

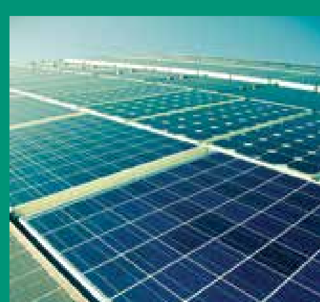
Innovative Energy Technologies: The Next Generation

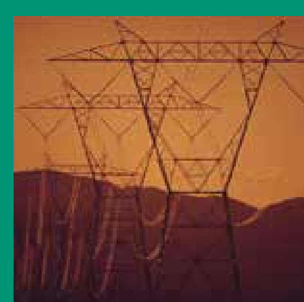
Carnegie Mellon University
Scott Institute
for Energy Innovation

TECHNOLOGY GUIDE

Our lifestyle is sustained by energy. Technologies developed at Carnegie Mellon have the ability to enhance energy generation and the consumption of that energy in our buildings, transportation, industry, and our homes. Some of these technologies are just emerging from the university while others have already entered, or are on the cusp of entering, the marketplace. These next generation technologies have been developed by undergraduate and graduate students, researchers, faculty, and alumni from all across Carnegie Mellon.

Technologies such as these can reduce the cost of energy generation and consumption, mitigate the resulting pollution emitted to the environment from that energy, and improve the reliability and resilience of our energy system. However, to reap the benefits of these technologies in our everyday lives it is critical that industry, policy makers and the public support their development from ideas generated in the laboratory to the commercial marketplace.





THE DEVELOPMENT AND DISSEMINATION OF THIS GUIDE WAS MADE POSSIBLE THROUGH THE GENEROSITY OF MICHAEL AND JANET JESANIS AND THE NISOURCE CHARITABLE FOUNDATION.

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ABOUT THE CARNEGIE MELLON UNIVERSITY

Wilton E. Scott Institute for Energy Innovation

Over the coming decades the world must make fundamental transformations in how energy is used and produced. This will require new science, technology and public policy innovations. That's the role of the Scott Institute.

The Carnegie Mellon University (CMU) Wilton E. Scott Institute for Energy Innovation is addressing several complex challenges:

- How to use and deliver the energy we already have with greatly improved efficiency
- How to expand the mix of **energy sources** in ways that are clean, reliable, affordable and sustainable
- How to create **innovations** in energy technologies, regulations and policies

Carnegie Mellon's longstanding **expertise** in technology, policy, integrated systems, and behavioral and social science is uniquely suited to addressing these challenges. What makes us different is our ability to seamlessly combine these areas for maximum impact.

The purpose of this technology guide is to document research from throughout Carnegie Mellon — to provide an up-to-date understanding of the next generation of energy technologies.

For more information about the Carnegie Mellon's Scott Institute for Energy Innovation and the research discussed in this guide, visit www.cmu.edu/energy. The institute's directors are Jared L. Cohon, President Emeritus and University Professor, Civil and Environmental Engineering & Engineering and Public Policy, and Andrew J. Gellman, Lord Professor of Chemical Engineering. Deborah D. Stine, Professor of the Practice, Department of Engineering and Public Policy, is the Associate Director for Policy Outreach for the Scott Institute for Energy Innovation. If you have questions about this guide, please contact Dr. Stine at dstine@andrew.cmu.edu.

This technology guide was developed by a team led by Deborah Stine and Reed McManigle, Senior Manager, Center for Technology Transfer and Enterprise Creation, Carnegie Mellon University. The names of the CMU-related students, faculty, and alumni who developed the technologies summarized in this guide is provided as each technology is described. They or the Center for Technology Transfer and Enterprise Creation should be contacted directly if you would like more information about their technology.

Most photos credit of the U.S. Department of Energy.

Overview

OVERVIEW

Our lifestyle is sustained by energy. Energy increases our daily productivity and quality of life. These may include daily activities such as making our homes warm or cool, moving us from one place to another in our car, or running machines like refrigerators, washers, televisions, and computers. Just as we draw upon the energy stored in fat cells in our body to move throughout our day, we draw upon energy stored as gasoline in our car when we need to move from one place to another. This Carnegie Mellon University (CMU) Scott Institute for Energy Innovation technology guide focuses on the host of next generation energy technologies started at CMU.

WHAT ARE NEXT GENERATION ENERGY TECHNOLOGIES?

Throughout history, society has evolved from reliance on one source of energy to another. We have evolved from using wood to coal, petroleum, wind, natural gas, solar, and nuclear. Over time, we have also discovered, the importance of being efficient in our use of energy, reducing our environmental impact, and enhancing our energy security. Next generation energy technologies can serve all these purposes so that, globally, we can reach these societal goals of energy availability, security, and sustainability.

These next generation energy technologies have the ability to enhance the efficiency of energy generation and its consumption in our buildings, transportation system, industry, and homes as well as inside our body and deep in the ocean. Some of these technologies are just emerging from the university while others have already entered, or are on the cusp of entering, the marketplace. Undergraduate and graduate students, researchers, faculty, and alumni from across Carnegie Mellon have developed these technologies.

HOW DO WE REALIZE THE BENEFITS OF NEXT GENERATION ENERGY TECHNOLOGIES?

The benefits of the next generation of energy technologies occur throughout the interconnected system of energy suppliers, transmitters, and consumers. These technologies, however, need support from industry and policy makers, and the public itself, to reach the point of competitive maturity. Doing so will help society realize the benefits of these nascent technologies as they move from ideas generated in laboratories to the marketplace and into our every day lives.

Figure 1 illustrates the interconnected U.S. energy system. The left side of the chart lists how much energy we obtain today from the wide variety of sources available. On the right side is information about how much of that energy in consumed in the residential, commercial, industrial and transportation sectors, and how much of the energy generated is lost due to inefficiencies throughout the system. The "rejected energy" at the far right of the figure, is the energy that is lost to due to inefficiency. While we cannot reduce this loss to zero, there is significant room for improvement. This is important as the energy rejected is more than the energy providing valuable services. The greater the degree to which we can improve our generation and consumption of energy, the more efficient will be the nation's use of energy. Energy technologies can help us reach that goal and the related societal benefits.

Some energy uses will not be apparent from this chart. For example, we also need energy storage and conversion technologies that power devices inside our bodies and in challenging environments such as deep in the ocean and in mines. In addition, the use of energy technologies can be enhanced by implementing policies that optimize their use. You can read about some of those policy issues in other Scott Institute guides. For more information, go to www.cmu.edu/energy.

Figure 1: Energy Generation and Consumption Flows, 2010. This diagram shows 2010 energy flow from primary sources (oil, natural gas, coal, nuclear, and renewables) through transformations (electricity generation) to end uses (transportation, industry, and residential, and commercial sectors). Oil provided the largest share of the 98 quads of primary energy consumed, and most of it was used for transportation. Consumption of natural gas, the nation's second largest energy source, is split three ways—electricity generation, industrial processing, and residential and commercial uses (mostly for heating). Coal, our third largest source, is used almost exclusively for electricity. Nuclear energy and renewables each meet less than 10% of U.S. energy demand.

Source: U.S. Department of Energy at http://science.energy.gov/bes/news-and-resources/energy-flow/energy-flow-diagram/.

Data Source: Data are from the U.S. Energy Information Administration's Annual Energy Review (www.eia.gov/aer/) and Lawrence Livermore National Laboratory (flowcharts.llnl.gov).

Energy Generation, Conversion, Storage and the Environment

STATIONARY SOURCE ENERGY STORAGE AND CONVERSION

Aquion Energy, a CMU spinoff company, has developed the aqueous hybrid ion battery, a low-cost, long-lasting, large-scale aqueous electrolyte sodium ion battery that uses salt water (sodium sulfate in water) to store electricity. In developing the battery, CMU researchers started out with a simple set of goals deemed necessary for economically competitive energy storage devices including necessary price point, environmental impact, cycle life, and efficiency. The result is a battery optimized for stationary storage applications such as micro-grid support, off-grid generator optimization, and grid-level energy services. Among its many awards are the 2011 World Technology Award, the Global Cleantech 100, MIT's TechReview 50 Disruptive Companies and 50 Smartest Companies, and funding from Bill Gates, Kleiner Perkins Caufield & Byers, Foundation Capital, Advanced Technology Ventures, and others. *Key Researcher:* Jay Whitacre. More information is at http://www.aquionenergy.com/.

A **Microfluidic Microbial Fuel Cell,** which includes the world's smallest low-cost fuel cell as developed at Carnegie Mellon, converts bacteria into power. The device, no bigger than a human hair and 300 times smaller than a raindrop, uses microbial electricity generation enabled by microfluidic flow control to produce power from natural organic compounds. This fuel cell can be used for remote electricity generation such as self-powered sensing devices in remote locations such as deep in the ocean, earth, or human body where batteries are impractical. For example, in the oil & gas industry, these fuel cells can be used to power devices that can communicate the degree of corrosion and pressure in pipelines located deep in the ocean, where changing batteries is challenging. In the human body, such devices can be used for a glucose sensor. In addition, biofuel cells could use waste biomass as a fuel for large-scale electricity generation. *Key Researchers:* Kelvin Gregory and Philip LeDuc. More information at: http://www.cmu.edu/cee/news/news-archive/2013/2013-energy-part-one.html.

Energy Harvesting Diodes being developed at CMU are able to generate an electric signal when 'detecting' energy in the terahertz (THz) bandwidth. Background heat energy that is released by bodies, buildings, furniture, etc. is in the ten's of THz bandwidth. With the CMU diodes and associated devices, this heat energy can be converted into DC electricity. Potential applications include energy generation for portable electronics, and room air conditioning/electricity generation. *Key Researcher:* Yi Luo. More information at: http://www.google.com/patents/WO2013158986A2?cl=en.

PERSONAL DEVICE ENERGY GENERATION AND STORAGE

SolePower is an innovative technology company striving to power small mobile electronic devices through the use of everyday movement of a person. First, a cut-to-fit SolePower insole is placed in any shoe. As an individual walks, the power generated is stored in an external Power Pack. This Power Pack is waterproofed and can be placed inside of a fabric holster that integrates with the shoelaces to create a secure and comfortable attachment. Mobile devices are then charged at the same rate as via a computer by connecting the device to the Power Pack's USB port. This invention, developed while the researchers were students CMU, has won several awards including a Popular Science 2014 invention award, an Africa Energy Award for Innovator of the Year, and AOL co-founder Steve Case's Rise of the Rest's Innovation Award. *Key Researchers:* CMU Alumni Matthew Stanton and Hahna Alexander. More information at: http://solepowertech.com/

Edible Electronics, such as an edible battery developed at Carnegie Mellon, can be used to power devices that monitor gastric problems, stimulate damaged tissue, or deliver drugs to specific organs. For example, the battery can be programmed to enter the gastrointestinal tract or the small intestine and power devices such as biosensors to measure biomarkers or monitor gastric problems, stimulate damaged tissue, or target drug delivery for certain types of cancer. The process begins with the patient's consumption of a pill made of biodegradable material that encapsulates the device. Flexible polymer electrodes and a sodium ion electrochemical cell allow the mechanism to be folded into an edible pill that encapsulates the device or drug at a low cost. After the capsule dissolves, power is generated when the sodium ions from the cell interact with the water in the body. Although you might wonder if eating a battery is safe, the battery is made of non-toxic materials passes through the human body in a few hours once the material encapsulating it biodegrades. *Key Researchers:* Christopher Bettinger and Jay Whitacre. More information at: http://www.cmu.edu/homepage/health/2013/spring/incredible-edible.shtml.

ENVIRONMENTAL SENSORS

Platypus LLC, a CMU spin-off company, manufactures small, low-cost autonomous robotic boats with the ability to sense environmental contaminants in large areas of calm water along with other critical data such as water depth, dissolved oxygen, and pH. The boats can work cooperatively, potentially in large groups, for environmental monitoring needs associated with the petrochemical industry (such as hydraulic fracturing), fish farming, and waterway, local, and dam management. Such tasks using the boats can be done more cheaply, efficiently, and quickly than by existing autonomous or manned boats. Each robotic boat uses a base station that can communicate using wireless, 3G, or EDGE within a 1.5 mile range. *Key Researcher: Paul Scerri*. More information is at http://senseplatypus.com/.

PLATYPUS

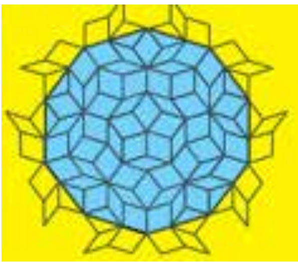
SenSevere, a CMU spin-off company, provides semi-conductor based sensors for severe environments such as elevated temperatures (500°C) and pressures (2500 PSI) as well as corrosive environments or deep sea wells. The sensors utilized can detect hydrogen, hydrocarbons, ammonia, and bromide improving both safety and environmental compliance for the power generation, environmental, and chemical industry. In the energy field, these sensors can be used in energy exploration, refineries, power generation, nuclear facilities, and transportation. *Key Researcher: Jason Gu*. More information is at http://sensevere.com/.

SENSEVERE environmental sensors

Industry Device Manufacturing and Energy Efficiency

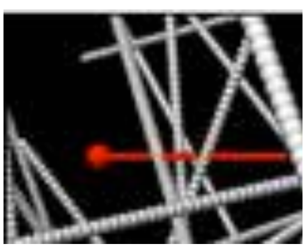
ENERGY, MATERIALS, AND MANUFACTURING

Plextronics is an international CMU-spinoff technology company that specializes in electronic inks for OLED (Organic Light Emitting Diode) displays and lighting and electronic polymers. The electronic "inks" are dissolved and printed onto other surfaces — enabling thinner, cheaper, more energy-efficient electronics. The company's focus is on OLEDs for large area TV and lighting applications, and it is in the process of developing electronic polymers that can be used for lithium ion battery and polymer metal capacity applications. Future applications are expected to be organic photodetectors, thin film transistors, and photovoltaics. Plextronics was acquired in 2014, and continues to operate in Pittsburgh as Solvay Pittsburgh. *Key Researchers:* Former CMU faculty Richard McCullough. More information is at http://www.plextronics.com/.



Southpole Magnetics, an upcoming CMU spin-off company, is focused on developing new magnetic materials that will be used in a variety of power electronics equipment such as transformers, inverters and motors. The novel magnetic materials developed at CMU will increase power density, lower losses, increase efficiency, and reduce size and cost in power electronics. For example, a large scale, 35 ton transformer could be redesigned to be ~450 pounds. Such dramatic improvements could enable more widespread adoption of rooftop solar energy production by commercial enterprises. *Key Researcher:* Michael E. McHenry. More information is at http://neon.mems.cmu.edu/mchenry/web/McHenryHome.html.

Industrial Learning Systems (iLS), a Carnegie Mellon spin-out company, leverages innovative, patented technology to develop products that enable manufacturers to increase productivity and yield and improve quality, reduce material and energy costs, maximize efficiency of engineering human resources, and eliminate or reduce down time. Among its most recent inventions are an improved continuous casting process for making solar silicon wafers based on the float-glass process used to make plate glass. The current process involves casting silicon in a cylinder shape and then taking thick slices from that cylinder to make the wafers resulting in 50% of the silicon being wasted. The new process will have dramatically lower waste and cost. *Key Researcher:* Erik Ydstie. For more information, see http://www.ilsystems.net/.



Carbon Nanotube (CNT) Aerogel-based Composites are formed around a very low density, three-dimensional lattice of nanotubes. These composite materials are highly-stretchable, electrically-conductive, and nearly as strong as aluminum, but at one-third of its density. They can be used in a variety of applications including as transparent electrodes in solar photovoltaic panels, and as structural materials in wind turbine blades. Use of these materials can reduce the cost of such applications since fabrication costs are lower, and processing is easier. *Key Researcher:* Mohammad Islam. More information is at http://onlinelibrary.wiley.com/doi/10.1002/adma.201100310/full.

OPTIMIZATION OF INDUSTRY ENERGY USE

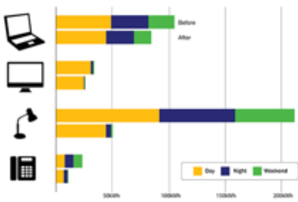
The Optimization Firm offers custom and packaged high-performance computing solutions for complex numerical optimization problems. These software solutions assist companies with complex decisions based on mathematical models. For example, the pooling problem is an optimization problem, solved using software packages, that is encountered by refinery operators worldwide in the transportation, mixing, and processing of crude oils. Even the slightest improvement in these refinery scheduling operations would yield savings of millions of dollars every month for each refinery. *Key Researcher:* Nick Sahinidis. More information at http://theoptimizationfirm.com/

Software for power grid management is being developed at CMU to enable the transition from today's centralized power management systems to a new paradigm of distributed control of power management systems. This will enable utilities to more effectively manage dynamic power grids, with greater resiliency for unforeseen events while reducing the need for spare capacity reserves. Further, such distributed approaches will ease the integration of intermittent power sources, such as wind and solar; the adoption of microgrids, and management of demand response programs. *Key Researchers:* Marija Ilic, Gabriela Hug, Soummya Kar, José M. F. Moura. For more information, see http://www.eesg.ece.cmu.edu/.

Commercial Facility and Residential Energy Management

COMMERCIAL FACILITY MANAGEMENT

Lean FM Technologies is a lifecycle software solution for economic, proactive and intelligent Facilities Management. Every year, operating the 5 million commercial buildings in the U.S. costs $700 billion. The efficiency of facilities management (FM) is low due to the complexity of buildings and limited access to information. By leveraging Building Information Modeling (BIM) and cloud computing technology, Lean FM addresses this challenge by integrating the heterogeneous building information that is recorded in design drawings, equipment manuals, building automation systems and computerized maintenance management systems. *Key Researcher:* Burcu Akinci and Xuesong Liu. For more information, see http://istart.org/startup-idea/internet-services-green-it-energy/lean-fm-technologies/6600.



The Intelligent Dashboard for Occupants (ID-O) helps people to see how much energy they use at work and how to reduce this use to help the environment by evaluating plug load energy savings in the workplace. By seeing plug load, the number of devices plugged into outlets at their desk and their actual energy use, building occupants have the information they need to take actions that will save energy including online ability to control plug loads at their desk. A field test with plug-in devices manufactured by Plugwise™ that measure the energy consumption of each device and provide digital on-off control showed a 35% reduction in energy consumption as a result of the dashboard. *Key Researcher:* Ray Yun. More information is at: http://www.cmu.edu/news/stories/archives/2014/april/april7_workplacedashboard.html.

Building model data extraction software automatically pulls data out of a digital building design models and populate that data into the correct fields of compliance documents. For example the initial application of this system is the LEED[1] application process. Currently it can take days to weeks to enter data into a LEED application just for the energy efficiency section, which contains approximately 1400 fields. Because of this, architects and developers are reluctant to go through the LEED certification process, and if they do, it is done at the end of the design process. The CMU software automatically pulls data out of a building design energy model and populates that data into the correct fields of the LEED application. Because this software can make the application process happen in a matter of minutes, it will enable the industry to not only save costs and reduce data entry errors, but also to do ‘what if’ assessments of different design options to determine their impact on LEED scores. *Key Researcher:* Khee Poh Lam. More information at: http://www.cmu.edu/architecture/research/cbpd/absic-cbpd.html.

Encapsulated phase change material containers can be used as heat sinks in buildings. Phase change materials store or release heat during a freeze/thaw phase change that can be calibrated to occur at room temperature. By storing excess heat, they can help to keep room temperature moderate while temperatures are rising, and then can release that heat when the room is cooling, all passively with potentially reducing the cost of heating and cooling by 25%. The team is designing a range of “containers” that are configured as decorative or functional architectural tiles, window shade louvers, furniture, and other devices that are optimized to enable air flow and heat exchange. *Key Researchers:* Dale Clifford and S.C. Yao. More information at: http://cmubiologic.weebly.com/.

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1 LEED, or Leadership in Energy & Environmental Design, is a green building certification program that recognizes best-in-class building strategies and practices. To receive LEED certification, building projects satisfy prerequisites and earn points to achieve different levels of certification. For more information, see http://www.usgbc.org/leed.

RESIDENTIAL ENERGY MANAGEMENT SERVICES

EEme, LLC, a Carnegie Mellon spin-out, processes smart meter interval data using proprietary load disaggregation algorithms to predict the technical and behavioral energy efficiency (EE) potential by EE measure for every residential user for a given service territory. Their Green Button[2] compatible platform solution is designed to connect all EE stakeholders. Upon login the residential user is given personalized EE recommendations along with the relevant economic metrics, i.e., financial savings potential, cost, utility rebate amount. The utility heat map dashboard is designed for the EE program managers to analyze their customer base with respect to predictive metrics of interest and target their traditional EE outreach and marketing campaigns. *Key Researcher:* Enes Hoşgör. More information at: http://www.energyefficiency.me/.

SparkMeter provides electricity meters for low-income households throughout the world. Central grid utilities, local initiatives, social entrepreneurs and global institutions around the world are striving to expand electricity access, yet sustainable business models to deliver grid-level electricity to these populations remain rare. The SparkMeter system enables grid operators to implement pre-payment as well as real-time monitoring and control to improve their ability to deliver electricity to low-income customers. By improving cost recovery, these electric grids become more reliable—a better outcome for customers whose only alternatives are expensive, inefficient, and dangerous fuels like kerosene and candles. *Key Researcher:* Anthony Rowe and Dan Schnitzer. More information at: http://www.sparkmeter.io.

Lumator uses statistical artificial intelligence and behavioral game theory to predict the best match between consumers and rate plans. The goal of the company is to help consumers reap the benefits of deregulated markets by becoming active technology-enabled decision makers in the Smart Grid. Lumator collects and analyzes all the rates available through consumer's utility, then selects and switches the consumer to the best option based on their preferences. *Key Researchers:* Manuela Veloso and Prashant Reddy. More information at: https://www.founder.org/lumator.

OPERETTA: "An Optimal Deployable Energy Efficient Bandwidth Aggregation System," builds on previous attempts to improve multi-interface mobile devices, such as smartphones, by allowing users to concurrently connect to the Internet in different ways, such as 3G, 4G, WiFi and Bluetooth. Imagine you're at a meeting and need to download a video on your phone. Instead of choosing between wireless and 3G, what if you could combine them to download the clip in half the time? Or, what if you've written an email, hit the send button, but don't want to pay for it to go out through 3G? Maybe your smartphone could wait until you're connected to free Wi-Fi before mailing it out. Users now choose between interfaces based on factors such as speed, energy consumption and cost. Operetta allows users to combine interfaces for optimal speed, or to choose 3G for a time-sensitive task while postponing another task until a cheaper option, such as Wi-Fi, opens up, with no changes in existing infrastructure. In other words, OPERETTA tells YouTube how best to download a video rather than YouTube having to make changes to accommodate his technology. *Key Researcher:* Khaled A. Harras. More information at: http://www.cmu.edu/homepage/society/2012/fall/mobile-solutions.shtml

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2 Green Button is a secure way for consumers to obtain their energy usage information electronically. More information is at: http://www.greenbuttondata.org/.

Traffic and Vehicle Energy Management

TRAFFIC MANAGEMENT

Surtrac Scalable Urban Traffic Control, is an innovative approach to traffic signal control, combining research from artificial intelligence and traffic theory to optimize the performance of signals for the traffic that is actually on the road. As a result, this technology improves traffic flow for both urban grids and corridors leading to less waiting, reduced congestion, shorter trips, less pollution, and happier drivers. A Pittsburgh demonstration project on nine intersections reduced travel time by 26 percent. The demonstration project is being expanded to 31 intersections. *Key Researchers:* Stephen Smith and Greg Barlow. More information at: http://www.surtrac.net/.

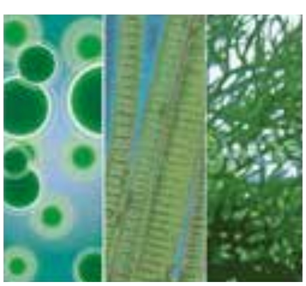
With **Virtual Traffic Lights** cars and trains autonomously communicate with each other to determine right of way at intersections without traffic lights. Computer simulations of this technology indicate a potential 60% improvement in traffic flow in a full-city simulation. *Key Researcher:* Ozan Tonguz. More information at: http://traffic21.heinz.cmu.edu/.

VEHICLE MANAGEMENT

Autonomous Cars, also known as self-driving cars, have been developed at Carnegie Mellon since the mid-1980s, culminating in the winning entry at the 2007 DARPA Urban Challenge which required driverless vehicles to travel 60 miles in less than 6 hours in urban-like conditions. These multiple generations of autonomous platforms, however, were designed to function only in limited operating scenarios and also looked like prototypes — both of which are significant barriers to popular adoption. Now, working closely with General Motors, and with additional support from the U.S. Department of Transportation and the National Science Foundation, CMU has created a normal-looking autonomous vehicle that boasts a broad set of capabilities including vehicular communications. Ottomatika, Inc. was spun out in 2014 to commercialize this technology. *Key Researcher:* Raj Rajkumar. More information at: http://www.cmu.edu/news/stories/archives/2014/june/june24_congressforaride.html.

Charge Car is an open, community centered teamwork at Carnegie Mellon for making electric vehicles practical and affordable enough to revolutionize urban commuting. It has developed a 'kit' to convert internal combustion vehicles to electric vehicles. *Key Researcher:* Illah Nourbakhsh. More information at: www.chargecar.org/.

FUEL GENERATION



Algae-based biodiesel generation uses passive/semi-passive systems to release the lipids from algae with little or no expenditure of energy. Although algae-based systems have the potential to generate far more energy per acre than corn-based systems and without competing with our food supply, a limitation of prior approaches is that the amount of energy required to release the energy-containing lipids within algae cells is greater than the amount of energy released. *Key Researchers:* Philip LeDuc and Fred Higgs.

Conclusion

Throughout this technology guide, you've seen next generation energy technologies developed at Carnegie Mellon to address the social imperative of meeting the energy needs of our homes, transportation system, businesses, and industry while taking into account economic, environmental, and security concerns. These technologies have great potential to address society's energy challenges, but it is also important to recognize that the invention of a technology is just the beginning of a challenging process to get that technology into the marketplace. Technology invention alone will not solve society's energy problems. Next generation energy technologies also face market and non-market policy challenges to entering the marketplace. In addition, next generation energy technologies may also face challenges related to human behavior. Finally, inventions developed by universities face additional challenges that differ from those in the private sector. Carnegie Mellon has instituted policies to help overcome these barriers to commercialization. The rest of this section provides more information on these challenges and policies.

VALLEYS OF DEATH AND NEXT GENERATION ENERGY TECHNOLOGIES

One of the challenges to technology implementation is collectively known as the "valley of death." For energy technologies, analysis conducted by the Bloomberg New Energy Finance[3] and the Breakthrough Institute[4] indicate that there are two valleys of death. As shown in Figure 2, the first is the technological valley of death – the challenge of obtaining venture capital to go from laboratory research to development of a product prototype and proof of that product's basic marketability. Once a product is shown to be marketable, it must cross the second, commercialization valley of death, by finding sufficient private equity and debt financing for demonstration projects, first-of-a-kind commercial-scale projects, and manufacturing facilities.

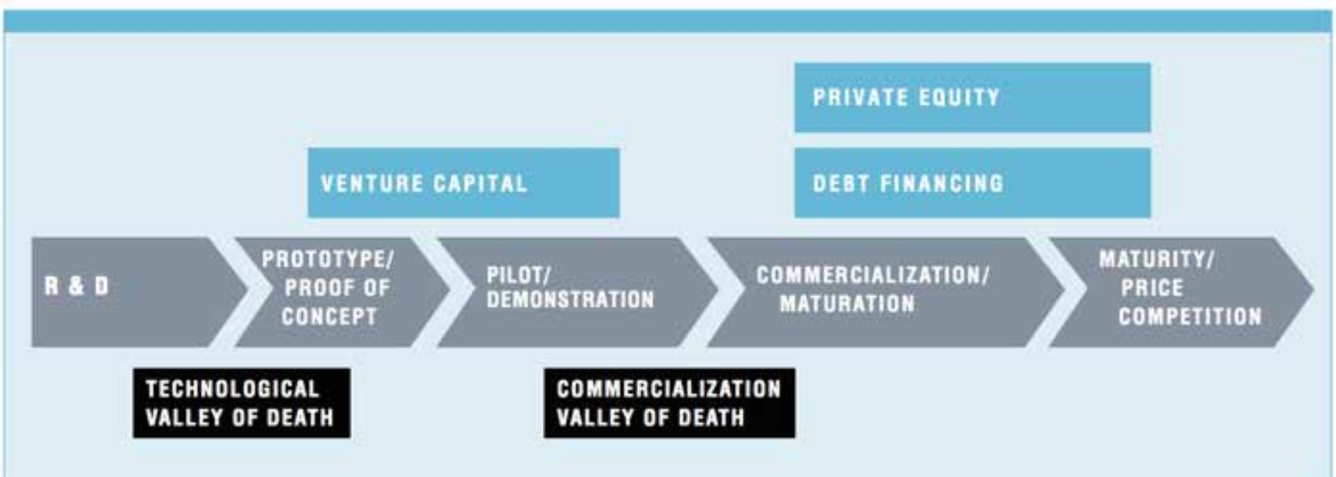


Figure 2: The Energy Innovation Cycle and the Clean Energy Valleys of Death

Source: Jenkins, J. and S. Mansur, "Bridging The Clean Energy Valleys Of Death: Helping American Entrepreneurs Meet The Nation's Energy Innovation Imperative," The Breakthrough Institute, November 2011 at http://thebreakthrough.org/archive/bridging_the_clean_energy_vall.

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3 Bloomberg New Energy Finance, "Crossing the Valley of Death: Solutions to the next generation clean energy project financing gap," June 21, 2010 at http://cleanegroup.bluehousegroup.com/assets/Uploads/CEGBNEF-2010-06-21valleyofdeath.pdf.

4 Jenkins, J. and S. Mansur, "Bridging The Clean Energy Valleys Of Death: Helping American Entrepreneurs Meet The Nation's Energy Innovation Imperative," The Breakthrough Institute, November 2011 at http://thebreakthrough.org/archive/bridging_the_clean_energy_vall.

ENERGY INNOVATIONS COMPARED TO PHARMACEUTICAL AND SOFTWARE INNOVATIONS

As illustrated in Table 1, these valleys of death for energy innovations versus those in the pharmaceutical and the software/information technology industries have created a "perception of risk and a scarcity of appropriately matched risk capital in the energy technology market."[5] This table, however, focuses on issues of energy supply technologies rather than end-use technologies that reduce energy consumption from residential and commercial buildings, industry, and transportation. Studies tell us that end-use technologies can provide a higher societal return on investment than energy supply technologies,[6] and possibly less risk perception or concerns about the risk of capital invested in them.

Many of the next generation of energy technologies developed by Carnegie Mellon researchers focus on these end-use technologies. For example, you've just seen software and information technology energy innovations focused on reducing energy consumption in residential and commercial buildings, which based on the analysis in Table 1 below, are likely to have an easier road to market than energy supply technologies; however, the competition in the marketplace may be more challenging for these same reasons.

Table 1: Innovation in Various Sectors

	PHARMACEUTICAL	SOFTWARE & IT	ENERGY
Time Required to Innovate	10-15 years	1-5 years	10-15 years
Capital Required to Innovate	Medium to High	Low to Medium	High
New Products Primarily Differentiated By	Function/Performance	Function/Performance	Cost
Actors Responsible for Innovation	Large Firms Reinvesting in R&D; Biotech startups, often VC & govt. funded; Govt. (NIH, NSF)	Dynamic Startups, often VC-funded; Large Firms Reinvesting in R&D	Various: Utilities, Oil & Gas Co.s, Power Tech Co.s, Startups, Govt.
Typical Industry Risk Tolerance	High	High	Low
Innovation Intensity	High	High	Low
Intellectual Property Rights	Strong	Modest	Modest

Source: Jenkins, J. and S. Mansur, "Bridging The Clean Energy Valleys Of Death: Helping American Entrepreneurs Meet The Nation's Energy Innovation Imperative," The Breakthrough Institute, November 2011 at http://thebreakthrough.org/archive/bridging_the_clean_energy_vall.

5 Ibid.

6 Wilson, C., Grubler, A., K.S. Gallagher, and G. Nemet, 2012 "Marginalization of end-use technologies in energy innovation for climate protection" Nature Climate Change, Vol. 2, November, pp. 780-788 at http://www.nature.com/nclimate/journal/v2/n11/full/nclimate1576.html.

In addition, some Carnegie Mellon next-generation technologies may not be viewed as energy technologies at all. For example, the edible battery may be viewed more as a biomedical device so the opportunities and challenges it faces are similar to those in the pharmaceutical industry. There a high tolerance for risk, innovation, and intellectual property rights increase its marketability, especially when considering options such as licensing. On the other hand, one also has to consider the considerable time and effort needed for approval by the Food and Drug Administration.

POLICY OPPORTUNITIES AND CHALLENGES FOR NEXT GENERATION ENERGY TECHNOLOGIES

That being said, the aqueous hybrid ion energy storage battery (Aquion) developed at Carnegie Mellon, which falls into the energy supply category, is now being manufactured and marketed – successful in reaching the final stage of the process where it now must face competition from other energy storage options.[7] One reason for its success is its ability to respond to an exploding market need for energy storage – recently documented by an IHS Technology analysis.[8] Some of that market was created as a result of non-market factors – government policies that can encourage or challenge the ability of a product to reach its full marketability – a particular issue for emerging technologies. In this situation, requirements for energy storage in California and renewable electricity policy goals in Japan and Germany are driving the market growth.[9]

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7 Fehrenbacher, K., "At a big solar show, batteries take center stage," gigaom.com, July 9, 2014 at http://gigaom.com/2014/07/09/at-a-big-solar-show-batteries-take-center-stage/.

8 Wilkinson, S., "The grid-connected energy storage market is set to explode, reaching a total of over 40 GW of installations by 2022," IHS Technology, January 15, 2014 at https://technology.ihs.com/483008/the-grid-connected-energy-storage-market-is-set-to-explode-reaching-a-total-of-over-40-gw-of-installations-by-2022.

9 Ibid.

Other Carnegie Mellon next generation energy technologies face policy challenges, however. For example, CMU's autonomous car faces communication, regulatory, and liability policy challenges unless a national law is put into place to govern these issues.[10] Platypus, the maker of autonomous boats used to monitor water quality, faces challenges related to certification by the Environmental Protection Agency whose procedures are designed for traditional samplers, not robotic sampling. The edible battery requires approval by the Food and Drug Administration, and Surtrac's smart traffic lights face a state and local contracting system that is designed for traditional technologies.

HUMAN BEHAVIOR AND NEXT GENERATION ENERGY TECHNOLOGIES

Another challenge related to next generation energy technologies is the human component – where the social sciences play an important role. For example, there is an inexpensive technology in our homes right now that can conserve energy immediately. It's called a light switch. Convincing a teenager to use that light switch every time they leave a room, however, is a social science challenge not a technology challenge. Utilities installing smart meters face privacy concerns. And sometimes, all we need is a change in behavior with no technology involved to achieve a societal goal. The American Academy of Arts and Sciences[11] provides six examples:

1. *Behavior and decision-making:* Analysis indicates that 20 percent of energy in the residential sector could be reduced with no- or low-cost behavioral interventions that require no significant lifestyle changes. Many of Carnegie Mellon's residential and commercial energy services technologies are designed to provide information to encourage people to reduce their energy consumption in their homes and offices.
2. *Public acceptance of new energy technologies:* New energy technologies often face social issues. For example, Carnegie Mellon's autonomous cars face not only policy challenges, but also public acceptance challenges as people give up control of their cars to this new technology.
3. *Incorporating behavior in policy analytic tools:* Energy-economic modeling used to inform public policies does not generally include the behavioral sciences. For example, the CMU technologies designed to provide information to encourage reductions in energy consumption need to link to the social sciences to incorporate human behavior information so that policy makers can better understand the "real-world" potential of such technologies.
4. *Policy durability and adaptability:* Energy technology is constantly changing, challenging the ability to develop long-lasting policies. For example, the challenges faced by the robotic devices developed at CMU to respond to energy challenges face policies designed for a world without robots. How can we design policies so that valuable technologies do not have this problem in the future?
5. *Federalism:* Energy policy is politically complex with actions taken by the federal government, regions, states and localities. For example, CMU's self-driving car must navigate plethora of laws at all level of government. . The social sciences can help identify options to respond to this challenge.
6. *New and updated regulation:* As our energy system changes, so do the regulations that govern it. As discussed earlier, non-market factors such as regulations can encourage or discourage the marketability of next-generation energy technologies.

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10 Anderson, J., Kalra, N., Stanley, K., Sorensen, P., Samaras, C., Oluwatola, O. Autonomous Vehicle Technology: A Guide for Policymakers, Santa Monica, CA: RAND Corporation, RR-443-RC, 2014 at http://www.rand.org/pubs/research_reports/RR443-1.html.

11 American Academy of Arts and Sciences, "Beyond Technology: Strengthening Energy Policy through Social Science," 2011 at https://www.amacad.org/multimedia/pdfs/publications/researchpapersmonographs/alternativeEnergy.pdf.

In sum, the invention of the next generation of energy technologies described in this guide have great potential to respond to the nation's energy goals. To reach these goals, however, these technologies must overcome market, non-market, and social challenges. In addition, technologies are not the only way to achieve societal goals; behavioral changes also play an important role in supporting the potential of both existing and next-generation technologies. These challenges apply to all technologies regardless of whether the source of the invention is industry, government, or universities. As described in the next section, university-developed energy technologies face even more challenges, and Carnegie Mellon has taken some unique actions to respond to those challenges.

CARNEGIE MELLON UNIVERSITY INVENTIONS AND NEW TECHNOLOGY COMMERCIALIZATION

While the process of commercialization of new technologies is challenging for experienced business enterprises, it is an even more challenging process to transition university inventions to commercialization. University inventions, often resulting from years of basic research funded by federal research agencies, are more likely to be fundamental developments that upend existing markets instead of incremental improvements to existing products and markets. Further, unlike their peers in industry, university researchers are not supported by business units which are tasked with identifying market opportunities and implementing go-to-market strategies. Those types of skills and resources must be developed and/or brought in through targeted mentoring and business partnering efforts. Carnegie Mellon is aggressively pursuing such activities in a variety of ways, making it a model for university efforts to support the creation of startup companies.

To encourage faculty and students to undertake what can be a daunting process of getting their technologies to the marketplace, and to take time away from their research and educational activities to do so, Carnegie Mellon has created a set of policies, programs and culture that encourage and actively support the transition of university-developed inventions into job-creating, market-changing startup companies.

One aspect of the CMU approach is a "porous" intellectual property policy, which allows inventors in a number of situations to independently pursue their commercial visions. If the research that led to the development of the technology was not externally-funded, the inventor personally owns his or her invention. CMU will provide mentoring and networking assistance to help the researcher achieve commercial success.

This provision of the CMU intellectual property policy is particularly relevant to and encouraging of student entrepreneurs, who typically have not had external funding for their commercial ideas—which may have arising in any of a broad variety of Senior Capstone courses across campus. Such student entrepreneurs can receive counseling on their intellectual property protection options from the Center for Technology Transfer and Enterprise Creation (CTTEC), and a variety of mentoring, workshops, incubation space and funding from the Center for Innovation and Entrepreneurship (CIE) and the Open Field Entrepreneurship Fund.

When the research work that led to the invention was externally funded, Carnegie Mellon does take ownership of the invention, to facilitate ongoing reporting and other obligations to the funder, but it offers substantial incentives to the inventors to participate in the technology commercialization process. Specifically,

- If revenues accrue to CMU from licensing of the invention to an existing company, the inventors receive 50% of the net proceeds, one of the most generous revenue sharing policies in the country.
- If the inventors form a startup company, Carnegie Mellon was the first, and is still among a small number of universities, to offer a highly transparent, 'standard deal' to reduce the burden of negotiation. In this deal, CMU only takes a 6% equity interest in the startup company, and assesses a 2% royalty. There is no upfront licensing fee, no annual minimum royalties, and no royalties assessed for the first three years of the startup's operations. The key parameters of the standard deal are designed to limit the cash drain on the startup in its early years, and are clear and widely acceptable to the many venture capital firms that have invested in CMU startups.
- Startup companies are also given the opportunity to 'incubate' on campus, and/or to defer the obligation to cover expenses for licensed patents for additional equity provided to CMU.

Another way in which CTTEC encourages exploration of the commercial potential of university inventions is through an approach of filing 'in-house' prepared provisional patent applications as a first step in protection of inventions. Since the legal costs are avoided by preparing such applications in-house, it is much easier for an inventor to say 'YES' to the initial exploration of a new invention. The provisional patent provides a one-year window to explore commercial interest before a more expensive decision is needed on filing a full patent application. During this one-year period, CTTEC staff actively work with inventors to talk to potential customers, entrepreneurs, funders and investors to explore the commercial potential and to develop a strategy for commercialization.

At this early stage of market exploration, it is often the case that additional resources are needed to help the inventors achieve an important technical milestone, or retain a consultant or entrepreneur to work with them to develop a business strategy. CTTEC has 'gap funds' from state and foundation sources, and partners with external organizations such as Innovation Works, to provide such critical funding that can help the inventor teams to position themselves for company launch and solicitation of investment.

Throughout this process, CTTEC, CIE, and CMU's Institute for Social Innovation provide a variety of mentoring and networking assistance to budding inventor entrepreneurs to help them connect with the wide variety of support available in the local economic development community, and the larger world of entrepreneurs, alums, and investors who are interested in tapping into the rich culture of innovation at Carnegie Mellon.

The result of these policies, programs and culture is a high degree of inventor engagement and participation in the technology transfer process, as evidenced by the top tier placement of CMU in the number of invention disclosure per research dollar, and the best (highest) ratio of startups to research funding in the country with 36 startups in fiscal year 2013.[12] Over the past five years, CMU faculty and students have spun out more than 130 companies with approximately $400 million of outside investment.

If you are interested in the inventions described in this technology guide, you can contact the researchers identified or CMU's Center for Technology Transfer and Enterprise Creation.

12 For more information, see http://www.cmu.edu/news/stories/archives/2013/november/nov13_36startups.html.

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