Innovative Energy Technologies: The Next Generation

Carnegie Mellon University
Wilton E. Scott Institute for Energy Innovation
Our lifestyle is sustained by energy.

Technologies developed at Carnegie Mellon University have the ability to enhance energy generation and the consumption of that energy in our buildings, transportation, industry and 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, policymakers 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 Team

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 Carnegie Mellon University’s Wilton E. Scott Institute for Energy Innovation. The Scott Institute works through CMU’s academic units to find solutions for the nation’s and world’s energy challenges through research, strategic partnerships, public policy outreach and education. The complex challenges that it addresses include:

- 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.

The Scott Institute’s directors are Jay Whitacre, Trustee Professor in Energy of Materials Science and Engineering & Engineering and Public Policy, and Andrew J. Gellman, Lord Professor of Chemical Engineering. Deborah D. Stine, Professor of the Practice in the Department of Engineering and Public Policy, is the associate director for Policy Outreach, and Anna J. Siefken is the associate director for Innovation and Strategic Partnerships.

This technology guide was developed by a team led by Deborah Stine and Reed McManigle, senior manager and mentor in residence, Center for Technology Transfer and Enterprise Creation, Carnegie Mellon University. Additional reviews of this guide were provided by Amanda King, Jenni Miller and Anna J. Siefken. The names of the CMU-related students, faculty and alumni who developed the technologies summarized in this guide are 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.
Overview
Overview

Our lifestyle is sustained by energy. Energy increases our daily productivity and quality of life. Daily activities that use energy include making our homes warm or cool, and 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 bodies 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.

UNDERGRADUATE AND GRADUATE STUDENTS, RESEARCHERS, FACULTY AND ALUMNI FROM ACROSS CARNEGIE MELLON HAVE DEVELOPED NEXT-GENERATION ENERGY 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 policymakers, 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 everyday 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 is consumed in the residential, commercial, industrial and transportation sectors, and how much of the energy generated is lost due to inefficiencies throughout the system (rejected energy). 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.

**FIGURE 1. Energy Generation and Consumption Flows, 2015.**
This diagram shows 2015 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 97.5 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 percent of U.S. energy demand.

Source: Data is from the Lawrence Livermore National Laboratory flowcharts.llnl.gov.

Caption modified from U.S. Department of Energy at science.energy.gov/bes/community-resources/energy-flow/energy-flow-diagram.
Some energy uses will not be apparent from this chart. For example, we also need energy storage and conversion technologies that store the energy generated by variable energy sources like wind and solar energy as well as those that power devices located 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. To read about some of those policy issues in other Scott Institute guides, refer to “Managing Variable Energy Resources to Increase Renewable Electricity’s Contribution to the Grid” (cmu.edu/epp/policy-briefs/briefs/Managing-variable-energy-resources.pdf). More information at: cmu.edu/energy.

For more information on various energy innovation topics, watch our educational videos on our YouTube channel, such as “Energy Storage and Conversion: The Next Generation” (youtube.com/watch?v=VjWw8UVLXDU) and “Do Hybrid and Plug-in Cars Really Save the Environment?” (youtube.com/watch?v=4cltYvCFzYw). Also, listen to “Energy Bite” (energybite.org), a 90-second podcast where listeners can learn about energy innovation opportunities and challenges related to everyday life.
Energy Generation, Conversion, Storage and the Environment
Stationary Source Energy Generation, Storage and Conversion

**THE AQUAPONICS PROJECT**

**Key Researchers:** Sasha Cohen Ioannides and Alexis Hoane

The Aquaponics Project created a food system that raises fish and grows basil inside a 20-foot-by-8-foot shipping container, all through a process known as aquaponics. Aquaponics combines aquaculture with hydroponics, a method of growing plants with a continuous supply of water containing nutrients, rather than soil. Solar panels are used to pump the waste from tilapia to the plants, providing nutrients for growth. Aquaponics' ability to produce both fish and plants in an enclosed environment enables urban agriculture and initiates the conversation around food and sustainability. Notable achievements:

- Won first place, $35K in project funding and Ford Transit Connect passenger van during the 10th Annual Ford College Community Challenge

More information at: theaquaponicsproject.com/home.html

**AQUION ENERGY**

**Key Researcher:** Jay Whitacre

Aquion Energy, a CMU spin-off company, has developed the aqueous hybrid ion (AHI) battery, a low-cost, long-lasting, large-scale aqueous electrolyte sodium ion battery that uses salt water (sodium sulfate in water) to store electricity. The Cradle to Cradle Certified battery is optimized for stationary storage applications, such as micro-grid support, off-grid generator optimization and grid-level energy services. Notable achievements:

- Won the 2011 World Technology Award
- Named to MIT Technology Review's 50 Disruptive and 50 Smartest Companies and the Global Cleantech 100 lists
- Received funding from Bill Gates, Kleiner Perkins Caufield & Byers, Foundation Capital, Advanced Technology Ventures and others
- Acquired in June 2017 by U.S.-based branch of Titans Energy Technology Group
- Whitacre, who was named to Fortune Magazine's Top 25 Eco Innovators List, has received the:
  - 2015 $500K Lemelson-MIT Prize
  - Carnegie Science Center Advances Materials Award
  - Caltech Resnick Sustainability Institute Award
  - 2017 $50K Leigh Ann Conn Prize for Renewable Energy

More information at: blog.aquionenergy.com
MICROFLUIDIC MICROBIAL FUEL CELL

Key Researchers: Kelvin Gregory and Philip LeDuc

The Microfluidic Microbial Fuel Cell developed at Carnegie Mellon, which includes the world’s smallest low-cost fuel cell, 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. Potential uses:

• Remote electricity generation
• Self-powered sensing devices for remote locations
• Glucose sensors in the human body
• Conversion of waste biomass to fuel for large-scale electricity generation

More information at:

SOLAR SELECTIVE ABSORBERS

Key Researcher: Sheng Shen

Solar Selective Absorbers utilize solar thermal energy conversion as opposed to solar photovoltaics. Metal-based wafer-scale nanophotonic solar selective absorbers with excellent solar selective absorptivity and thermal stability are utilized, using a template (mold) stripping method that can drastically increase throughput and decrease fabrication cost. These new solar selective absorbers with 3-D nanophotonic structures can significantly impact transformative advancements in the design and performance of solar thermal systems.

Energy Generation, Conversion, Storage and the Environment

TERATONIX
Key Researcher: Yi Luo
For IoT system integrators and IoT end users who deploy low-power devices at scale and face the challenges of expensive installation and high lifetime maintenance costs, Teratonix develops a maintenance-free power source to replace batteries. The company converts ambient radio waves, ubiquitously available in urban environments, to electricity. Notable achievements:

• Placed second in the Allegheny Cleantech University Prize Collegiate Competition sponsored by CMU’s Scott Institute and DOE
• Won the Transformational Idea Award at the First Look West (FLoW) Competition, sponsored by DOE
• Placed second in the TransTech Energy Business Development Conference's Pitch Competition
• Placed second in CMU’s McGinnis Venture Competition

More information at: teratonix.com

Personal Device Energy Generation and Storage

EDIBLE ELECTRONICS
Key Researchers: Christopher Bettinger and Jay Whitacre
CMU researchers have developed edible electronics that are sensors made of nutrients — powered by stomach acid. Ingestible sensors could provide information on early signs of bacterial infection, look for symptoms of gastrointestinal disorders, monitor uptake of medications, and even study the microbiome living inside people. All components are made of organic and biosafe materials. After the capsule dissolves, power is generated when the sodium ions from the cell interact with the water in the body. The battery is made of nontoxic materials that pass through the human body in a few hours once the material encapsulating it biodegrades.

More information at: cmu.edu/homepage/health/2013/spring/incredible-edible.shtml
HILLSIDE HYDRO
Key Researcher: Hunter Hartshorne
Hillside Hydro has developed a micro hydroelectric generator that can recharge electronic devices from the energy of moving water. Their design utilizes the kinetic energy of moving water to spin a turbine. The energy generated is stored in an internal battery while the device is in the water. Once removed from the water, the energy can be used to charge any device via USB. To charge fully, the generator can be left in the stream overnight or for about eight hours. This will provide enough power to charge a smartphone three times.
More information at: hillsidehydro.com

SOLEPOWER
Key Researchers: CMU alumni Hahna Alexander and Matthew Stanton
SolePower has created self-powering smart work boots. They can be embedded with electronics including GPS, motion sensors, Wi-Fi, RFID and lighting. All are charged by the power of walking. They can help provide data, signal unsafe conditions, and simplify monitoring of industry and company standards. As an individual walks, the power generated is stored in an external Power Pack. Mobile devices are then charged at the same rate as via a computer by connecting the device to the Power Pack’s USB port. Notable achievements:

- Popular Science 2014 invention award
- Africa Energy Award for Innovator of the Year
- AOL co-founder Steve Case’s Rise of the Rest’s Innovation Award

More information at: solepowertech.com

Sensing and Mapping

GECKO ROBOTICS
Key Researcher: Troy Demmer
Gecko Robotics has developed robotic systems to facilitate the inspection of boiler tubes in power plants. Their system is faster, more accurate and safer than current techniques. The company was assisted in its launch by Y Combinator. Notable achievements:

- 1st place in Energy category of the 2016 Rice Business Plan Competition
- 1st place at 2016 TransTech Energy Business Development Conference
- Gecko Robotics is working in 14 states.

More information at: geckorobotics.com
MINE VISION SYSTEMS
Key Researcher: Brett Browning
Mine Vision Systems has created a visual system that can be used for the mapping of underground mines. Unlike prior systems, this system provides a high degree of accuracy. This accuracy enables monitoring for production and safety. It can also provide visual information from different perspectives for equipment operators.

More information at: minevisionsystems.com

PLATYPUS TECHNOLOGIES, LLC
Key Researcher: Paul Scerri
Platypus Technologies, LLC manufactures small, low-cost autonomous robotic boats. They have the ability to sense environmental contaminants, along with other critical data, such as water depth, dissolved oxygen and pH. The boats can work toward environmental monitoring needs associated with the petrochemical industry. Such tasks using the boats can be done more cheaply, efficiently and quickly than other existing technologies. Each robotic boat uses a base station that can communicate using wireless, 3G or EDGE within a 1.5-mile range. Notable work:

• In 2014, the company’s boats helped scientists measure water quality in Kenya’s Mara River.

More information at: senseplatypus.com

SENSEVERE
Key Researcher: Jason Gu
SenSevere provides semiconductor-based sensors for severe environments. These include elevated temperatures (500°C) and pressures (2500 PSI) as well as corrosive environments or deep sea wells. The sensors can detect hydrogen, hydrocarbons, ammonia and bromide. This has the power to improve both safety and environmental compliance for the power generation, environmental and chemical industries. These sensors can also be used in energy exploration, refineries, nuclear facilities and transportation. Notable achievement:

• Participant in the National Science Foundation I-Corps program

More information at:
engineering.cmu.edu/news-events/news/2017/05/19-hydrogen-sensor.html
Industry Device Manufacturing and Energy Efficiency
ARIECA

**Key Researcher:** Carmel Majidi

CMU researchers have developed soft and stretchable materials that have the elastic properties of rubber and the electrical and thermal properties of metal. These materials can be used as stretchable circuit wiring, insulators and heat dissipating substrates. Potential uses:

- Wearable technologies like smart textiles and orthotics
- Human-compatible robotics
- Electrically and thermally conductive rubber in uses such as:
  - Thermal pads in computing
  - Gaskets in machinery and automobiles

More information at: sml.me.cmu.edu?p=640

BLADE DIAGNOSTICS CORPORATION

**Key Researcher:** Jerry Griffin

Blade Diagnostics Corporation develops tools and methods for evaluating and controlling how mistuning affects the vibratory response of Integrally Bladed Rotors. Their innovations identify and predict effects of mistuning and vibration in these critical and expensive engine blades. Notable achievements:

- Received four Phase II SBIR awards
- Awarded RIF post-SBIR transition contract in 2012
- Their tool, SmartBlend, is now a part of the repair workflow at the U.S. Tinker Air Force Base in Oklahoma City.

More information at: bladediagnostics.com
CARBON NANOTUBE AEROGELS

**Key Researcher:** Mohammad Islam

CMU researchers are developing methods to link carbon nanotubes in aerogel constructs to provide materials that are lightweight and high strength. Carbon nanotubes (CNTs) have been shown to give a remarkable range of performance enhancement qualities to materials in which they are incorporated. Aerogel constructs enable these performance qualities to be achieved with very low concentrations of CNTs. Potential applications:

- Polymeric strengthening applications
- Transparent or non-transparent electrodes for computer displays, touchscreens and photovoltaics
- Uses for supercapacitors and batteries with high storage density

More information at: [sites.google.com/site/islamgroupcmu](http://sites.google.com/site/islamgroupcmu)

CARNEGIE ROBOTICS

**Key Researcher:** John Bares

Carnegie Robotics is the industry leader in building highly reliable robotics products to improve productivity, reliability and safety. The company's products have applications in the agriculture, mining, defense and oil and gas production markets. Notable achievements:

- Products are based on prototypes developed at the CMU National Robotics Engineering Consortium.
- Awarded $23 million AMDS contract in 2014

More information at: [carnegierobotics.com](http://carnegierobotics.com)

FABRICATION OF SOLAR SILICON

**Key Researcher:** Erik Ydstie

CMU researchers are developing an improved continuous casting process for making solar silicon wafers. The process is based on the float-glass process used to make plate glass, and will have dramatically lower waste and cost. For instance, the process will lower the cost of solar electricity by simplifying a formerly complex, expensive and wasteful process.

More information at: [youtube.com/watch?v=Wji3YBrxvHA](http://youtube.com/watch?v=Wji3YBrxvHA)
Industry Device Manufacturing and Energy Efficiency

LIQUID X PRINTED METALS

Key Researcher: Richard McCullough (former CMU faculty member)

Liquid X Printed Metals (Liquid X) is an advanced material manufacturer of functional metallic inks with a wide range of applications within the printed electronics and additive manufacturing markets. The company's technology is at the atomic level, which allows for processing advantages and better film properties than other metallic links. Processing advantages include:

- Inks are particle free with tunable viscosity and low conversion temperatures.
- Thin films can be made with high conductivity and excellent adhesion
- Inks can be printed via inkjet, flexography, gravure and aerosol jet.
- Upon application of energy (thermal, photonic, IR), inks convert to metal films/traces that have electrical conductivities close to that of the bulk metal — even at nanometer scale thickness.

More information at: liquid-x.com

MAGNETIC MATERIALS

Key Researcher: Michael E. McHenry

The magnetic materials developed at CMU will increase power density, lower losses, increase efficiency and reduce size and cost in power electronics. The materials are essential elements of a variety of power electronics equipment, such as transformers, inverters and motors. Potential applications and funding information:

- A large-scale, 35-ton transformer could be redesigned to about 450 pounds.
- Could enable more widespread adoption of rooftop solar energy production by commercial enterprises
- Funded by the Advanced Research Projects Agency – Energy

More information at:
arpa-e.gov/?q=slick-sheet-project/magnet-technology-power-converters

PLEXTRONICS

Key Researcher: Richard McCullough (former CMU faculty member)

Founded in Pittsburgh, this international technology company specializes in electronic inks for OLED (Organic Light Emitting Diode) displays, and lighting and electronic polymers. Electronic “inks” enable cheaper, more energy-efficient electronics, such as TVs and lighting applications. Plextronics was acquired by Solvay in March 2014. Current and future research includes:

- Developing electronic polymers that can be used for lithium-ion battery and polymer metal capacity applications
- Future applications expected to be organic photodetectors, thin film transistors and photovoltaics

More information at:
Optimization of Industry Energy Use

ANACTISIS

**Key Researcher:** Athanasios Karamalidis

Anactisis economically recovers rare earth elements from coal combustion fly ash and water that is used for hydraulic fracturing, geothermal energy and mine tailing settlement. Rare earth elements are needed for many electronic technologies, but material supply is limited, and access is often restricted. Notable achievements:

- Funded by a U.S. Department of Energy SBIR grant
- Participant in the National Science Foundation I-Corps program
- Funded by National Science Foundation SBIR grant

More information at: youtube.com/watch?v=3CWhyhST6hs&feature=youtu.be

ATRP SOLUTIONS

**Key Researcher:** Krzysztof Matyjaszewski

ATRP Solutions specializes in atom transfer radical polymerization (ATRP), developed by CMU Professor Krzysztof Matyjaszewski. ATRP creates well-defined polymeric materials that are used in a variety of commercial products and applications. For example, ATRP has created custom materials for oil field chemicals, which are used for hydraulic fracturing cleanout and drilling. Notable accomplishments:

- Raised a Series A round lead by Birchmere Ventures in June 2014
- Acquired by Pilot Chemical Co. in July 2017

More information at: atrpsolutions.com

D-POWERNET

**Key Researchers:** Gabriela Hug, Soumya Kar and Javad Mohammadi

CMU researchers developed a software that enables dynamic, distributed and parallel management of load balancing in electric power distribution networks. Potential applications include management of microgrids; integration of intermittent power sources; communications/control for demand response programs at the utility and large user levels; and parallelization of computing in centrally controlled utilities to increase speed of decision-making, reduce vulnerabilities and reduce reserve capacity requirements. Developing methods for dynamic control of commercial refrigeration and water heating to reduce peak demand charges and overall energy usage. Notable accomplishments:

- A participant in the National Science Foundation I-Corps program
- Approved as a DOE SHINES project to demonstrate "Sustainable and Holistic Integration of Energy Storage and Solar Photovoltaics"

More information at: energy.gov/eere/solar/project-profile-carnegie-mellon-university-shines
**Industry Device Manufacturing and Energy Efficiency**

**GREENOX CATALYSTS, INC.**

**Key Researchers:** Terry Collins and Colin Horwitz

GreenOx Catalysts, Inc. designs, develops and supplies iron-based oxidation catalysts. These “green” catalysts reduce energy, water and chemical use, which lowers waste disposal costs, and can be used in many commercial applications. Development partners include VeruTEK Technologies, Recombinant Innovation and Scion laboratories.

More information at: greenoxcatalysts.com

**THE OPTIMIZATION FIRM**

**Key Researcher:** Nick Sahinidis

The Optimization Firm offers high-performance computing solutions for complex numerical optimization problems. These solutions help companies make complex decisions based on mathematical models. An example of what the company can assist with is the pooling problem that refinery operators worldwide encounter. Even the slightest improvement in these refinery scheduling operations yields savings of millions of dollars. The company offers:

- ALAMO software for building models from data and simulations
- BARON software for global optimization of mixed-integer nonlinear optimization problems

More information at: theoptimizationfirm.com

**VORTXX SEMICONDUCTOR**

**Key Researcher:** Wojciech Maly

This CMU spin-off is designing products that will reduce the density of electronics, therefore lowering power consumption. This approach achieves “next-generation” Moore's Law levels of performance while being able to utilize current generation fabrication equipment. While it is in its early stages, simulations prove the feasibility of this approach. Notable achievement:

- Funded by the Defense Advanced Research Projects Agency (DARPA)

More information at: bit.ly/2j4ZHqa
Commercial Facility and Residential Energy Management
Commercial Facility and Residential Energy Management

**BUILD FIT**

**Key Researcher:** Azizan Aziz

BuildFIT is an upcoming CMU spin-off that develops systems for data collection using analytics and visualization on energy usage to reveal actionable information for building occupants, managers and owners. BuildFIT’s review of energy savings opportunities over a portfolio of buildings helps facility managers target projects with the best return on investment. Notable accomplishment:

- Helped reduce PNC Bank’s energy consumption by 35 percent during a pilot project

More Information at: cmu.edu/cbpdanalytics

**BUILDING MODEL DATA EXTRACTION SOFTWARE**

**Key Researcher:** Khee Poh Lam

Lam’s building model data extraction software automatically pulls data out of digital building design models and populates data into the correct fields of compliance documents. While the LEED application process can take days to weeks just for the energy efficiency section, which contains approximately 1,400 fields, this software can make the application process happen in a matter of minutes.

- Saves costs and reduces entry errors in LEED application process
- Facilitates “what if” assessment of different design options to determine their impact on LEED scores
- Has been licensed to DesignBuilder

More information at: designbuilder.com

**BUILDSIMHUB INC.**

**Key Researcher:** Weili Xu

BuildSimHub Inc. provides energy modeling solutions throughout a building’s lifecycle. It brings innovative technologies to make energy modeling efficient and more accessible by the AEC industry. Since 2017, the company has launched its cloud-based product, BuildSimHub, which is the first GIT-based (version control software system) energy model management platform. The platform offers project management, team collaboration and workflow automation, creating an end-to-end solution for architecture and engineering firms and building system manufacturers.

More Information at: buildsim.io
ENCAPSULATED PHASE CHANGE MATERIAL CONTAINERS

**Key Researchers:** Dale Clifford and S.C. Yao

These phase change materials store or release heat during a freeze/thaw phase calibrated to occur at room temperature, potentially reducing the cost of heating and cooling by 25 percent. 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.

Notable achievements:
- Currently funded by the National Science Foundation and the American Institute of Architects

More information at: cmubiologic.weebly.com/frick-environemental-center.html

LEANFM TECHNOLOGIES

**Key Researchers:** Burcu Akinci and Xuesong Liu

LeanFM Technologies is a lifecycle software solution for economic, proactive and intelligent Facilities Management (FM). LeanFM leverages Building Information Modeling (BIM) and cloud computing technology to integrate the heterogeneous building information that is recorded in disparate media, making FM greener and more efficient.

Notable achievements:
- Recipient of the *Pittsburgh Business Times* inaugural 2017 Innovation Award
- Recipient of a National Science Foundation SBIR grant

More information at: leanfmtech.com

Residential Design and Energy Management Services

**EEME, LLC**

**Key Researcher:** Enes Hoşgör

This Carnegie Mellon spin-off 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 in a given service territory. Residential users are given personalized EE recommendations along with relevant economic metrics, while program managers can analyze their customer base using the utility heat map dashboard.

Notable achievement:
- Their Green Button compatible platform solution is designed to connect all EE stakeholders.

More information at: eeme.io

New in 2018

**MODULE**

**Key Researcher:** Hallie Dumont

Module housing creates a more sustainable, energy-efficient starter home. Their end-to-end platform and construction technology provides an affordable and flexible entry point for homeownership. With this pay-as-you-go housing solution, a one bedroom starter unit can turn into a three bedroom house, providing buyers with the right amount of space at the right time.

More information at: modulehousing.com
OPERETTA

Key Researcher: Khaled A. Harras

OPERETTA is an energy-efficient optimal deployable bandwidth aggregation system. It 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, Wi-Fi and Bluetooth. The systems allows users to choose between interfaces based on factors such as speed, energy consumption and cost. It also operates without changes in existing infrastructure.

More information at: cmu.edu/homepage/society/2012/fall/mobile-solutions.shtml

SPARKMETER

Key Researchers: Anthony Rowe and Dan Schnitzer

SparkMeter electricity meters enable grid operators to implement pre-payment as well as real-time monitoring and control. By improving cost recovery, these electric grids become more reliable for lower-income households throughout the world whose only alternatives are expensive, inefficient and dangerous fuels like kerosene and candles. Notable achievement:

• SparkMeter supports connections in 15 countries, with more added daily

More information at: sparkmeter.io

Residential Environmental Monitoring

MELLONHEAD LABS

Key Researcher: CREATE LAB

MellonHead Labs is a CMU spin-off commercializing the CATTfish and FlaminGO water sensors developed in the CREATE Lab at CMU. These sensors can be used to monitor changes in water quality inside the home or outside in streams, rivers and ponds, with a simple graphic representation of the interpreted data collection.

More information at: cattfish.com

SPECK

Key Researcher: Illah Nourbakhsh

The Speck airborne particle counting device was developed in the CREATE Lab at Carnegie Mellon. It monitors fine particle concentration levels in homes and displays the data in an understandable way. This knowledge empowers people susceptible to asthma or other conditions to reduce particulate exposure by opening or closing windows, altering activities or taking action such as using HEPA air filters. Notable work:

• Citizen groups have used Speck to monitor particulates emitted by coke batteries or by natural gas production
• Currently being commercialized by CMU spin-off company Airviz
• Recently obtained an investment from InfoSys

More information at: specksensor.com
Transit Energy Management
Traffic Management

RAPID FLOW TECHNOLOGIES

Key Researchers: Greg Barlow and Stephen Smith

Rapid Flow Technologies combines research from artificial intelligence and traffic theory to optimize traffic signals for the traffic that is actually on the road. This leads to less waiting, reduced congestion, shorter trips, less pollution and happier drivers. Notable achievements:

- A Pittsburgh demonstration project on nine intersections reduced travel time by 26 percent
- Technology is now implemented in 47 Pittsburgh intersections
- The spin-off is developing a ubiquitous Bluetooth AVI sensor network technology for ITS performance modeling and other applications through a Small Business Innovation Research (SBIR) grant from the U.S. Department of Transportation
- Recipient of the Pittsburgh Business Times 2017 Innovation Award

More information at: rapidflowtech.com

VIRTUAL TRAFFIC LIGHTS

Key Researcher: Ozan Tonguz

With this technology cars and trains autonomously communicate with each other to determine right of way at intersections without traffic lights. Computer simulations indicate a potential 60 percent improvement in traffic flow in a full-city simulation.

More information at: ece.cmu.edu/directory/department/faculty/T/Ozan_Tonguz_179.html

Light Duty Vehicle Management

HYLIION

Key Researcher: Thomas Healy

Hyliion has developed an add-on hybrid suspension system for long-haul, over-the-road delivery fleets that face large costs associated with diesel fuel. The system uses regenerative braking to capture power when the vehicle is slowing down and reuses the energy to accelerate, reducing fuel consumption. Notable benefits:

- Reduces energy consumption by over 30 percent
- Return on investment in less than one year
- Award winning system: Winner of DOE student business competition in 2015

More information at: hylion.com
OTTOMATIKA

Key Researcher: Raj Rajkumar

Ottomatika provides software and systems development for autonomous cars. It focuses on automating driving functions of automobiles and other transportation to increase the safety, efficiency and affordability of vehicles in the transportation sector. Notable achievements:

• Partnered with General Motors
• Additional support from the U.S. Department of Transportation and the National Science Foundation
• Acquired by Delphi Automotive PLC in 2015
• Ottomatika-powered Delphi self-driving vehicles received a Best of CES (International Computer Electronics Show) 2015 award from Mashable

More information at:

Fuel Generation

BIOHYBRID SOLUTIONS

Key Researchers: Kris Matyjaszewski and Alan Russell

BioHybrid Solutions commercializes polymer-based protein engineering technology based on the controlled radical polymerization for applications in such areas as pharmaceuticals, biocatalysis and energy. It allows for targeted and predicted modification of proteins, resulting in high-efficacy protein-polymer conjugates. Notable achievements:

• Named one of 40 “Best University Startups” by the National Council of Entrepreneurial Tech Transfer
• Awarded DOE SBIR grant

More information at biohybridsolutions.com/

Public Transportation

ROADBOTICS

Key Researcher: Christoph Mertz

RoadBotics uses computer vision and machine learning to analyze and map road conditions and irregularities, as a tool for decision-makers. The technology:

• Detects and assesses severity of potholes
• Detects snow conditions on roads
• Detects road signage conditions and visibility
• Mounts on the windshield of a car or plow
• Analyzes and maps data

More information at: roadbotics.com
Transit Energy Management

**TIRAMISU TRANSIT**

*Key Researcher: Anthony Tomasic*

This CMU spin-off has developed a crowd-powered transit bus information system that gives information on bus schedules, seat availability and problematic situations. It encourages use of public transportation, thus reducing energy consumption by motor vehicles used typically as an alternative, as well as overall congestion by vehicles on the road. Notable features:

- Useful for riders in wheelchairs and those with visual disabilities
- Available on iTunes and Android Market for bus systems in Pittsburgh and New York City
- Funded by SBIR grants

More information at: [tiramisutransit.com](http://tiramisutransit.com)

**Industry Vehicles**

**CARBON FREIGHT**

*Key Researchers: John Dieser and Glen Philen*

Carbon Freight builds durable, lighter-weight shipping pallets that reduce the amount of energy consumed for freight transportation. Notable features:

- Reduces number of trips by shipping more pallets per mile
- Increases miles per gallon by reducing weight of transported goods
- Part of the National Science Foundation I-Corps program

More information at: [carbonfreight.com](http://carbonfreight.com)
Conclusion
Conclusion

Throughout this technology guide, you’ve seen next-generation energy technologies developed at Carnegie Mellon or by CMU alumni 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 and the Breakthrough Institute 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

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.” 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; 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


<table>
<thead>
<tr>
<th>Time Required to Innovate</th>
<th>Pharmaceutical</th>
<th>Software &amp; IT</th>
<th>Energy</th>
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<tbody>
<tr>
<td>10-15 years</td>
<td>1-5 years</td>
<td>10-15 years</td>
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<table>
<thead>
<tr>
<th>Capital Required to Innovate</th>
<th>Pharmaceutical</th>
<th>Software &amp; IT</th>
<th>Energy</th>
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</thead>
<tbody>
<tr>
<td>Medium to High</td>
<td>Low to Medium</td>
<td>High</td>
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<table>
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<tr>
<th>New Products Primarily Differentiated by</th>
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<th>Software &amp; IT</th>
<th>Energy</th>
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<tr>
<td>Function/Performance</td>
<td>Function/Performance</td>
<td>Cost</td>
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<th>Actors Responsible for Innovation</th>
<th>Pharmaceutical</th>
<th>Software &amp; IT</th>
<th>Energy</th>
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</thead>
<tbody>
<tr>
<td>Large firms reinvesting in R&amp;D; Biotech startups, often VC and government funded; Government (NIH, NSF)</td>
<td>Dynamic startups, often VC funded; Large firms reinvesting in R&amp;D</td>
<td>Various: Utilities, oil &amp; gas companies, power tech companies, startups and government</td>
<td></td>
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</table>

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<th>Typical Industry Risk Tolerance</th>
<th>Pharmaceutical</th>
<th>Software &amp; IT</th>
<th>Energy</th>
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<tbody>
<tr>
<td>High</td>
<td>High</td>
<td>Low</td>
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<th>Innovation Intensity</th>
<th>Pharmaceutical</th>
<th>Software &amp; IT</th>
<th>Energy</th>
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</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
<td>Low</td>
<td></td>
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<tr>
<th>Intellectual Property Rights</th>
<th>Pharmaceutical</th>
<th>Software &amp; IT</th>
<th>Energy</th>
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<tbody>
<tr>
<td>Strong</td>
<td>Modest</td>
<td>Modest</td>
<td></td>
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</tbody>
</table>
Conclusion

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

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 Rapid Flow Technologies’ 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 Sciences11 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 policymakers 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 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 a plethora of laws at all levels 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.

In sum, 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 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. These ideas may have arisen 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 Swartz Center for Entrepreneurship, including Project Olympus and the NSF-sponsored I-Corps program.

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 percent 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 percent equity interest in the startup company, and assesses a 2 percent 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 to say “yes” to filing a provisional patent application and then to support the inventor in an initial exploration of market interest in the 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, the Swartz Center 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.
Conclusion

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 disclosures per research dollar, and the best (highest) ratio of startups to research funding in the country with 41 startups in fiscal year 2014. CMU directly and indirectly launched 200 companies from FY2011-2017. CMU startup companies have raised over $1B in venture capital investment since 2011.

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.
LEED (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. More information at: usgbc.org/leed.

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


CMU internal data from CTTEC and Swartz Center for Entrepreneurship.
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