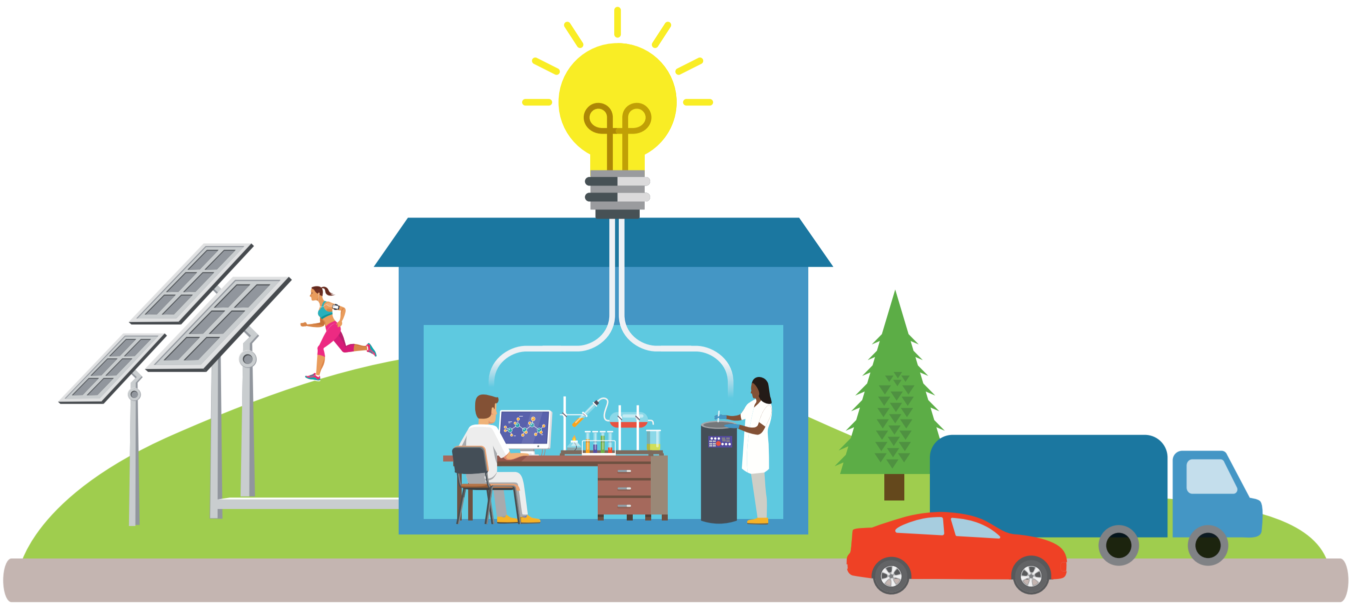
TECHNOLOGY GUIDE

Innovative Energy Technologies: The Next Generation



Carnegie Mellon University
Scott Institute
for Energy Innovation

Our lifestyle is sustained by energy.

Scott Institute for Energy Innovation Director, CMU Professor and Aquion Energy Founder and former Chief Scientist Jay Whitacre, stands next to the company's high-performance Aspen battery. Jay was also Chief Technical Officer.

Hyliion created a regenerative braking device that can be installed on long-haul trucks. Pictured here is Hyliion CEO and CMU alumnus Thomas Healy, who was named to *Forbes* 30 under 30 Energy 2017.

Hahna Alexander, a CMU alumna and the co-founder and CEO of SolePower, creates products, like the one pictured at the right, to generate on-the-go, renewable power for mobile energy needs.

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

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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**

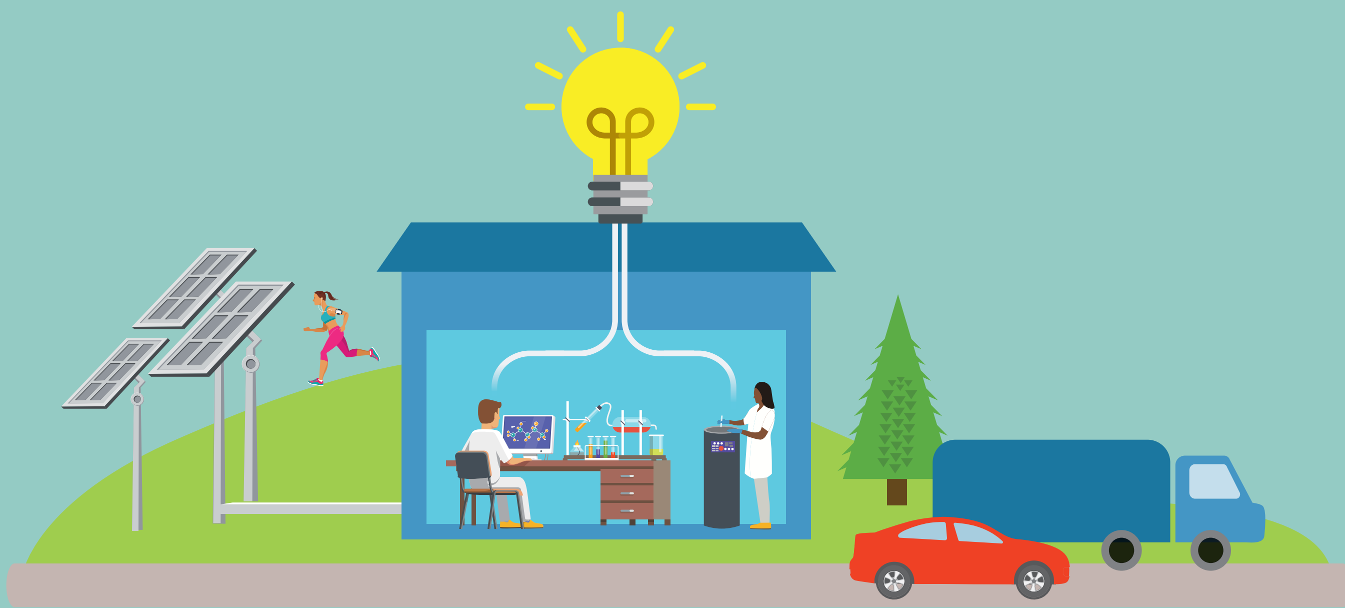
Carnegie Mellon's longstanding expertise in technology, policy, integrated systems and behavioral and social science is uniquely suited to addressing these challenges. What makes us different is our ability to seamlessly combine these areas for maximum impact.

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, Professor 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 and Jenni Miller. 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.

FOR MORE INFORMATION about Carnegie Mellon's Wilton E. Scott Institute for Energy Innovation and the research discussed in this guide, visit cmu.edu/energy. If you have questions about this guide, please contact Dr. Deborah Stine, Associate Director for Policy Outreach of the Scott Institute, at dstine@andrew.cmu.edu.



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.

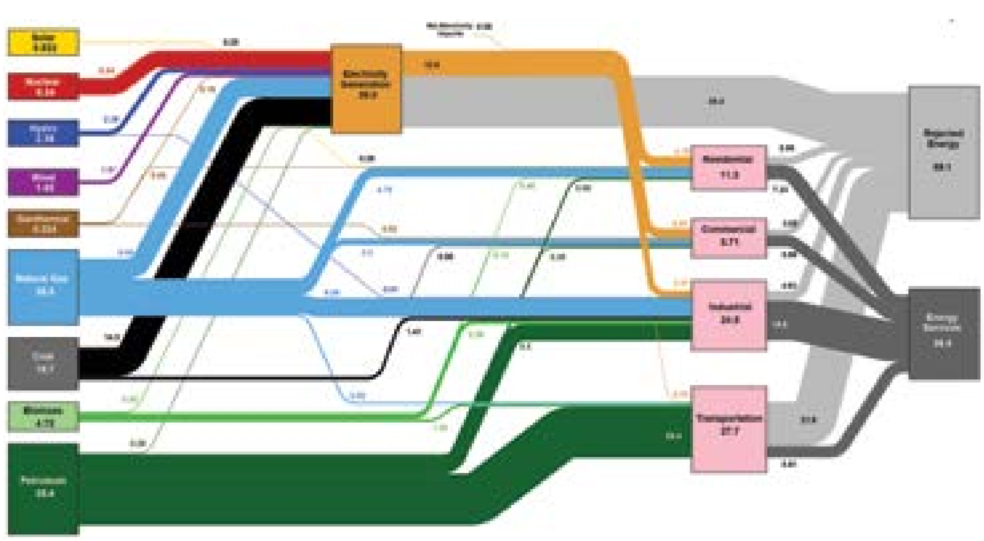


FIGURE 1.
Energy Generation and Consumption Flows, 2015. This diagram shows 2015 energy flow from primary sources (oil, natural gas, coal, nuclear and renewables) through transformations (electricity generation) to end uses (transportation, industry and residential and commercial sectors). Oil provided 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.

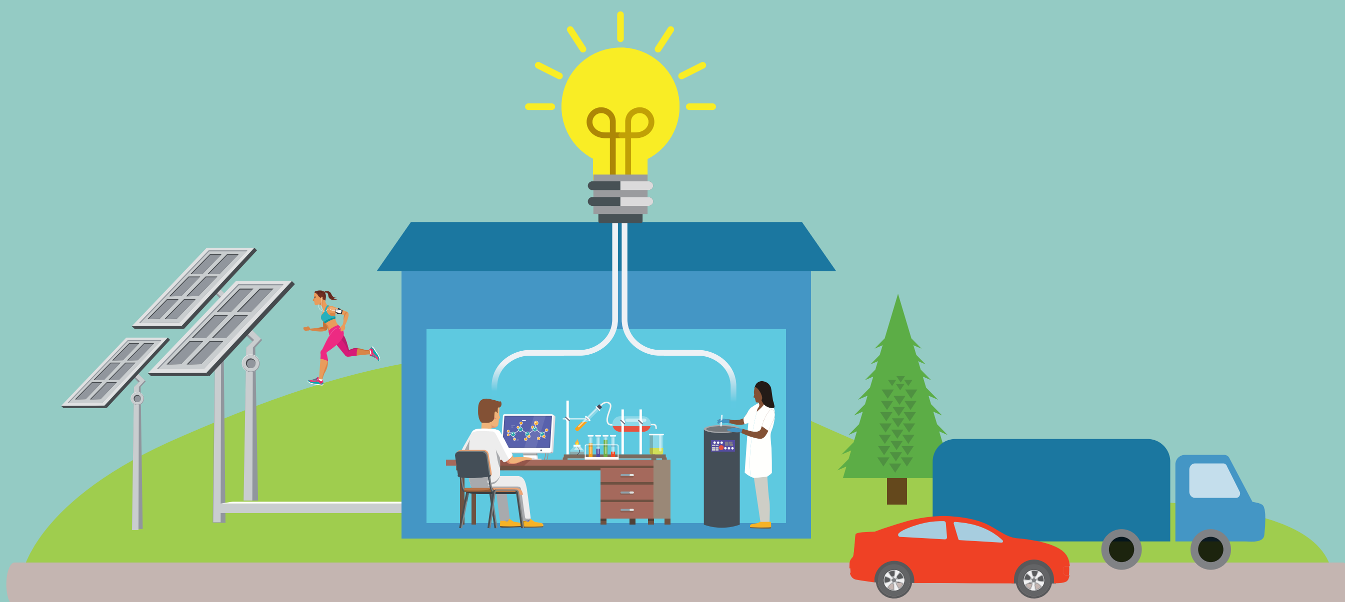
Source: Data is from the Lawrence Livermore National Laboratory flowcharts.llnl.gov.

Caption modified from U.S. Department of Energy at science.energy.gov/bes/community-resources/energy-flow/energy-flow-diagram.

Overview

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" (http://www.cmu.edu/energy/public-policy/Managing%20variable%20energy%20resources.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 weekly 90-second radio program in partnership with Pittsburgh's NPR News Station where listeners can learn about energy innovation opportunities and challenges related to everyday life.

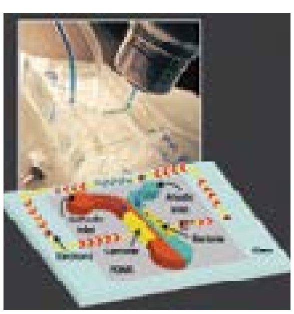


Energy Generation, Conversion, Storage and the Environment

Energy Generation, Conversion, Storage and the Environment

Stationary Source Energy Generation, Storage and Conversion

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. 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. The AHI battery is the only sustainable battery ever to be Cradle to Cradle Certified. Among its many awards are the 2011 World Technology Award, the Global Cleantech 100, MIT Technology Review's 50 Disruptive and 50 Smartest Companies. Aquion has received funding from Bill Gates, Kleiner Perkins Caufield & Byers, Foundation Capital, Advanced Technology Ventures and others. The Founder and former Chief Scientist and Technical Officer, Professor Jay Whitacre, received the 2015 $500,000 Lemelson-MIT Prize for "his groundbreaking sustainable inventions to improve our world and dedication to the next generation." He developed the first mass-produced, low-cost, eco-friendly battery. He was also named by *Fortune Magazine* as one of the world's Top 25 Eco Innovators, and received the Carnegie Science Center Advanced Materials Award and the Caltech Resnick Sustainability Institute Award "for research and development of scalable, environmentally benign, low cost grid-scale energy storage." Aquion was acquired in June 2017 by a U.S.-based branch of Titans Energy Technology Group. Aquion retains its separate corporate identity. Key Researcher: Jay Whitacre. More information at: 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. In the human body, such devices can be used for glucose sensors. 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: cmu.edu/cee/news/news-archive/2013/2013-energy-part-one.html.

Teratonix, an upcoming CMU spin-off, is developing high-speed diodes that have extremely high cut-off frequencies, in the hundreds of terahertz range. Other technologies can work in the high gigahertz and single digit terahertz range. The ability to operate in frequency ranges at that scale could lead to a variety of applications including medical imaging without radiation, aerial surveillance through clouds, airport security screening, pharmaceutical product inspection and energy harvesting (the capturing and storage of energy from an external power device like a solar panel) with potential efficiencies of 80 percent. Teratonix is focused on the development of energy harvesting devices that could initially power sensors, phones and computers. In the future, it could provide room air conditioning while generating power. Key Researcher: Yi Luo. More information at: http://bit.ly/2jWifIb.

Solar Selective Absorbers: At present, the conversion of solar energy into electricity mainly relies on two approaches: solar photovoltaics that convert solar photons directly into electricity, and solar thermal energy conversion in which solar photons are first converted into thermal energy, then converted to electricity. Compared to traditional photovoltaics, one major advantage of solar thermal energy conversion is the utilization of nearly the entire solar spectrum, allowing for higher energy conversion efficiency. However, developing cost-effective and large-scale solar selective absorbers with both high-conversion efficiency and high-temperature stability remains a challenge. CMU researchers have demonstrated metal-based, wafer-scale nanophotonic solar selective absorbers with excellent solar selective absorptivity and thermal stability. Key Researcher: Sheng Shen. More information go to: onlinelibrary.wiley.com/doi/10.1002/adma.201501686/full.

Energy Generation, Conversion, Storage and the Environment

Personal Device Energy Generation and Storage

SolePower is an innovative technology company striving to power small mobile electronic devices through the use of a person's everyday movement. 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 waterproof and can be placed inside 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 at 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: 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. The process begins with the patient's consumption of a pill made of biodegradable material. 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 that pass through the human body in a few hours once the material encapsulating it biodegrades. Key Researchers: Christopher Bettinger and Jay Whitacre. More information at cmu.edu/homepage/health/2013/spring/incredible-edible.shtml.

Hillside Hydro: Hillside Hydro has developed a micro hydroelectric generator to recharge electronic devices from moving water. Their design harnesses 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, the energy can be used to charge any devices via USB. Founded by Mechanical Engineering student, Hunter Hartshorne. Key Researcher: Hunter Hartshorne. More information at: hillsidehydro.com.

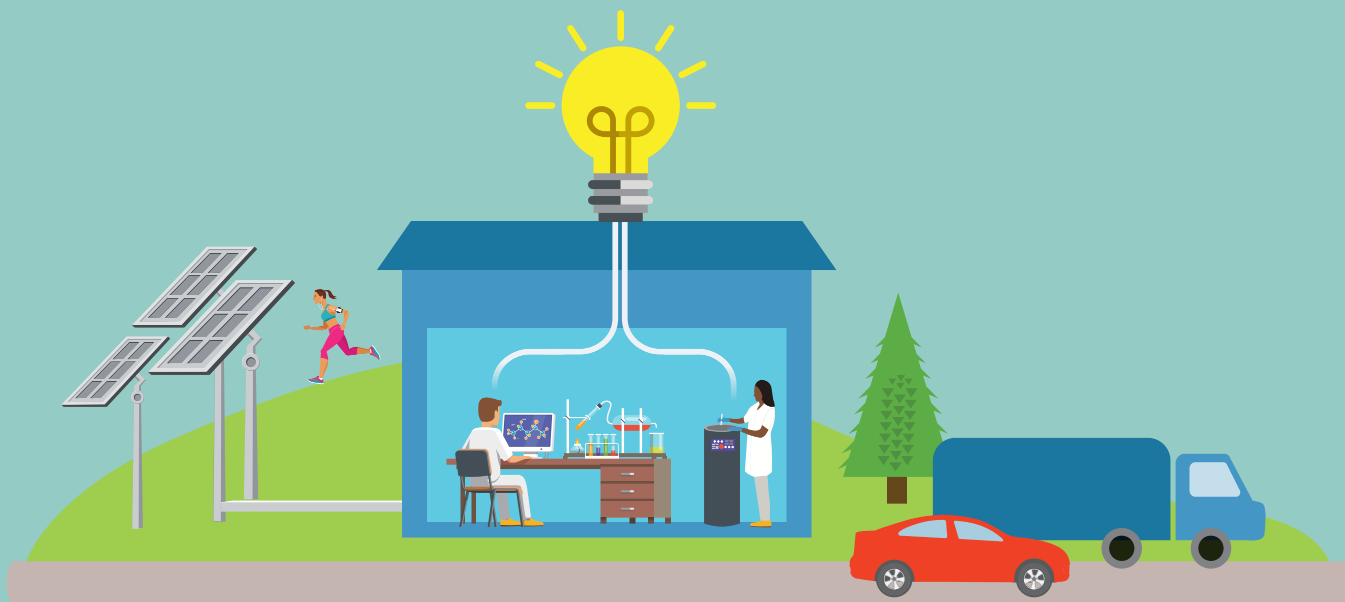
Sensing and Mapping

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, plus waterway 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 at: senseplatypus.com.

SenSevere, a CMU spin-off company, provides semiconductor-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 industries. In the energy field, these sensors can be used in energy exploration, refineries, power generation, nuclear facilities and transportation. SenSevere was a participant in the National Science Foundation's I-Corps program. Key Researcher: Jason Gu. More information at: sensevere.com.

Mine Vision Systems, a CMU spin-off, is commercializing a vision-based system that can be used for the mapping of underground mines. Unlike prior systems based on accelerometers, this system provides a high degree of accuracy. This accuracy enables monitoring for production and safety, and can also provide visual information for equipment operators from additional perspectives. Key Researcher: Brett Browning. More information at: minevisionsystems.com.

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 manual inspection techniques. The company was assisted in its launch by Y Combinator. The founders won the energy category in the Rice Business Plan Competition in 2016, and Gecko Robotics was the overall winner at the TransTech Energy Conference at West Virginia University in 2016. The system was developed by students at CMU and Grove City College. Key Researcher: Troy Demmer. More information at: geckorobotics.com.

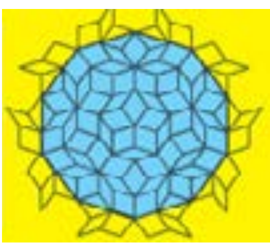


Industry Device Manufacturing and Energy Efficiency

Industry Device Manufacturing and Energy Efficiency

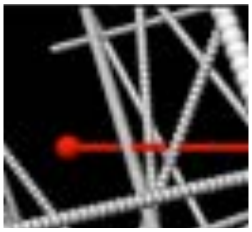
Energy, Materials and Manufacturing

Plextronics is an international CMU spin-off 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 Researcher: Former CMU faculty Richard McCullough. More information at: plextronics.com.



Magnetic Materials are essential elements of a variety of power electronics equipment, such as transformers, inverters and motors. The novel magnetic materials being 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. This work has been funded by the Advanced Research Projects Agency-Energy (ARPA-E). Key Researcher: Michael E. McHenry. More information at: https://arpa-e.energy.gov/?q=slick-sheet-project/magnet-technology-power-converters.

Fabrication of solar silicon is a complex, expensive and wasteful process, adding significantly to the cost of solar electricity. The current process involves casting silicon in a cylinder shape and then cutting thin slices from that cylinder to make the wafers, resulting in 50 percent of the silicon being wasted. CMU researchers are developing an improved continuous casting process for making solar silicon wafers based on the float-glass process used to make plate glass. The new process will have dramatically lower waste and cost. Key Researcher: Erik Ydstie. More information at: youtube.com/watch?v=WJi3YBrxvHA.



Carbon Nanotube Aerogels: Carbon nanotubes have been shown to give a remarkable range of performance enhancement qualities to materials in which they are incorporated. CMU researchers are developing methods to link carbon nanotubes (CNTs) in aerogel constructs to provide materials that are lightweight and high strength, with multiple commercial applications including polymeric strengthening applications. The aerogel constructs enable these performance qualities to be achieved with very low concentrations of CNTs. Other properties of the aerogels make them suitable for use as transparent or non-transparent electrodes for computer displays, touchscreens and photovoltaics. Other potential applications include supercapacitors and batteries with very high storage density. Key Researcher: Mohammad Islam. More information at: sites.google.com/site/islamgroupcmu.

Liquid X Printed Metals (Liquid X) is an advanced material manufacturer of functional metallic inks. It is pushing the boundaries of functional electronics fabrication by enabling additive manufacturing techniques. The inks can be printed via inkjet, flexography, gravure and aerosol jet and upon applying energy (thermal, photonic, IR), convert to metal films/traces that have electrical conductivities close to that of the bulk metal — even at nanometer scale thickness. The technologies apply to a wide range of applications within the printed electronics and 3-D printing markets. These inks are unique because unlike other metallic inks, they are not nanoparticle or flake-based. Since the technology is at the atomic level, Liquid X has processing advantages (particle free, tunable viscosity, low conversion temperatures) and achieves better film properties (high conductivity, thin films, excellent adhesion) than competitive metallic inks. Key Researcher: Former CMU faculty Richard McCullough. More information at: liquid-x.com.

Carnegie Robotics, a CMU spin-off, builds highly reliable robotics products to improve productivity, reliability and safety in the agriculture, mining, defense and oil and gas production markets. These products are based on prototypes developed at the National Robotics Engineering Consortium. For example, robust perception sensors are used to explore tunnels, mines and underground pipes. More information at: carnegierobotics.com.

Blade Diagnostics Corporation (BDC): BDC develops tools and methods for evaluating and controlling how mistuning affects the vibratory response of Integrally Bladed Rotors. BDC technologies identify and predict the effects of mistuning and vibration on these critical and expensive engine blades. Spun out by former professor of Mechanical Engineering, Jerry Griffin. Key Researcher: Jerry Griffin. More information at: bladediagnostics.com.

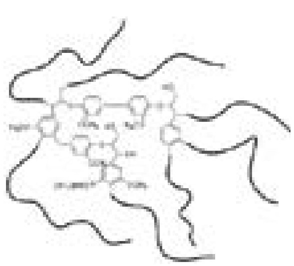
Industry Device Manufacturing and Energy Efficiency

Optimization of Industry Energy Use

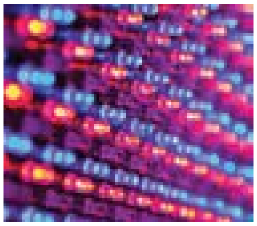
The Optimization Firm offers custom and packaged high-performance computing solutions for complex numerical optimization problems. These software solutions assist companies with complex decisions based on mathematical models. For example, the pooling problem is an optimization problem, solved using software 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: theoptimizationfirm.com.

D-Power Net, an upcoming CMU spin-off, is developing software that will enable dynamic, distributed, parallel management of load balancing in electric power distribution networks. Potential applications include management of microgrids; integration of intermittent power sources; communication/control for demand response programs at the utility and larger-user levels; and parallelization of computing in centrally-controlled utilities to increase the speed of decision-making, reduce vulnerabilities and reduce reserve capacity requirements. This company is a participant in NSF's I-Corps Program. D-Power Net was approved as a Department of Energy SHINES project to demonstrate "Sustainable and Holistic Integration of Energy Storage and Solar Photovoltaics." For their project, they will dynamically link solar production, storage and a utility grid. Key Researchers: Gabriela Hug, Soummya Kar and Javad Mohammadi. More information at: energy.gov/eere/sunshot/project-profile-carnegie-mellon-university-shines.

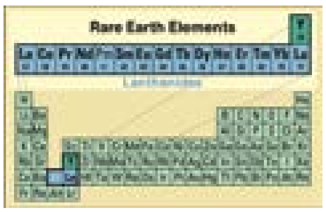
ATRP Solutions, a CMU spin-off, manufactures custom materials and specializes in atom transfer radical polymerization (ATRP). ATRP, developed by CMU Professor Krzysztof Matyjaszewski, is a highly evolved process that creates well-defined polymeric materials. ATRP has rapidly emerged as the leading process for generating these materials for a wide variety of commercial products and applications, including oil field chemicals for hydraulic fracturing cleanout and drilling. ATRP raised a Series A round lead by Birchmere Ventures in June 2014. Key Researcher: Krzysztof Matyjaszewski. More information at: atrpsolutions.com.



Salix Lignopolymers, a CMU spin-off, is developing a sustainable lignin-based technology for use in the hydraulic cement market as a novel cement additive. These additives allow a significant reduction in the amount of water needed, which lowers costs and increases the strength of the concrete. The materials can also be used as a foaming agent for natural gas extracting. This innovation has received an SBIR grant and is part of the NSF I-Corps program. Key Researcher: Newell Washburn. More information at: sbir.gov/sbirsearch/detail/966773.

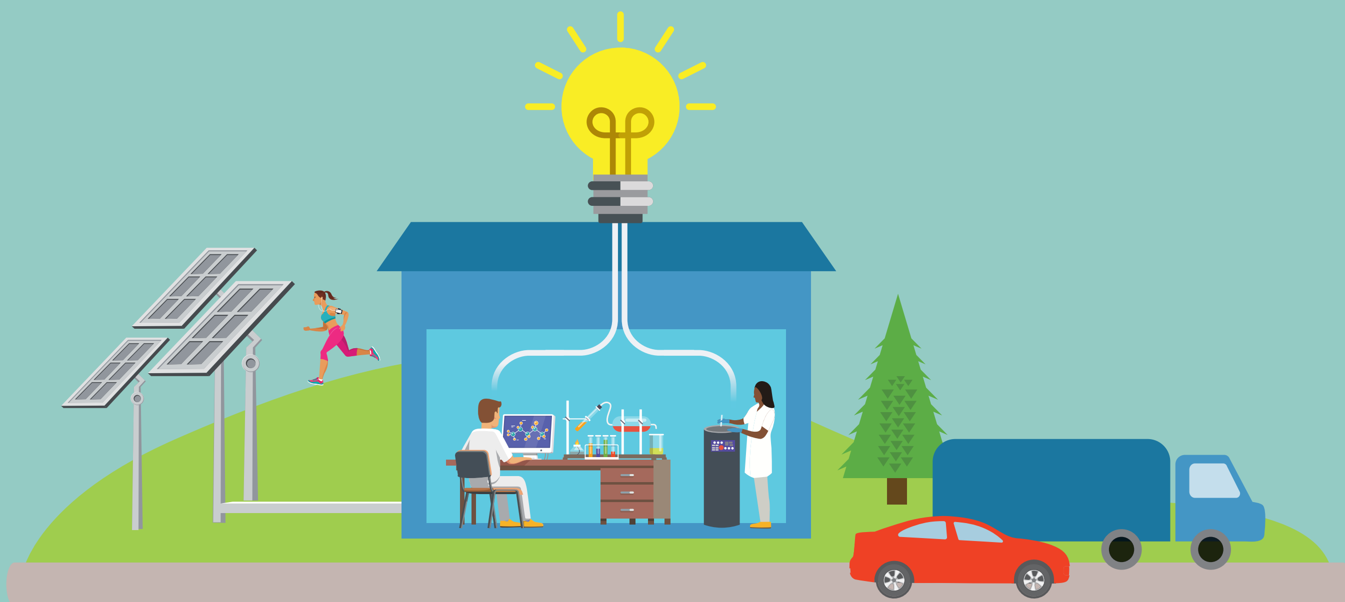


Vortxx Semiconductor, a CMU spin-off, is developing a new approach to designing electronics that would result in significant improvements in the density of the electronics and therefore also lower power consumption. This approach achieves "next-generation" Moore's Law levels of performance while being able to utilize current generation fabrication equipment. The development is in the early stage, but extensive simulations and initial silicon manifestations demonstrate the feasibility of the approach. Vortxx is funded by the Defense Advanced Research Projects Agency (DARPA). Key Researcher: Wojciech Maly. More information at: http://bit.ly/2j4ZHqa.



Anactisis, a CMU spin-off, develops methods to economically recover rare earth elements from water. For example, it can recover these elements from water used for hydraulic fracturing, geothermal energy and mine tailings settlement. These rare earth elements are needed for a wide range of electronic technologies, but the supply of materials is limited. Further, since most of the mines that hold these materials are in China, which sometimes has restricted access to these materials, it is important to have alternative ways of gathering them. This work has been funded by a U.S. Department of Energy SBIR grant, and is a participant in the NSF I-Corps Researcher: Athanasios Karamalidis. More information at: sbv.org/projects/geothermal-round2-anactisis.html.

GreenOx Catalysts, Inc. designs, develops, and supplies iron-based oxidation catalysts for a broad range of commercial applications. The "green" catalysts create value by reducing energy, water and chemical usage; lowering waste disposal costs; and improving overall process efficiencies. Development partners include VeruTEK Technologies, Recombinant Innovation and Scion laboratories. Key Researchers: Terry Collins and Colin Horwitz. More information at: greenoxcatalysts.com.

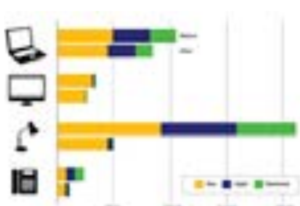


Commercial Facility and Residential Energy Management

Commercial Facility and Residential Energy Management

Commercial Facility Design and 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. They are a recipient of an NSF SBIR grant. Key Researchers: Burcu Akinci and Xuesong Liu. More information at: linkedin.com/company/leanfm-technologies-llc.



BuildFit, an upcoming CMU spin-off company, is developing systems for data collection, analytics and visualization on energy usage to reveal actionable information for building occupants, managers and owners. Their approach to analyzing energy usage at the individual occupant level led to a 35 percent reduction in energy consumption in a pilot project with PNC Bank. Their system scales to enable a review of the energy savings opportunities over an entire portfolio of buildings, and to target investments toward projects with the best return on investment. Key Researchers: Azizan Aziz and Bertrand Lasternas. More information at: cmu.edu/cbpdanalytics.

Building model data extraction software automatically pulls data out of digital building design models and populates that data into the correct fields of compliance documents. 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 1,400 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. This technology has been licensed to DesignBuilder: designbuilder.co.uk.

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, 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. Key Researchers: Dale Clifford and S.C. Yao. More information at: cmubiologic.weebly.com/frick-environemental-center.html.

BuildSimHub: Harnessing the powerful GIT and advanced data mining technology, BuildSimHub is an innovative big data management and cross-functional collaboration platform tailored for building energy modeling. They are creating a data-driven and agile development framework for the architecture industry. Key Researcher: Weili Xu, Entrepreneurial/Academic Lead, Ph.D. student, CMU School of Architecture/CBPD.

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: www.eeme.io.

Commercial Facility and Residential Energy Management

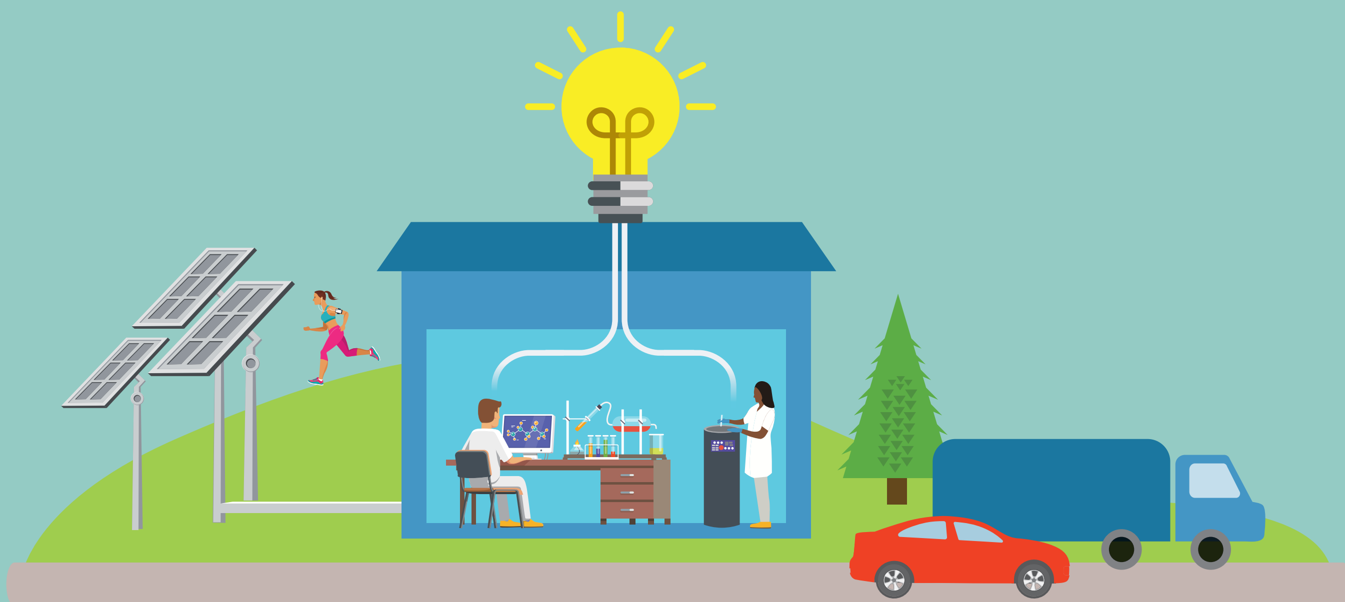
SparkMeter provides electricity meters for low-income households throughout the world. Central grid utilities, local initiatives, social entrepreneurs and global institutions around the world are striving to expand electricity access, yet sustainable business models to deliver grid-level electricity 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 Researchers: Anthony Rowe and Dan Schnitzer. More information at: www.sparkmeter.io.

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, Wi-Fi 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 this technology. Key Researcher: Khaled A. Harras. More information at: cmu.edu/homepage/society/2012/fall/mobile-solutions.shtml.

Residential Environmental Monitoring

Speck is an airborne particle counting device developed in the CREATE Lab at Carnegie Mellon. Speck monitors fine particle concentration levels in homes and can be used by people susceptible to asthma or other conditions. Citizen groups have also used Speck to monitor particulates emitted by coke batteries or by natural gas production. Knowledge of particulate levels empowers people to reduce exposure by opening or closing windows, altering activities or taking action such as using HEPA air filters. Speck is being commercialized by CMU spin-off company Airviz, and recently obtained an investment from InfoSys. Key Researcher: Illah Nourbakhsh. More information at: specksensor.com.

MellonHead Labs, a CMU spin-off, is 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. The data collection (e.g., water conductivity, temperature, etc.) and interpretation is simplified and large data sets can be graphically visualized. Key Researchers: CREATE Lab. More information at: cattfish.com.



Transit Energy Management

Transit Energy Management

Traffic Management

Rapid Flow Technologies, a CMU spin-off, 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: rapidflowtech.com.

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 percent improvement in traffic flow in a full-city simulation. Key Researcher: Ozan Tonguz. More information at: users.ece.cmu.edu/~tonguz/vtl/about.html.

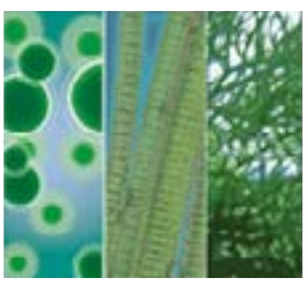
Light Duty Vehicle Management

Ottomatika is a CMU spin-out focused on automating driving functions of automobiles and other transportation that will increase the safety, efficiency and affordability of vehicles in the transportation sector. It provides software and systems development for autonomous cars. 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 six 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. Working closely with General Motors, and with additional support from the U.S. Department of Transportation and the National Science Foundation, CMU created a normal-looking autonomous vehicle that boasts a broad set of capabilities including vehicular communications. Ottomatika, Inc. was 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.
Key Researcher: Raj Rajkumar. More information at: https://www.cmu.edu/news/stories/archives/2015/august/spinoff-acquired.html.

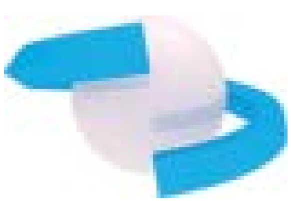
Charge Car is an open, community-centered teamwork at Carnegie Mellon for making electric vehicles practical and affordable enough to revolutionize urban commuting. It has developed a "kit" to convert internal combustion vehicles to electric vehicles. Key Researcher: Illah Nourbakhsh. More information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

Hyliion is developing an add-on hybrid suspension system for long haul, over-the-road delivery fleets that face large costs associated with diesel fuel. Fuel accounts for nearly 40 percent of operating costs in the trucking industry. Use of the Hyliion hybrid system will reduce energy consumption by over 30 percent with a return on investment in less than one year. The system uses regenerative braking to capture power when the vehicle is slowing down and reuses it to accelerate — reducing fuel consumption. The system won a DOE CleanTech student business competition in 2015. Key Researcher: Thomas Healey. More information at: hyliion.com.

Fuel Generation



InnovAlgae, an upcoming CMU spin-off, is developing a system that uses passive/semipassive systems to release the lipids and other beneficial products 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. This technology is being developed as part of the NSF I-Corps program, and received an NSF SBIR grant. Key Researchers: Philip LeDuc, Fred Higgs and Jeremiah Mpagazehe. More information at: scitation.aip.org/content/aip/journal/apl/105/16/10.1063/1.4898636.



Biohybrid Solutions is a CMU spin-off company that is commercializing multiple applications of polymer-based protein engineering technology, based on the controlled radical polymerization. This technology allows the targeted and predicted modification of proteins with polymers, which results in protein-polymer conjugates that have magnitude higher efficacy, and are stable in environments hostile to unmodified proteins, such as low or high pH, high temperatures and organic solvents. Such technology is aimed to extend protein applications in such areas as pharmaceuticals, biocatalysis and energy. Lead researchers: Alan Russell and Kris Matyjaszewski. More information at: http://www.post-gazette.com/business/tech-news/2016/11/08/Hamar-startup-Biohybrid-Solutions-LLC-hopes-to-bring-new-developments-to-the-market/stories/201611030014.

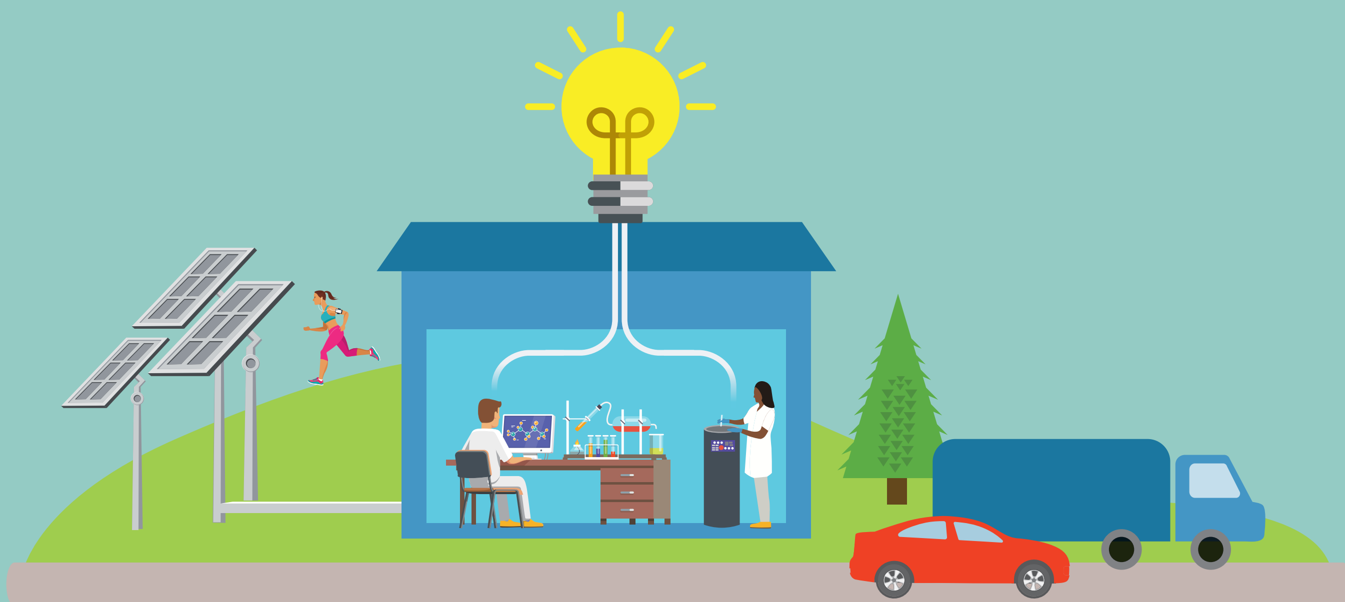
Public Transportation

Tiramisu Transit, a CMU spin-off, has developed a crowd-powered transit bus information system that provides information on bus schedules, seat availability and problematic situations. It has proved particularly useful for riders in wheelchairs and those with visual disabilities. Tiramisu is on iTunes and the Android Market for bus systems in Pittsburgh and New York City. Its goal is to encourage use of public transportation, thus reducing energy consumption by the motor vehicles typically used as an alternative, as well as overall congestion that increases energy consumption by all vehicles on the road. Tiramisu Transit has received SBIR grants. Key Researcher: Anthony Tomasic. More information at: tiramisutransit.com.

RoadBotics, an upcoming CMU spinoff company, is developing a computer program to detect potholes, cracks and other irregularities as well as snow conditions on roads; and road signage conditions and visibility. Mounted on the windshield of a car or plow, a camera captures images of the street and measures the severity of potholes, cracks and weather. Utilizing computer vision and machine learning, the irregularities/conditions are analyzed and mapped as a tool for decision makers. Key Researcher: Christoph Mertz. More information at: www.roadbotics.com.

Industry Vehicles

Carbon Freight builds durable, lighter-weight shipping pallets. Firms can use these shipping pallets to reduce the amount of energy consumed for freight transportation through the ability to include more shipping pallets per mile (reducing the number of trips) or by reducing the overall weight of the transported goods (reducing the miles per gallon). Carbon Freight is part of the NSF I-Corps program. Key Researchers: John Dieser and Glen Philen. More information at: carbonfreight.com.



Conclusion

Conclusion

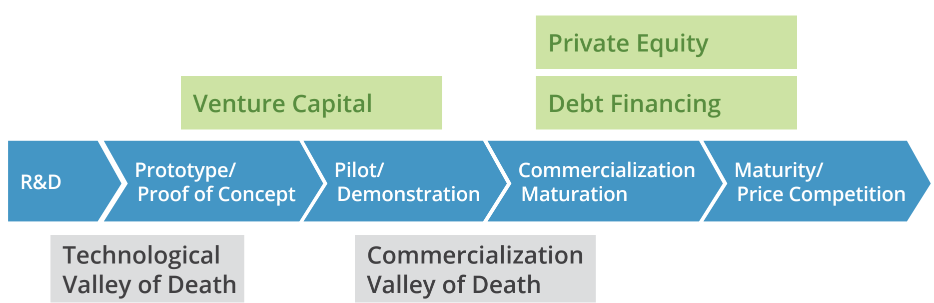
Throughout this technology guide, you've seen next-generation energy technologies developed at Carnegie Mellon or by CMU alumni to address the social imperative of meeting the energy needs of our homes, transportation system, businesses and industry while taking into account economic, environmental and 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[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 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

Table 1: Innovation in Various Sectors

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 thebreakthrough.org/archive/bridging_the_clean_energy_vall.

	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 and government funded; Government (NIH, NSF)	Dynamic startups, often VC funded; Large firms reinvesting in R&D	Various: Utilities, oil & gas companies, power tech companies, startups and government
Typical Industry Risk Tolerance	High	High	Low
Innovation Intensity	High	High	Low
Intellectual Property Rights	Strong	Modest	Modest

supply technologies; however, the competition in the marketplace may be more challenging for these same reasons.

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.

ANOTHER CHALLENGE RELATED TO NEXT-GENERATION ENERGY TECHNOLOGIES IS THE HUMAN COMPONENT — WHERE THE SOCIAL SCIENCES PLAY AN IMPORTANT ROLE.

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 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 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.

Conclusion

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.

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.

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.

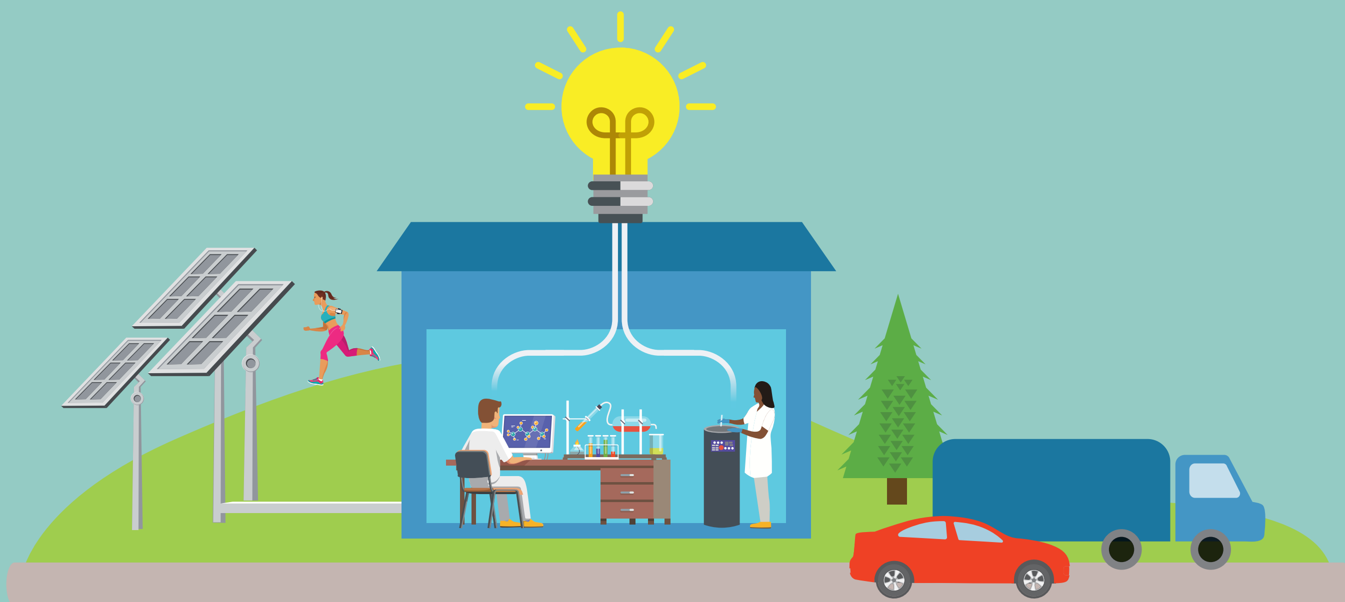
At this early stage of market exploration, it is often the case that additional resources are needed to help the inventors achieve an important technical milestone, or retain a consultant or entrepreneur to work with them to develop a business strategy. CTTEC has "gap funds" from state and foundation 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.[12] Since 2011, CMU faculty and students have spun out more than 170 companies and raised over $1 billion 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.



References

References

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

[12]CMU internal data from CTTEC and Swartz Center for Entrepreneurship.

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August 2017