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The U.S. enjoys a high standard of living due, in part, to its research universities. In the 1940s, the federal government realized that scientific progress would garner the nation's prosperity and security. Backed by government support, far-flung ideas gave way to fundamental research and new industries—the semiconductor, computer, software and biomedical—were born. Millions of jobs were created worldwide, a clear indication that economic growth is directly linked to technological innovation.

Innovation Leads to Solutions and Success

Our accomplishments have served the U.S. well, but we can't rest on our laurels. The global marketplace has changed. We are moving from an industrial age, based on natural resources and the production of goods, to an age that will be defined by creativity in areas like biotechnology, nanotechnology and information technology. Transitioning is not easy. In the flux, there are concerns that the U.S. is graduating fewer engineers than China or India. Economic conditions constrain government and industry research investments. Fossil energy, which has underpinned our economy for nearly a hundred years, is not sustainable. The infrastructure that supports our energy-intensive lifestyles, namely, power grids, roads and bridges, needs overhauling to the tune of \$2.2 trillion. To remain prosperous, business as usual won't work. Like we did in the 1940s, the U.S. must revamp itself, and create an economy that's based on innovation. So where does the research university fit into this scenario?

"Our job in the College of Engineering is to position ourselves for the future so that we maintain our competitive edge in education and research," says Pradeep K. Khosla, dean of the College. This past summer, Khosla was appointed to the Council on Competitiveness' Technology Leadership Strategy Initiative. For the next three years, he will work with elite academic

researchers and business leaders to identify the most promising frontiers of technology and competitive advantage for the U.S. and for Carnegie Mellon.

Khosla explains that the symbiotic relationship between academia, government and industry is essential in the pursuit of innovation. While the federal R&D budget is not expected to grow at the rate necessary to meet academia's requests, the government will continue to be the largest supporter of fundamental research. Competition for federal monies remains tight, however, the College has grown adept at identifying research areas that are worthy of large-scale funding, such as energy and security.

Our ability to identify projects that exercise our interdisciplinary strengths is not lost on industry. We attract domestic and international corporate partners for several reasons: first, companies have cut back on in-house research and working with universities saves them money. Second, the College has access to experts in a variety of fields, allowing us to tackle problems from multiple approaches. Through our research centers, the barriers that limit collaboration between industry and academia are minimized, facilitating innovation.

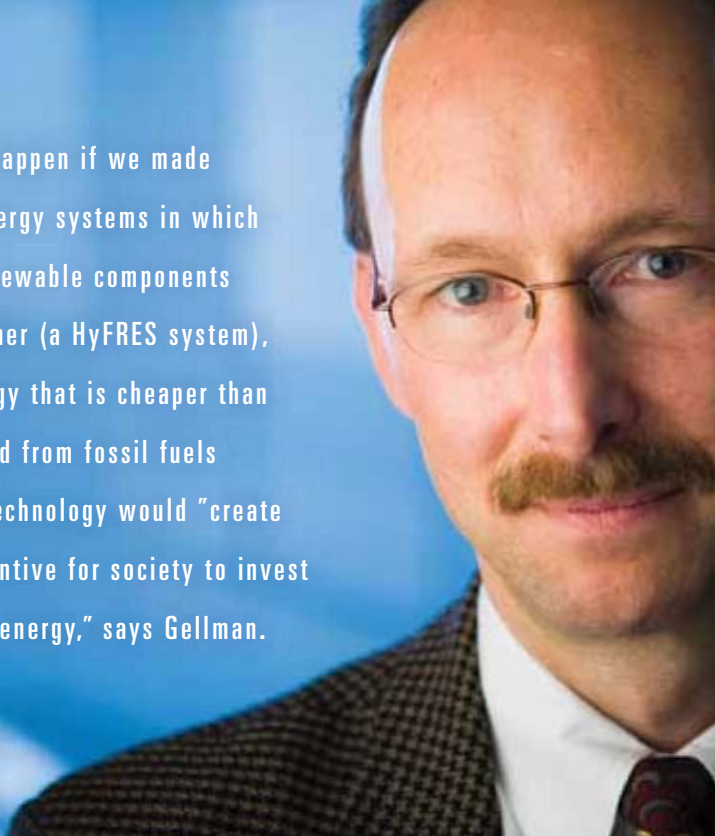
Policy, too, plays an essential role in bringing about innovation. Regulatory issues influence if and how new technologies will

be implemented, industry support of R&D, technology transfer, related tax policies, etc. The College's Department of Engineering and Public Policy has a long and respected record of guiding decision makers on important problems in technology policy and management.

"Within the College, we rely on creativity and pragmatism to maintain our momentum as a leading research institution," says Khosla. By tapping into our resources, both human and technological, the College has the power to develop and implement innovations that will transform the world and retain America's competitive strengths.



What would happen if we made integrated energy systems in which fossil and renewable components worked together (a HyFRES system), creating energy that is cheaper than energy derived from fossil fuels alone? This technology would “create financial incentive for society to invest in renewable energy,” says Gellman.



Andrew Gellman
Head, Chemical Engineering

example, carbon taxes could provide strong incentives for the deployment of carbon-reducing technologies.

It's obvious that a comprehensive approach, one that combines technology, policy and economic drivers, is necessary to bring sustainable energy systems to fruition. Professor John Kitchin, who leads the IAES research efforts in the area of carbon management, shares Gellman's views. Historically, Kitchin says, there hasn't been incentive to invest in carbon capture, but this is changing now that industry anticipates changes in environmental policy. In the private sector, activity is underway to develop technologies that will meet probable regulatory specifications and allow companies to profit through future licensing agreements. This work comes with a hefty price tag and risks. For example, no one knows when carbon laws will be passed or what they will look like. “Will we have to capture 10% in 5 years or 90% in 5 years?” asks Kitchin. Another issue is that no one knows what technologies will prove to be the best and how long they will take to develop.

Kitchin says that researchers in the IAES Carbon Management group are investigating the range of performance that is possible with emerging CO₂ capture technologies. “CO₂ capture is a separation challenge,” he says. In addition to CO₂, the flue gases emitted by power plants contain a number of gases, including large volumes of nitrogen. Power plants produce millions of tons of flue gases daily, and all this cannot economically be pumped underground, so CO₂ must be separated. IAES is looking into three types of separation processes: post-combustion (separating CO₂ from nitrogen), oxy combustion (separating nitrogen from oxygen), and pre-combustion approaches (separating hydrogen and CO₂). By 2020, the Carbon Management group wants to develop systems that achieve 90% CO₂ capture with 99% storage permanence, and at an increase in cost of electricity generation below 35%. How this will affect consumer costs is uncertain. While the price of electricity will increase, more efficient power-consuming devices will change the way we use electricity and reduce consumption.

“If you can't switch to renewables, and you can't massively increase the efficiency of your systems, all you are left with is capturing

The Pursuit of Energy: We're in It for the Long Haul

Achieving a sustainable energy platform, free of fossil fuel, won't happen soon. According to Andy Gellman, head of Chemical Engineering and the director of the National Energy Technology Laboratory – Institute for Advanced Energy Solutions (NETL-IAES), it could take several hundred years to develop efficient, renewable energy sources that don't damage the earth. With the looming threat of climate change and a finite supply of fossil fuel, Gellman believes that now is the time to begin a transition to systems that integrate fossil energy with renewable energy. He refers to these systems as “hybrid fossil renewable energy systems” or HyFRES for short.

Weaning ourselves off of coal and oil will be arduous because of technology barriers, politics, and economics – think of the trillions of dollars invested into our existing energy infrastructure. For now, fossil fuels, especially coal, will remain an important part of our energy portfolio, and this is why IAES is advocating for the intelligent use of fossil energy resources as a stepping-stone in the development of a sustainable energy system. HyFRES research falls under this umbrella, and Gellman says there are strong economic motives for this approach.

On the whole fossil fuel energy is currently cheaper and more reliable than energy obtained from renewable sources. Naturally, this impedes investment into

alternative energy technologies and sources. But the cheap cost of fossil energy today does not include the future costs of climate change. We have to consider what would happen if we made integrated energy systems in which fossil and renewable components worked together synergistically (a HyFRES system), creating energy that is cheaper in the long run than energy derived from fossil fuels alone. This technology would “create financial incentive for society to invest in renewable energy,” says Gellman. Both components of HyFRES systems would add value. The systems would use fossil fuels more efficiently and mitigate the costs of emerging renewable technologies. The renewable component, in turn, would reduce carbon emissions and environmental harm. In the long run, which could be hundreds of years, as renewable energy systems become more robust, reliance on fossil fuel would decrease and then disappear; thus, enabling a smooth societal transition to true sustainability.

HyFRES technologies sound appealing, but Gellman points out, “We have to learn how to design integrated fossil and renewable energy systems. We must then build them and make them work.” And getting industry to promote their development is not easy. While the Department of Energy supports emerging research, more must be done to advance new energy systems. Gellman explains that policy can play an important role in this effort. For

Environmental Innovation: Technology and Policy Go Hand-in-Hand

and sequestering,” says Kitchin. Kitchin says “there isn’t a silver bullet solution,” and each technology contributes different possibilities and challenges. “The market will determine which technologies we end up using. Whoever can develop new cost-effective technologies will win,” he says, adding, “We’ll have to pass laws that require them, too. Being a realist, if there was money in CO₂ capture today, we would be doing it.”

On the other hand, if we don’t start reducing CO₂ emissions now, the consequences of climate change are very likely to be expensive in ways that are difficult to anticipate in the future. The price of doing nothing may be in large changes where food is grown or in weather patterns around the world. If natural resources such as water cross national borders, there may be diplomatic crises or disease and famines that are expensive to resolve. We are facing an expensive change in the way we live and do business in the future. The question is which expensive option will we live with.

David Dzombak
Director, Steinbrenner Institute

“Much of the technological innovation for environmental protection is driven by policy change,” begins David Dzombak, the director of Carnegie Mellon’s Steinbrenner Institute for Environmental Education and Research. “For example, we know that using fossil fuels has many negative effects on the environment and human health, yet fossil fuels are relatively inexpensive. If we don’t account for human health and environmental effects, which for the most part we don’t, it is hard for technological innovation to occur. Without a policy decision to include these external costs in the price of fossil fuels, technological innovation is stymied.”

“In the environmental domain, policy and technology go hand-in-hand, and sometimes policies are developed for the purpose of forcing technological change,” he says. The Clean Air Act, for example, contains provisions to stimulate improved fuel efficiency for automobiles. In a similar way, the Clean Water Act has technology-based water-quality standards for municipal and industrial wastewater dischargers. These provisions have led to the widespread deployment, and improvement through innovation, of wastewater treatment technologies. Technology-forcing policy and regulation has had a big role in the advancement of environmental protection in the United States.

“Something we do very well at Carnegie Mellon is that we look at the interplay between policy and technology development,” says Dzombak. Leading the charge is the College’s Department of Engineering and Public Policy (EPP), which focuses on important problems in technology and policy, and energy and environmental issues are high on their priority list. EPP’s influence permeates throughout the university, including most of the 20 research centers affiliated with the Steinbrenner Institute. In the Center for Atmospheric Particle Studies (CAPS), for example, Dzombak says, “we are looking at the scientific, technological and regulatory aspects of monitoring and characterizing fine air particles. This information is critical to establishment of workable and meaningful national regulations for fine air particles.” These particles have been attributed to tens of thousands of premature deaths in the U.S.

Integrated innovation in environmental science, technology, and policy is clearly important for regulating known pollutants, and such innovation is even more important in regulating emerging chemicals and materials with unknown environmental and health effects. But, how do you regulate the unknown? This question is being explored by investigators in the Center for the Environmental Implications of Nanotechnology (CEINT).



“Much of the technological innovation for environmental protection is driven by policy change.”

"Nanotechnology is evolving very fast," says Dzombak. "We don't want to repeat past mistakes by inventing materials for specific functions and then find out later that they are harmful to human health and the environment." CEINT interdisciplinary research teams are working to develop experimental and analytical tools to evaluate potential environmental effects of nanotechnology products before they are put into widespread use. Science, in this case, is helping to inform regulation that may determine how these materials are developed and used.

A case in point: silver oxide nanoparticles. "Silver can be toxic in different contexts and yet silver oxide nanoparticles are being used, essentially without regulation, as an antimicrobial in fabrics, including in socks," says Dzombak. When socks are laundered, some of the nanoparticles are released into the wash water. The wash water is discharged into a sewer or septic tank, after which the fate of the nanoparticles is unknown. "The mobility properties of these particles make them of concern in the environment. Studying these particles and their release could lead to controls. As policy develops, it will stimulate technological development for controlling nanoparticles in products in both the manufacturing and use phases of the product's life," he says.

Carbon capture and sequestration (CCS) is another area in which regulation influences technology development. In the CCS Regulatory Project researchers and other stakeholders are working together to design and facilitate a U.S. regulatory environment for the capture, transport and deep geologic sequestration of carbon dioxide (CO₂). "How carbon is captured and sequestered will depend on how policy and regulation develop," states Dzombak.

He believes that a primary feature of environmental innovation at Carnegie Mellon is the deep understanding of the tight linkage of environmental technology and policy development. "We all recognize that environmental policy and technology are closely related, and even researchers who work strictly on technology development have an eye toward what their work means with respect to regulation and policy. This helps us choose problems that have the potential for high impact."



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Cybersecurity Can Make Profits Happen

Security measures that are integrated throughout our computing systems have transformed the way we use and disseminate information. Yet, as much as cybersecurity affects our daily lives, it is "not traditionally viewed as a market enabler," says Virgil Gligor, the co-director of Carnegie Mellon CyLab.

The old-school view is that security is "a consumer of resources," begins Gligor. This is founded on the idea that the return on investment is difficult to quantify primarily because it is based on risk assessment, which very few users can perform well – with security, you are trying to prevent what *may* happen. This traditional view is not entirely shared by Gligor and others in CyLab, "We argue that security can have a very positive economic effect."

Gligor offers an analogy. Across from the Carnegie Mellon campus, in Schenley Park, is a statue of George Westinghouse. On the statue is a plaque, crediting Westinghouse for inventing the air brake and revolutionizing the railroad industry. Gligor explains that because of airbrakes, trains were able to run faster, leading to significant gains in commerce. This example can be generalized to explain the positive effects of cybersecurity: Secure web sites gave rise to the proliferation of online shopping, banking and electronic commerce, in general.

"We look for places where security can defend us, of course, but we also look at how security can open new avenues of commerce and bring innovations to market," he says. CyLab's engineers examine security from a broad and comprehensive context. Worldwide, there are institutions that focus on either secure systems design or cyber policy, but CyLab researchers approach both problems in an integrated matter. This is what sets CyLab apart from the others. "Most academics look at the intellectual challenges of designing new security mechanisms. For us, that's not satisfying. We design security mechanisms that address larger policy issues and are usable," says Gligor. With usability in mind, CyLab is exploring how to make home computing systems more secure.

Password-based logins is under CyLab's scrutiny, from both a computer science and psychology perspective. People forget passwords that contain strings of unrelated letters and numbers, and worse, hackers figure them out. Current projects examine the development of memorable but tough-to-crack passwords, password theft via phishing scams, image-based passwords, and cell phones that deliver text messages containing disposable passwords. (See page 12 to read about our new Ph.D. program in usable privacy and security.)



Transforming the Data Storage Industry, Again

Another intrusion is malware—worms, viruses and pesky spyware. “Malware is a fact of life,” says Gligor. “We want to give people the opportunity to partition their computing from other computing activities that are infected by malware.” Eradicating malware is extremely difficult because it results from human creativity. For example, when you buy a bundle of banking software, in most cases it is not designed by a single company. The vendor will buy components for its product from different companies. There is no uniform, high assurance of quality across the board, and this facilitates opportunities for introducing malware. “Real-life business models make it difficult to exterminate opportunities for malware infection,” says Gligor. Best estimates wage that we are many years away from ridding our computers of malware, but in the meantime “we must enable people to operate their computers in spite of it.”

An insidious aspect of malware is that victims often unwittingly invite attacks upon themselves. In phishing scams, people email credit card information or passwords to bogus banks. People can load viruses into their laptops with infected USB drives. As we become savvy to one type of attack, different ones appear. “New technology introduces new vulnerabilities. It also changes the notion of who our adversaries are. We can’t always identify attackers and hold them accountable for their actions,” says Gligor. To stay ahead of hackers, Gligor advocates for engineers and others to think about security when they are creating mechanisms, software, etc. Doing so will alleviate retrofitting, which generally occurs after an attack and the damage is done. This proactive mindset, which is evident throughout all of CyLab’s research areas, allows Carnegie Mellon to shape the face of cybersecurity. Security means more than taking a defensive stand: available, secure and trustworthy computing will pave the way for innovations we have yet to realize.

“The Data Storage Systems Center (DSSC) is not just about doing research, it’s about transforming an industry,” says Jimmy Zhu, the DSSC director. This critical distinction has established the center as a world leader in data storage and earned Zhu an invitation to speak at the National Science Foundation Engineering Research Centers Annual Meeting (2008) on transformational research, a topic that clearly excites Zhu.

Presently the DSSC has an annual research budget of \$4 million dollars, with \$2 million coming from government sources and the rest from industry. Almost every major disk drive company in the world belongs to the center’s affiliate program. The DSSC generates this level of support because “industry trusts us to innovate,” says Zhu. This trust has been earned thanks to DSSC inventions like the “B2 Underlayer,” which made possible the mobile disk drives found in laptops and iPod applications.

Zhu explains that innovation entails cutting-edge research and pioneering development in memory storage. Focusing on speed, capacity and portability, current DSSC research areas include: hard disk drives, tape drives, probe and holographic storage, novel non-volatile memory technologies, and memory-intensive self-configuring integrated circuits (MISCICs). Yet, innovation means more than invention. Technology must be

transferred to industry and implemented. The DSSC is quite adept at working with companies, and this eases the transference of information from Carnegie Mellon to industry. “We enable industry to do things that they could not do without us, and this drives innovation,” says Zhu. Companies focus on the bottom line, which curtails them from investing into long-term research that may not bear tangibles for 10 years or more. Government funding of universities ensures that fundamental data storage research continues as well as work that promises quick deliverables.

Reflecting on the next wave of innovation in data storage, Zhu believes that interdisciplinary efforts will play a huge role in creating future memory systems. He proposes that an increased focus on systems may transform the industry again. “There are lots of preliminary schemes to do much higher density and faster data storage, but there are no systems designed to realize this,” says Zhu. Hard drive technology is maturing. This is forcing us to imagine what our storage devices will look like 10 or 15 years from now and forecasting the future isn’t easy. Twenty years ago, it was difficult for people to imagine a need for having large amounts of information on their hard drives. Yet, imagination is part of the innovative processes, and DSSC researchers are anticipating future storage needs as they redefine data storage in the 21st century.



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