of a wide range of industrial and commercial products, including polyurethanes, propylene glycols, and glycol ethers. Historically, the production of PO has required either the production of significant volumes of co-products or the recycling of organic intermediates. The new process is based on the reaction of

FIGURE 1 The new HPPO plant at the BASF site in Antwerp, Belgium, completed the startup phase in 2009. With a new process for producing propylene oxide jointly developed by BASF and Dow, wastewater is reduced by up to 80 percent, and energy use is reduced by 35 percent compared to conventional processes. Source: BASF.

hydrogen peroxide, a clean, versatile, environmentally benign oxidant, and propylene to PO. The reaction is facilitated by a proprietary titanium-silicalite catalyst.

In the hydrogen peroxide-PO (HPPO) process, propylene is contacted with hydrogen peroxide in a tubular reactor at moderate temperature and low pressure over a solid catalyst. The reaction occurs in the liquid phase using methanol as a solvent. The process is characterized by both high conversion and high selectivity to the PO, made possible by the unique catalyst material. The co-product of this reaction is water. Hydrogen peroxide is completely converted while the excess unconverted propylene is recycled back to the reactor inlet. The crude PO product is purified by distillation, and the methanol solvent is recycled. The final water stream is discharged to a water treatment unit.

The integration of raw material for the HPPO process is simple—hydrogen peroxide and propylene are the only raw materials. Thus there is no need for additional infrastructure or markets for co-products. HPPO has significant efficiency benefits over conventional processes. Wastewater is reduced by as much as 80 percent, and energy use is reduced by 35 percent. The simple integration of the raw materials and the avoidance of co-products has reduced the infrastructure requirements and physical footprint of the plant.

Recycling Waste

The chemical industry continues to find creative ways of recycling and reusing waste streams. Dow recently began operating a novel system for reusing municipal wastewater at the Terneuzen site in the Netherlands. In collaboration with local authorities and a local water producer, this site accepts more than 2.6 million gallons of municipal household wastewater every day. The local water producer removes residual contaminants, and Dow then uses more than 70 percent of this water to generate high-pressure steam. After the steam is used in production processes, the water is again used in cooling towers until it finally evaporates into the atmosphere.

This is the first time municipal wastewater is being reused on such a large scale in the industry. Three million tons of water per year was previously discharged into the North Sea after a single use. Now this water is recycled for two more applications and has resulted in 65 percent less energy use at this facility compared to the alternative option of desalinating seawater. The reduction in energy use is the equivalent of lowering carbon dioxide emissions by 5,000 tons per year. This concept can be applied at other locations around the world.

Another unique case of recycling is the use of landfill off-gas (Figure 2). Instead of using natural gas, Dow has

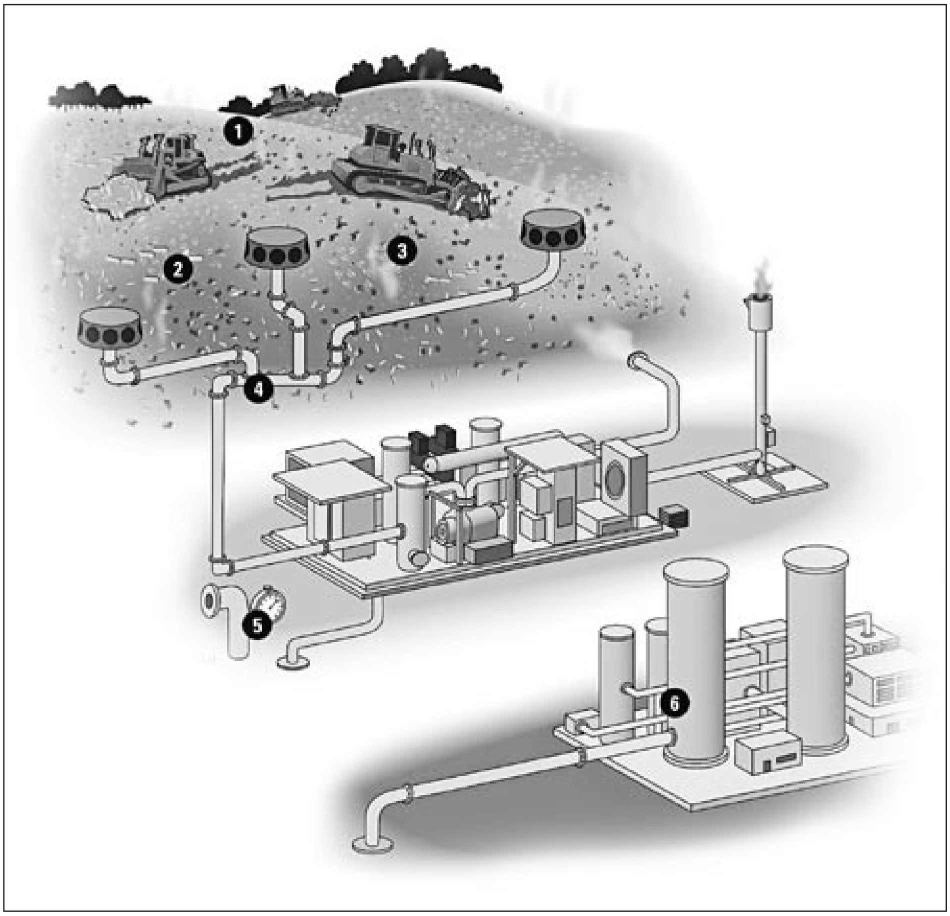

FIGURE 2 Recycling landfill off-gas for energy in Dalton, Georgia. (1) Landfill waste is structured. (2) Anaerobic bacteria decompose the municipal solid waste. (3) Methane off-gas is generated. (4) A system of pipes and blowers collects gas and delivers it to a central location. (5) Gas is used as fuel to make steam. (6) Steam is used by the Dow emulsion polymers plant to manufacture latex carpet backing.

piped methane off-gas from a local landfill to its Dalton, Georgia, latex manufacturing plant. The gas is used as fuel to generate steam for the production of latex carpet backing. This site is expected to use approximately 160 billion BTUs per year of landfill gas (the energy equivalent of 1.4 million gallons of gasoline) that would otherwise be emitted into the atmosphere.

Municipal landfills are the largest source of human-generated methane emissions in the United States. As a greenhouse gas, methane has more than 20 times as much global warming potential as carbon dioxide. By capturing and burning methane, the Dalton facility will reduce the use of fossil fuels and will reduce methane emissions from the landfill. The reduction of greenhouse gases is equivalent to 24 million pounds of carbon dioxide per year.

Investing in Renewable Raw Materials

Producing Epichlorohydrin from Glycerine

Many chemical companies are introducing more efficient processes based on renewable raw materials. One such process at Dow is used to make liquid epoxy resins, which are used in coatings, including marine and automotive applications. The new process involves making epichlorohydrin (EPI) from glycerine. EPI, a key raw material for epoxy resins, is traditionally made from propylene, a derivative of oil or natural gas liquids. In contrast, glycerine is a byproduct of biodiesel production, an alternative fuel made from renewable vegetable oil feedstocks. By using this new EPI process, Dow will reduce wastewater generation from a production facility by more than 70 percent, as compared to conventional technology. In addition, the formation of organic by-products will be considerably lower. Overall, the process will significantly reduce the environmental footprint of an EPI plant. Dow has announced plans for a world-scale glycerine-to-EPI unit in China, and a stand-alone pilot plant for this technology began operating in 2006 at Dow's production site in Stade, Germany.

Producing Polyols from Natural Oils

Another new investment in raw materials is the production of polyols from renewable natural oils, primarily soybean oils. Polyols are a component in the production of polyurethanes (foams and elastomers used in appliances, automotive parts, adhesives, building insulation, furniture, bedding, footwear, and packaging). Traditionally, polyols have been made from PO, a derivative of propylene. The new chemistry based on natural-oil feedstock will reduce the environmental impact of a facility compared to conventional production. The new chemistry is greenhouse-gas neutral and uses less than half of the petroleum-based fuel and raw materials of current technology.

Creating Products That Enable Energy Savings

Products made by the chemical industry are part of nearly all manufactured goods. Therefore, a chemical company has the opportunity to improve energy usage for the consumer through the careful shaping of the life cycle of its products. The creation of materials with unique properties and novel applications can yield significant energy savings for consumers everywhere. The following examples describe materials in the construction, automotive, packaging, refrigeration, water purification, and power generation sectors.

> *The new chemistry for producing polyols from natural-oil feedstock is greenhouse-gas neutral.*

Construction

One option for constructing a flat roof is a protected-membrane roof (PMR) system, that is, foamed polystyrene insulation that shields and protects the waterproof membrane of the roof. By contrast, a traditional system does not cover the membrane. The PMR roof protects the membrane against the most common causes of failure, including sun damage, extreme temperatures, weather, and foot traffic. Traditional flat roofs must be replaced every 7 to 10 years, while PMR roofs have lasted more than 30 years.

In addition, the polystyrene insulation is so durable it can be reused if the PMR roof membrane is ever replaced. Currently, 3 to 4 percent of all waste in U.S. landfills comes from old roofing material. Tripling the lifetime of a roof conserves raw materials and landfill space.

Automotive Manufacturing

Specialized polyurethane foams have been formulated to improve the stiffness and crash performance of vehicles. The foam, which is formulated to adhere to primed metal surfaces, is injected into automotive body cavities where it quickly cures to fill up to 100 percent of the cavity space. By improving the rigidity of body joints with foam, less metal is required to achieve equivalent strength. In one case, the use of polyurethane foam has enabled more than 36 pounds of net mass reduction per vehicle without lowering safety performance (Figure 3). A study of passenger vehicles has shown a 0.6 percent improvement in fuel economy for each 1 percent reduction in weight (Casadei and Broda, 2008).

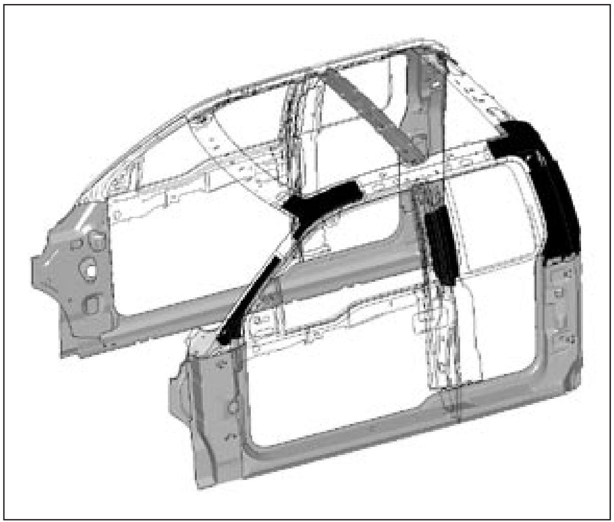

FIGURE 3 Use of structural foam in the pillars of a vehicle (darkened areas). In this case, the use of 4.3 lbs of specialty polyurethane foam yielded more than 36 lbs of net mass reduction as compared to conventional designs that use thicker metal to meet structural requirements.

Packaging Industry

Industrial stretch films manufactured from high-performance polyethylene resins are used to wrap and contain pallet loads during shipment and storage. Stretch films are also used for specialty wrapping applications for lumber, paper rolls, and agricultural silage. With improvements in resin design and polymer processing, industrial stretch film has been down-gauged (made thinner) by more than 25 percent in the last decade without compromising key properties, such as elongation and load-holding force.

This improvement has reduced the amount of polyethylene required for making stretch film by more than 1 billion pounds per year. The energy savings are equivalent to 293 million gallons of gasoline, or the heating and cooling of 643,000 homes for one year.

Refrigeration

A propylene glycol-based heat-transfer fluid is being used in Wal-Mart's experimental Supercenter store in Aurora, Colorado, in a refrigeration system for meat, dairy, produce, and other medium-temperature foods. Unlike traditional systems that require a separate motor for each cold case, the new system employs "secondary loop refrigeration," which requires only one motor. This setup, which is made possible by the unique properties of the heat-transfer fluid, has reduced energy consumption by up to 24 percent over traditional systems.

Water Purification

Reverse osmosis membranes are being used in three major wastewater reclamation and reuse facilities in the city of Beijing. These novel membranes consist of three layers (Figure 4). The major structural support is provided by a non-woven polyester web. Because this web is too irregular and porous to provide a proper substrate for the salt-barrier layer, a polysulfone interlayer is cast onto the surface of the web. The interlayer is an engineering plastic with pore diameters controlled to approximately 150 Angstroms. The final layer is a polyamide that acts as the salt barrier; this layer is only 2,000 Angstroms thick but can withstand high pressures because of the underlying support.

The membrane materials have been continuously updated and refined to improve efficiency through higher rejection, improved flux, and low fouling performance. They will be used to treat 45,000 cubic meters per day of water at the three sites—BeiXiaoHe Wastewater Treatment Plant, Beijing International Airport,

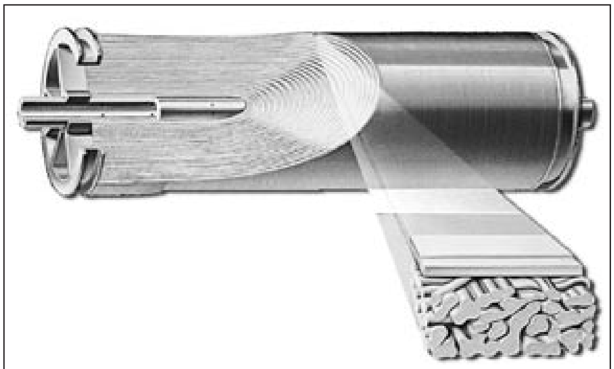

FIGURE 4 Reverse-osmosis membranes consist of (top to bottom) an ultra-thin polyamide barrier layer, a microporous polysulfone interlayer, and a high-strength polyester support web. The materials have been continuously updated and refined to provide higher rejection, improved membrane flux, and reduced fouling thus improving energy efficiency in the production of clean water.

and the Beijing Economic-Technological Development Area. This technology will help the city reach its goal of reusing half of its water, significantly extending a limited natural resource.

Power Generation

A solar energy initiative being led by Dow is intended to make solar energy cost competitive by 2015. The solar project is based on Dow's extensive materials, engineering, and design and fabrication technologies. The project will accelerate research and development on building-integrated photovoltaics (BIPVs), solar energy generating materials that can be incorporated directly into the design of commercial and residential building materials, such as roofing systems and exterior sidings. BIPVs eliminate the traditional trade-offs necessary with solar cells because they serve as the outer protective surface of the building and generate power.

Technology Pathway Partnerships for the solar initiative are comprised of more than 50 companies, 14 universities, three nonprofit organizations, and two national laboratories. The ultimate goal is to reduce the cost of electricity produced by photovoltaics from current levels of $0.18 to $0.23 per kWh to a target of $0.05 to $0.10 per kWh by 2015—a price that will be competitive in markets nationwide.

Conclusions

The chemical industry consumes large amounts of finite energy sources to process raw materials that are in limited supply. The industry has undertaken five major initiatives to improve its energy efficiency: (1) improving existing processes; (2) commercializing new processes; (3) recycling waste; (4) investing in renewable raw materials; and (5) creating products that enable energy savings. Innovation in all of these areas is an absolute necessity for long-term sustainability.

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