Emerging Industrial Innovations to Create New Energy Efficient Technologies

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ABSTRACT

A significant part of the discussion surrounding industrial efficiency gains focuses on industry's own use of technologies. Often overlooked in the discussion is industry's role as a developer of the technologies used both by industry and all other sectors within the economy. For example, industry may perhaps adopt new technologies or processes which provide cost-effective energy bill savings. At the same time, however, its role as a technology innovator — whether developing a new generation of fuel cell vehicles, "on-demand" manufacturing capabilities, or new plastics that double as integrated photovoltaic systems — may play an even larger role in the more productive use of our energy resources. This paper explores recent work on industrial innovation, often involving public-private partnerships, and provides a context to understand the role of innovation. It highlights a number of emerging technologies that may foster an even greater energy savings than might be apparent from looking at industry's own energy use patterns alone.

Introduction

If analysts think at all about energy use within industry, they are likely to focus on the magnitude of energy needed to power industrial processes and equipment. And the amount is huge, requiring about 33 quadrillion Btus of total primary energy on an annual basis which is about one-third of the nation's total energy requirements. What America's industries use in energy is more than Japan uses to power its entire economy. The forward looking analyst might also think in terms of how industry could become more energy efficient. Indeed, the industrial sector has already made significant improvements in recent years with its overall energy intensity declining at a more rapid rate than the economy as a whole. Over the period 1970 through 2002, for example, the decline in industrial energy intensity dropped by about 2.6 percent annually while it declined only 1.9 percent annually for the economy as a whole. But industry has another and perhaps bigger dimension that is typically ignored when we consider the demand for energy — and that is industry as the innovator of technologies which will greatly shape this nation's energy use for decades to come. This is true whether we are thinking in terms of the production of cars, the installation of combined heat and power systems, or the manufacturing of consumer electronics. This paper explores a number of different aspects of industry as technology innovator, a process that often requires and involves significant public-private partnerships. In that regard, it highlights possible implications and opportunities for this nation's energy future.

If that same policy analyst were to pick up almost any business or trade magazine, there will undoubtedly be any number of stories or news summaries about some form of innovation. Directly and indirectly, each of those innovations will impact energy use, some more than others. Whether it's Boeing creating instant manufacturing capabilities using redesigned inkjet printers to deposit and fuse powdered ceramics and other materials into a new consumer device, or

Konarka developing light emitting polymers that can generate both light and electricity from thin plastic sheets, industry as innovator may have a huge impact on national or even worldwide energy demand compared to industry as user of that same energy (see, for example, Zachary et al. 2004).

In this paper we will briefly explore some of the opportunities for improving the economic use of energy, and then describe a broad family of technologies with working estimates of reducing near term energy consumer through all sectors of the U.S. economy. Finally, we will conclude with conditions that will foster greater opportunities to capture these efficiency improvements in ways that might also benefit both the economy and the environment.

Background

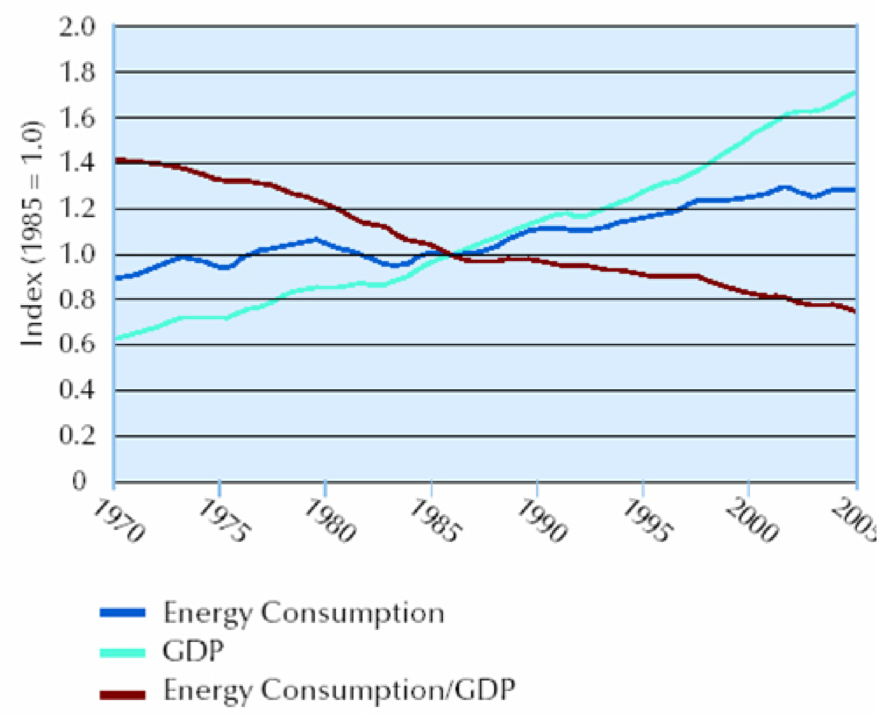
The U.S. and the world face enormous energy challenges. Recent trends in world oil markets, including the emergence of China as a major contributor to global demand and continuing instability in the Middle East, bring new urgency to perennial concerns about oil dependence. At the same time, sustained price increases and extreme volatility in natural gas markets are prompting new concerns about this environmentally valuable fuel. Climate change and air pollution resulting from fossil fuel combustion are threatening human health and the future of our ecosystems. Finally, in the wake of the largest cascading power outage in North America's history, urgent questions are being raised about the prospects for needed investment in an infrastructure that is essential to nearly every facet of modern life. Using energy more efficiently can help to address each of these concerns.

Energy efficiency is particularly valuable as a "front-line" strategy because it offers a "no regrets" approach. By this we mean that investments in energy-efficiency technologies can save consumers and businesses money while reducing pollution and greenhouse gas (GHG) emissions, and stretching our energy resources. Energy efficiency has already played a significant role in our nation's economy. Before the 1970s, U.S. energy growth grew in lock step with the nation's GDP. If we had continued along that trend, U.S. energy demand would be almost twice what it is today (Brown 2005). Thirty years following the Arab oil embargo, the U.S. has significantly reduced the energy intensity of its economy. This change has resulted from a combination of energy efficiency investments and structural shifts in the economy away from energy-intensive manufacturing and toward a service and information-based economy.

Despite these significant historical improvements in the nation's energy intensity, more must be done. For example, if current conditions and economic trends continue, U.S. energy consumption is projected to grow 1.5% annually. At this rate, energy use will increase ~40 percent by 2025 and jump to more than a four-fold increase by 2100. At the same time, U.S. energy production is not projected to keep up with this rate of growth in the demand for energy; as a result, energy imports are expected to bridge the gap. On the other hand, if the nation could cut in half the growth rate of its energy consumption, energy use would increase ~16 percent by 2025, and only a two-fold increase by 2100.

History has shown that energy efficiency can play a large role in curbing the nation's appetite for energy. As the figure suggests on the following page, the size of our nation's economy nearly tripled in the period 1970-2005. Energy intensity, on the other hand, was cut roughly in half over that same period. Thus, energy efficiency played an important role in limiting the growth of energy use to about half of GDP growth.

Figure 1. U.S. Energy Trends 1970-2005



Source**:** National Commission on Energy Policy 2004

Despite the significant contributions from past efficiency gains, there is a tendency in economic models and conventional policy analyses to assume that energy efficiency can make only a limited — and "not always cost-effective" — contribution to our nation's energy future. The operative assumption is that we've pushed the efficiency frontier as far and as fast as it can reasonably go. The good news, however, is that the evidence points to the possibility of substantially greater gains in energy efficiency — especially when one explores the role of industry as innovator and champion of new and more productive technologies. Hence, the assumption that there are near-term "practical limits" to further gains in energy efficiency is not defensible (Laitner 2004; Laitner 2005a).

At the same time, other analysts demonstrate that improvements in energy services may be the critical factor in the growth of an economy, perhaps one of the primary drivers that underpin "technological progress" (Ayres and Warr 2005). From a longer term perspective, if sustainable economic activity is to continue — but without proportional increases in emissions and waste, it is essential to reduce energy use per unit of work or dollar of economic activity. In other words, increased energy efficiency may be the key to long-term sustainable development; and, one might add, the key to long-term global development and security.

In effect, energy efficiency improvements do not have to be about ratcheting down the economy. Instead, they can be all about providing new services, making new products, and providing new ways to both work and play (Hanson et al. 2004).

A Different Perspective on Old and New Technologies

In looking to the future, it is clear that new materials and technologies on the horizon can take us further than we might imagine. Today, materials research and development (R&D) is moving to the nanoscale (1 to 100 nanometers), at which the fundamental properties of materials and systems are established (melting temperature, magnetism, and even color) and can be manipulated. The realm of molecular biology also now operates largely at the nanoscale. This scale of research provides greater understanding of "how things work" and the ability to tailor properties to produce new functionalities. And sometimes innovations emerge simply by giving ourselves a moment to think differently about both old and new technologies. This different take can decidedly shape an entirely new perspective which might emerge. To highlight this part of the innovation process, we provide brief glimpses into three intriguing technologies – each with a distinct role and impact.

Light Emitting Polymers as a Convergent Technology

If technology is explicitly represented in economic forecasts and policy models at all, it tends to reflect only discrete structures and isolated energy systems; for example, a model might recognize a separate photovoltaic (PV) system which is then mounted on a separate building rooftop. But, what if we add a new twist to the concept of Building Integrated PV systems (BIPV) — one that relies on light emitting polymers and other complementary materials that are integrated into a single structural composite? In such a case we can then imagine individual structural components that converge to do the work of five separate systems, providing: (i) structural support, (ii) thermal comfort, (iii) lighting needs, (iv) power generation; and (v) information flow and processing capabilities. In this example: efficiency improvements can be perhaps two or three times as large as conventional energy models might otherwise reflect, and conventional concepts like energy intensity may no longer have the same relevance as today's familiar set of metrics. The reason? It would be difficult to decide just how the energy consumption might be allocated to each of the five services delivered as part of the building activity.

Emergence of Instant Manufacturing

While clearly not your typical Star Trek "replicator," ink jet printers may provide the backbone for an entirely new generation of instant manufacturing technologies (Amato 2003), producing everything from hearing aids, shoes, and cell phone covers to replacement bones and body tissue, and even large-scale buildings. What's the technique? Selective laser sintering of materials deposited by dozens or hundreds of micro-nozzles according to a pattern embodied within a 3-D print file (Khoshnevisk 2004). Such processes may be more energy-efficient and use a greater array of basic materials; they also benefit from negligible economies of scale — which means they can rely more on local resources and be located closer to local production needs. The implications for both direct and transportation energy use may be significant — and positively beneficial.

The Intriguing Possibility of CO_2 Fuel Cells

Under the existing paradigm, carbon dioxide (CO_2) is viewed only as a problem; but from perhaps a different perspective it becomes a useful energy resource. How? The continuous oxidation of scrap iron in the presence of a constant CO_2-rich gas stream and water can be a means to sequester CO_2 as well as generate hydrogen gas and electricity. Imagine the possibilities of using Fe/CO_2 fuel cells for both CO_2 mitigation and energy production — at a net profit rather than a net cost of $30/t$CO_2$ (Rau 2004). While this specific technology is far from being commercially ready, it underscores the point that looking at things differently might provide an entirely different and more beneficial outcome.

Other Emerging Technology Trends

These and the other potential innovations are likely to be reinforced by a series of complementary trends. For example, the movement away from commodity-based ownership to service-based leasing may encourage a whole new set of opportunities that promote efficiency. As but one example, Ray Anderson's Interface America leases carpets to customers which can be periodically recycled and reused – at no increased bother or disruption to the customer. This kind of service innovation combines very nicely with product innovation to reduce waste and energy needs (Vorobej 2001; and HARC 2001). At the same time, there are increased linkages between waste minimization and product maximization (Bailey and Worrell 2004). New industrial technologies, for example, can reconfigure pollution control technologies to deliver combined heat and power services as a byproduct (Sexton and Laitner 2005). Moreover, the continued opportunities for decentralized generation, showing net economic and environmental benefits including the possibility of a more secure electric grid, further accelerate the opportunities for innovation (Casten and Downes 2005). Finally, and perhaps a critical part of the innovation process, increased environmental awareness growing international concerns about energy security — all enabled by the availability of new services and technologies, are likely to facilitate changes in consumer and business preferences. This is one of the reasons for the success of the ENERGY STAR® programs, for example. As momentum shifts toward increased environmental concerns, the demand for even more innovation is likely to emerge.

An ORNL Survey of Emerging Technologies

Exploring issues that underpin what he calls "catalytic leadership," industry consultant Jeffrey Luke, notes that individuals have "a natural tendency to choose from *an impoverished option bag* (emphasis in the original). Cognitive research in problem solving shows that individuals usually generate only about 30 percent of the total number of potential options on simple problems, and that, on average, individuals miss about 70 to 80 percent of the potential high-quality alternatives" (Luke 1998). To see how big our "option bag" might be in the near term, the Oak Ridge National Laboratory (ORNL) conducted a review of what might be called "nano-info-bio discoveries" within industry that could lead to a next generation of highly efficient technologies. Several of these are described below, and where possible, estimates of possible future gains in energy efficiency are provided (Brown 2005).

Super-Strong Lightweight Materials

New classes of bulk materials can retain nanograin size structures and display enhanced or new properties at the macroscale, including enhanced mechanical strength, which is critical to enabling lightweight materials to provide stronger components for transportation. Other applications include advanced nanostructured magnetic materials for motors and transformers that result in lighter and smaller parts that can lead to energy savings. For example, nano structures can significantly improve the strength of magnesium alloys, and the incorporation of dispersed nanosized particles has the potential to dramatically increase the strength of carbon fiber polymer matrix composites (National Nanotechnology Initiative 2004).

Such advances offer the potential for mass reductions of more than 50 percent with respect to conventional steel (USCAR 2004). A 50 percent weight reduction in the light duty fleet would have saved 3.3 million barrels of oil per day in 2002.

Energy-Efficient Distillation Through Supercomputing

Advanced modeling and simulation of complex industrial processes can lead to significantly improved designs and operations. For example, modeling of counterflows through structured packings can improve packing geometries for more efficient hydrodynamics in distillation columns within the chemical industry and elsewhere. Empirically characterizing the hydrodynamics of a single 10-cm packing element requires a high-end supercomputing cluster capability. Terascale computers will enable integrated hydrodynamic calculations for an entire distillation column, which can be tens of meters in height.

The potential for saving energy from improved hydrodynamics in distillation columns is large. Distillation accounts for approximately 3 quads of energy usage annually, about half in petroleum refineries. It has been estimated that 10 to 20 percent reductions are possible with improved geometries of packing elements. Distillation columns are usually run at lower-than optimum throughputs to provide margins against the onset of column flooding – a phenomenon that cannot be reliably predicted in industrial distillation systems. Improved flow modeling might eventually allow better understanding and prediction capability of column flooding – further increasing throughput and energy efficiency (de Almeida 2004). Comparable savings are possible through steam system engineering such as introducing feed pre-heating and recuperators to enable the beneficial use of waste heat.

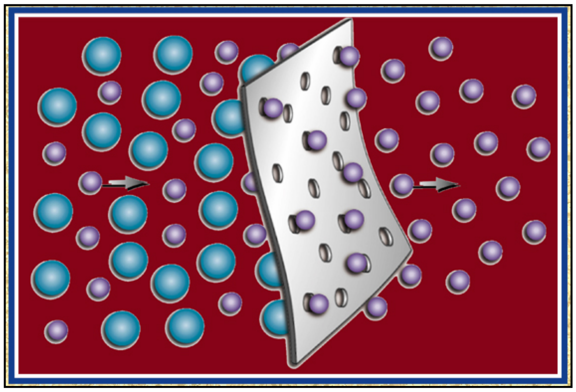
Novel Energy-Efficient Membrane Separations

Nanoporous materials allow selective, molecular-scale separations at very high throughput. Further advancements could derive from improved understanding of transport mechanisms at the nanoscale and from advances in nanomanufacturing to fabricate media with engineered pore sizes and desired functionality. The potential opportunities and annual energy savings are significant.

It is estimated that U.S. industry today consumes approximately 6 quads of energy to perform various separation processes (National Nanotechnology Initiative 2004). Replacing high-energy usage separation methods by less energy-intensive methods – such as membrane separation or adsorption – would result in substantial future energy savings in the following industries: chemicals: ~0.32 quads; wastewater: ~0.23 quads; food and beverages: ~0.17 quads;

black liquor concentration: ~0.11 quads; and petroleum hydrogen recovery from mixed gases: ~0.01 quads. Other opportunities for energy-efficient membrane separations are in mining, textile industries, metals industries, hydrogen recovery from mixed gas streams, thermochemical cycles for hydrogen production, desalination, and in solid oxide fuel cells (BCS, Inc. and Oak Ridge National Laboratory 2004; Worrell, Price, and Galitsky 2004).

Figure 2. Molecular Sieve Membrane for Separating Gas Molecules



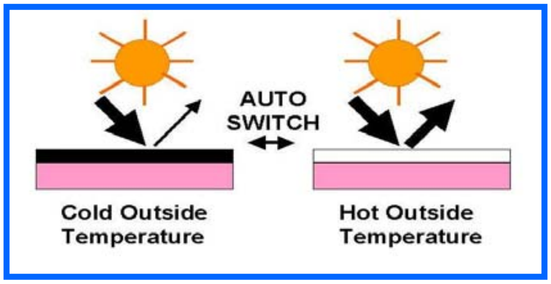
Source: Judkins 2001

Smart Roofs

Nanotechnologies can change the reflectance of roof materials as a function of temperature. The key is to combine sub-wavelength optical structures and temperature-sensitive polymers to provide high reflectance to IR solar radiation in summer and low reflectance in winter. The design of these nanomaterials could mimic the structure of a moth's eye, which contains small cone-shaped periodic structures that provide an efficient anti-reflection "coating." To develop these technologies for "smart roofs," additional research is needed to provide robust, cost-effective large area surfaces with nanoscale structures.

Smart roofs could reduce the energy requirements of buildings significantly. Hadley et al. (2004) estimate that low-slope roofs with a reflectivity of 85 percent above 65ºF and 5 percent below 65ºF could save 1.2 quads annually in the U.S. by the year 2025. This estimate of energy savings assumes that 25 percent of residential energy is lost through the roof, and smart roofs reduce this by 50 percent. For commercial buildings, the parallel assumptions are that 15 percent of commercial energy is lost through the roof, and smart roofs reduce this by 25 percent.

Figure 3. Moth Eye Nanostructure Alters Reflectance As a Function of Temperature

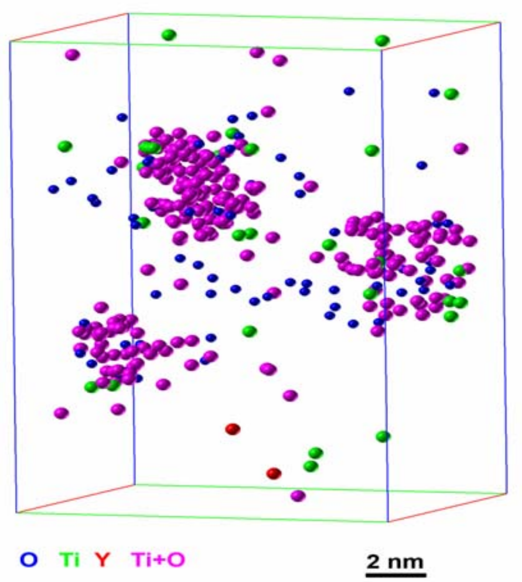


Super-Durable Materials for Aggressive Environments

Building at the molecular level as shown in Figure 4, nanostructures and phases can produce materials with new and enhanced properties at the macroscale. Such breakthroughs include stronger and more degradation-resistant materials for industrial processes that involve aggressive environments such as high temperatures, corrosive chemicals, and radiation. In addition to saving energy by allowing higher temperature processing, these materials result in less downtime, greater product throughput, and less material waste (e.g., corroded trays).

Many of these nano-engineered alloys are already saving energy (U.S. Department of Energy 2005). With full-scale market penetration the potential energy-savings are large. Alloys for rolls, trays, fixtures in steel, heat treating industries can produce savings on the order of 5–20 percent over current technology. New high-temperature, crack-resistant alloys for boiler tubes might generate another 5 to 10 percent savings. For purposes of scale, a 10 percent impact on industrial boilers, chemical reaction vessels, and furnaces can lead to a total U.S. energy savings of ~1 quad.

Figure 4. Nano Structures of ~5 nm in Iron-Based Alloy Enable 150° C Higher Temperature



Molecular-Level Control of Catalytic Materials

Catalysis – involving molecular-scale structures that drive chemical conversions – may be the most successful and broadly applied nanotechnology. It is the selectivity of catalytic materials that will be important to saving energy, so that “energy is invested” only in the impurity chemical to be removed rather than in the bulk chemical material itself (ORNL Review 2002). Continued scientific and technological developments are needed in the areas of characterization tools, theory, computational models of the governing catalytic reactions, and synthesis techniques (Stringer and Hortin 2003).

With the right support and policy signals, these can lead to unprecedented tailoring of catalysts and large increases in activity and selectivity, including increased efficiency of existing catalytic processes (0.09 - 0.23 quads of annual energy savings), less waste from byproduct formation, and reduced use of precious metal catalysts (Tonkovich and Gerber 1995). Moreover, catalysts for highly selective conversions will enable entirely new processes that we have not been able to quantity at this point.

Self-Optimizing Sensor Systems

Micro-sensors, using ultra-low power electronics that flow through industrial process or become part of the product could transform industrial plant operations. Such systems, with wireless telemetry to enable adaptive, flexible control, and optimization, are already being used in a growing number of production activities. A recent example is the successful development and use of a laser-generated ultrasound sensor system that produces on-line measurements of the thickness of hot seamless steel tubing and enables real-time process optimization (U.S. Department of Energy 2001). Anticipatory prognostics will enable even greater improvements in the continuous optimization of industrial plant goals, ranging from added efficiency gains and increased yield to greater dollar savings and reduced emissions.

Such self-optimizing sensor systems could reduce energy use in small motors by ~0.3 quads and industrial buildings energy management systems by ~0.75 quads. Further industrial energy systems might include savings in petroleum refining of ~0.1 quad; chemicals ~0.13 quad; forest products ~0.15 quad; food & beverage ~0.05 quad; and general manufacturing ~0.65 quad (Energetics, Inc. 2004).

Solid State Lighting

Solid state lighting has the potential to revolutionize the lighting market. It uses the emissions of semiconductor diodes to directly produce light and by concentrating these emissions in the visible spectrum, little energy is wasted. In solid state lighting, electrons and holes are injected into a solid state semiconductor material. These recombine and light is emitted at around the wavelength corresponding to the energy bandgap of the material. Once the light is created internally, a high fraction of it must reach the surface and escape rather than be absorbed; this is done either through the shape of the light emitting diode (LED) or the type of material used. Relative to the two conventional lighting alternatives (incandescent lamps where a wire is resistance heated and fluorescent lamps where a gas is excited), the two main categories of solid state lighting (LEDs and organic LEDs) are much more energy efficient (Hadley et al. 2004).

A key difficulty that LED lighting faces is that it is inherently monochromatic. Several methods are being researched to produce white light. Given this flexibility, solid state lighting has the potential to replace incandescent and fluorescent lighting in a broad variety of end-uses, saving perhaps ~3.5 quads per year in 2025 (Navigant 2003).

Superconducting Electric Transmission and Distribution

High-temperature superconductors have demonstrated significant enhancement to the capacity of transmission cables. They have been shown to offer 3 to 5 times the capacity of conventional conductors located in the same sized ducts under city streets. They also offer improved siting options for utilities (i.e., no “soil thermal limits”). The opportunity for saving energy by reducing electricity line losses is significant. Currently, line losses in the U.S. average

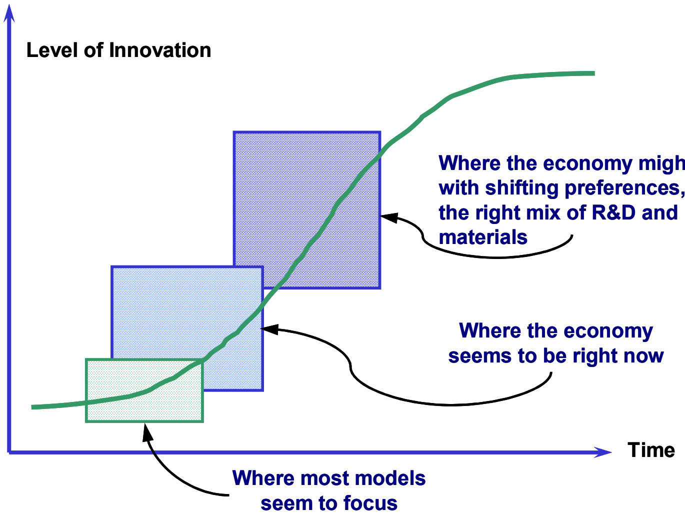
7 to 8 percent. These losses could be reduced by approximately 20 percent, even accounting for the energy requirements of cryogenic cooling.

According to Mulholland, Sheahen, and McConnell (2003), increased efficiency of superconducting motors, transformers, generators, and transmission lines could produce energy savings of 10,000 gigawatt-hours (GWh) in 2025. High-temperature superconductors can also enable fault-current limiting (to protect substation switchgear from ultra-high faults), more efficient energy storage, power quality enhancement, more efficient magnetic separation of waste water streams and kaolin clay (used in papermaking), and oil-free, efficient power transformers.

Extending the Efficiency Boundaries

From a purely innovation and technology perspective, the evidence seems to support the availability of significantly greater opportunities for energy efficiency improvements than is generally acknowledged. Indeed, as Figure 5 indicates, the evidence also appears to suggest a stronger near-term opportunity for the market penetration of new innovations than many of the current energy policy models might otherwise suggest. The question might then be posed, what is the right mix of policy signals and public-private partnerships that will stimulate a greater and presumably more cost-effective level of industrial innovation?

Figure 5. Standard Forecasts and the Technology Gains from Efficiency and Structural Improvements



In talking with a large number of business and industry leaders, three key themes emerge: (i) there is a strong need to market energy efficiency in more concrete terms so that the opportunity seems more real and more compelling; (ii) the market needs a clear and persistent policy signal that will direct the creative resources toward greater efficiency innovations; and (iii) there is a need to encourage appropriate but flexible efficiency standards on the one hand, but to also provide greater support for research and development on the other. We will briefly expand on these ideas one at a time.

Since the 1980s the attention of many innovators has been directed away from energy towards many other areas of research and innovation. Moreover, the many institutions that shape the market have received mixed signals about what innovations to encourage and how best to bring them forward. In our opinion, two things might help make the efficiency resource seem more compelling and stem the erosion of good thinking about further gains in productive technologies. The first is to help establish an improved understanding of the potential for energy efficiency. When we ask the question, for example, what is the current world record for fuel economy in a research vehicle, even knowledgeable policy analysts and engineers think perhaps 80 to 100 miles per gallon; and occasionally, 120 or 200 miles per gallon.

But the correct answer (at this time) seems to be about 10,000 miles per gallon (Shell Eco-Marathon 2004) — two orders of magnitude greater than our best thinking might allow. While the vehicle is clearly not practical for people to drive in their normal daily patterns, its revolutionary fuel efficiency shows how important it is for people to think more boldly. We have a limited understanding of what it means to be energy-efficient, and that tends to bind our thinking and prevent new opportunities and new technologies from emerging.

Other examples of potential “extreme” efficiency improvements include nanoelectromachines that imitate what protein pumps and motors do in living cells – “convert chemical energy into mechanical work with almost 100 percent efficiency” (Astumian 2001). Another recent article references ultralow power levels of such devices that use “a millionth to a billionth the amount of power used for conventional transistors” (Roukes 2001). This is not to say there aren’t substantial difficulties in developing practical devices that are commercially viable. Rather, it is to point out that, at worst, the practical limits have yet to be defined. As science writer Michael Roukes further notes, “we are only *beginning* to acquire the detailed knowledge” that will be at the heart of future technologies (emphasis in the original). The second critical item necessary to make the resource seem more compelling is to underscore the point that many of these innovations may provide net benefits rather than imposing huge costs (Laitner 2005b). Of course, it is important to note the potential for negative consequences, such as the possibility of air and water pollution from large-scale fabrication of some nanomaterials.

Notwithstanding a more compelling story, a clear and persistent policy signal is also a critical requirement. If the signal, preferably a combination of price and non-price policy drivers (the latter ranging from standards and incentives to information, technical assistance, and voluntary programs), remains in place over a longer period of time and actually strengthens as new technologies increase the capacity of the economy to respond to the new prices or standards, then momentum will undoubtedly shift toward greater levels of innovation. Finally, we believe both the government and industry is now underinvesting in R&D efforts. Jones and Williams (1998) have suggested, for example, that given the kinds of returns anticipated from R&D expenditures, the U.S. could increase overall R&D expenditures by 2 to 4 times. Unfortunately, it appears that R&D in general, and especially energy-efficiency related R&D has diminished since that time — despite the documented success of many of DOE’s energy efficiency research programs (National Research Council 2001).

Conclusions

This paper focuses on opportunities for energy efficiency that far exceed the incremental improvements envisioned in most energy forecasts. At the same time, we recognize that economic barriers and environmental issues may need to be resolved as we seek an appropriate level and mix of energy efficiency technologies and policies. And such opportunities will require a coordinated and persistent policy signal. Yet the level of innovation within industry and its many public and private sector partners is enormous. The potential for significant efficiency improvements over the longer period of time is also large — should we choose to recognize and pursue them.

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