Since the beginning of the industrial age, the growth in the world economy has been driven by the increased use of energy. Between 1970 and 2000, primary energy production worldwide grew by 84 percent (see Figure 1). In 2000, fossil fuels accounted for 85 percent of all energy produced. The reason for this large share is that fossil fuels are relatively inexpensive, abundantly available and convenient to transport and use.

The improvement in the world standard of living has been dependent in large part on the increased use of fossil fuels. However, it is becoming clear that the growth in their use cannot continue indefinitely at its present rate. Fossil fuel reserves are finite and are being depleted. More seriously, environmental pollution and climate change are having a detrimental effect on our world.

If we are to continue to increase our standard of living, we must find ways to do so more efficiently, using less energy per capita. At the same time, we must increase utilization of renewable sources of energy.

To put the challenge of improving the efficiency of energy use in perspective, I would like to summarize the use of energy in the United States, where reasonably complete data are available. With less than 5 percent of the world’s population, the U.S. consumes 25 percent of the world’s total energy (see Figure 2). In the U.S. in 2001, the industrial sector was the largest user of energy, accounting for 33 percent of total energy use (see Figure 3). Within that sector, manufacturing accounts for about 73 percent of industrial energy use (the other industrial sectors include agriculture, forestry, mining and construction).
Process manufacturing is by far the most energy-intensive type of manufacturing. The five largest segments of the process industries – petroleum refining, chemicals, pulp and paper, metals and food – consume more than 80 percent (see Figure 4) of all the energy used in U.S. manufacturing. Therefore, if we can improve energy efficiency in this sector, we can have a significant impact on the world requirements for fossil fuels. Now let us focus on what can be done to reduce the energy required for process manufacturing.

**Analysis: Process Manufacturing**

The energy required for process manufacturing is met primarily by the combustion of fossil fuels to produce steam, generate electrical power and provide high-temperature heating in furnaces. The cost of primary fuel, the performance of the process technology and business economics all play a large part in determining actual energy efficiency.

Energy is the single largest operating expense after raw materials in the process industries. The primary fuels used are petroleum oils and natural gas, whose prices follow that of crude oil. Crude oil price and the quantity of energy consumption therefore largely set industrial energy costs.

In relative terms, crude oil price, and hence the cost of energy, remains cheap. In constant (1996) dollar terms, the price of crude per barrel was about $10 in the 1960s; it peaked at $70 in the early 1980s; and it settled at around $20 on average in the 1990s. Today, due to global uncertainties, we have seen crude oil prices rise to $35. However, over the past 20 years, the price of oil has remained fairly static at about $20 per barrel.

Industry has become accustomed to cheap energy, and business investment and technology development have been influenced by this fact. When energy prices are high or increase quickly, there is increased activity to reduce energy consumption and hence to lower manufacturing cost. When energy prices remain constant, at whatever level, then an acceptance of the cost prevails and a new equilibrium establishes. Energy conservation is therefore driven primarily by short-term economics.
The industrial sector has a good track record at reducing its specific energy consumption per unit of production (energy intensity). Over the past 30 years, the energy intensity has been nearly halved (see Figure 5). This increase in energy efficiency has been driven by the increased cost of oil following the oil price shocks of the 1970s and more recently by greater environmental awareness. However, on average, the total energy consumption within the industrial sector has risen due to growth in production – which is expected, given the combination of population growth and an ever-increasing demand for products to improve the quality of life.

There have been periods of reduction in energy consumption, especially during periods of sharp rise in crude oil price both in the past (particularly the early 1970s and 1980s) and in the present, but overall the trend will be upwards until fundamental self-limiting mechanisms prevail.

The challenge to reduce industrial energy consumption will be translated by industry into the problem of reducing the total cost of energy used. This is a more appropriate restatement of the problem, assuming that the prices set by the marketplace properly reflect the value of each form of energy. The cost of energy use, for example, may be reduced by energy conservation, using a lower-cost fuel source or by using energy during off-peak times when the cost is lower.

New Technology for Improving Energy Efficiency
A lot has changed in recent years with regard to technology that can bring about significant reductions in the cost of energy required for manufacturing. New software exists to better design, operate and manage industrial processes. New methodologies exist for modeling, simulation and conceptual design. We have an improved ability for online monitoring, operation and management of these complex systems and for real-time decision making and execution. And, of course, the Internet dramatically improves our ability to communicate.

Processes are now better understood, technologies have advanced in many sectors and the precision of design and operation has been taken to new levels. However, industry is complex, and there are many challenges to promote the uptake and implementation of these new technologies and practices.

In most industrial sectors, the spread of energy intensity from the best operator to the worst varies by at least a factor of two, sometimes more. There are many reasons for this, including risk aversion, capital availability, scale, established technology and management practices, and local economics. However, as a general strategy, we should find ways to improve the performance of the best operators and then get the less-efficient operators to adopt the best practices of the leaders.

Improving the Energy Efficiency of Manufacturing
The energy efficiency of a process manufacturing facility can be impacted at three stages in its life cycle.

- **Initial Design.** The initial design of the plant strongly influences the energy required for operation. Because there is a trade-off between the initial capital investment and the operating costs, engineering and smart design play an important role to improve the energy efficiency of a new plant.

- **Process Operation.** Once the plant is built, many decisions are made every day during the operation of the process that have an impact on energy consumption and the variable cost of production. The computer systems used for process control and production management can have a substantial impact on energy efficiency.

- **Plant Retrofitting.** No production facility is static; for example, most are regularly modified to de-bottleneck the process for increased throughput. Also, changes in plant equipment are made throughout the life of the plant to adapt to changing circumstances and to...
improve process performance. Each of these revamps provides an opportunity to retrofit the plant with new, more energy efficient technology.

We will give some specific examples in each of these areas.

Initial Design. Almost all process-manufacturing facilities share some common features. Typically, a utility system consumes fuel to provide steam and power to a manufacturing process (see Figure 6). These utilities may themselves be used to provide further utilities, such as hot oil or refrigeration. The process is often comprised of a reaction section to convert feeds, followed by a separation section enabling recovery of valuable products. It is this section of the process that generally consumes energy (although some are net producers of energy).

Careful selection of available technology, intelligent process design and effective integration of the process and utility systems are all areas that can contribute to minimizing energy consumption. However, the trade-off is one of capital investment versus performance; and while return on capital for manufacturing facilities is generally viewed over a 10-15 year period, capital investments for energy conservation alone are often expected to create a return in a much shorter period. Surprisingly, industry generally looks at the simple payback on incremental energy-related investments over a two- to three-year time frame. This is blatantly short term, especially when compared with government initiatives that provide grants for domestic energy conservation, which typically have a five- to ten-year payback.

However, it is possible to create manufacturing facilities that combine optimized process design with improved energy efficiency, as long as design decisions are taken with a thorough understanding of all the issues. For example, AspenTech and BP are currently engaged in the design of a next-generation olefin plant separation system in a project that is partly funded by the U.S. Department of Energy Office of Industrial Technology. The olefin manufacturing process is very mature, producing over 100 million tons of ethylene annually worldwide, and consuming 2.5 quadrillion ($10^{15}$) Btu of energy per annum. The new design is planned to reduce energy consumption by 15 percent compared to the best available technology, and be at least capital neutral. If this reduction could be achieved across the whole of the ethylene industry, the energy saving would be substantial.

This challenging project has made extensive use of integrated process engineering. Using the latest smart software technologies, it has been possible to adopt a new design approach that combines process synthesis, process simulation, economic analysis and engineering design to thoroughly investigate, evolve and compare different concepts and designs.

Detailed and rigorous computer-based process simulation provides a platform for the design and improvement of most industrial processes. The physical understanding and representation of process operations using process flowsheet simulation (see Figure 7) has long been a vital tool for chemical engineers. Over time, these process simulators have become more capable of representing the behavior of solids, liquids and vapor fluids and can also better represent unit operations, such as the reaction and separation steps that are the fundamental building blocks of many processes. With continued improvement in simulation technology, large and complex steady-state simulations are now commonplace, enabling many design optimization and trade-off issues to be investigated. Additionally, dynamic simulation can be used to improve the process design and its regulation and control, as well as to provide training for process operators.

Improvements in the integration of engineering design and costing tools with the process simulator enable more comprehensive and rapid assimilation of equipment performance and capital cost trade-offs. Energy intensity
can always be reduced by investment in more hardware – to improve heat recovery or to reduce separation costs, for example – but the penalty is often a higher investment cost. This economic juggling between process performance improvement and capital cost is prevalent throughout industry, but can now be better handled by integrated software tools.

**With continued improvement in simulation technology, large and complex steady-state simulations are now commonplace.**

If simulation provides a platform for design, then computer-based conceptual design tools and methodologies (such as process synthesis) enable the development of design insights that can lead to fundamental design and efficiency improvements. Fundamental process analysis techniques exist to identify the optimality of heat and mass exchange network design. Heat recovery within a process – from hotter streams that need to be cooled to colder streams that need to be heated – can be optimally determined using Pinch analysis (see Figure 8). The design of the utility system (which can be above or below ambient temperature), the selection of optimum utility temperature levels and optimal integration with the process all are key to minimizing the energy intensity of the final design. AspenTech has been instrumental in applying these concepts to industry through its engineering services.

In the area of separation, distillation is a key unit operation that can be responsible for the greater part of the energy consumption of a process. The optimal selection of separation sequence, operating conditions for each separation step, thermal design and thermal integration with the remaining process and utility systems are design challenges. Add the difficulty and additional constraints posed by azeotropic separation systems, and the design issues are considerable. It is a combination of technology know-how embedded in software and the experience and knowledge of design and process engineers that enables optimal, energy-efficiency designs.

Process Operation. Today’s complex industrial processes present many operational challenges that need to be overcome. The optimal operating point for a process is at the intersection of multiple constraints. This complexity of running simultaneously at multiple constraints presents challenges to an operations team. Even simple processes can be operated inefficiently, because it is easier to run the process in a “comfort zone” at some distance from the constraints. Modern advanced process control (multi-variable model predictive control) and real-time optimization technologies can hold processes at multiple constraints and perform thousands of trade-offs every day to give maximum production for minimum cost. More throughput, greater yield and better selectivity achieved with a 1-3 percent lower specific energy consumption are typical.

Advisory tools, such as utility system optimizers, can assess current and future energy requirements from the process users; with knowledge of utility availability and price contracts, equipment performance efficiency and capability, they can also optimize the complete site energy requirements. Integrated management of factory-wide utilities has been proven to save 2-5 percent of site energy cost. Some of the saving is due to smart contract management – consuming the same amount of energy for less cost – and some comes from reduced energy consumption from optimal use of the assets.

Today, utilities are among the top operating expenses for manufacturers in the chemicals industry, reflecting elevated energy prices and the fact that chemical manufacturers are using an average of 10 to 30 percent more energy than necessary. A major European chemical manufacturer, DSM, implemented a utility system management solution on a large and complex site where there is a strong interaction between gas purchases, power trading and asset optimization.

The business challenges included:

- Increasing volatility of demand from processes, which created a need for more flexibility in energy consumption.
- Energy market deregulation, which increased the number of organizations providing energy, allowing more leverage in electricity and gas supply contracts,
as well as greater flexibility in the selection of fuel and equipment.

- Stricter energy consumption limitations, which could lead to financial penalties if the contracted amount of energy is exceeded.
- The need for continuous monitoring and improvement of operations, so that optimum decisions could be taken to allocate steam and power generation across the available utility system equipment, resulting in minimum utilities consumption for the site as a whole.

In the first year, DSM achieved millions of dollars of savings through the utilities optimization of its 55 plants, with recurring annual benefits. They now have an improved understanding of their processes, which is helping them make better decisions at the business level.

To further underscore the effectiveness of this approach, one of the top U.S. refiners, Valero Energy Corporation, has recently carried out an energy and productivity assessment, which includes the development of a refinery energy optimization and management system by AspenTech. Potential cost saving benefit is estimated at up to $27 million per annum at 12 refineries.

Aspen Utilities is an example of a utility system management tool. It provides operations decision support by combining online rigorous process simulation with case comparison and optimization technologies to investigate the solution space and trajectory for performance improvement. The basis for this advice is fully exposed, so process operators can understand the reasons behind recommendations for process improvement.

Another example of an operations decision support tool, providing a different process operation solution, has been provided for an ethylene plant. Here, a rigorous plant model enabled optimization of feed conversion and provided advice on how to overcome equipment capacity constraints. The result was improved energy efficiency and a benefit of $6 million per annum due to an increase in product yield. Moreover, the simulation model was built to be usable by process operations staff on a daily basis for operations support, thus providing valuable insight into the understanding of process and equipment performance.

Process Retrofitting. Development and selection of better process technology can lead to more efficient processes with lower energy consumption. However, once a plant has been built, the opportunity for uptake of new technology is infrequent. In our experience, process retrofits provide the best chance to introduce a smart design approach that can significantly influence capital investment decisions, and enable energy-saving initiatives to be considered as an integral part of the retrofit process.

For example, a leading Asian chemical company was conducting a retrofit within a large aromatics plant. As part of this process, an energy improvement study was performed that considered the energy needs of the aromatics complex as a whole, and not just the individual units. This study showed that by incorporating process design changes to the separation system, significant operating cost benefits could be achieved. The result was a 20 percent reduction in the overall energy required by the plant complex.

A further example illustrates how integrating process simulation, process synthesis and economic analysis can provide much better investment decisions in a retrofit situation. In this case, the business driver was to achieve lower capital expenditure. Using an integrated analysis design approach, the client reduced incremental investment cost by 32 percent compared to an existing solution, with 4 percent more capacity than thought possible and a 2 percent specific energy reduction. The approach used was to develop a detailed predictive model of the process and utility system, including all major equipment constraints. Conceptual design techniques, such as Pinch analysis, then identified heat integration opportunities and exposed potentially beneficial process design changes. This type of analysis can help identify and diagnose reasons for energy inefficiency in a process and set optimal consumption targets for each utility type. Having determined the necessary process design changes to approach these energy targets, smart engineering techniques can be applied to identify capital cost, capacity and energy trade-offs and to determine the economic optimum solution. Often, the optimum solution requires process design changes to be considered simultaneously with heat integration and capacity issues.

The smart engineering approach can also generate a range of options in a process revamp (see Figure 10), where a clear understanding of the investment cost breakpoints is obtained. In terms of capital cost per unit
of extra production, not all new production has the same incremental cost. Minor upgrade modifications to equipment may be sufficient to provide a certain capacity increase, but a greater increase will require expensive new equipment or a different technology. An insight into these major investment breakpoints can assist greatly in the selection of the most favorable process capacity increase and can make economically marginal projects more favorable. This could enable inclusion of energy conservation process improvements that were previously unjustifiable.

**Saving energy in manufacturing needs to become a key part of the global strategy to reduce our dependence on fossil energy. Fortunately, the technology exists today to make processes more efficient.**

Dr. Lawrence B. Evans, the principal founder of Aspen Technology, Inc., serves as chairman of the board of directors, and was also CEO until October 2002. Under his leadership, the company has grown from eight founding employees in 1981 to approximately 1,700 today. A public company since 1994, it is a leader in providing software and solutions that enable process manufacturers to increase the efficiency and profitability of their manufacturing and supply chain operations.

Dr. Evans was professor of chemical engineering at the Massachusetts Institute of Technology from 1962 to 1990, where he was the principal investigator of the ASPEN Project that developed the original software which led to the formation of AspenTech. (ASPEN is an acronym for Advanced System for Process Engineering.) His research at MIT led to pioneering new approaches to the simulation and optimization of complex chemical processes. In addition to his academic experience, Dr. Evans served as a consultant to more than 25 companies.

Well known for his work in computer-aided process design and process control, Dr. Evans was one of the founders of CACHE (Computer Aids for Chemical Engineering Education), a not-for-profit organization devoted to spreading the use of computers in chemical engineering education. He served as executive officer of CACHE from 1974 to 1980. He was a director of the American Institute of Chemical Engineers (AIChE) from 1981 to 1983.

Dr. Evans has received numerous awards. In 1982 he received the Computing and Systems Technology (CAST) Award from the AIChE. In 1997 he was named Entrepreneur of the Year for high technology in the New England Region. In 1999 he was named by Fortune as one of the Heroes in Manufacturing; he received the Award in Chemical Engineering Practice from the AIChE, and the Alumni Achievement Award from the University of Michigan. In 2001 he was elected to the National Academy of Engineering and cited for “leadership in the development and application of integrated systems for modeling, simulation and optimization of industrial chemical processes.” In 2002 Dr. Evans received the Award for Personal Achievement in Chemical Engineering from Chemical Engineering magazine.

He holds a bachelor’s degree in chemical engineering from the University of Oklahoma, and a master’s degree and Ph.D. in chemical engineering from the University of Michigan.