

ARPA-E Impacts:

A Sampling of Project Outcomes, Volume III



Top Left: Aeris Technologies, Inc. has partnered with Rice University and Los Alamos National Laboratory to develop a complete methane leak detection system.

Top Right: The projects that comprise the Methane Observation Networks with Innovative Technology to Obtain Reductions, MONITOR, program are developing innovative technologies to cost-effectively and accurately locate and measure methane emissions associated with natural gas production.

Bottom Left: ARPA-E's METALS program, short for "Modern Electro/Thermochemical Advances in Light Metal Systems," aim to find cost-effective and energy-efficient manufacturing techniques to process and recycle metals for lightweight vehicles and aircraft.

Bottom Right: Purdue University, along with IBM Research and international partners from the Commonwealth Scientific and Industrial Research Organisation (CSIRO, Australia) utilize remote sensing platforms to collect data and develop models for automated phenotyping and predictive plant growth.



Letter from the ARPA-E Principal Deputy Director

Dear Colleagues,

As the Advanced Research Projects Agency-Energy (ARPA-E) enters its ninth year of funding transformative R&D in energy technology, we are proud to present the third compilation booklet of project impact sheets. This booklet provides a glimpse into the diverse and sophisticated research portfolio of advanced energy technologies that will enable the United States to tackle our most pressing energy challenges. The projects in this booklet illustrate a wide range of impacts—from scientific breakthroughs to products in the marketplace.

Statistical measures help demonstrate the achievements of ARPA-E funded projects at different stages of innovation. Since 2009, ARPA-E has provided approximately \$1.8 billion in R&D funding for more than 660 potentially transformational energy technology projects. As of February 2018, ARPA-E project teams have published 1,724 peer-reviewed journal articles that have been cited 42,535 times, and have been awarded 245 patents by the U.S. Patent and Trademark Office. Moreover, 71 ARPA-E project teams have formed new companies, 127 have partnered with another government agency to continue their technology development, and 149 teams have together raised more than \$2.9 billion in reported funding from the private sector to bring their technologies to market.

Another way to understand the Agency's success is through the specific scientific and engineering challenges that ARPA-E project teams have overcome. To provide greater insight into ARPA-E's project successes, this booklet documents the opportunities and challenges project teams have faced in technologies related to energy efficiency, energy storage, and transportation. The booklet also includes a review of ARPA-E's power electronics portfolio.

We expect that ARPA-E's project teams will continue to demonstrate impact, and that, as a result, we will continue to publish their successes. Please share this report with your colleagues—we hope to encourage innovative scientists and engineers to continue to engage us with their ideas and consider joining our team.

Sincerely,

Dr. Chris Fall
Principal Deputy Director of ARPA-E
U.S. Department of Energy
May 7, 2018

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CHANGING WHAT'S POSSIBLE

EFFICIENCY



LOW NICKEL, HIGH TEMPERATURE METAL ALLOYS WITH SUPER-CORROSIVE RESISTANCE

Updated: January 3, 2018

TITLE: New, High Temperature, Corrosion-Resistant Cast Alloys for Operation in Industrial Gaseous Environments

PROGRAM: OPEN 2015

AWARD: \$3,900,000

TEAM: Oak Ridge National Laboratory, University of Wisconsin – Milwaukee, Metaltek International, Duraloy Technologies, ArcelorMittal

TERM: April 2016 – April 2019

PRINCIPAL INVESTIGATOR (PI): Govindarajan Muralidharan

MOTIVATION

Transporting and handling corrosive gases at high temperatures is ubiquitous in industrial chemical processing and power generation, but corrodes conventional metal alloys. Austenitic steel, a stainless steel alloy commonly used in harsh environments, forms a chromia (Cr_2O_3)-scale oxide layer to help protect alloys from corrosion. However, the chromia protective layer can deteriorate. This significantly reduces component lifetime, as well as the energy efficiency of processes that use this metal's products. Although chromium (Cr) metal is critically important to the energy efficiency of the U.S. industrial infrastructure, it is not available domestically. Therefore, the development of a cost-effective alternative to chromia-forming alloys that uses lower amounts of Cr is of high importance.

TECHNICAL OPPORTUNITY

An alternative to chromia-forming alloys are those that form alumina (Al_2O_3) as their protective layer. Alumina-forming alloys exhibit superior high-temperature corrosion resistance, due to slower oxide scale-growth rate and greater thermodynamic stability at high temperatures (900-1200°C). Numerous attempts to produce Fe-base alumina-forming casting alloys on a commercial scale with the high-temperature strength needed for structural use have failed. Prior to this project, Oak Ridge National Laboratory (ORNL) patented several, new Fe-base austenitic alloy compositions with excellent "creep" (sagging under structural loads at high temperatures) resistance and alumina-forming capability at temperatures of 900-1100°C. However, in order to make this technology industrially relevant, alloy development must scale using new methods that can operate in a large commercial foundry.

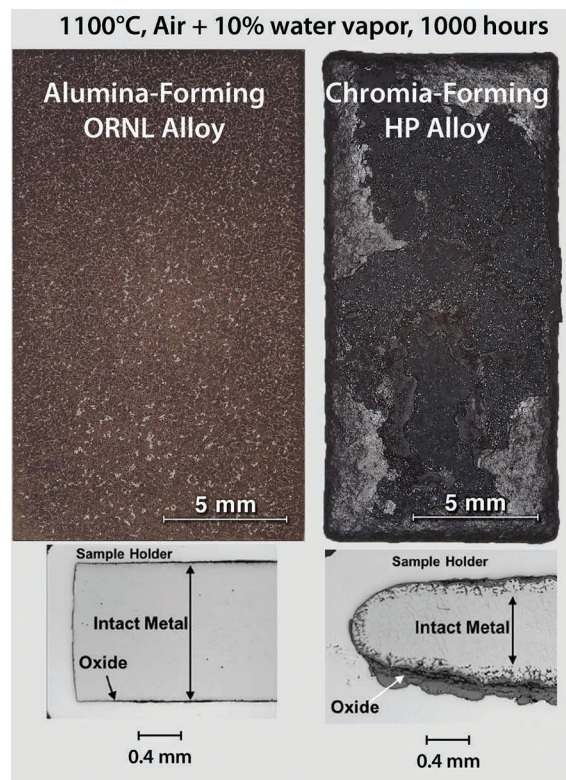


Figure 1: The new alloy developed by the ORNL team is up to 10x longer lasting than the industry standard alloy used for ethylene cracking furnaces.

INNOVATION DEMONSTRATION

This project aims to translate the laboratory development of ORNL's patented alumina-forming austenitic casting alloys into industry-applicable materials that can survive production practices and still operate in high temperatures and caustic environments. ORNL devised the new alloys under tightly controlled mixing, heating, and quenching conditions. However, these conditions are cost prohibitive if scaled up and must be reengineered. The ORNL team has tested over 60 formulations of its alloys, and has down-selected the optimized versions for ton-scale production. ORNL is working with its partners to produce these alloys and processing technologies necessary to use them industrially. ORNL is developing unique formulations that utilize the minimum amount of aluminum for scale formation in the alloy. The alloy is then stabilized with additions of niobium, titanium, zirconium, and other elements to achieve the best properties in industrial use. The team is fabricating and testing a prototype industrial component from one alumina-forming alloy with tenfold oxidation resistance and twice the resistance to creep compared to chromia-forming alloys, with functionality in excess of 1100°C. The goal is for these alloys to be produced at scale for the same cost, last up to ten times longer, and maintain the same creep life as austenitic steels.



Figure 2: Furnace roll made with the ORNL team's alloy. This roll appears pristine after being in a plate austenitizing furnace at 900°C for 4000 hours. Compared to state-of-the-art alloy furnace rolls, the new rolls result in significantly lower maintenance costs and improved productivity.

IMPACT PATHWAY

This project united the material developer, ORNL, materials producers and component manufacturers, Duraloy Technologies and MetalTek International, and a potential end-user, ArcelorMittal. The team identified furnace rolls for steel production as the first application. Furnace rolls are rotating pieces of a conveyor that move steel plates through an austenitizing furnace. These rolls experience drastic changes in temperature and constant stresses, requiring regular replacement. ArcelorMittal successfully tested a prototype roll in April 2017. The trial roll showed no appreciable degradation after 4,000 hours at 900°C. Under similar conditions, current commercially available rolls corrode, forming oxide layers. The periodic maintenance to remove the oxide results in furnace downtime, loss of production, and roll replacement.

LONG-TERM IMPACTS

The high temperature, corrosion-resistant alloy developed in this project will increase the efficiency and longevity of equipment used in fossil fuel extraction, chemical processing, and transportation fuel production. The potential cost and energy savings are significant given the wide range of applications. The commercial availability of this alloy will enable disruptive improvements in energy efficiency for critical U.S. industrial processes by increasing productivity, reducing costs, increasing equipment life, and decreasing process downtime.

INTELLECTUAL PROPERTY AND PUBLICATIONS

The ORNL team has published the scientific underpinnings of this technology twice in open literature.

ADAPTIVE APPAREL FOR PERSONALIZED THERMAL COMFORT

Updated: December 15, 2017

TITLE: Passive Thermo-Adaptive Textiles with Laminated Polymer Bimorphs

PROGRAM: Delivering Efficient Local Thermal Amenities (DELTA)

AWARD: \$5,439,748

TEAM: Otherlab

TERM: May 2015 – May 2019

PRINCIPAL INVESTIGATOR (PI): Brent Ridley

MOTIVATION

Heating, ventilation, and air conditioning (HVAC) account for 13% of energy consumed in the United States. That energy is used to control the comfort of the entire space, which is a much larger area than the thermal environment around each individual in the building. Passive, thermally adaptive clothing that changes insulation in response to the local temperature has the potential to broaden the range of comfortable temperatures for building occupants. ARPA-E estimates that relaxing building temperature set point requirements from 70°F for heating and 75°F for cooling to 66°F and 79°F, respectively, will reduce annual HVAC energy consumption by 15%.¹ For a typical building occupant to remain comfortable over this widened range of temperatures—both warmer and cooler than typical workplace conditions—clothing would need to nearly double its insulation value in response to an ambient temperature change of 13°F, or about 7°C. Although 13°F is large with respect to human comfort, in physical terms, this is a large insulation change in response to a small difference in temperature, and therefore, requires the invention of a textile with unique behavior. At the same time, the textile should also remain familiar enough to be accepted by consumers.

TECHNICAL OPPORTUNITY

Textile production technologies are highly developed, but recent advances in computer-controlled production and low-cost sensing enable precision yarn and fabric prototyping at a much faster rate than ever before. These advances accelerate fabric R&D and reduce the time required for design iteration. Additionally, coupling advanced production techniques with standard materials creates an opportunity for thermally responsive textiles with a low barrier to adoption.

INNOVATION DEMONSTRATION

The first phase of work focused on the demonstration of a textile that passively doubled its insulation value in response to a change in ambient temperature from 81°F to 63°F (27°C to 17°C), an expanded temperature range slightly larger than specified in ARPA-E's pro-

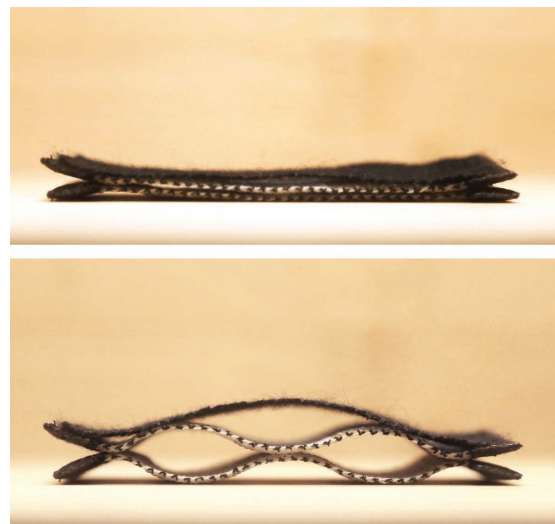


Figure 1: Thermally responsive textile at room temperature (top, textile is flat) and at a cold temperature (bottom, textile is lofted).

¹ Detailed calculations of the energy savings and program metrics were laid out in the DELTA Funding Opportunity Announcement (FOA). A synopsis of the FOA can be found at: https://arpa-e.energy.gov/sites/default/files/documents/files/DELTA_ProgramOverview.pdf

gram goals. The textile's adaptive structure intentionally pairs mismatched materials with advanced fabrication processes, where one material responds much more strongly to a temperature change than its complement. Temperature changes cause the textile to go from a flat, thin textile, to a slightly wavy textile that traps air in the small pockets that form between layers, where the trapped air increases the effective insulation value. The textile requires no external power and responds to temperature through a natural material response.

These results were achieved with commodity polymers that are commonly used in the industry. For this concept, utilization of commodity polymers is critical for the production of a cost-effective adaptive garment. To realize the large change in insulation, Otherlab made a number of yarn and fabric iterations, and precision control of yarn and fabric production made the rapid iterations possible.

The first phase of work demonstrated that a textile can achieve the targeted temperature-triggered change in insulation. As such, ARPA-E has awarded Otherlab additional funding for a second phase of development, during which the project will demonstrate paths to production and to market. In this phase, Otherlab will identify potential commercialization partners and demonstrate reliable yarn and fabric production at a level adequate for sampling to these partners. Further, Otherlab will optimize the fabric, including fine-tuning practical characteristics such as feel, breathability, and washability, and complementing the thermal response of the fabric. Simultaneous product planning, go-to market sourcing, and partnering will inform and support the ultimate project deliverable—a thermally adaptive garment providing comfort from 66-79°F (19-26°C).

IMPACT PATHWAY

Based on the lab-scale success demonstrated in this project and following the award of the second phase, this work has attracted private investment to establish a spin-out company to commercialize the technology. The apparel, outdoor, and home textiles business sectors all have commercial interest in thermally adaptive textiles. The temperature-sensitive materials under development do not have an analog or direct competitor in the market. These materials compete with conventional, non-responsive, incumbent materials that have gained wide acceptance and have generally reached technological maturity and production scale. While there is a clear performance advantage—improved thermal comfort over a wider range of ambient temperatures—there are a number of practical barriers, including production reliability and performance characteristics, that are being addressed through additional research in the second phase of this project. Upcoming ARPA-E milestones will systematically address development goals related to the practical considerations of moving this research to market. In the final stages of the ARPA-E project, the project is expected to advance to material sampling and identify go-to-market partners who can assist with practical, real-world prototype testing and with forming domestic mill production agreements.

LONG-TERM IMPACTS

The team's temperature-sensitive textile is the first known to demonstrate such a large change in insulation. If widely adopted, the thermal properties of these adaptive garments would enable a savings of 2% of domestic energy and associated greenhouse gases. Upcoming ARPA-E project milestones will address technical barriers to widespread adoption. The doubling of insulation over a relatively small temperature change is unique and offers a dramatic improvement in thermal performance that might make widespread adoption conceivable. The doubling of insulation value also means that a single garment might take on the role of two garments, leading to cost savings for the consumer in addition to energy savings. Otherlab has also made conscious efforts to use conventional materials throughout and to consider product lifecycle and recyclability.

INTELLECTUAL PROPERTY

As of December, 2017, the Otherlab team's project has generated four invention disclosures to ARPA-E, and one U.S. Patent and Trademark Office (PTO) patent application has been filed on the disclosed inventions.

MICRO-ENVIRONMENTAL CONTROL SYSTEM

Updated: November 30, 2017

TITLE: Micro-Environmental Control System

PROGRAM: Delivering Efficient Local Thermal Amenities (DELTA)

AWARD: \$3,199,963

TEAM: Syracuse University (Lead), United Technologies Research Center, Air Innovations, Bush Technical, LLC, and Cornell University

TERM: May 2015 to July 2018

PRINCIPAL INVESTIGATOR (PI): H. Ezzat Khalifa

MOTIVATION

Heating, Ventilation, and Air Conditioning (HVAC) accounts for 13% of U.S. energy consumption. ARPA-E estimates that relaxing building temperature set point requirements from 70°F for heating and 75°F for cooling to 66°F and 79°F, respectively, could reduce annual HVAC energy consumption by 15%. This could be achieved by tailoring the thermal environment around the individual, thereby ensuring comfort and maintaining productivity in this expanded temperature range. ARPA-E's Delivering Efficient Local Thermal Amenities (DELTA) program set performance metrics that localized thermal management systems (LTMS) should remove 23 W of energy from human skin in a cooling setting, and provide 18 W of energy in a heating setting.²

TECHNICAL OPPORTUNITY

Almost all existing LTMS developed or sold commercially have relied on pre-conditioned air that goes through a central Air Handling Unit (AHU). The pre-conditioned air is then delivered through ceiling ducts or underfloor plenums, which is intrusive, noisy, high cost, and high energy. Local thermal storage using phase change materials (PCMs) provides a more cost-effective approach. PCMs allow the system to discharge heat at night when the area is unoccupied, shifting the electric load to off-peak hours. Using PCMs eliminates the limitations on placement (i.e. not in a window) and the need to connect to building services other than an outlet.

INNOVATION DEMONSTRATION

The Syracuse team's goal is to develop a compact, quiet, and ergonomic micro-environmental control system, named μ X. μ X utilizes a thermal storage module containing PCM that freezes at about 60°F to store 10 hours worth of "cooling." This cooling capacity is produced in approximately eight hours at night by a novel, high-performance micro vapor-compression system (μ VCS) whose evaporator is embedded in the PCM module. During the day, small fans blow about 20 cfm (ft³/min) of room air at 79°F through the frozen PCM module, cooling the air to a comfortable 71-72°F, delivering no less than 50 W of cooling to the near-range environment. By freezing PCM at night, the system avoids releasing noise and heat when the workstation is occupied. In the heating season, a heat delivery device is used to add 18 W of heat to a person.

A focus of the project was to build a high-performance micro-compressor to enable system functionality. Among the many compressors, the team chose scroll compressors because they are valveless, quieter, more efficient,

² Detailed calculations of the energy savings and program metrics were laid out in the DELTA Funding Opportunity Announcement (FOA). A synopsis of the FOA can be found at: https://arpa-e.energy.gov/sites/default/files/documents/files/DELTA_ProgramOverview.pdf

and have fewer moving parts. Scroll compressors have a built-in compression ratio, which can be optimized to match the narrow operating conditions needed to meet DELTA metrics. Because of the small size (<5 cm diameter) and tight tolerances required for high efficiency, developing the compressor presented a significant challenge. Syracuse worked with Bush Technical to design a micro-compressor, and validated its performance experimentally and against the predictions of a proprietary compressor simulation tool developed by United Technologies Research Center (UTRC). The prototype compressor features a small cooling capacity of about 60 W, consumes less than 11 W of electricity, and has fewer moving parts.



Figure 1: Prototype μ X product and its under-the-desk setup.

Another challenge was to engineer a PCM/evaporator module. The size and efficiency requirements of μ X dictates that the critical design aspects of heat exchanger, refrigerant, and PCM be carefully selected and engineered. Guided by numerical models, the team designed the PCM/evaporator module to meet these requirements. The team optimized air and refrigerant channel sizes and spacings through computational analysis and experimentation in order to achieve desired heat transfer and refrigerant and air flow rates. Experiments confirmed that the PCM/evaporator can meet its performance targets.

Preliminary test results using a prototype of the integrated system with a thermal manikin illustrate that the prototype is able to remove more than 32 W of heat from the manikin, surpassing the DELTA target of 23 W.

IMPACT PATHWAY

The innovative design of the μ X is compatible with automated, high volume, cost-effective manufacturing techniques. The first market envisioned is for peak demand reduction in offices that integrate this technology into desks. Because of the technology's potential in load shifting, New York State Energy Research and Development Authority (NYSERDA) provided Syracuse University a follow-on grant of \$400,000 to apply the technology in demand reduction prototypes aimed primarily at New York City.

Syracuse University has formed strategic partnerships with Air Innovations (AI) and UTRC and its affiliate, Carrier. AI and UTRC have agreed to terms defining market thresholds for exclusive licenses to the μ X technology. Both companies bring distribution channels, extensive experience, and strong relationships with suppliers and subcontractors. The current price point of μ X is likely to first suit niche applications, such as mission-critical facilities and historic buildings. Mass production will reduce the price for high-volume markets.

LONG-TERM IMPACTS

A low-cost LTMS using μ X technology can reduce HVAC electricity consumption, thereby saving consumers on energy costs, reducing greenhouse emissions, and enabling more sustainable heating and cooling architectures for energy-efficient building design. The thermal storage technology can also potentially enable shifting of the electric load to off-peak hours, further improving the stability of the electric grid.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of October 2017, the project has generated two invention disclosures to ARPA-E, and two provisional patent applications have been filed on the disclosed inventions. The team has also published the scientific underpinnings of this technology three times in open literature.

MODERN ELECTRO/THERMOCHEMICAL ADVANCES IN LIGHT METAL SYSTEMS (METALS)



MOTIVATION

In recent years, automakers have begun to increase fuel economy and performance in their vehicle fleets by replacing steel components with lighter aluminum alloys. Industry estimates indicate that aluminum use in vehicles will increase by more than 40% by 2028.³ Increased use in the auto industry creates new post-consumer waste streams that generate large amounts of mixed metal alloy scrap, which contain significant embodied energy. Currently, this scrap and its embodied energy is largely wasted in reuse; it is too expensive to sort out specific alloys using existing technology. As such, much of the scrap metal is shipped overseas to countries with low cost, manual labor to be hand sorted and converted to lower grade metal products. A means to cost-effectively recycle aluminum alloy scrap into a high quality product in the United States creates a three-pronged opportunity to reduce energy consumption: through vehicle light-weighting, in primary energy demand from aluminum production and recycling, and through decreased exports of scrap metals and their embodied energy.

ARPA-E has selected two projects that illustrate different approaches in the METALS program:

1. Energy Research Company's "Development of an Integrated Minimill for the Aluminum Industry: From Scrap to Product in One Step"
2. University of Utah's "Electrodynamic Sorting of Light Metals and Alloys"

1. TURNING SCRAP ALUMINUM INTO A HIGH-VALUE PRODUCT

Updated: January 18, 2018

TITLE: Development of an Integrated Minimill for the Aluminum Industry: From Scrap to Product in One Step

PROGRAM: Modern Electro/Thermochemical Advances in Light Metals Systems (METALS)

AWARD: \$3,815,131

TEAM: Energy Research Company (ERCo), WPI, wTe, Melt Cognition

TERM: January 2014 – September 2018

PRINCIPAL INVESTIGATOR (PI): Robert De Saro

TECHNICAL OPPORTUNITY

Automakers are interested in producing high-quality aluminum from recycling due to forecasted increases in scrap production. The growing demand requires an aluminum minimill that can separate, clean, melt, and certify that alloy from scrap has the same quality as new. The scanning technology for identifying metal alloy pieces is used in the medical diagnostics industry, but it lacks the accuracy and automation necessary for this application. Likewise, food processors use high-volume sorters, but they have not been adapted for alloys. Melting exists that can perform the job, but not with the kind of autonomy necessary. Laser-induced breakdown spectroscopy

³ Aluminum Use in Autos Advances, Recycling Today, <http://www.recyclingtoday.com/article/aluminum-automotive-content-usa-growing/>, 11/7/17

(LIBS) can measure solid metal, but it had never been used to measure molten aluminum at a commercial plant prior to this project. These approaches have never been successfully integrated. The challenge is to do so cost effectively and to apply the technology to a very risk-averse industry.

INNOVATION DEMONSTRATION

Traditional aluminum alloy scrap recycling has a large and disparate value chain that requires efficient sorting, cleaning/melting, casting, and recertification to be profitable. These steps are performed at separate facilities. The ERCo team identified inefficiencies in scrap sorting, integrated waste heat reclamation from de-coating, and scrap melters. ERCo's aluminum integrated minimill (AIM) integrates alloy recycling into one process at a single facility (Figure 1) located near the factory where scrap is processed, and where the certified product may be effectively used without costly re-melting of the product for transport. In addition, each of AIM's components listed below adds to the overall energy efficiency improvement and emissions reductions:

Sorter: First, a sorter divides aluminum scrap pieces (known as "twitch") into individual alloy bins. The ERCo team's original effort was suitable for heavy metals such as copper, but AIM needs an accurate and cost-effective sorter for aluminum alloy scrap. ERCo is integrating the sorter from UHV Technologies, another ARPA-E METALS performer, which uses X-ray fluorescence detectors to auto-sort aluminum alloys. UHV is providing ERCo with a pilot sorter for AIM integration in 2018.

Vertical floatation de-coater (VFD): ERCo's VFD unit then uses aerodynamics and conventional heat transfer to remove organic impurities such as oil or paint from a given alloy. High velocity gas flows simultaneously separate and heat scrap pieces to de-coat materials at lower temperatures than other techniques. This system can produce 99% organic-free metal scrap material that requires no further treatment—a major improvement over the more traditional techniques of oil dissolution and flame pyrolysis.

Melter: Once the scrap is cleaned, it is melted to be cast into a form that can either be transported or sold. AIM can be used with any melting equipment. While melting itself does not represent a technological innovation, melting alloy onsite for immediate use directly represents an energy savings of about 30%.

OnSpec for melt chemistry measurements: Finally, a LIBS analysis unit (branded OnSpec) measures the chemical composition of molten aluminum in situ and in less than two minutes by a probe immersed in the molten metal. The plasma caused by an incident laser can quickly determine the melt's exact composition, representing a greater than 50% energy savings over melting and certifying virgin metal ingot from a foundry. AIM's collective improvements to the process are projected to save more than 80% of the energy needed to make aluminum products, compared to conventional methods.

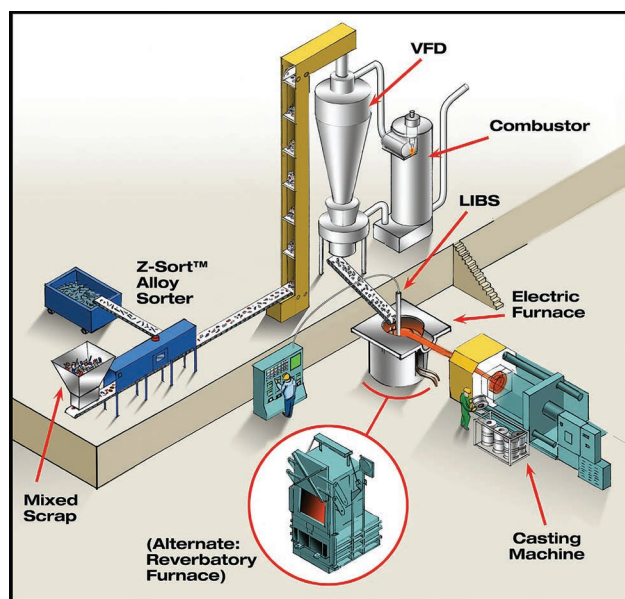


Figure 1: Diagram of ERCo's aluminum integrated minimill: the world's first system capable of reclaiming virgin-like aluminum alloy from scrap at manufacturing sites.

IMPACT PATHWAY

The OnSpec technology is the first of this project's technical components to reach commercial maturity. VFD has also been well received in the industry. Six successful demonstrations of the OnSpec technology have been undertaken at commercial industrial plants, leading to licensing of the technology to Altek, a Pennsylvania-based manufacturer of industrial test equipment.

In addition, ERCo founded a joint venture, Melt Cognition, with several partners to further develop and commercialize the AIM system. ERCo has successfully raised about \$1.8 million in follow-on funding, while Melt Cognition is raising funding to integrate the AIM components into a single pilot plant at a commercially operating aluminum processor.

LONG-TERM IMPACTS

The AIM could reduce energy usage in the U.S. aluminum metal casting industry and repurpose the aluminum scrap streams for use by domestic industry, rather than have this valuable, energy-intensive product exported. If widely adopted by U.S. industry, AIM could eliminate more than 80% of the total energy required for aluminum production, increase metal yield, allow the use of lower cost scrap, and reduce wasted embodied energy in aluminum scrap.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of January 2018, the ERCo team's project has generated three invention disclosures to ARPA-E. Three U.S. Patent and Trademark Office (PTO) patent applications have been filed on the disclosed inventions.

2. ELECTRODYNAMIC SORTING OF LIGHT METALS AND ALLOYS

Updated: January 10, 2018

TITLE: Electrodynamic Sorting of Light Metals and Alloys

PROGRAM: Modern Electro/Thermochemical Advances in Light Metals Systems (METALS)

AWARD: \$2,980,000

TEAM: University of Utah

TERM: January 2014 – March 2018

PRINCIPAL INVESTIGATOR (PI): Raj Rajamani

TECHNICAL OPPORTUNITY

One major challenge with aluminum recycling is sorting. Scrap metals rarely manifest in a clean, high-purity state, but instead bundle together in dirty mixtures of several distinct metals. The recycling industry would benefit significantly from a technology that can reliably sort aluminum and its alloys from fine-sized feedstocks with high throughput. Unfortunately, many technologies suffer from major technical limitations in attempting to meet this goal. For example, dense media separation is an expensive, highly regulated process that requires heavy capital investment and can cost as much as \$70/ton. It is also incapable of sorting metals with similar densities (e.g. copper and zinc) or that are very small (less than 4 mm radius). Methods based on x-ray fluorescence (XRF) are

also available, but require a two-step process of analysis and separation for each individual particle. As a result, XRF struggles with throughput demands when particles are very small (typically less than 2 cm radius).

INNOVATION DEMONSTRATION

Electrodynamic sorting (EDX) is a technology developed with ARPA-E support at the University of Utah. It is similar to a traditional eddy current separator in that it uses time-varying magnetic fields to sort scrap. As a metal particle passes through the alternating magnetic field, electrical eddy currents are induced throughout its volume and give rise to a distinct, repulsive force. Instead of mechanically rotating a fixed drum of permanent magnets, however, EDX utilizes a fixed array of stationary electromagnets (Figure 1). Thus, without the limitation of moving parts, the EDX technology can achieve far higher frequencies of magnetic excitation. While a traditional eddy current separator may reach as high as 1 kHz, the EDX magnets can excite metal particles with frequencies as high as 50 kHz or more. This allows EDX to recover far smaller particles of scrap metal, since smaller particles often require higher frequencies in order to significantly deflect. Through the proper choice of frequency, it also becomes possible to sort nonferrous metals by both conductivity and density (e.g. aluminum from copper). The process is clean and dry, thereby eliminating the environmental concerns that arise with flotation-based methods.

To date, the EDX testbeds have demonstrated reliable sorting with scrap mixtures ranging in particle size from 1 to 30 mm. The prototypes have successfully sorted copper scrap from heavy brass mixtures and also separated aluminum scrap from copper/brass/zinc mixtures. Typical grade, or purity, of the recovered metals can reach as high as 97% with recovery values likewise reaching well over 90%. The technology has also demonstrated a capacity to sort aluminum scrap metals by alloy, which can add significant value for scrap metal recycling. Throughput rates are also very promising, with current testbeds reaching 0.25 tons/hour (t/h). In the future, next-generation testbeds are expected to pass the 1.0 t/h threshold typically demanded by industrial-scale recyclers. Finally, the EDX systems are expected to be cost-effective to operate, with typical operating costs as low as \$1.00-2.00/t for energy and labor. Likewise, assuming a mere \$0.10/lb in value added after sorting, an EDX machine operating at 0.5t/h could generate \$100/h in revenue.

IMPACT PATHWAY

EDX Magnetics LLC, was formed in 2017 to commercialize this technology. This small business intends to license the intellectual property of EDX from the University of Utah and manufacture the basic drive electronics (magnetic cores, amplifiers, process controls, etc.). A second joint venture company will likely be necessary to manufacture the conveyor system, catch basins, and feeding mechanisms.

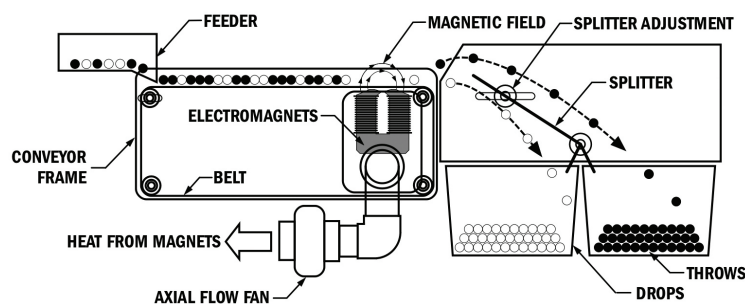


Figure 1: A schematic of a solid-state electrodynamic sorter.

LONG-TERM IMPACT

The EDX technology could reduce energy usage in the U.S. aluminum metal casting industry and repurpose U.S. aluminum scrap streams for use by U.S. industry, rather than export this valuable, energy-intensive material. Since aluminum recycling is also far more energy efficient than mining and processing new ore, this process could help save as much as 1% of total U.S. electricity consumption. Furthermore, by extracting more of the finely sized particles inaccessible to traditional sorters, EDX can potentially save another 0.5 million metric tons of aluminum metal annually that today ends up in landfills.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of January 2018, the Utah team's project has generated two invention disclosures to ARPA-E. The team has also published three times the scientific underpinnings of this technology in open literature.

METHANE OBSERVATION NETWORKS WITH INNOVATIVE TECHNOLOGY TO OBTAIN REDUCTIONS (MONITOR)



MOTIVATION

The United States has leveraged its shale resources to become the world's largest natural gas producer. However, an average of about 2% of natural gas (primarily methane) is emitted inadvertently. Industry and environmentalists are increasingly focused on reducing methane leaks from the gas supply chain to reduce the loss of valuable product, improve safety, and mitigate methane's environmental impact. Low cost and effective methane monitoring technologies that can be widely deployed to promptly detect leaks and quantify flow rate will improve the efficiency and safety of natural gas production while minimizing environmental impact.

ARPA-E has selected four projects that illustrate the various approaches in the MONITOR program:

1. Aeris Technologies, Inc.'s "Miniaturized Laser Point Sensor For Natural Gas"
2. Bridger Photonics, Inc.'s "Mobile LiDAR For Methane Detection"
3. Rebellion Photonics' "Wearable, Continuously Monitoring Methane Imagers"
4. University of Colorado, Boulder's "A Regional Methane Monitoring System"

1. MINIATURIZED LASER POINT SENSOR FOR NATURAL GAS

Updated: November 20, 2017

TITLE: Autonomous, High Accuracy Natural Gas Leak Detection System

PROGRAM: Methane Observation Networks with Innovative Technology to Obtain Reductions (MONITOR)

AWARD: \$2,494,131

TEAM: Aeris Technologies, Inc. (Lead), Los Alamos National Laboratory, Rice University

TERM: March 2015 – August 2018

PRINCIPAL INVESTIGATOR (PI): James Scherer

TECHNICAL OPPORTUNITY

Most existing methane detection devices are point sensors, carried by onsite personnel or vehicles to locate natural gas emissions. The most precise, high-sensitivity point sensors typically use laser-based absorption techniques. The state of the art can be mostly classified into two approaches: 1) cell-based detectors, with laser path lengths of a few meters and 2) cavity-based approaches, which use precisely aligned, highly reflective mirrors to obtain path lengths 100 times greater in the same sample volume. Cell-based approaches are limited in sensitivity, while cavity-based approaches can have reliability issues. Both use a wavelength in the near-infrared because of the low cost of detectors and lasers available. In the mid-infrared range, the absorption of methane is over 200 times stronger than in the near-infrared but lasers and detectors in the mid-infrared range have been expensive. However, as larger markets for these devices emerge, more companies are interested in producing the appropriate components, thereby decreasing the cost and creating an opportunity to utilize mid-infrared wavelengths in point sensors. Additionally, recent advances in machine learning such as deep neural networks

have enabled more sophisticated modeling of leakage and location. The combination of highly sensitive point sensors and advanced leak characterization algorithms presents an opportunity to detect leaks reliably and cost-effectively.

INNOVATION DEMONSTRATION

The Aeris team set out to develop a natural gas leak detection system consisting of a sensitive and compact laser sensor and an embedded artificial neural network characterization algorithm for the location and quantification of natural gas leaks. Point sensors have been used to perform measurements attached to mobile units but have not been coupled with inversion approaches in such a way that a single point sensor can measure leak flow rate and location. This is precisely the problem that Aeris aims to solve.

At the heart of Aeris' system is a cell-based sensor using mid-infrared laser sources that have no moving parts and can be mass produced. Because methane is emitted from both natural gas leaks and biogenic sources, the detection concentration alone is not sufficient evidence. Conversely, because ethane is not biogenic and comprises 2-15% of natural gas, the correlated detection of both methane and ethane clearly identifies a gas leak. As such, Aeris' mid-infrared sensor is unique in its ability to discriminate between methane from biological sources and methane from leaks in the natural gas supply chain. Aeris was also able to build a sensor at a much lower cost than the current state of the art for this sensitivity. A key performance benchmark for cell-based detectors is path-length-to-volume ratio. A detector with a high path-length-to-volume ratio is desirable due to its sensitivity and compactness. The team designed a cell that obtains a 13-meter path length in a 60 cm³ volume, a greater path-length-to-volume ratio than other cells, and near the theoretical limit for an optimized mid-infrared cell. With the use of mid-infrared wavelengths and optimized cell design, the produced sensor is compact, highly reliable, and has detection sensitivity on the few parts-per-billion level.

Additionally, Aeris has integrated an artificial neural network inversion approach to enable the laser-based point detector to automatically measure, locate, and quantify methane emissions. In contrast to previous inversion approaches that relied on driving a vehicle around an area and performing quantification and localization offline, this system leverages a network of sampling ports to provide information about concentrations at specific areas on the site. The artificial neural network will then, in real time, provide information on local methane emissions.

These advances have resulted in the Aeris PICO system (Figure 1). The core sensing part of the Aeris PICO system contains a 13-meter path length wrapped into a hand-sized cell. The whole unit fits in a standard protective case shown with a coffee mug for perspective. Aeris will then integrate this sensor into a multi-point sampling system.

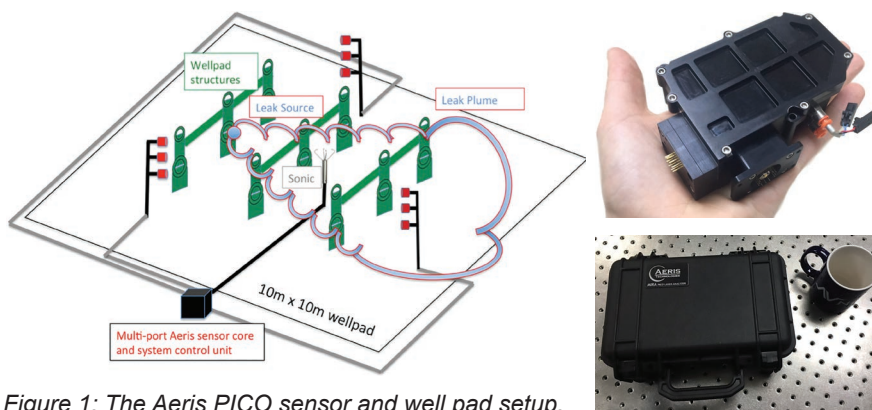


Figure 1: The Aeris PICO sensor and well pad setup.

IMPACT PATHWAY

The Aeris team is currently selling beta units of the sensor. The team started taking orders in December 2016. The team plans to sell the miniature portable unit, the PICO, as well as a temperature-controlled rack-mounted unit, the ULTRA, which enables single digit part-per-billion sensitivity. The team is also taking orders from university researchers and professionals in the oil and gas industry.

LONG-TERM IMPACT

In the long term, the technology developed could help reduce methane emissions across the natural gas supply chain, reducing costs, improving operational efficiency, and enhancing workplace safety. The portable sensor technology can help gas producers minimize the time and costs associated with sending crews to individual sites—and therefore identify unintentional emissions more quickly. If this project succeeds, the resulting system will enable cost-effective, 24/7 natural gas leak detection at well pads and in the distribution systems.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of November 2017, the Aeris project has generated one invention disclosure to ARPA-E. The Aeris project team has presented its work at conference proceedings worldwide.

2. MOBILE LIDAR FOR METHANE DETECTION

Updated: January 13, 2018

TITLE: Mobile LiDAR Sensor for Rapid and Sensitive Methane Leak Detection Applications

PROGRAM: Methane Observation Networks with Innovative Technology to Obtain Reductions (MONITOR)

AWARD: \$2,556,529

TEAM: Bridger Photonics, Massachusetts Institute of Technology (MIT) Lincoln Laboratory

TERM: June 2015 – October 2018

PRINCIPAL INVESTIGATOR (PI): Mike Thorpe

TECHNICAL OPPORTUNITY

Low cost electrochemical or infrared (IR) approaches used in safety systems to monitor for flammability typically do not have sufficient sensitivity to identify emissions, except when in close proximity. Conversely, high-sensitivity gas sampling equipment, such as cavity ring down or tunable diode laser absorption spectroscopy (TDLAS) can detect leaks at long distances, but are inefficient for localization and quantification. IR cameras, on the other hand, that can image methane emissions perform better at leak localization. However, IR cameras have low sensitivity leading to missed leaks, and are strongly affected by environmental parameters, making them unsuitable for leak quantification. These restrictions limit their effectiveness and applicability to occasional use by trained users.

Monitoring pipelines, in particular, requires the ability to rapidly inspect hundreds, if not thousands, of miles of infrastructure. As the United States transports more natural gas via pipeline, and with clusters of oil and gas production sites in specific basins, there is a growing need for a low cost, mobile system, such as a sensor attached to a fixed-wing aircraft or a helicopter, that can quickly survey infrastructure, detect intrusion, and sense potential pipeline damage across wide areas while pinpointing emission locations. Combining two existing systems—light detection and ranging (LiDAR) and backscatter spectroscopy—presents an opportunity to deliver sensitivity and precision in a small, lightweight unit at a low cost.

INNOVATION DEMONSTRATION

Bridger Photonics, Inc. (Bridger) is developing an aerial-deployable LiDAR system capable of simultaneous, rapid, and precise 3D topography and methane concentration measurements. The team's compact, low cost, high power, laser amplifier system operates at 1650 nanometers (nm), allowing them to exploit a strong methane absorption feature while taking advantage of low cost, commercially available fiber optic components. Previously, commercial optical amplifiers did not exist at the 1650 nm wavelength, and diode laser source powers alone typically do not exceed milliwatt levels, a power output too low for long-range measurements and rapid scans. Through the ARPA-E MONITOR program performer network, Bridger partnered with MIT-Lincoln Laboratory, which had previously developed a high power ($>0.5W$), slab-coupled optical waveguide amplifiers (SCOWA), and under this award improved the SCOWA to perform at the wavelengths near 1650 nm and at low cost.

The improved SCOWA performance enabled Bridger's LiDAR system to be integrated onto unmanned aerial vehicles (UAVs) and fixed-wing aircrafts. The Bridger team then combined the laser amplifier system with a frequency modulation continuous wave (FMCW) LiDAR approach and a high signal-to-noise wavelength modulation spectroscopy to obtain high sensitivity measurements very rapidly. The hardware used for competing state-of-the-art systems is 100-240 lbs. and has a ~ 5 ft³ volume, which limits the types of aircraft and amount of flight time for deploying these systems. In contrast, Bridger's SCOWA-based system for manned aircraft is 40 lbs. and ~ 1 ft³, which enables lighter payloads, greater measurement sensitivity, and lower costs.



Figure 1: Bridger is currently building versions of their sensor for manned and unmanned aircraft.

The team also leveraged its previous expertise in LiDAR mapping, originally developed for the Department of Defense, to integrate precision range measurements with gas measurements. The technology can map the geo-referenced topography of an oil and gas production site with GPS-limited accuracy and point cloud precisions of a few centimeters for the manned aircraft system and sub-centimeter for the UAV system. Additionally, the team developed 3D tomographic reconstruction of the methane emissions from its aerial data and a quantitative measure of the emission flow rate.

IMPACT PATHWAY

The Bridger team is currently partnering with aerial companies that provide inspection services for oil and gas companies. For initial market entry, the team is focused on pipeline monitoring and is actively testing and pursuing deployment opportunities with service providers. The team has obtained follow-on funding from the Alberta Upstream Petroleum Research Fund to perform initial flight tests of their technology.

LONG-TERM IMPACTS

If successful, the technology developed under this project could help reduce fugitive methane emissions across the natural gas supply chain, helping to reduce costs, improve operational efficiency, and enhance workplace safety for natural gas operations. The mobile monitoring system could help gas producers pinpoint emissions across a large number of sites at a low cost per site. If this project succeeds in fully demonstrating its mobile methane leak detection system, the resulting system will enable cost-effective, highly scalable natural gas leak detection at oil and gas production facilities across a basin and along pipelines.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of January 2018, the Bridger project has generated two invention disclosures to ARPA-E. Two U.S. Patent and Trademark Office (PTO) patent applications have been filed on the disclosed inventions.

3. WEARABLE, CONTINUOUSLY MONITORING METHANE IMAGERS

Updated: January 15, 2018

TITLE: goGCI: Portable Methane Detection Solution

PROGRAM: Methane Observation Networks with Innovative Technology to Obtain Reductions (MONITOR)

AWARD: \$4,250,000

TEAM: Rebellion Photonics

TERM: April 2015 – October 2018

PRINCIPAL INVESTIGATOR (PI): Robert Kester

TECHNICAL OPPORTUNITY

Low cost electrochemical or infrared (IR) approaches lack the sensitivity to identify emissions except in close proximity. Conversely, high resolution monitoring equipment and IR cameras that can image methane emissions are expensive. Also, high-resolution instruments are often bulky, use high power, need regular maintenance, and are not user-friendly. Since methane emissions are often intermittent, reducing the cost, size, weight, and power will allow for constant monitoring, enabling the detection and repair of leaks sooner. Rebellion Photonics' existing product, a large spectral imaging camera called the gas cloud imager (GCI, see Figure 1), uses snapshot spectral imaging, which is well suited to size and cost reduction. Snapshot imaging can also leverage uncooled detectors, which have dropped in price from ~\$5,000 to \$200 due to Defense Advanced Research Projects Agency (DARPA) research.⁴ Leveraging these developments into a deployable product has not been done before and requires cross-disciplinary collaboration.

INNOVATION DEMONSTRATION

Rebellion Photonics began by reducing the form factor of the GCI to the size of a soda can. The smaller unit can be mounted on a worker's personal protective equipment (PPE) (Figure 2). As of 2017, the team has reduced the camera's optics size to support this goal and is selling that as part of a mini-GCI unit, which is the size of a shoebox, allowing for easy deployment through parcel shipment.

Rebellion Photonics also developed the analytics to calculate flow rates from the obtained images, and developed an approach that works for high and low flow rates, as well as when part of the gas cloud is obscured.

The team had to then address several challenges related to the ability of a small, battery-operated camera to communicate remotely. Spectral imaging cameras obtain massive amounts



Figure 1: Under this project, Rebellion has miniaturized their gas cloud imager – the GCI (right). The mini-GCI (middle) is a mid-project functional prototype for which the team has already taken orders. The team will be shortly testing an even smaller goGCI (left) which will be 4.25in x 3.25in x 2.60in, 1 lb., battery powered, and will include embedded gas detection analytics.

⁴ <http://www.flir.com/flirone/>

of data in a short timeframe. This requires significant data compression or on-board analytics to send data via satellite, which affects battery life. This makes spectral imaging cameras difficult to operate autonomously with batteries. Rebellion is porting the flow rate algorithms and detection algorithms to field programmable gate arrays (FPGAs) that can handle the processing onboard with less power. The minimum required data is sent via 4G to a remote control center to communicate an alarm, and if control center staff need to investigate further, a complete image can be sent.

The team's progress is paving the way for an industrial goGCI, a wearable, continuous-monitoring IR camera.

IMPACT PATHWAY

Rebellion Photonics is already selling the intermediate result from the ARPA-E project, the mini-GCI, for a variety of applications. The mini-GCI's are deployed in fixed-use installations to provide methane and volatile organic compounds detection and safety monitoring. A key feature of the mini-GCI is its ability to quantify flow rate, which provides a competitive advantage for prioritizing which issues to fix first. Rebellion Photonics has conducted more than 12 product demonstrations with potential customers, including many large oil and gas firms. Customers have ordered 15 mini-GCIs to date. As the goGCI is developed, Rebellion Photonics will expand its offering, including both a PPE-mounted goGCI and a small, fixed-mounted camera that can be installed at a variety of wellheads, compressor stations, and offshore rigs. Rebellion Photonics has developed a cloud-based user interface that support staff at control centers.



Figure 2: Year 1 helmet-mounted goGCI prototype.

LONG-TERM IMPACTS

If successful, this technology could help reduce methane emissions across the natural gas supply chain, helping to reduce costs, improve efficiency, and enhance workplace safety. The wearable technology could also help gas producers minimize the time and costs associated with sending crews to individual sites and therefore allow for quicker identification of unintentional emissions. If the wearable technology is successful, current estimates indicate the cost per year for monitoring methane at a well site could be reduced by more than an order of magnitude.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of January 2018, the Rebellion Photonics project has generated two invention disclosures to ARPA-E. One U.S. Patent and Trademark Office (PTO) non-provisional patent application has been filed on the disclosed inventions.

4. A REGIONAL METHANE MONITORING SYSTEM

Updated: January 16, 2018

TITLE: Frequency Comb-Based Remote Methane Observation Network

PROGRAM: Methane Observation Networks with Innovative Technology to Obtain Reductions (MONITOR)

AWARD: \$2,125,469

TEAM: University of Colorado, Boulder, National Institute of Standards and Technology, National Oceanic and Atmospheric Administration, First Tracks Consulting, Longpath Technologies, Inc.

TERM: May 2015 – March 2020

PRINCIPAL INVESTIGATOR (PI): Gregory Rieker

TECHNICAL OPPORTUNITY

A regional monitoring approach would allow an operator to monitor multiple natural gas sites simultaneously, identify specific sites in need of repair, and quantify the leak's flow rate. Technologies with the capacity to detect and locate emissions over kilometer-long distances could enable this approach.

Precision spectroscopy, based on Nobel prize-winning frequency comb lasers, can readily identify methane and other molecules. A laser frequency comb simultaneously produces hundreds of thousands of distinct wavelengths of light, which can be transmitted coherently over kilometer distances. Each gas absorbs a unique combination of wavelengths (an absorption fingerprint). The comb light is combined with a second frequency comb to measure the fingerprints using an optical interference technique, dual-comb spectrometry (DCS). By measuring the unique absorption signature of many gas species simultaneously, these devices can determine the individual concentrations with high precision, stability, and without calibration between instruments or over time. Prior to the ARPA-E award, the research team demonstrated that DCS could be used over large distances for sensitive, accurate measurements of multiple trace gases, including methane. However, at the time, the DCS technology was an expensive, delicate laboratory device not suited for field deployment.

INNOVATION DEMONSTRATION

The University of Colorado, Boulder (CU-Boulder) project seeks to develop a regional natural gas leak detection system by creating a field ruggedized, autonomous DCS and combining the system with inversion modeling. The sensor serves as the focal point of a methane detection system that can monitor hundreds of sites. The laser is sent out to reflectors, which return the light to the detector to determine the concentration of methane. These measurements, coupled with atmospheric transport modeling and inversion techniques, calculate the emission flow rate and identify the location to within five meters of the actual source of emission.

Prior to this project, frequency comb spectroscopy was largely a laboratory exercise requiring highly specialized and sensitive laser technology arrayed across multiple large optical tables. Miniaturizing and ruggedizing the optics on an individual frequency comb generated by a femtosecond laser was a critical first step. Dual-comb spectroscopy further requires that the combs generated by two femtosecond laser systems be carefully stabilized to one another. The team overcame these challenges, increased the ruggedness, and reduced the cost with two key innovations: 1) utilizing digital controls in order to achieve fast, robust phase locking between frequency combs, and 2) developing a feedback system to stabilize the two combs with a simpler, commercially available

diode laser. The final cost of the DCS is significantly less than the original and has been reduced in size to four shelves on a standard 19-inch rack mount.

For efficient leak mitigation, industry requires a technology that can locate leaks, quantify the emission rate, and identify faulty equipment. This requires concentration measurements and meteorological data to identify and characterize specific sources. The team developed multiple new inversion methods utilizing different gas transport models and statistics-driven observation configurations to overcome challenges associated with long-path inversion modeling. The DCS-based technology was able to locate small methane emissions from a distance of >1 km, and is being tested over greater distances. The technology is able to differentiate multiple leaks from a field containing many possible emission locations.

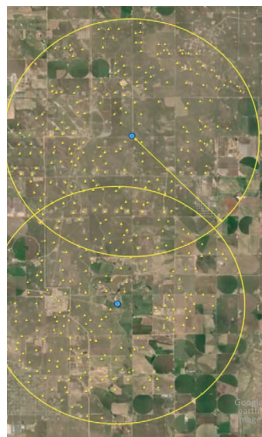


Figure 1: Under this project, the CU-Boulder team developed a solution capable of monitoring hundreds of wellpads from a central location (left). The dual-comb spectrometer has been reduced to a system that fits in a 19-inch rack mount and is robust and portable (right).

Cost is a major concern when using advanced laser technology. The team developed ways to reduce the cost of the reflectors, identifying cases that either minimized the required reflectors or maximized their use. The resulting system is currently on track to achieve a tenfold monitoring cost reduction per well per year.

IMPACT PATHWAY

While the team was developing the DCS technology, they met with potential customers and technology partners to identify upstream oil and gas production and natural gas storage as viable commercial uses. The team secured two field demonstration partnerships with an electric and natural gas utility company and an upstream natural gas production company, and is discussing demonstration partnerships with multiple, large strategic players across the natural gas supply chain. The team recently spun out a company, Longpath Technologies, to provide natural gas emissions monitoring as a service for the oil and gas industry.

LONG-TERM IMPACTS

In the long term, the CU-Boulder team's technology will help reduce fugitive methane emissions across the natural gas supply chain at low cost. This will help reduce overall system costs, improve operational efficiency, and enhance workplace safety. The regional methane monitoring system can help gas producers minimize the costs and allow for quicker identification of unintentional emissions. If this project succeeds, the resulting system will enable cost effective, highly scalable natural gas leak detection at well pads.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of December 2017, the CU-Boulder project has generated two invention disclosures to ARPA-E. Two U.S. Patent and Trademark Office (PTO) patent applications have been filed on the disclosed inventions. The project has also published the scientific underpinnings of this technology six times in open literature.



CHANGING WHAT'S POSSIBLE

ENERGY STORAGE



IRON SLURRY FOR LONGER DURATION FLOW BATTERY

Updated: January 21, 2018

TITLE: High Energy Storage Capacity Low Cost Iron Flow Battery

PROGRAM: OPEN 2012

AWARD: \$3,247,909

TEAM: Case Western Reserve University (CWRU)

TERM: January 2013 – September 2018

PRINCIPAL INVESTIGATOR (PI): Robert Savinell

MOTIVATION

Low cost energy storage with an increased lifetime promises to play a key role in the modernization of our nation's electricity grid. Future grid development will likely require large scale energy storage that not only enables the integration of increasing amounts of renewables and distributed generation, but also improves the grid's operating capabilities, enhances reliability, allows deferral of infrastructure investments, and provides backup power during emergencies. To expand the benefits of grid energy storage, electrochemical storage systems must match both the time and energy scale of intermittent renewable energy sources while minimizing impact on the cost of power delivery. Developing technology for large scale energy storage is difficult because of extreme cost constraints. The Department of Energy (DOE) has set cost targets for its widespread adoption at \$100/kWh for capital and a \$0.025/kWh per cycle over lifetime.

TECHNICAL OPPORTUNITY

A flow cell generates power by pumping the electrolyte through the electrode/membrane stack. Duration of power generation increases with the amount of available electrolyte, or the size of the electrolyte storage tank. The incumbent flow battery technology is the all-vanadium flow battery, but vanadium is expensive.¹ The aqueous iron/iron (Fe/Fe) system is a low-cost alternative that requires less ancillary safety equipment. Existing Fe/Fe cells tend to feature a hybrid design, plating iron metal directly on a two-dimensional, flat-surface negative current collector plate electrode.² As such, a hybrid Fe/Fe flow cell may encounter capacity limitations due to the surface area of the negative electrode. Cell capacity can increase significantly when plating occurs on three-dimensional (3D) carbon particles instead of a flat surface. This is the objective of this Case Western Reserve University (CWRU) project. While the 3D approach (Figure 1) is fundamentally sound, there are several barriers to practical implementation, such as the maintenance of slurry rheology at different states of charge over long periods of time and the uniformity of deposition onto flowing particles. If successful, CWRU's design should enable long duration storage with abundant, inexpensive, and safe electrolytes in a fully scalable design.

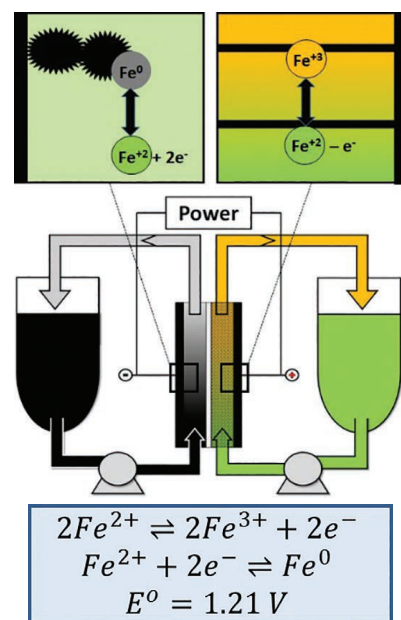


Figure 1: Concept of the decoupled iron flow battery with a negative slurry electrode.

¹ Nguyen, T. and R. F. Savinell, R. F. (2010) Flow batteries, *Electrochem. Soc. Interface*, 19, 54.

² Selverston, S., Savinell, R. F., & Wainright, J. S., In-tank hydrogen-ferric ion recombination, *Journal of Power Sources*, 324 (2016) 674-678

INNOVATION DEMONSTRATION

The key to CWRU's project is the capability to reversibly electroplate iron metal (Fe^0) at high power on carbon particles suspended in the flowing liquid electrolyte. The CWRU researchers calculated the requisite current densities as a function of the slurry particle specific area and electrical conductivity.³ Balancing the competing trends of sufficient particle concentration for high power versus too high a concentration, which leads to slurry solidification, is crucial. This fundamental understanding helped researchers select a commercially available, low cost carbon material that provides sufficient electrode conductivity for efficient battery operation at low viscosity for acceptable pump losses. Critically, this slurry does not settle when flowing or at rest, and changes in the particles over the full range of state of charge do not negatively impact the slurry rheology. The team was able to design a relatively low solids loading of carbon slurry, which can support electron transfer in the region near the current collector surface, but not on the current collector. Their ability to utilize the slurry electrode near the current collector creates an enhanced reaction zone that uniquely enables high-power capability of this electrode stack.

Additionally, CWRU developed a low-cost separator specifically for this unique slurry-based system. In related work sponsored by DOE's Office of Electricity and Energy Reliability, they addressed the parasitic hydrogen evolution issue through a hydrogen recombination concept that maintains the electrolyte balance. These complementary efforts enhance the viability of CWRU's iron flow battery.

The final deliverable for this project will be a 1 kW, 6 kWh slurry flow battery (six-hour duration), with a complete balance of plant ready for third-party testing.

IMPACT PATHWAY

This all iron flow cell chemistry is low cost, non-flammable, and non-toxic. This combination makes it suitable across a variety of application scales, ranging from distributed energy storage in commercial and industrial buildings to very large, commodity grid-scale storage. Moving beyond the academic bench, CWRU has partnered with Fusion Power Systems (FPS), an Australian energy storage provider. FPS has licensed the CWRU technology and is working closely with CWRU on prototype demonstrations—building the same devices on both continents. FPS intends to leverage its own investments, expertise, and market knowledge to develop a commercial product that can be sold globally.

LONG-TERM IMPACTS

The success of this project can help the United States lead in an expanding global market. CWRU's iron slurry flow battery is among the first full flow battery systems utilizing a low cost and safe active material. The successful application of a slurry cell design and the development of approaches to address chemical imbalances and incorporate lower cost materials have overcome the two most serious barriers to commercial applications of flow batteries for grid storage. CWRU's results will help position flow cells for larger applications in the grid, which will significantly expand integration of intermittent renewable power sources.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of December 2017, the CWRU project has generated five invention disclosures to ARPA-E. Four U.S. Patent and Trademark Office (PTO) patent applications have been filed on the disclosed inventions, and one U.S. patent has been issued (U.S. Patent 9,559,375B2, Jan 31, 2017) with allowances also granted in Japan, and with actions pending in China, South Korea, and Europe. The CWRU researchers have also published the scientific underpinnings of this technology eight times in the open literature.

³ Petek, T. J., Hoyt, N. C., Savinell, R. F., & Wainright, J. S. (2016). Characterizing slurry electrodes using electrochemical impedance spectroscopy. *Journal of The Electrochemical Society*, 163(1), A5001-A5009.

PROTON-CONDUCTING FUEL CELLS FOR STATIONARY POWER

Updated: December 11, 2017

TITLE: Low-Cost Intermediate-Temperature Fuel-Flexible Protonic-Ceramic Fuel Cell and Stack

PROGRAM: Reliable Electricity Based on Electrochemical Systems (REBELS)

AWARD: \$3,997,457

TEAM: Colorado School of Mines (Lead), FuelCell Energy

TERM: October 2014 – September 2020

PRINCIPAL INVESTIGATOR (PI): Ryan O'Hayre

MOTIVATION

Large, centralized power plants are the most efficient way to convert fuels such as natural gas to electricity. However, current 25 kilowatts (kW) natural gas generators are typically only 25-30% efficient and expensive to maintain. Fuel cells with an electrical efficiency of 50% could displace generators of 25kW or less in remote power, telecommunications, and residential cogeneration uses. Furthermore, fuel cells could provide valuable grid services, such as ramping power up or down to match load conditions. The challenge to adoption is that both low- and high-temperature fuel cells are very expensive. Moreover, low-temperature fuel cells can be started up quickly, but require highly pure hydrogen fuel and expensive catalysts. High-temperature fuel cells can operate on a range of fuels, but they have costly system components and can degrade rapidly.

TECHNICAL OPPORTUNITY

Recent advances in fuel cell materials and manufacturing present an opportunity to develop an intermediate temperature (200-500°C), high-efficiency system. This operating range requires new materials for the electrolyte and the electrodes. High-temperature solid oxide fuel cells (SOFCs) perform poorly at temperatures less than ~650°C, in part because the transport of oxygen ions in the electrolyte is sluggish at lower temperatures. New materials based on barium-zirconium-cerium-yttrium oxide now make it possible to employ a mixed proton and oxygen-ion conducting ceramic electrolyte to create a fuel-flexible fuel cell. Protons can move through solid electrolytes more quickly, thus lowering the resistance at intermediate temperatures. Researchers at the Colorado School of Mines (CSM) had previously discovered a solid-state reactive sintering (SSRS) process that combines materials-synthesis and fuel-cell-fabrication processes within a single step,⁴ thereby reducing manufacturing costs. Significant work remains to translate these technical advances into large area proton-conducting fuel cells (PCFCs), assemble them into stacks, and test them on fuels.

INNOVATION DEMONSTRATION

The CSM project focused on creating commercially relevant, proton-conducting ceramic fuel cell stacks capable of operating on natural gas fuel. The project team's initial phase was cell scale-up and stack integration, and the team is under a second phase of scaling up from laboratory-scale to pre-commercial stacks (Figure 1).

The team, through a new fabrication process, increased the active area 40-fold (from 0.1 to 4 cm²). They modified their SSRS process to create a thin, uniform, and dense protonic-ceramic electrolyte and composite anode,

⁴ Tong, J., Clark, D., Bernau, L., Sanders, M., & O'Hayre, R. (2010). Solid-state reactive sintering mechanism for large-grained yttrium-doped barium zirconate proton conducting ceramics. *Journal of Materials Chemistry*, 20(30), 6333-6341.

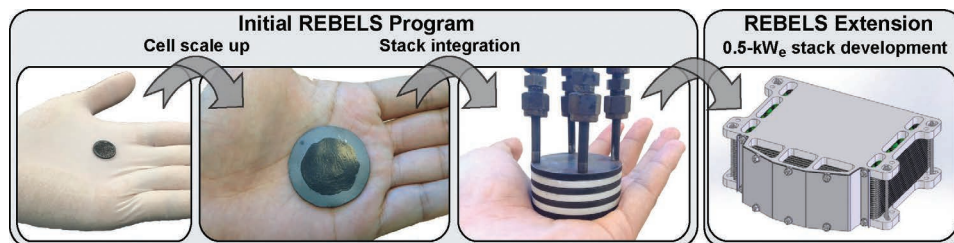


Figure 1: Technological road map for CSM's protonic-ceramic fuel cells.

power density at 550°C on methane fuel from 100 mW/cm² to approximately 250 mW/cm². Furthermore, the cells could operate directly on methane at 550°C or less without degradation, avoiding the tendency for carbon deposits that degrade performance (coking) at these temperatures. Finally, the new PCFCs were robust and could be operated on a variety of fuels—pure methane, methanol, natural gas with impurities, ethanol, propane, ammonia, and hydrogen—for thousands of hours with minimal degradation.

The cells were integrated into a stack with frames, interconnects, and seals. Overcoming the many challenges of stack design, the CSM team built a three-cell stack with a power density of approximately 200 mW/cm². Techno-economic models were developed to estimate technology cost at scale. Existing cost studies for traditional SOFCs operating at 800°C assume a fuel cell stack cost of \$300-340/kW. In contrast, the PCFC operating at 550°C is projected at approximately \$235/kW.⁶ The PCFC power density is 15-25% lower than SOFCs, but analysis shows substantial cost savings at the stack and system level, related to the cell materials, current collectors, seals, interconnects, and balance-of-plant components at lower temperatures.

IMPACT PATHWAY

The CSM team partnered with FuelCell Energy to further scale up their cell area, create a 500 W prototype operating on natural gas, and quantify the degradation behavior under different types of fuels. Working with FuelCell Energy will allow CSM to further prove the commercial viability of the PCFC with more data and better cost models to compare its benefits to the state of the art. A particular area of focus is whether the PCFC material set has the mechanical strength and properties needed to create larger area cells and stacks.

LONG-TERM IMPACTS

The typical electrical efficiency of a small, stationary generator operating on a fuel such as natural gas is 25-30%. The target efficiency for the PCFC technology is 50%—an improvement that would reduce fuel consumption and emissions. A potential entry market is the electrification of off-grid oil and gas wellpads that currently rely on the pneumatic pressure of natural gas for power, with the concomitant atmospheric release of gas. In the long term, the PCFC technology could be used for residential or commercial heat and power—with heat utilization increasing the system's overall energy efficiency to 85% or higher. The fuel flexibility of the PCFC system means that it could be operated on low-carbon fuels such as biogas, ammonia, or ethanol.

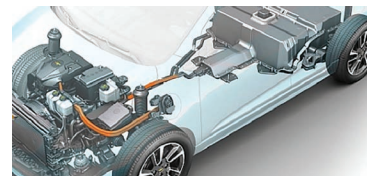
INTELLECTUAL PROPERTY AND PUBLICATIONS

As of December 2017, the CSM project has generated two invention disclosures to ARPA-E. One U.S. Patent and Trademark Office (PTO) patent application has been filed on the disclosed inventions. The CSM team has also published six times the scientific underpinnings of this technology in open literature.

⁵ C. Duan, J. Tong, M. Shang, S. Nikodemski, M. Sanders, S. Ricote, A. Almonsoori, R. O'Hayre, "Readily Processed Protonic Ceramic Fuel Cells with High Performance at Low Temperatures," *Science* 349, 1321-1326 (2015).

⁶ A. Dubois, S. Ricote, R. J. Braun, "Benchmarking the expected stack manufacturing cost of next generation, intermediate-temperature protonic ceramic fuel cells with solid oxide fuel cell technology," *J. Power Sources* 369, 65-77 (2017).

ROBUST AFFORDABLE NEXT GENERATION ENERGY STORAGE SYSTEMS (RANGE)



MOTIVATION

In 2017, 91% of U.S. transportation energy came from petroleum, nearly half of which came from foreign sources.⁷ Widespread adoption of electric vehicles (EVs) can substantially reduce U.S. oil imports, increase the energy efficiency of transportation, and reduce greenhouse gas (GHG) emissions. To realize these benefits, EVs must compete with conventional vehicles in terms of price and driving range, both of which are influenced by the cost and storage capacity of the EV's battery. ARPA-E's RANGE program aims to maximize a battery's energy storage potential and minimize its cost at the vehicle system level. This will require robust energy storage chemistries and new battery cell and pack architectures. RANGE technologies seek to reduce the weight of vehicle energy storage systems while curtailing the need for added impact protection and enabling systems to perform additional functions.

ARPA-E has selected four projects that illustrate the various approaches in the RANGE program:

1. Cadenza Innovation's "Novel Packaging Architecture for Lithium-Ion Batteries"
2. Stanford University's "Structurally Integrated Batteries"
3. University of California, San Diego's "Safe, Impact-Absorbing Batteries for Electric Vehicles"
4. University of Maryland's "Novel Structure for Solid State Lithium-Ion Batteries"

1. NOVEL PACKAGING ARCHITECTURE FOR LITHIUM-ION BATTERIES

Updated: January 19, 2018

TITLE: Novel Low Cost and Safe Lithium-Ion Electric Vehicle Battery

PROGRAM: Robust Affordable Next Generation Energy Storage Systems (RANGE)

AWARD: \$3,995,980

TEAM: Cadenza Innovation, Fiat Chrysler Automobiles, Morgan Advanced Materials, Karotech Inc., Alcoa, National Renewable Energy Laboratory, Magna Styer, MGA Research Corp, AVL

TERM: February 2014 – December 2017

PRINCIPAL INVESTIGATORS (PI): Christina Lampe-Onnerud; Per Onnerud

TECHNICAL OPPORTUNITY

There are generally two approaches to EV battery design: a small number of large-format cells or a large number of small-format cells. EV manufacturers have traditionally favored the first approach because there are fewer cells to assemble into a pack. However, larger cells exhibit many limitations: they require significant control hardware to prevent thermal runaway; cost more; have a lower manufacturing yield; exhibit lower energy density; and require additional protective structure. By contrast, small-format cylindrical wound lithium-ion (Li-ion) batteries

⁷ U.S. Energy Information Administration, Monthly Energy Review, Tables 2.5 and 3.8c, April 2017.

have a mature manufacturing process and all aspects of the cylindrical wound (“jelly-roll”) cell design have been optimized at very large scale, which has led to lower costs, higher product yield, and higher energy density. If a large number of jelly-rolls can be successfully integrated into packs, then an opportunity to improve EV batteries arises.

INNOVATION DEMONSTRATION

Under its RANGE award, Cadenza Innovation designed and built a large-format “supercell” (Fig. 1) that combines 24 jelly-rolls into a single container. This supercell behaves like a small-format, cylindrical wound cell, but with several key enhancements designed to improve safety. The jelly-roll cells within the supercell are open, which provides new opportunities for how safety abuse scenarios are managed, including single cell thermal runaway, mechanical abuse, and over pressurization due to gas formation. A single rupture disc is located on the supercell wall with a flame arrestor so that even when a cell creates a thermal event, there is no flame outside the supercell. A metal shunt connected to all of the jelly-roll cells will stop further discharge by fusing when the cell is directly shorted. Finally, the ceramic material surrounding the

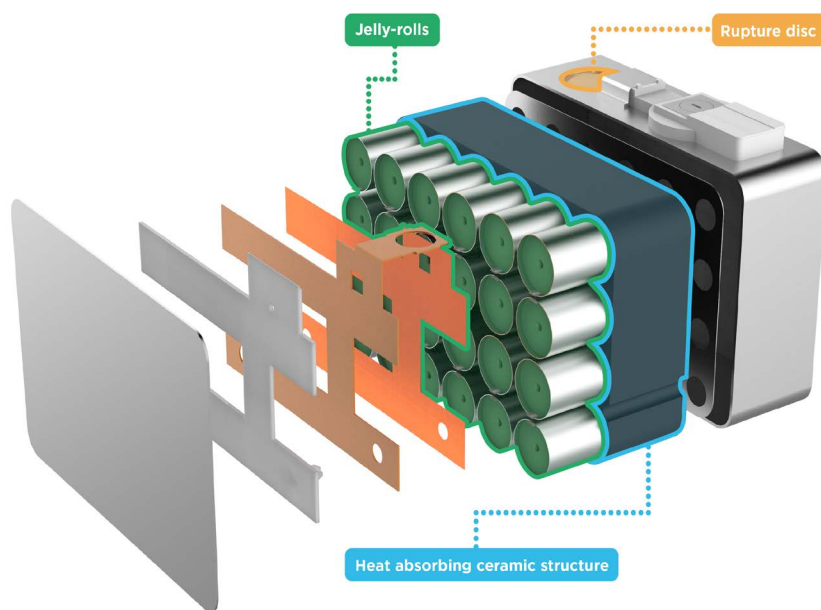


Figure 1: Cadenza Innovation Supercell.

jelly-roll cells absorbs heat and discharges gas, allowing the heat to be effectively removed from the supercell and preventing cascading thermal events of neighboring jelly-roll cells. The jelly-rolls are designed to maximize energy density without making any compromise to pass industry-required safety tests (e.g. nail penetration test).

The project team drew on the expertise of a number of partners to engineer a high-performance supercell that is competitively priced and can prevent a catastrophic thermal event in the case of overcharging, shorting, or mechanical deformation. NREL contributed modeling expertise to confirm that the supercell system could prevent cascading thermal runaway. Morgan Advanced Materials’ novel ceramic, originally developed to fireproof airplane “black boxes,” is used as the protective and heat-absorbing structure surrounding the cells. Alcoa supported the design of the rupture disc for the supercell, and FCA provided an EV platform to test the supercells.

By the end of its ARPA-E award, the team had demonstrated key safety features in the supercell design and had established a semi-automated manufacturing line capable of producing significant volumes of supercells to evaluate all production steps and support more extensive testing for safety and performance, including application level. Evaluation of both the design and manufacturing process enabled verification of cost targets that meet the RANGE EV pack goal of \$125/kWh. In addition, independent third-party safety testing is underway at Carderock Naval Warfare Center.

IMPACT PATHWAY

Cadenza Innovation has raised funding from investors to grow to a 25-person company and is currently marketing its technology to potential licensees. Battery system demonstrations include a stationary energy storage system and a battery pack for a Fiat 500e. Cadenza Innovation also won a contract with New York State Energy

Research and Development Authority (NYSERDA) to develop the technology into a product optimized for the peak shaving market in New York State. With lower costs, driven by higher energy density and simplified safety control features, this supercell could disrupt both the EV and stationary storage markets.

LONG-TERM IMPACTS

ARPA-E funding enabled the development of this novel packaging architecture that now opens an innovative approach to meeting the cost and performance requirements needed for the widespread adoption of EVs. Such inexpensive and safe batteries could also find application in stationary energy storage, especially for behind-the-meter storage, which can help increase penetration of intermittent renewable energy.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of January 2018, Cadenza Innovation's project has generated nine invention disclosures to ARPA-E.

2. STRUCTURALLY INTEGRATED BATTERIES

Updated: January 13, 2018

TITLE: Robust Multifunctional Battery Chassis Systems for Automotive Applications

PROGRAM: Robust Affordable Next Generation Energy Storage Systems (RANGE)

AWARD: \$2,744,657

TEAM: Stanford University (lead); Farasis Energy, Inc.

TERM: February 2014 - September 2017

PRINCIPAL INVESTIGATOR (PI): Fu-Kuo Chang

MOTIVATION

In 2017, 91% of U.S. transportation energy came from petroleum, nearly half of which came from foreign sources.⁸ Widespread adoption of electric vehicles (EVs) can substantially reduce U.S. oil imports, increase the energy efficiency of transportation, and reduce greenhouse gas (GHG) emissions. To realize these benefits, EVs must compete with conventional vehicles in terms of price and driving range, both of which are influenced by the cost and storage capacity of the EV's battery. ARPA-E's RANGE program aims to maximize a battery's energy storage potential and minimize its cost at the vehicle system level. This will require robust energy storage chemistries and new battery cell and pack architectures. RANGE technologies seek to reduce the weight of vehicle energy storage systems while curtailing the need for added impact protection and enabling systems to perform additional functions.

TECHNICAL OPPORTUNITY

Multifunctional batteries have been an area of interest for over a decade with some limited success in the small unmanned aerial vehicle (UAV), WASP, funded by the Defense Advanced Research Projects Agency (DARPA).⁹ Developments in tangential fields present great opportunities to advance multifunctional batteries; however,

⁸ U.S. Energy Information Administration, Monthly Energy Review, Tables 2.5 and 3.8c, April 2017.

⁹ Thomas, J.P. & Qidwai, M.A., "The Design and Application of Multifunctional Structure-Battery Materials Systems," JOM 57(3) (2005) 18-24.

incorporating advances from other fields requires breaking disciplinary barriers. Advanced computation capabilities have improved mechanical models for multifunctional batteries, which opens up opportunities for optimizing load-bearing structures. Second, improved sensing technologies, such as actuating and sensing ultrasonic transducers, can now be leveraged to determine the health and residual monetary value of partially spent batteries.¹⁰ This ability could further reduce battery costs.

INNOVATION DEMONSTRATION

Under its RANGE award, a team from Stanford University united with Farasis Energy, Inc to bring advanced mechanical modeling and sensing expertise to battery design and production. The Stanford team developed a multifunctional structural battery with integrated sensors that assist with real-time assessment of the state of charge (SoC) and state of health (SoH). The team explored various configurations for adding the load-bearing capability without sacrificing energy storage performance. As a mechanism for adding structural strength, they developed Multifunctional Energy Storage Composites (MESCs), seamlessly embedding Lithium-ion battery materials into high-strength carbon-fiber composites or automotive-grade aluminum. The MESCs employ polymer rivets to lock the electrodes and current collectors in place. The rivet structures prevent the typical shear movement of the electrode stack, akin to stabilizing a loose deck of cards. The rivets improve the load transfer between the cell layers and enable the constituent layers to contribute to the battery's structural and mechanical load-bearing performance. Key design parameters were optimized through electrochemical-mechanical experiments and computational modeling. Standard industry electrodes can be adapted to function in this design, which is critical to industry adoption.

To further reduce cost, the Stanford team applied advanced, non-destructive material testing techniques to battery sensing, resulting in an integrated system that assesses SoC/SoH continuously in real time. This monitoring system is based on a network of actuators and sensors that measure strain, temperature, and ultrasonic guided-waves. Stanford's discovery of the correlation between waveform signal parameters and battery SoC/SoH made this technique possible.¹¹ This technology could be applied not only to multifunctional batteries, but also to conventional batteries. This technique also works for pure structural systems. A similar sensor technology, also developed by the team, is being implemented in purely mechanical (not multifunctional) structures today.

The Stanford team has successfully built and tested prototypes of these multifunctional battery I-beams (Figure 1). The beams' mechanical tests show that significant load (no fewer than 1,500 lbs.) does not alter electrical performance. Ultimately, the team expects to be able to achieve an energy density of ~180 Wh/kg, comparable to leading available EV batteries. Compared to commercially available packs with protective plates, the multifunctional battery could achieve up to 30% overall weight savings, which will translate to substantial reduction in fuel consumption.¹²

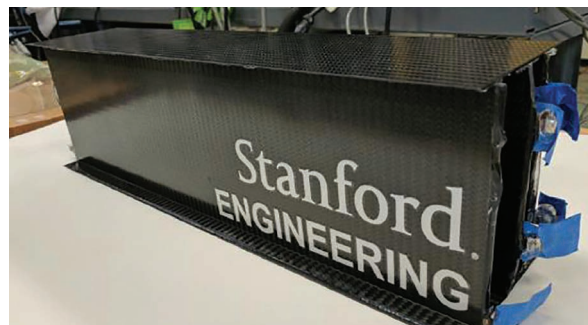


Figure 1: Stanford's I-beam multifunctional battery carries load and stores energy.

10 Gallego-Juarez, J., "Piezoelectric ceramics and ultrasonic transducers," J. Phys. E.: Sci. Instrum. 22 (1989) 804-816

11 Ladpli, P. et al., "Battery charge and health state monitoring via ultrasonic guided wave-based methods using built-in piezoelectric transducers" in the Proceedings of the SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring, March 2017, Portland, OR, USA

12 Joost, W., "Reducing Vehicle Weight and Improving U.S. Energy Efficiency Using Integrated Computational Materials Engineering," JOM, 64(9) (2012) 1032-1038.

IMPACT PATHWAY

Companies from various industries, including automotive, aeronautical, and aerospace, are interested in seeing this technology further developed. Airbus, RUAG, Ford, BMW, and Linamar are among the most enthusiastic about the structural battery technology. For aeronautical and aerospace manufacturers, this multifunctional battery could serve as a wing for drone aircraft, or as a chassis for a satellite, whereas automanufacturers could integrate these batteries into the vehicle frame for future EVs. Because satellites and unmanned air vehicles are high value, niche markets that are not very cost sensitive, they are likely first markets for the batteries.

LONG-TERM IMPACTS

The Stanford team has translated to practice multifunctional batteries that synergistically carry mechanical loads and store electrical power, thus minimizing EV weight and enabling paradigm-shifting design concepts. The advances that Stanford has developed with cost-competitive manufacturing, weight savings, and battery design offer a significant, innovative approach to meeting the cost and performance requirements for the widespread adoption of EVs. Although the long-term impact of these multifunctional batteries outside the automotive industry is difficult to predict, the spill-over effect is promising in the broader economy.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of December 2017, the Stanford team's project has generated two invention disclosures to ARPA-E, and two U.S. Patent and Trademark Office (PTO) patent applications have been filed on the disclosed inventions.

3. SAFE, IMPACT-ABSORBING BATTERIES FOR ELECTRIC VEHICLES

Updated: January 13, 2018

TITLE: Developing Low-Cost, Robust, and Multifunctional Battery System for Electric Vehicles: A Non-Chemical Approach

PROGRAM: Robust Affordable Next Generation Energy Storage Systems (RANGE)

AWARD: \$3,498,061

TEAM: University of California, San Diego (lead), American Lithium Energy, University of California-Merced, Columbia University

TERM: February 2014 – April 2017

PRINCIPAL INVESTIGATOR (PI): Yu Qiao

MOTIVATION

In 2017, 91% of U.S. transportation energy came from petroleum, nearly half of which came from foreign sources.¹³ Widespread adoption of electric vehicles (EVs) can substantially reduce U.S. oil imports, increase the energy efficiency of transportation, and reduce greenhouse gas (GHG) emissions. To realize these benefits, EVs must compete with conventional vehicles in terms of price and driving range, both of which are influenced by the cost and storage capacity of the EV's battery. ARPA-E's RANGE program aims to maximize a battery's energy storage potential and minimize its cost at the vehicle system level.

¹³ U.S. Energy Information Administration, Monthly Energy Review, Tables 2.5 and 3.8c, April 2017.

This will require robust energy storage chemistries and new battery cell and pack architectures. RANGE technologies seek to reduce the weight of vehicle energy storage systems while curtailing the need for added impact protection and enabling systems to perform additional functions.

TECHNICAL OPPORTUNITY

To increase the appeal of EVs, automakers are seeking to extend EV range, while reducing the total volume battery systems occupy in the vehicle. One approach is to reduce the cumbersome, high-strength packaging that protects cells from temperature swings and crushing during an accident and develop alternative means of ensuring safety. Innovations that make batteries more tolerant to physical abuse, so that they may be used as multifunctional structural materials in the car would eliminate the need for such packaging. The past decade of investigations in thermal runaway mitigation for Lithium-ion (Li-ion) batteries has yielded several promising but disparate techniques. Evaluating and integrating these distinct techniques presents an opportunity to optimize system performance for multifunctional batteries.

INNOVATION DEMONSTRATION

The University of California, San Diego (UCSD) team sought solutions to the RANGE challenges at both the vehicle system level and the cell level. At the vehicle level, the team employed computer models to determine how a battery pack could replace other parts of the car. At the cell level, the team developed multiple techniques to build battery cells that are more tolerant to abuse. Computer simulations were used to optimize structures and locations of battery packs for both occupant survivability in a frontal crash and net cost and weight savings. The simulation complied with Standard U.S. Federal Motor Vehicle Safety Standard (FMVSS) tests; specifically the Occupant Compartment Acceleration zone had to be kept below 30G during a simulated crash.

The team successfully designed a pack that passed this simulation with a peak acceleration of 29.5G while reducing the car's net weight by 136 lbs.

Additionally, the team constructed a partial mock-up of the design that passed impact tests, further substantiating the viability of the design.

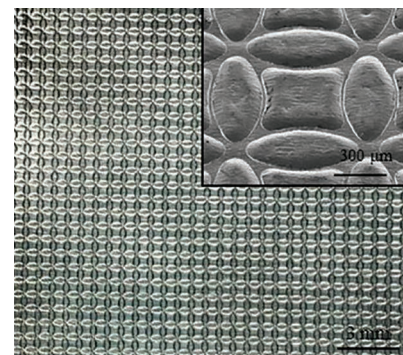


Figure 1: Image of the UCSD patterned current collector used to prevent cell thermal runaway.

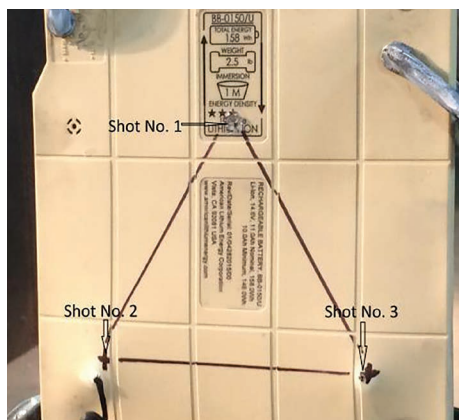


Figure 2: UCSD cells packed into a military battery pack. The three points on the triangle indicate high-caliber rifle shots.

At the cell level, multiple approaches were taken to improve cell robustness by reducing or eliminating Li-ion battery thermal runaway against thermal, mechanical, and overcharge abuse. The three most successful technologies were: 1) a proprietary safety coating that separates damaged portions of the cathode from the current collector when the cell is penetrated; 2) a patterned or “debossed” current collector that disconnects damaged battery parts when crushed (Figure 1); and 3) fire retardant additive pouches surrounding the cell that assure battery safety in a crash without significant weight/volume burdens on the cell. Cells made with UCSD’s safety coating and debossed current collectors successfully passed standard abuse tests that included nail penetration, overcharging at 2.5 factor capacity, heating to 160°C, and shooting through by a high-caliber rifle (Figure 2). Li-ion cells employing conventional cathode materials with the UCSD modifications passed all of these tests without the usual catastrophic cell deflagration. Cells treated with the UCSD safety technologies showed no appreciable change in overall performance during normal operation and maintained their volumetric energy density.

At project completion, the UCSD team produced a 1 kWh battery pack using their safety coating technology, with an energy density of 163 Wh/kg at an additional cost of only \$0.30/kWh. This additional cost constitutes less than 0.2% of the current cost of storage in EV packs.

IMPACT PATHWAY

UCSD's technology is currently being tested by the U.S. Department of Defense (DOD). The team developed a prototype for a standard DOD Model T6 battery pack, made with cells of conventional Li-ion chemistry but employing the UCSD team's safety layer technology. Currently, T6 cells provide power for ancillary electronics on 95% of all U.S. military vehicles. If testing is successful, the DOD will provide funding to manufacture a 1 kWh battery pack with the technology. UCSD's partner, American Lithium Energy (ALE), recently announced a new joint venture company with Bren-Tronics to manufacture these cells. As this technology improves, it could enable the sale of commercial battery packs with higher energy density that otherwise could not be used today due to safety concerns.

LONG-TERM IMPACTS

The UCSD battery cell and pack safety technology is expected to reduce the cost of EV battery packs by making the individual cells safer, thereby reducing the overall weight necessary to encase and protect the cells from damage during a crash. UCSD modeling efforts show that specially designed battery packs can be used to help absorb the impact of a crash, while decreasing vehicle weight. The combination of these two features would increase range and decrease costs to promote large-scale EV adoption.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of January 2018, the UCSD team's project has generated three invention disclosures to ARPA-E, and three U.S. Patent and Trademark Office (PTO) patent applications have been filed on the disclosed inventions. The UCSD team has also published the scientific underpinnings of this technology 15 times in open literature.

4. NOVEL STRUCTURE FOR SOLID STATE LITHIUM-ION BATTERIES

Updated: January 14, 2018

TITLE: Safe, Low Cost, High Energy Density, Solid State Li-Ion Batteries

PROGRAM: Robust Affordable Next Generation Energy Storage Systems (RANGE)

AWARD: \$4,683,452

TEAM: University of Maryland, University of Calgary, Ion Storage Systems, TransTech

TERM: January 2014 – January 2020

PRINCIPAL INVESTIGATOR (PI): Eric Wachsman

MOTIVATION

In 2017, 91% of U.S. transportation energy came from petroleum, nearly half of which came from foreign sources.¹⁴ Widespread adoption of electric vehicles (EVs) can substantially reduce U.S. oil imports, increase the en-

¹⁴ U.S. Energy Information Administration, Monthly Energy Review, Tables 2.5 and 3.8c, April 2017.

energy efficiency of transportation, and reduce greenhouse gas (GHG) emissions. To realize these benefits, EVs must compete with conventional vehicles in terms of price and driving range, both of which are influenced by the cost and storage capacity of the EV's battery. ARPA-E's RANGE program aims to maximize a battery's energy storage potential and minimize its cost at the vehicle system level. This will require robust energy storage chemistries and new battery cell and pack architectures. RANGE technologies seek to reduce the weight of vehicle energy storage systems while curtailing the need for added impact protection and enabling systems to perform additional functions.

TECHNICAL OPPORTUNITY

Current lithium-ion (Li-ion) technology consists of a graphite negative electrode coupled with a metal oxide positive electrode. This design suffers from performance limitations that incremental progress cannot address. Its energy density is limited by the amount of charge that can be practically stored inside its components; Li-ion's upper operating temperature of $\sim 50^{\circ}\text{C}$ requires expensive cooling systems; and current Li-ion cells use a flammable liquid electrolyte, prompting safety concerns.

Replacing the negative electrode with Li metal and the liquid electrolytes in the separator and the porous positive electrode with solid ion conductors can address these limitations.¹⁵ An appropriate solid electrolyte separator can enable Li metal as the negative electrode by eliminating dendrites—small needles that cause cells to short and limit the use of high capacity Li-metal anodes. Non-combustible, solid-state electrolytes can also reduce temperature and flammability constraints, though they faced challenges in conducting lithium ions and interfacing with other cell components. Advances such as the synthesis of $\text{Li}_7\text{La}_3\text{Zr}_2\text{O}_{12}$ ("LLZO"), a new garnet-ceramic material with a room temperature Li-ion conductivity nearly equivalent to state-of-the-art Li-ion liquid electrolytes, could enable a new generation of safe batteries without sacrificing performance.

INNOVATION DEMONSTRATION

Garnet-ceramic-based solid-state batteries are highly conductive, stable, safe, and can prevent lithium dendrites from forming. However, garnet-electrolyte batteries have long faced challenges related to electrolyte thickness, low surface area at the electrode/electrolyte interface, and inherently poor solid-solid interfacial contact. To address this, the University of Maryland (UMD) team combined expertise from disparate fields, including experience with solid oxide fuel cells, in-depth knowledge about the LLZO material, and battery manufacturing capability.

The team built a tri-layer electrolyte structure from LLZO that features a porous structure for both the positive and negative electrodes, with a dense, thin, solid electrolyte sandwiched between them. The thin, dense center layer prevents dendrite growth. The porous support on either side of the dense center layer provides mechanical strength and helps overcome electrode/electrolyte interfacial impedance by increasing the surface area between the two.

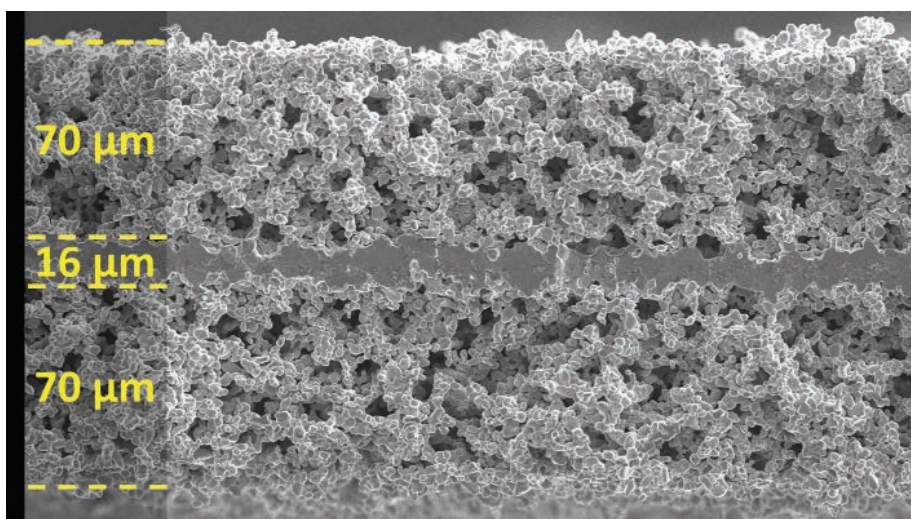


Figure 1: Sample unfilled garnet tri-layer porous electrolyte with dense interlayer.

¹⁵ Albertus, P. Integration and Optimization of Novel Ion-Conducting Solids (IONICS) Funding Opportunity Announcement (2016); <https://arpa-e-foa.energy.gov/FileContent.aspx?FileID=cfac9ce8-5a19-4623-b942-c3e65f3ccf77>.

The team also leveraged a new atomic layer deposition technique in which a thin aluminum oxide (or other composition) coating is deposited onto the garnet electrolyte surfaces. The coating reduces LLZO resistance to both electrodes and prevents water from reacting with the lithium in the garnet, but does not increase cell resistance.

Tests show that lithium ions can be shuttled across the separator layer with 100% coulombic efficiency (i.e. no loss of lithium) and with no increase in cell resistance for greater than 300 cycles. The team is working to scale up while refining their cost model, which indicates that with high-volume manufacturing, this solid-state system may be cost competitive with traditional Li-ion batteries with decreased weight thanks to fewer control and protection systems.

IMPACT PATHWAY

UMD has spun-off a company, Ion Storage Systems (ISS), which has begun fabricating sample cells and distributing them to potential customers. ISS is focusing on scale-up and manufacturing of supported garnet electrolytes with major ceramic manufacturer, TransTech, and coating developer, PneumatiCoat, for first sales. The technology has generated interest from the automotive, consumer electronic, and aerospace industries. Unmanned aerial vehicles (UAVs) are a likely first market, as these aircraft require higher energy density and can bear the costs associated with initial low-volume production. Additional funding has also been received, including three Department of Energy, Energy Efficiency and Renewable Energy (EERE) contracts and two NASA Game Changing Program contracts, as well as support from Lockheed Martin.

LONG-TERM IMPACTS

With the development of a highly conductive lithium electrolyte, a rigid, self-supporting architecture, and low internal resistance, the UMD team's battery has the potential to overcome the energy density plateau of Li-ion chemistry. Such a design could be used in large format battery manufacturing plants for EVs. Inexpensive and safe batteries using this technology could also be used for grid energy storage, consumer electronics, and UAVs. In the long term, the success of this technology will provide U.S. manufacturing a new battery platform with higher capacity, lower cost, and greater safety.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of January 2018, the UMD team's project has generated six invention disclosures to ARPA-E. One U.S. Patent and Trademark Office (PTO) patent applications is currently pending for these inventions. The team has also published the scientific underpinnings of this technology six times in open literature.

TRANSPORTATION



A BRAND NEW CLASS OF LIGHT-DUTY VEHICLE ENGINES

Updated: November 30, 2017

TITLE: Gasoline Compression Ignition Light Duty Multicylinder Opposed Piston Engine Demonstration

PROGRAM: OPEN 2015

AWARD: \$9,002,985

TEAM: Achates Power, Inc.(Lead); Argonne National Laboratory; Delphi Powertrain

TERM: April 2016 – November 2018

PRINCIPAL INVESTIGATOR (PI): Fabien Redon

MOTIVATION

Approximately 29% of U.S. energy consumption is used for transportation, with 58% of that consumed in light-duty vehicles (cars, light trucks, and motorcycles).¹ In 2017, 91% of U.S. transportation energy came from petroleum, nearly half from foreign sources.² Moreover, average light-duty vehicle fuel economy has plateaued over the last 30 years.³ Improved engine technologies and powertrain systems can enable more efficient and cleaner vehicles, which can substantially reduce U.S. oil imports, increase the energy efficiency of transportation, and mitigate greenhouse gas (GHG) emissions. Although vehicle original equipment manufacturers (OEMs) are investigating various technologies to improve efficiency, increased costs present challenges. Blending innovations to both the hardware architecture and combustion strategies has the potential to increase efficiency and reduce emissions, while satisfying the cost and performance expectations.

TECHNICAL OPPORTUNITY

A high-performing engine embodies two well-coordinated design aspects: hardware architecture and combustion strategy. The incumbent technology for light-duty vehicles is the four-stroke spark-ignition engine. A paradigm shift away from the spark ignition strategy towards completely changing the four-stroke architecture could yield transformational gains. On the combustion side, gasoline compression ignition (GCI) has garnered significant attention from OEMs and automotive Tier-1 suppliers in the last few years.⁴ GCI exploits the high-efficiency benefits of a compression ignition engine,⁵ a characteristic of diesel engines, while utilizing gasoline or gasoline-like fuels to reduce emissions. However, significant challenges remain to unleash the full benefits of GCI, such as low load and low temperature combustion stability and high load combustion noise and high cylinder pressure.

On the hardware side, the opposed-piston (OP) engine design offers significant efficiency benefits over the four-stroke architecture by reducing heat transfer and eliminating the valve train. Intake ports and exhaust ports are opened by piston location, enabling effective uniflow air scavenging necessary for efficient two-stroke engine operation and replacing the complex poppet valves and valve trains of traditional engines. The OP engine's lower heat loss and decoupling of piston motion from air induction provides thermally favorable ignition conditions

¹ <https://www.afdc.energy.gov/data/10566>

² U.S. Energy Information Administration, Monthly Energy Review, Tables 2.5 and 3.8c, April 2017.

³ <https://www.afdc.energy.gov/data/10305>

⁴ <http://articles.sae.org/12823/>

⁵ Compression ignition engines compress air to a much greater degree than spark ignition engines. The higher compression ratio leads to higher efficiency from the engine and improved fuel economy.

for GCI, minimizing low load combustion variability, while the two-stroke operation reduces the high load combustion noise and cylinder pressure challenges. The flexibility in controlling the combustion conditions and fuel injection strategy through multiple injectors per cylinder solves some of the hurdles that the four-stroke engine has in delivering GCI. Compression ignition OP engines are inherently more efficient than conventional gasoline spark-ignited four-stroke engines, with potential for up to 50% higher thermal efficiency, while providing comparable power and torque. They also show the potential to meet future tailpipe emissions standards.

INNOVATION DEMONSTRATION

Achates Power, Inc., Argonne National Laboratory (ANL), and Delphi Powertrain united to integrate a nascent GCI combustion strategy with the OP engine architecture to demonstrate a high efficiency, cleansheet-design gasoline engine. The team's OP-GCI engine is the only spark-free opposed-piston gasoline engine in the industry. The newly designed three-cylinder is a 2.7-liter OP engine with a 270 horsepower rating. Researchers at ANL and Achates Power conducted three-dimensional computational fluid dynamic (CFD) simulations and one-dimensional simulations to arrive at an optimum design. Delphi led the development of the gasoline fuel injection system and designed the fuel injectors to provide the appropriate fuel spray characteristics to enable clean and efficient combustion. The engine design has the potential to meet the 36.5% brake thermal efficiency target over a standard drive cycle and a peak brake thermal efficiency of greater than 45%.⁶



Figure 1: three-cylinder OP-GCI engine.

Early experiments performed in a single-cylinder research engine at ANL at low- and medium-loads indicate thermal efficiencies between 45-50% for the OP-GCI technology. The project team has performed extensive cost analysis that projects the OP-GCI technology will cost less than current technology trajectories for the year 2025 and beyond, when OP-GCI engines could significantly penetrate the light-duty and heavy-duty engine markets.

IMPACT PATHWAY

The OP-GCI engine has generated interest from defense, automotive, marine, and oil and gas industries. Among its follow-on investors, the Oil and Gas Climate Initiative (OGCI), a CEO-led initiative of 10 oil and gas companies, has funded Achates Power to accelerate development and commercialization.⁷ Achates Power is working with a leading automotive engineering service provider to build a light-duty pickup truck demonstrator vehicle, a version of which showcased at the North American International Auto Show in January 2018.

LONG-TERM IMPACTS

The OP-GCI technology shows a 30%-50% efficiency improvement over current gasoline engines without increasing cost relative to conventional engines. Such improvements will result in significant energy savings and emissions reductions. When integrated with current vehicle hybridization technologies, the OP-GCI powertrain could be the most efficient, liquid-fuel driven powertrain. The suite of technologies developed in this project could also have far-ranging impact beyond the transportation industry, such as in power generation, oil and gas, and marine industries.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of November 2017, the Achates Power project has generated eight invention disclosures to ARPA-E.

⁶ The fourth generation Toyota Prius 1.8-liter engine achieves a peak brake thermal efficiency of 40% (<http://toyotanews.pressroom.toyota.com/releases/2016+toyota+prius+technology.htm>), which is notionally considered as the yardstick for light-duty engines.

⁷ <https://www.prnewswire.com/news-releases/achates-power-announces-new-investor--ogci-climate-investments-300543840.html>

A INCENTIVIZING INDIVIDUAL TRAVEL BEHAVIOR CHANGES FOR SYSTEM-LEVEL ENERGY SAVINGS

Updated: January 13, 2018

TITLE: Integrated, Personalized, Real-Time Traveler Information and Incentive Technology for Optimizing Energy Efficiency in Multimodal Transportation Systems

PROGRAM: Traveler Response Architecture using Novel Signaling for Network Efficiency in Transportation (TRANSNET)

AWARD: \$3,780,000

TEAM: University of Maryland (UMD), Arizona State University, North Carolina State University, and University of Michigan

TERM: November 2015 – August 2018

PRINCIPAL INVESTIGATOR (PI): Lei Zhang

MOTIVATION

The transportation sector accounts for over 25% of total energy use in the United States. Significant energy savings could be realized in personal transportation by improving vehicle occupancy, correcting poor driving styles, and reducing congestion. Occupancy is only 40% of nominal capacity for passenger vehicles,⁸ poor driving styles (e.g. rapid acceleration) contribute to a 45% reduction in on-road fuel economy per driver,⁹ and congestion (which is related to non-optimal route choice) increases the energy used by up to 33%.¹⁰ Better use of modes of transportation, including public transit and rideshare programs, can reduce overall energy use by increasing vehicle occupancy and mitigating traffic. A 1% reduction in overall energy use in the United States could be achieved by a relatively small number of travelers adjusting their current travel choices and driving style. The challenge is how to show the right travelers the right incentives delivered at the right time, for maximum energy savings.

TECHNICAL OPPORTUNITY

Widespread smartphone and location-based technologies enable researchers to reach individual travelers with a smartphone app and/or technology APIs (application programming interfaces) that are integrated into existing private-sector apps and government-operated commuter service platforms. Existing travel guidance and planning tools focus on helping individuals make travel choices optimized at the user level for objectives often unrelated to energy. Incentives through status-quo technologies are often static and impersonal, and consequently not always effective. Recent advances in the fields of large-scale transportation system modeling, agent-based simulation in transportation, dynamic network optimization, data analytics, cloud-based computing, and artificial intelligence applications in behavioral sciences have enabled the development and implementation of architectures that can deliver dynamic, personalized, and optimized incentives to travelers in a multimodal transportation system and at the metropolitan scale.

⁸ The National Highway Transportation Survey reports average occupancy of 1.67 persons over all types of trips. The average number of seats is assumed to be 4.

⁹ Sivak, M. & Schoettle, B. "Eco-driving: Strategic, tactical, and operational decisions of the driver that influence vehicle fuel economy", Transport Policy 22 (2012) 96–99. See also LeBlanc, D., Sivak, M., and Bogard, S. "Using Naturalistic Driving Data to Assess Variations in Fuel Efficiency among Individual Drivers" University of Michigan Report UMTRI-2010-34, December 2010.

¹⁰ This is an approximation of the maximum effect. See Roughgarden, T., "The Price of Anarchy in Games of Incomplete Information", <http://theory.stanford.edu/~tim/papers/inc.pdf>.

INNOVATION DEMONSTRATION

The University of Maryland (UMD) project seeks to optimize monetary and non-monetary incentives to gain maximum energy reduction in the Baltimore-Washington metropolitan area. These incentives will help guide travelers to adjust their travel mode, departure time, route, and driving style for energy efficiency. The UMD project has developed a system model (SM) that utilizes real-time and archived data from the Regional Integrated Transportation Information System (RITIS) hosted at UMD, and consists of integrated dynamic traffic, individual travel behavior, and energy use simulators. RITIS provides real-time data regarding incident, event, detector, probe, weather, transit, and other data including ITS device status. The dynamic traffic simulator uses Intel's multi-core parallel computing technology, the OpenMP, to ensure rapid analysis. The model employs a novel behavioral user equilibrium theory that focuses on actual traveler behavior. The energy use estimator utilizes real-world vehicle trajectories supplemented with in-vehicle powertrain control parameters to enhance accuracy. The SM is integrated with an incentive structure referred to as the incentive/control architecture (IA). The IA was tested and verified via a market adoption survey and incentive framing experiment with more than 2,000 participants in the Baltimore-Washington metro area. An algorithm coupled with a decentralized method for large-scale incentive allocation problems optimally allocates real time and personalized incentives for energy savings.

The integrated SM and IA (named incenTrip, see Figure 1) are capable of simulating all trips of multimodal vehicles in the Baltimore-Washington metro area, covering 5,744 square miles with more than 8.2 million people, for real-time energy use prediction at the trip level and incentive optimization at the user level. For comparison, the traditional travel demand model of a similar network requires about 30 hours of processing time on a high-end workstation. incenTrip works with OpenMP and Spark to process 8 billion data records each day. UMD also successfully developed and tested a new smart phone app to be deployed in the Baltimore-Washington metro area.

IMPACT PATHWAY

Commuter Connections, a regional network of transportation organizations coordinated by the Metropolitan Washington Council of Governments, deployed the incenTrip technology to incentivize departure time shifts. Over 20,000 commuters rely on Commuter Connections for free up-to-the-minute ridesharing information. The project team is collaborating with private sector mobility service partners to deploy incenTrip APIs that enable dynamic and personalized incentives in existing travel services. The incenTrip app, encompassing all new technologies from this ARPA-E project, is ready for deployment and officially launched in Washington, D.C. in early 2018. The project team has established a startup company to take the technology to market, and is exploring how to take the technology to more cities.

LONG-TERM IMPACTS

The complex nature of transportation system dynamics means that significant energy savings could be realized with even small behavior adjustments by a few travelers. Connected and automated vehicles will further facilitate the implementation of dynamic trip incentives. Successful demonstration of the incenTrip technology in the Baltimore-Washington metro area could pave the way for long-term energy savings across the United States.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of November 2017, the UMD team has produced 20 peer-reviewed publications.

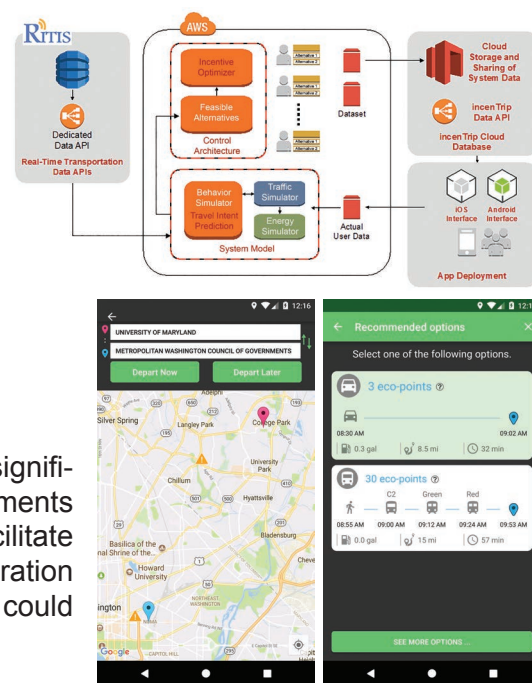
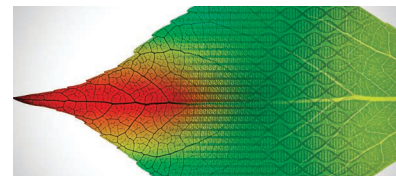


Figure 1: incenTrip Technology Overview (top), incenTrip Technology Deployment via a Smartphone App (bottom).

TRANSPORTATION ENERGY RESOURCES FROM RENEWABLE AGRICULTURE (TERRA)



MOTIVATION

As global energy demand increases, bioenergy remains an important fuel alternative. However, current yields of bioenergy crops, like biomass sorghum, are insufficient to produce large volumes of domestic biofuel. High-throughput strategies that can identify improved crop genotypes earlier in the growth cycle are needed to quickly develop new, high-yield varieties. Greater knowledge of factors that influence crop development can improve breeding. Genomics tools have advanced, and the pace of genotyping has accelerated exponentially while the cost of sequencing has dramatically decreased. The technological challenge has shifted from understanding the genotype to understanding the phenotype – the traits exhibited by the plant as a result of its genotype and its environment (Figure 1). Because traditional breeding approaches are slow and labor-intensive, new approaches to accelerate phenotyping are needed.

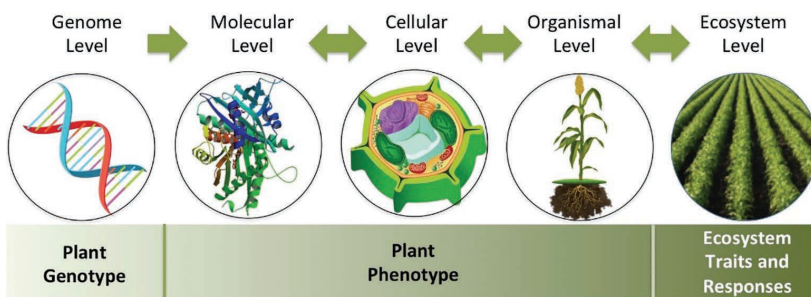


Figure 1. Information in the plant genome interacts with biotic and abiotic factors to inform emergent properties across scales.

TECHNICAL OPPORTUNITY

Sorghum plants possess many valuable attributes, including high biomass-yield potential, drought tolerance, and a sequenced genome. Advanced phenotyping could lead to the identification of new sorghum variants with even higher biomass or increased tolerance. Advances in robotics, remote sensing, and software allow for extraction of massive volumes of data from crops, allowing high-throughput evaluation of traits throughout the growing season. When combined with next-generation DNA sequencing and molecular profiling, these advances enable breeders to rapidly develop crops with desired traits. Nevertheless, complexities in data processing, feature extraction, and data analytics make predictions of crop performance challenging.

ARPA-E has selected four projects that illustrate the various approaches in the TERRA program:

1. Clemson University's "Low-Cost Robotics for Crop Improvement"
2. Pacific Northwest National Laboratory's "Accelerating Sorghum Breeding With Unmanned Aerial Vehicles"
3. Purdue University's "Automated Sorghum Phenotyping Platforms"
4. University of Illinois at Urbana-Champaign's "Low-Cost Robot for Crop Improvement"

1. LOW-COST ROBOTICS FOR CROP IMPROVEMENT

Updated: December 14, 2017

TITLE: Biofuel Organism Observation Science and Technology (BOOST)

PROGRAM: Transportation Energy Resources from Renewable Agriculture (TERRA)

AWARD: \$6,149,998

TEAM: Clemson University, Carnegie Mellon University, Near Earth Autonomy, Donald Danforth Plant Science Center

TERM: September 2015 – September 2018

PRINCIPAL INVESTIGATOR (PI): Stephen Kresovich

INNOVATION DEMONSTRATION

The Clemson team seeks to accelerate genetic gain in biomass sorghum by adopting a “system of systems” approach (Figure 2), including robotics, sensing, computer vision, machine learning, and genomics to inform breeding decisions. Specifically, the team is developing sorghum varieties adaptable to hot and high-moisture environments, and to sandy or clay soil. These environments are typical of the challenges in the U.S. Southeast, which are different from production conditions for grain sorghum. These varieties will be optimized for energy biomass grown on land in the Southeast not suitable for food production.

The team developed three sensor packages on autonomous ground rovers and unmanned aerial vehicles (UAVs). The ground-based and aerial platforms use visual, thermal, and LiDAR sensors to evaluate the structure of sorghum. A third platform uses a robotic arm to grasp plant stems and evaluate physiological or compositional traits, including stalk strength. All three platforms have modular sensor packages and can add upgraded sensors.



Figure 2: A ground robot (left) and unmanned aerial vehicle (top right) automatically collect data in the field, which is then processed to extract phenotypic measurements. For example, RGB images can be used to quantify leaf necrosis (bottom right).

After collecting data, the team needed to extract phenotypic data to identify optimal trait values. To accomplish this, the team is developing learning algorithms that draw plant boundaries and evaluate traits, and predictive algorithms that estimate end-of-season harvest attributes with early season characteristics. The final step identifies causal genes for optimal trait values and design crossing strategies. If successful, the results will be high-yielding plants (Figure 3) that are well suited to their environment.

IMPACT PATHWAY

The team has formed or partnered with several companies to bring different aspects of the project to market. Carolina Seed Systems, a genetics company, will produce sorghum and

other seed, bred for Southeastern conditions; TERRA-SCAN a start-up that provides phenotyping and field scouting services; and Near Earth Autonomy, another start-up, that will market a data collection product derived from the team's aerial platform. The project expects significant intellectual property in computer vision and machine learning that will be broadly applicable for plant breeding and other agricultural research.

LONG-TERM IMPACTS

The USDA forecasted that over 90% of U.S. cellulosic bioenergy needs will be met through production in the southern United States, with sorghum as a key feedstock.¹¹ Success in meeting these demands hinges, in part, on the ability to rapidly identify and breed plants with favorable phenotypes for fuel production in the southern United States. If successful, this project's technologies will produce precise measurements of plant performance. This data, coupled with genomic technologies and new algorithms, could enable the development of bioenergy crops that sustainably lead to a large supply of biomass for biofuel production.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of December 2017, the Clemson University project had generated three invention disclosures to ARPA-E. This project has also published the scientific underpinnings of this technology four times in open literature.



Figure 3: A high-yield biomass sorghum plant (right) compared to a normal sorghum plant (left).

2. ACCELERATING SORGHUM BREEDING WITH UNMANNED AERIAL VEHICLES

Updated: December 16, 2017

TITLE: Consortium for Advanced Sorghum Phenomics (CASP)

PROGRAM: Transportation Energy Resources from Renewable Agriculture (TERRA)

AWARD: \$7,033,003

TEAM: Pacific Northwest National Laboratory, Blue River Technology, Department of Energy's Joint Genome Institute, Kearney Agricultural Research Extension Center, Chromatin

TERM: September 2015 – December 2018

PRINCIPAL INVESTIGATORS (PI): Christer Jansson (PNNL); Matt Colgan (BRT)

INNOVATION DEMONSTRATION

This project aims to develop high-biomass sorghum with superior drought/salinity tolerance. The CASP team has developed phenotyping test sites in California and Texas to provide ideal conditions and real environments. The lack of rain during the field trial period allowed irrigation to be precisely controlled in California, and Texas is one of the top sorghum producing states in the United States.

¹¹ https://www.usda.gov/sites/default/files/documents/USDA_Biofuels_Report_6232010.pdf

The CASP team uses a sensor suite of LiDAR, multispectral cameras, and thermal cameras on an unmanned aerial vehicle (UAV) that detects traits indicative of improved yield and tolerance of drought and salinity. Data-processing software translates UAV-based imagery into measurements within the same day as UAV flights.

To link the phenotypes observed by the UAV to specific DNA sequences (markers or candidate genes), the team has applied large collections of diverse sorghum germplasm for genome-wide association studies to field phenotypic data. Over 200 genetic markers associated with drought tolerance and/or biomass accumulation were identified over an entire growing season to ensure accurate phenotyping. The temporal information obtained by phenotyping throughout the season allows researchers to confidently identify genetic markers associated with the traits measured and identify genes that are important at specific life stages.



Figure 4: UAV with sensor payload.

In parallel, combining field phenotyping of morphological and behavioral traits with molecular phenotyping of transcript, protein, and metabolite profiles provides a mechanistic understanding of observed traits, such as biomass and leaf size. Generated metabolite and protein profiles correlated to plant functional traits can be used with low cost, rapid detection to identify superior sorghum genotypes in marker-assisted selections.

IMPACT PATHWAY

The development and commercialization of high value, generalized genome-to-phenome tools will enable advances in energy crop yields like biomass sorghum. Currently, advanced tools for genetic improvement in bioenergy feedstocks are not available as they are for row crops.

In 2017, the team completed a proof-of-concept project on field corn with a major U.S. seed company, collecting data in the Midwest and demonstrating the successful collection of plot-level plant traits. Over the next few years, the CASP team expects to expand into the plant breeding industry.

Other applications of UAV-based phenotyping include research in precision agriculture contexts, such as characterizing performance of various precision machinery. The UAVs developed by Blue River Technology (BRT), a member of the CASP team, produce plant field maps that provide breeders and growers with unprecedented insight into crop health and yield, with the fastest turnaround time in the market. In September 2017, John Deere acquired BRT for its expertise in applying computer vision, machine learning, and robotics to agriculture. This acquisition opens up the possibility of UAVs phenotyping for other applications.

LONG-TERM IMPACTS

Breakthroughs in field-based phenotyping technology coupled with molecular profiling for plant traits could decrease costs for developing sorghum cultivars and screening methods for other crops. Application of the new phenotyping methods could accelerate the sorghum breeding process by as much as three years (on a typical 10-year development cycle) and save millions of dollars in bringing a sorghum cultivar to market. CASP's findings will contribute toward the development of high-biomass sorghum with superior drought/salinity tolerance. The expanded use of resource-efficient energy crops could minimize competition with food crops. If successful, these technologies will enable greater U.S. production of renewable bioenergy and bioproducts, which will enhance U.S. economic and sustainable energy security.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of December 2017, the CASP team has published the scientific underpinnings of this technology once in open literature.

3. AUTOMATED SORGHUM PHENOTYPING PLATFORMS

Updated: December 21, 2017

TITLE: Automated Sorghum Phenotyping and Trait Development Platform

PROGRAM: Transportation Energy Resources from Renewable Agriculture (TERRA)

AWARD: \$6,662,287

TEAM: Purdue University, IBM, University of Queensland

TERM: August 2015 – August 2018

PRINCIPAL INVESTIGATOR (PI): Mitch Tuinstra

INNOVATION DEMONSTRATION

Purdue seeks to optimize sorghum energy yield for transportation fuel. The team uses advanced sensors mounted on ground-based systems (Figure 5) and unmanned aerial vehicles (UAVs) to monitor several traits throughout the growing season, including plant height, canopy cover, leaf-area index, spectral indices, and leaf number. The data are combined with traditional measures of productivity and agronomic performance to develop trait indices for high-throughput phenotyping.

The team developed an integrated calibration procedure for various sensors onboard the UAV and PhenoRover systems. The calibration process has demonstrated accuracy near the pixel resolution of the sensor. This resolution enables an unprecedented level of automatic analysis—from entire plots all the way down to individual plants and leaves (Figure 6).

Purdue developed machine learning algorithms to identify plots of field trials, identify centers of all plants in each plot, and estimate plant and leaf counts, plant height, panicle counting, and canopy cover. The team then combines these measurements with visualization tools to provide interactive analytical capabilities. Algorithm users can investigate which varieties are similar according to selected plant traits, discovering genes for plant performance, architecture, and composition in diverse collections of sorghum. The team is working to identify genes and alleles that can be used to enhance the bioenergy value of sorghum feedstock. The team has already identified 22 mutants with modified lignin content and composition and improved efficiency in biofuels production. They also identified genetic loci that contribute to sugar release during ethanol production, enabling potentially higher yields in biofuel conversion. To enable applications beyond sorghum, the team is working to ensure its tools can be used in other remote sensing platforms.

IMPACT PATHWAY

The team received approximately \$200,000 in follow-on funding from the United Sorghum Checkoff to develop and deploy a platform of sensors and algorithms to identify reproducible, physiologically relevant



Figure 5 (left): The PhenoRover integrates visible, multispectral, ranging, and hyperspectral sensors
Figure 6 (right): Automated plant identification.



changes in crop plant tissues under stresses. Additionally, a major agricultural corporation has provided \$150,000 to develop new phenotyping technologies for maize breeding and genetics.

In 2016, Purdue University devoted \$15 million in a new field phenotyping facility, the Indiana Corn and Soybean Innovation Center, which brings together Indiana farmers, industry, university faculty and students. By using state-of-the-art technology to measure and analyze characteristics of crops, the Center seeks to translate information about individual plants to field scale.

In August 2017, the project leads launched CROPi Analytics, a company that provides data processing software for remote sensing applications in agriculture. In October 2017, CROPi Analytics agreed to commercialize two patents from the Purdue Research Foundation related to remote plant sensing and improved algorithms.

LONG-TERM IMPACTS

Previously, the difficulty of identifying relevant information from plant data limited the application of whole genome data to sorghum breeding. Thanks to the remote sensing tools and data processing systems developed in this project, breeders now have detailed, precise measurements of plant performance. These data, coupled with genomic technologies and new algorithms, will enable the development of bioenergy crops that can sustainably generate a large supply of biomass for biofuel production.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of December 2017, the project has generated five invention disclosures to ARPA-E. One U.S. Patent and Trademark Office (PTO) patent application has been filed on the disclosed inventions. The project has also published the scientific underpinnings of this technology five times in open literature and presented at conferences around the world.

4. LOW-COST ROBOT FOR CROP IMPROVEMENT

Updated: January 29, 2018

TITLE: TERRA Mobile Energy-Crop Phenotyping Platforms (MEPP)

PROGRAM: Transportation Energy Resources from Renewable Agriculture (TERRA)

AWARD: \$5,100,000

TEAM: University of Illinois at Urbana-Champaign (UIUC) (Lead), Cornell University, and Signetron, Inc.

TERM: October 2015 – December 2019

PRINCIPAL INVESTIGATOR (PI): Stephen Long

INNOVATION DEMONSTRATION

The University of Illinois, Urbana-Champaign (UIUC) project aims to: (1) develop low cost, autonomous robots with sensors to rapidly collect phenotypic information within large field trials (Figure 7); (2) develop software to deliver high-throughput phenomics from the sensor data; (3) use a model-based data synthesis system to capture physiological parameters and predict yield; and (4) integrate this diverse information with whole-genome DNA sequencing technologies to identify genes underlying the traits and their genetic markers that will maximize the pace of trait discovery.



Figure 7: One of two trials at UIUC. Ground robots collect sensor data from a diverse set of sorghum varieties at a rate of one acre every two hours using autonomous navigation.

team also developed germplasms, living genetic resources, such as seeds, that are maintained for plant breeding and other research uses.

The team also developed TerraMepp, an over-canopy, high-payload robot for versatile phenotypic measurements, and TerraSentia (Figure 8), a low cost, under-canopy robot for early adoption in commercial applications. Whereas manual phenotyping of a single field requires several days, a single TerraSentia can survey a trial plot in just one day. Fleets of TerraSentia robots can operate as a team to offer nearly unlimited

To improve accuracy for automated phenotypic data processing, the team developed point cloud algorithms to identify individual stems and age-adaptive algorithms to estimate stem width and plant height. These algorithms can be applied to field data with over 80% accuracy. The team used the data to develop a model able to predict end-of-season performance of individual plants.

The team created a high-throughput sequence data analysis pipeline for whole-genome resequencing to identify genes underlying specific traits. Some traits, such as plant height, were found to be highly heritable, and a number of genetic markers have been linked to these traits. High quality genetic markers allow researchers to determine the best crosses to make between sorghum varieties, and then select the plants with the highest yield potential early in the season. As a result, the



Figure 8: TerraSentia is an ultra-compact 3D-printed robot.

IMPACT PATHWAY

Potential commercial products from this project include the autonomous robots, novel algorithms for analyzing plant data, and new germplasms with crop-improving genetic markers. Through an early adopter program, the TerraSentia robots are already available to industry, academia, and others at a cost of \$5,000.

LONG-TERM IMPACTS

The difficulty of identifying relevant plant data limits the application of whole genome data to sorghum breeding. The low-cost robots and novel approaches being developed in this project could allow researchers to obtain statistically reliable and biologically meaningful candidate links between genotypes and phenotypes. These new tools could enable more efficient use of diverse genetic resources for crop improvement, including increased resilience and productivity. Ultimately, these phenotyping technologies could lead to new varieties of bioenergy that require less agronomic inputs and are more productive, sustainable, and resilient.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of November 2017, the project has generated five invention disclosures to ARPA-E. The team has also published the scientific underpinnings of this technology twice in open literature.



CHANGING WHAT'S POSSIBLE

ADDENDUM: Wide Bandgap Semiconductor Based Power Electronics for Energy Efficiency

Isik C. Kizilyalli, Eric P. Carlson, Daniel W. Cunningham, Joseph S. Manser, Yanzhi "Ann" Xu, Alan Y. Liu
March 13, 2015
United States Department of Energy
Washington, D.C. 20585



ABSTRACT

The U.S. Department of Energy's Advanced Research Project Agency for Energy (ARPA-E) was established in 2009 to fund creative, out-of-the-box, transformational energy technologies that are too early for private-sector investment at make-or break points in their technology development cycle. Development of advanced power electronics with unprecedented functionality, efficiency, reliability, and reduced form factor are required in an increasingly electrified world economy. Fast switching power semiconductor devices are the key to increasing the efficiency and reducing the size of power electronic systems. Recent advances in wide bandgap (WBG) semiconductor materials, such as silicon carbide (SiC) and gallium nitride (GaN) are enabling a new generation of power semiconductor devices that far exceed the performance of silicon-based devices. Past ARPA-E programs (ADEPT, Solar ADEPT, and SWITCHES) have enabled innovations throughout the power electronics value chain, especially in the area of WBG semiconductors. The two recently launched programs by ARPA-E (CIRCUITS and PNDIODES) continue to investigate the use of WBG semiconductors in power electronics. From materials and devices to modules and circuits to application-ready systems integration, ARPA-E projects have demonstrated the potential of WBG semiconductors to lower the cost of high-efficiency power electronics to enable broad adoption in energy applications.

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INTRODUCTION

Electricity generation currently accounts for 40% of primary energy consumption in the U.S.¹ and over the next 25 years is projected to increase more than 50% worldwide.² Electricity continues to be the fastest growing form of end-use energy. Power electronics are responsible for controlling and converting electrical power to provide optimal conditions for transmission, distribution, and load-side consumption. Estimates suggest that the fraction of electricity processed through some form of power electronics could be as high as 80% by 2030 (including generation and consumption), approximately a twofold increase over the current proportion.³ Development of advanced power electronic devices with exceptional efficiency, reliability, functionality, and form factor will provide the U.S. with a competitive advantage in deployment of advanced energy technologies. Additionally, widespread integration of innovative converters offers substantial energy saving opportunities both directly, by inherently more efficient designs, and indirectly, by facilitating higher levels of adoption for fundamentally higher performing applications and technology solutions.

Technical Opportunity

Achieving high power conversion efficiency requires low-loss power semiconductor switches. Today's incumbent power silicon (Si) based switch technology includes metal oxide field effect transistors (MOSFET), IGBTs and thyristors. Silicon power semiconductor devices have several important limitations:

- *High Losses:* The relatively low silicon bandgap (1.1 eV) and low critical electric field (30 V/μm) require high voltage devices to have substantial critical layer thickness. The large thickness translates to devices with high resistance and associated conduction losses.
- *Low Switching Frequency:* Silicon high voltage power MOSFETs require large die areas to keep conduction losses low. Resulting high gate capacitance and gate charge produce large peak currents and losses at high switching frequencies. Silicon IGBTs have smaller die than MOSFETs due to utilization of minority carriers and conductivity modulation, but the relatively long lifetime of minority carriers reduces the useful switching frequency range of IGBTs.
- *Poor High-Temperature Performance:* The relatively low silicon bandgap also contributes to high intrinsic carrier concentrations in silicon-based devices, resulting in high leakage current at elevated temperatures. Temperature variation of the bipolar gain in IGBTs amplifies the leakage and limits the maximum junction temperature of many IGBTs to 125°C.

Figure 1 illustrates the opportunity space associated with silicon performance limitations. As switching frequency increases, converter power is reduced. In practice, high power silicon systems operate at low frequencies (<10 kHz). This translates to larger passive components (e.g. inductors, capacitors) which increases volume and weight. Wide bandgap (WBG) systems can be operated at higher power and higher frequency within the space silicon devices cannot.

As a result, new opportunities for higher efficiency have emerged with the development of WBG power semiconductor devices, driven by the fundamental differences in material properties between Si and semiconductors such as Silicon Carbide (SiC) and Gallium Nitride (GaN). Higher critical electric fields in these WBG materials (≥ 2 MV/cm) enable thinner, more highly doped voltage-blocking layers, which can reduce on-resistance by two orders of magnitude in majority carrier architectures (e.g., Metal Oxide Field Effect Transistors, MOSFETs)

¹ U.S. Energy Information Administration, Monthly Energy Review (March, 2015)

² U.S. Energy Information Administration, International Energy Outlook 2016 (May, 2016)

³ L.M. Tolbert, et al. Power Electronics for Distributed Energy Systems and Transmission and Distribution Applications: Assessing the Technical Needs for Utility Applications. Oak Ridge, TN: Oak Ridge National Laboratory (2005)

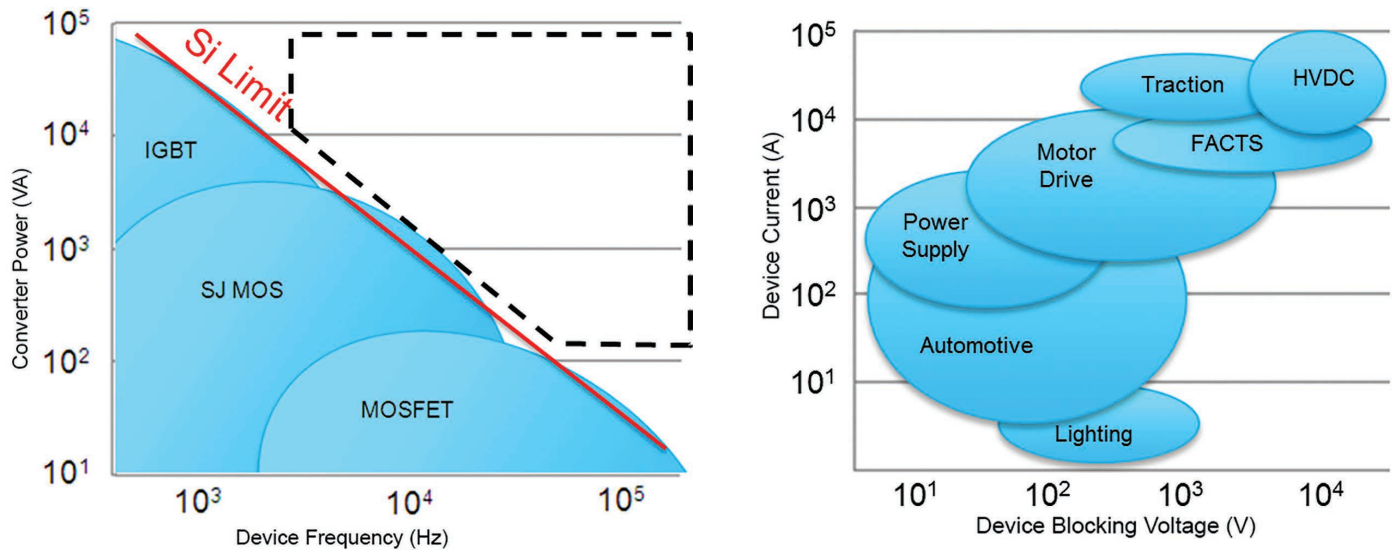


Figure 1: (Left) Relationship of converter power vs switching frequency where the red line indicates the limit of silicon operation. The dotted line area illustrates the opportunity space where WBG systems can operate where silicon devices cannot. (Right) Application areas that lie within the dotted line area include motor drives, automotive, power supplies, aerospace, and distributed energy resources.

relative to an equivalent Si device.⁴ Moreover, high breakdown electric field and low conduction losses mean that WBG materials can achieve the same blocking voltage and on-resistance with a smaller form factor. This reduced capacitance allows higher frequency operation compared with a Si device. The low intrinsic carrier concentration of WBG materials enables reduced leakage currents and robust high-temperature performance. WBG semiconductors therefore provide a pathway to more efficient, lighter, high temperature capable (reduced cooling requirements), and smaller form factor power converters. However, to unlock the potential of WBG based devices, intensive and systematic R&D efforts need to take place at every stage of the power electronics value chain, as depicted in Figure 2.

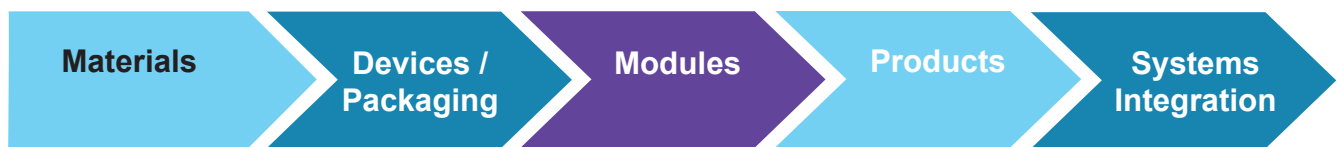


Figure 2: Power Electronics Value Chain.

⁴ Heffner, A. et al. Recent Advances in High-Voltage, High-Frequency Silicon-Carbide Power Devices. Industry Applications Conference, 41st IAS Annual Meeting (2006)

Application Space

High impact opportunities exist across a variety of applications, including:

Motor Drives: Across all sectors, electric motors account for approximately 40% of total U.S. electricity demand.⁵ It is estimated that 40-60% of currently installed electric motors could benefit from variable frequency drives (VFDs),⁶ which enable efficient adaptation to speed and torque demands. Depending on the application, incorporation of VFDs can reduce energy consumption by 10-30%.⁷ Conventional VFDs for high power applications are bulky and occupy significant space. Size, power density and efficiency can be improved, and the overall system cost reduced, by using WBG-based VFDs.

Automotive: Power electronics such as traction inverters, DC boost converters, and on-board battery chargers are critical elements in hybrid and electric vehicles (EVs). They affect energy efficiency in two ways: directly through switching and other losses, and indirectly by adding volume and weight to the vehicle. WBG inverters can reduce both direct and indirect losses by operating at higher switching frequencies, efficiencies, and temperatures.⁸ As a result, 15% improvement in energy efficiency has been predicted for representative hybrid EVs employing SiC traction inverters, with even larger energy savings possible given greater degrees of drivetrain electrification.⁹ Assuming aggressive market adoption of EVs in the U.S., use of WBG vehicle power electronics could save as much as 1 quadrillion Btu of energy per year by 2050 relative to conventional Si-based systems.¹⁰ Additionally, efficient, lightweight, and low-cost DC fast charging infrastructure (≥ 120 kW) enabled by WBG converters will advance the commercial viability and adoption rate of EVs. In conjunction with a cleaner electricity generation portfolio, this has the potential to significantly reduce the one quarter of total U.S. greenhouse gas emissions that stem from the transportation sector.¹¹

Data Centers: Energy consumption in data centers accounted for approximately 2% of total electricity use in the U.S. in 2014.¹² The power delivery architecture of most modern data centers consists of a line frequency transformer, low voltage power distribution network, centralized backup unit, and inefficient voltage regulators.¹³ Strategies to improve energy efficiency range from integration of lower loss power converters to complete redesign of the power delivery network.¹⁴ The latter approach often involves converting higher voltages at the rack level, where space is limited and proper thermal management is imperative. High power density converters based on WBG devices can be key enablers for more efficient systems, as higher temperature tolerance can reduce cooling loads and further boost data center grid-to-chip efficiency.

5 Waide, P.; Brunner, C. U. Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems. IEA (2011)

6 Energy Efficiency Roadmap for Electric Motors and Motor Systems. *Energy Efficient End-use Equipment*, IEA (2015)

7 Energy Efficiency and Power Electronics. Danfoss, ATV Seminar, March 1, 2012

8 Hamada, K. et al. SiC-Emerging Power Device Technology for Next-Generation Electrically Powered Environmentally Friendly Vehicles. *IEEE Transactions On Electron Devices* (2015)

9 Zhang, H. et al. Impact of SiC Devices on Hybrid Electric and Plug-In Hybrid Electric Vehicles. *IEEE Transactions on Industry Applications* (2011)

10 U.S. Department of Energy. Quadrennial Technology Review (2015)

11 Williams, J.H. et al. Pathways to Deep Decarbonization in the United States (2014)

12 Shehabi, A. et al. United States Data Center Energy Usage Report. Berkeley, CA: Lawrence Berkeley National Laboratory (2016)

13 Zhabeloval, G. et al. Data center energy efficiency and power quality: an alternative approach with solid state transformer. *41st Annual conference of the IEEE Industrial Electronics Society* (2015)

14 Candan, E. et al. A Series-Stacked Power Delivery Architecture with Isolated Differential Power Conversion for Data Centers. *IEEE Transactions On Power Electronics* (2016)

Aerospace: Longer, thinner, and lighter wings can reduce fuel consumption and carbon emissions by 50% relative to current commercial aircraft.¹⁵ Such a reduction would save approximately 1 quadrillion Btu of energy per year across the U.S. fleet at current demand.¹⁶ Achieving this transformative wing design requires electromechanical actuators that are small and lightweight with robust operation over a wide temperature range.¹⁷ Moreover, electrification of environmental controls, fuel pumps, brakes, and de-icing systems can further reduce weight and increase efficiency through elimination of bleed air controls and pneumatic/hydraulic systems.¹⁸ WBG-based converters, with high gravimetric and volumetric power density plus high temperature operation, offer a pathway to achieving significant energy savings in air transport. These key attributes will contribute to weight reduction, enabling new paradigms in body design.

Distributed Energy Resources: In grid applications, such as solar photovoltaic (PV) and wind, as well as the emerging fields of high voltage direct current (HVDC) and flexible alternating current transmission systems (FACTS), power conditioners are required to control the flow of electricity. This is achieved by supplying voltages and currents in a form that is optimally suited to the load. Traditional Si power electronics are responsible for a loss of approximately 4% of all of the electricity generated in these applications and are the dominant point of failure for installed systems. For instance, a typical maximum conversion efficiency for a silicon-based PV inverter is approximately 96% (AC output/DC input)¹⁹ including transformer losses, which drops significantly at operating temperatures above 50 °C. Novel WBG electronic circuits present a route to lower system-level costs by operating at higher switching frequencies that reduce the size of passive components and lower the overall system footprint. In addition, WBG circuits will increase system-level efficiency by allowing PV arrays to operate at higher voltages (e.g. $> 1,500V_{DC}$). This will enable DC systems with fewer voltage conversions/transformers, replacing traditional combiner boxes with DC/DC converter. The need for on-site AC transmission lines will ultimately allow for easier integration of energy storage solutions in the central substation. Together with a higher semiconductor operating temperature, the advantages of WBG electronics offer a pathway to more robust power converters with mean time to failure (MTTF) comparable to the PV and wind system lifetime (typically 25 years or longer). This will lower the equipment replacement cost and total plant Operation & Maintenance and can have a significant impact on the levelized cost of electricity in distributed resource applications.

15 Slimmed Down Aircraft Wing Expected to Reduce Fuel and Emissions by 50%. NASA, accessed November 29, 2016, <https://www.nasa.gov/image-feature/ames/slimmed-down-aircraft-wing-expected-to-reduce-fuel-and-emissions-by-50>

16 Transportation Energy Data Book. Oak Ridge National Laboratory, 35th edition (2016)

17 Thin-Wing Electromechanical Actuation (EMA) Demonstration. Department of Defense Air Force Research Lab.

18 Wheeler, P. The More Electric Aircraft: Why Aerospace Needs Power Electronics. Accessed November 29, 2016, http://www.lboro.ac.uk/microsites/research/iemrc/Events%20write%20up/Power%20Electronics%2014.05.09/More_Electric_Aircraft_000.pdf

19 SMA Technical Information, Efficiency and Derating, WKG-Derating-US-TI-en-15, Version 1.5, 2016

EVOLUTION OF ARPA-E'S FOCUSED PROGRAMS IN POWER ELECTRONICS

ARPA-E has catalyzed innovations in power electronics ever since its inception in 2009. The exploration began with OPEN 2009 projects in GaN materials as well as packaging for automotive and LED applications. In 2010, ARPA-E launched its first focused program in power electronics, Agile Delivery of Electric Power Technology (ADEPT), which cast a broad net for innovations in power conversion. ADEPT sought breakthrough technologies in magnetic materials with high operating flux densities, advanced solid-state switch technologies, advanced circuit topologies and converter architectures, and advanced charge storage devices. A year later, Solar ADEPT was launched to bring the general approach of ADEPT to PV power electronics. The successes in ADEPT and Solar ADEPT, along with four WBG related projects in OPEN 2012, showed that WBG semiconductor devices held exceptional potential in dramatically improving energy efficiency, broadening the application space of power electronics. Therefore, ARPA-E initiated the Strategies for Wide-Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems (SWITCHES) program with a focus on material- (e.g. GaN substrates) and device-level technologies (diodes and transistors). The experience and lessons learned from SWITCHES have revealed the need for further exploration both further up and down the value chain. Down the value chain, the major obstacle experienced by many SWITCHES project teams was selective area p-type doping of GaN. This initiated the Power Nitride Doping Innovation Offers Devices Enabling SWITCHES (PNDIODES) program, a supplementary program that would seek the fundamental understanding of material properties and processing technologies for selective area doping of GaN. Up the value chain, ARPA-E recognized the opportunities that harness recent advancements at the component level for transformational developments at the circuit and system levels. Hence the launch of Creating Innovative and Reliable Circuits Using Inventive Topologies and Semiconductors (CIRCUITS) Program. The time evolution of ARPA-E power electronics programs is depicted in Figure 3.

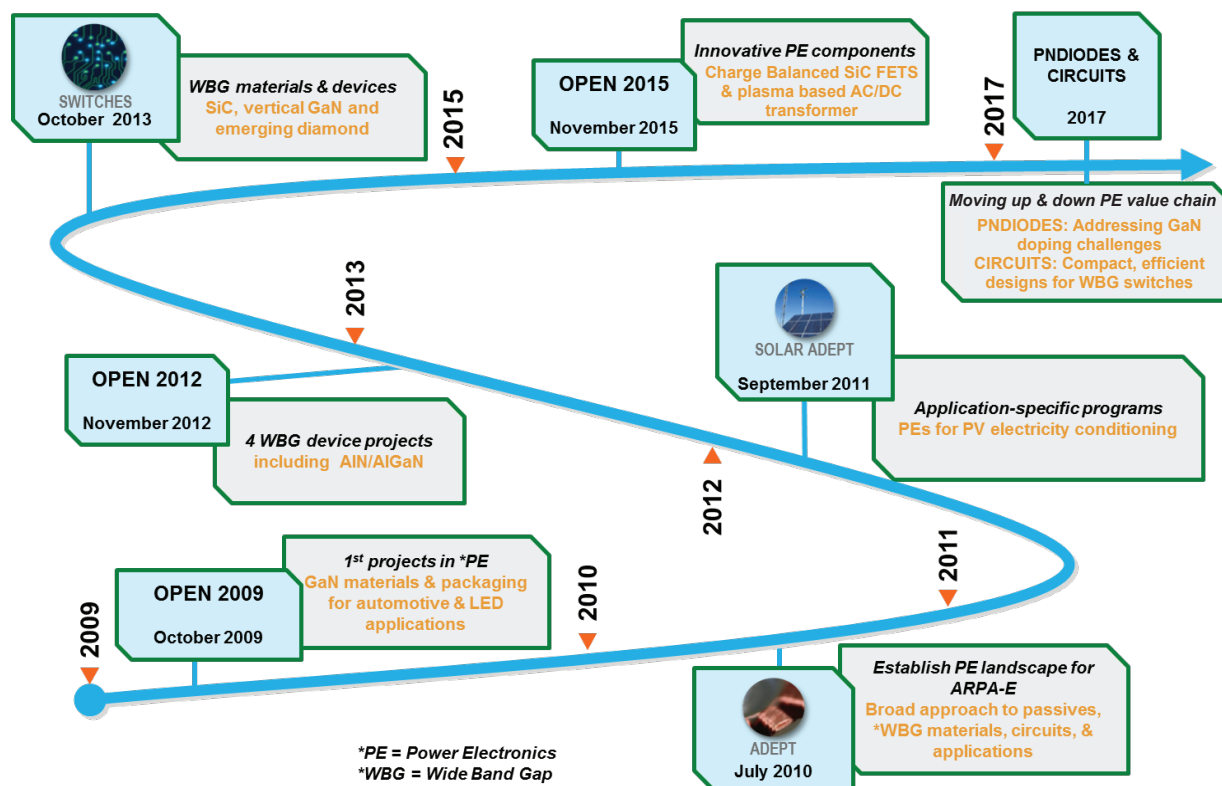


Figure 3: ARPA-E's Power Electronics Timeline.

BROAD EXPLORATION OF POWER ELECTRONICS LANDSCAPE - ADEPT

In 2010, the ADEPT program set out to lower the cost and improve performance of power converters and associated management systems. The program sought innovations across the entire value chain in power electronics from advanced component technologies and converter architectures, to packaging and manufacturing processes. The program aimed to address three categories of performance and integration levels: 1) fully-integrated, chip-scale power converters, 2) package-integrated power converters, and 3) lightweight, medium voltage energy conversion for high power applications. The original program areas of interest included magnetic materials with high operating flux densities, advanced solid-state switch technologies, advanced circuit topologies and converter architectures, and advanced charge storage devices. The most successful projects in the ADEPT program were those that utilized WBG components.

One example of a successful project is the development of a SiC-based EV battery charger, led by Arkansas Power Electronics International (APEI). The project was titled “10 times smaller EV charger using SiC based power transistors”, and APEI later won a 2014 R&D100 award.²⁰ On-board battery chargers for EVs and plug-in hybrid electric vehicles (PHEV) such as the Toyota Prius offer the convenience of universal charging from any available power outlet, but this functionally adds additional volume and weight to the system. WBG power electronics based chargers can enable operation at higher switching frequencies as well as elevated temperatures, thus allowing for a more compact system size/weight via reductions in passive component sizes as well as simplification of the thermal management system.

The APEI team designed a two-stage architecture with topologies that optimized for system density and efficiency. This leveraged the benefits of SiC power devices over traditional Si power diodes into significant system level

improvements. In the first stage AC-DC converter, a bridgeless boost power factor correction (PFC) topology was chosen. This capitalizes on the negligible reverse recovery current of SiC devices over Si power diodes, resulting in performance advantages especially at frequencies in excess of 100 kHz. The second stage was a DC-DC converter utilizing a phase-shifted full-bridge (PSFB) topology. This took advantage of the low output capacitance, high voltage blocking capability, and stable on-resistance at elevated temperatures of SiC devices for greater overall converter performance.²¹

The experimental implementation of the charger utilized commercially available 1200V/20A SiC MOSFET and Schottky Diodes from Cree packaged in a multi-chip power module designed by APEI. The full system housed three such models each with different device configurations. The SiC based charger, shown in Figure 4, operated at a

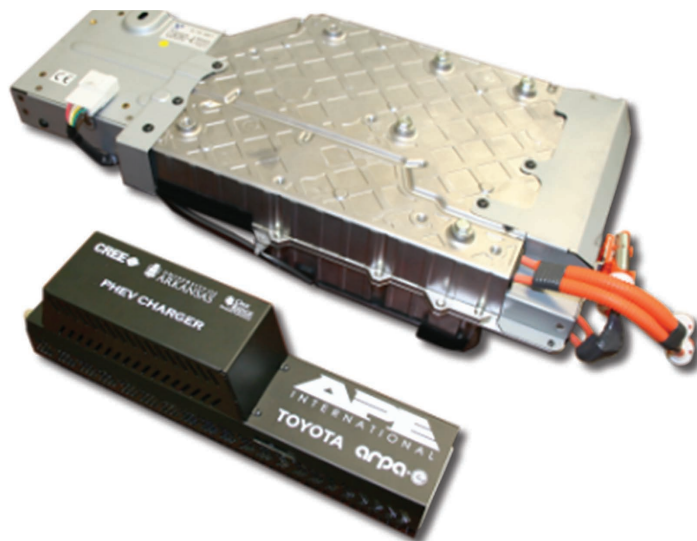


Figure 4: (bottom) APEI's prototype charger compared to (top) 2010 Toyota Prius plug-in hybrid battery charger (from ref 22).

²⁰ “2014 Awards Highlight New Trends,” *R&D Magazine*, Ed. T. Studt, Vol 56, no. 5, pg. 22, October 2014

²¹ B. Whitaker, A. Barkley, Z. Cole, B. Passmore, D. Martin, T. R. McNutt, A. B. Lostetter, J. S. Lee, and K. Shiozaki, “A High-Density, High-Efficiency, Isolated On-Board Vehicle Battery Charger Utilizing Silicon Carbide Power Devices,” *IEEE Transactions on Power Electronics*, vol. 29, no. 5, May 2014. DOI: 10.1109/TPEL.2013.2279950

switching frequency of 200 kHz with a total weight of 1.6 kg and volume of 1.2 L. This demonstrated a 10x increase in volumetric power density and 9x increase in gravimetric power density compared to the 2010, Si based Toyota Prius plug-in battery charger. At the highest tested peak power level of 6.1 kW the system efficiency was 94%, with an overall peak efficiency of 95% at an output power of 3.1 kW. This is a clear demonstration of the added value that WBG power electronics provides for automotive technologies.

Two ADEPT projects investigating the potential of GaN devices were also able to advance significantly. Transphorm's project "High Performance GaN HEMT modules for Agile Power Electronics" aimed to develop kW class inverters with greater efficiency and power density than incumbent Silicon based Insulated Gate Bipolar Transistor (IGBT) motor drives. To achieve this, the team had to overcome material challenges associated with the epitaxial growth of GaN on 6-inch Si with low defect density, fabricate GaN-on-Si High Electron Mobility Transistors (HEMTs), and demonstrate improved power module performance over the state of the art Si IGBTs.

Transphorm developed 600V normally-on HEMTs and achieved enhancement mode, or normally-off, operation by integrating a Si FET in a cascode configuration.²² Under resistive load switching, an inverter using the 600V GaN e-mode HEMTs hard switched at 100 kHz PWM frequency and demonstrated 98.5% efficiency. When evaluated in a motor drive test lab side to side with a Si IGBT-based motor-drive inverter operating at 15 kHz PWM frequency, the GaN inverter showed 8, 4, and 2% improvement in efficiency at low, mid, and full loads (roughly 500, 1000, and 1500 W) respectively operating at 7x higher PWM frequency.²³ In 2015, Transphorm, Inc. announced that its 600V GaN transistor has been fully Joint Electron Device Engineering Council (JEDEC) qualified and is slated for mass production in an industry standard TO-247 size package.²⁴

The ADEPT project led by the Massachusetts Institute of Technology took a broader approach to the challenge and addressed three areas needed to improve power conversion: switching devices, inductors, and circuit design in their work on a novel GaN device, with an application focus on power converters for driving light emitting diode (LED) loads. In the device arena, MIT pioneered a tri-gate normally off metal-insulator-semiconductor field-effect transistor and demonstrated it with a breakdown voltage of 565 V at a drain leakage current of 0.6 $\mu\text{A}/\text{mm}^2$.²⁵ In parallel, MIT also developed novel circuit topologies that leveraged wide-bandgap power electronics to break the performance constraints of commercially available systems. An LED driver employing a new power conversion architecture for single-phase AC grid interfaces was developed. The driver operated from 120 V_{AC}, while supplying a 35 V, 30 W output. Operating at a variable switching frequency of 5-10 MHz with an efficiency of >93%, the converter had a power factor of 0.89 with an overall box power density of 2.7 W/cm³. For comparison, commercial LED drivers typically operate in the 50-100 kHz frequency range, with maximum efficiencies around 88% and power densities <1.0 W/cm³.

The technologies and related IP developed at MIT is now being commercialized at several different start-ups. The circuit design concepts developed during ADEPT and lessons learned informed the design of a new laptop charger now being commercialized by FINsix, a MIT spin-out. The charger – named DART – is a 65 W charger that is 3 times smaller and lighter than conventional chargers. FINsix and Lenovo are currently in a partnership to make the smaller charger available for select ThinkPad models. Another MIT spinout – Cambridge Electronics – was started by students whose research was funded by ADEPT and are offering state-of-the-art GaN devices for sale. The company has received numerous awards including the Massachusetts's MassVentures Start Award as well as the 2016 Compound Semiconductor Industry Award.

22 P. Parikh, Y-F. Wu, L. Shen, "Commercialization of High 600V GaN-on-Silicon Power Devices," ISCRM, September 2013.

23 Y-F. Wu, D. Kebort, J. Guerrero, S. Yea, J. Honea, K. Shirabe, and J. Kang, "High-Frequency, GaN Diode-Free Motor Drive Inverter with Pure Sine Wave Output," *Power Transmission Engineering*, October 2012.

24 <http://www.transphormusa.com/news/transphorm-announces-industrys-first-600v-gan-transistor-247-package/>

25 B. Lu, E. Matioli, and T. Palacios, "Tri-Gate Normally-Off GaN Power MISFET," *IEEE Electron Device Letters*, vol. 33, no. 3, March 2012. DOI: 10.1109/LED.2011.2179971

SOLAR PHOTOVOLTAICS APPLICATIONS – SOLAR ADEPT

Solar ADEPT held similar aspirations to ADEPT but specifically focused on packaging and manufacturing processes for power converters to reduce costs for photovoltaic systems. Similar to ADEPT, Solar ADEPT aimed to address technical challenges at different performance and integration levels, from chip-scale all the way to utility-scale. Tailored for the solar PV application space, Solar ADEPT defined its technical targets into four categories: 1) fully-integrated, chip-scale power converters for sub-module applications, 2) package-integrated microinverters with reduced size and improved performance, 3) lightweight inverters for commercial roof-top and wall-mount applications, and 4) lightweight, solid-state, medium voltage energy conversion for high-power applications such as utility-scale inverters with direct grid connection.

In their “Bidirectional GaN-on-Si transistors for more compact and reliable power converters” project Transphorm aimed to develop GaN-on-silicon based four quadrant switches for residential and commercial solar micro-inverters. Most silicon based switches, with the exception of the triode for alternating current (TRIAC), block voltage only in one direction when gated off - and are thus unidirectional. Bidirectional switches – also called four quadrant switches (FQS) - that allow current flow in both directions when on would enable many new circuit topologies and applications. Building upon their expertise and experience from the ADEPT program, Transphorm demonstrated high voltage (both 600 V and 1200 V) FQs with maximum switching frequencies > 25 MHz for a 400 V bus. The single monolithic GaN FQS, replacing four discrete Si devices, enabled a 4% improvement in converter efficiency at low power and 0.2% improvement at full power, approximately a 50% lower power device loss.

The ADEPT and Solar ADEPT program successes were significant in advancing commercial applications of SiC and GaN devices. However, SiC and GaN device technology remained immature relative to Si and carried a substantial cost premium, limiting their widespread adoption. Many of the largest opportunities for increased energy efficiency and reduced energy-related emissions exist in extremely cost conscious industries, including markets for railway traction drives, automotive applications, and industrial motors. Unit cost for equivalent functional system performance remains a major barrier to the widespread adoption of WBG devices, despite opportunities related to their superior attributes (including reductions in system costs).

WIDE-BANDGAP MATERIALS AND DEVICES – SWITCHES

Analysis of market drivers showed that accelerating the commercial uptake of more efficient approaches enabled by WBG devices requires driving down the costs of the components. This led to the creation of the Strategies for Wide Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems (SWITCHES) program. The SWITCHES program was aimed at transformational advances that address key materials, device fabrication, and device architecture issues that drive costs for SiC and GaN devices, as well as to evaluate ultra-wide-bandgap (UWBG) materials such as a diamond. The goal was to enable the development of high voltage ($>1,200\text{V}$), high current (100A) single die power semiconductor devices that, upon ultimately reaching scale, would have the potential to reach functional cost parity with Si power transistors. Additionally, they would offer breakthrough relative circuit performance through low losses, high switching frequencies, and high temperature operation. These transformational technologies would have promise to reduce the barriers to ubiquitous deployment of low-loss WBG power semiconductor devices in stationary and transportation energy applications. From a cost basis perspective, the barrier to market entry needs to be competitive. Low current silicon switching devices ($<50\text{A}$) can be purchased as low as $\$5/\text{A}$ ²⁶. However, this is not the case for high current applications. The SWITCHES cost target for WBG packaged devices was $\$10/\text{A}$ for a 100A device, which would make them competitive with the best silicon IGBT devices in the same class.

The SWITCHES program has made tremendous advances in SiC device fabrication. In their project “Lower cost SiC manufacturing using existing low-cost, high-volume silicon manufacturing” Monolith Semiconductor, Inc. was able to make great strides in developing large-area, high-voltage, SiC devices. Before the SWITCHES program, planar and vertical SiC MOSFET power devices were limited in availability and were typically fabricated in relatively low volume at dedicated facilities that utilized unique process steps. This resulted in high cost and prohibitively expensive devices. Monolith Semiconductor partnered with XFab Inc., an automotive qualified Si Complementary Metal-Oxide Semiconductor (CMOS) manufacturing foundry, to develop and implement an advanced SiC power MOSFET process on their 150mm diameter silicon production line. Working in an active Si foundry provides significant cost benefits. Using an existing Si manufacturing infrastructure, the overhead costs to manufacture SiC devices can be reduced. The innovation in Monolith’s approach centered on adopting commercially available 150mm SiC wafers and designing SiC devices and fabrication processes that are compatible with existing, high-volume Si manufacturing facilities.²⁷

This allows for highly competitive products, rapidly deployed in the market. Monolith successfully demonstrated fabrication of MOSFETs on XFab’s production line with blocking voltage of 1700V and a specific on-resistance as low as $3.1\text{ m}\Omega\text{-cm}^2$ at room temperature, increasing to $6.7\text{ m}\Omega\text{-cm}^2$ at 175°C . Clamped inductive switching characterization of the SiC MOSFETs showed turn-off losses as low as $110\text{ }\mu\text{J}$. After 750 hours of gate stress at a gate bias of $V_{\text{GS}} = +20\text{V}$ and 175°C , only a 250mV shift in the threshold voltage was observed²⁸. Design changes and processes improvements increased the production line yield of the devices to commercially acceptable levels which illustrated the promise for high-volume production of reliable SiC MOSFETs on 150mm wafers. The company anticipates to reach $\$10/\text{A}$ for their devices in the near future.

The SWITCHES program also made significant advances in GaN device design and fabrication. Before the SWITCHES program, the majority of GaN power device development had been directed toward lateral architectures, such as high-electron mobility transistors (HEMTs). There were no vertical GaN devices commercially

26 ARPA-E SWITCHES FOA, <https://arpa-e-foa.energy.gov/FileContent.aspx?FileID=1f3b152b-a75a-4118-a6a6-30868377dac8>

27 S. Banerjee, K. Matocha, K. Chatty, J. Nowak, B. Powell, D. Gutierrez, and C. Hundley, “Manufacturable and rugged 1.2 KV SiC MOSFETs fabricated in high-volume 150mm CMOS fab.” Paper presented at 2016 28th International Symposium on Power Semiconductor Devices and ICs (ISPSD), Prague, Czech Republic, June 2016, DOI: 10.1109/ISPSD.2016.7520832

28 K. Matocha, S. Banerjee, and K. Chatty, “Advanced SiC Power MOSFETs Manufactured on 150mm SiC Wafers”, *Materials Science Forum*, vol. 858, pp. 803-806, 2016, DOI: 10.4028/www.scientific.net/MSF.858.803

available. The lateral devices suffered from well-known issues such as current-collapse, dynamic on-resistance, inability to support avalanche breakdown²⁹, and usable breakdown voltages of no greater than 650V. Vertical devices on the other hand offer the possibility to realize the potential of GaN including true avalanche-limited breakdown. Two projects in the SWITCHES program (Avogy, Inc. and Cornell University) were able to demonstrate near theoretical, high-power vertical GaN diodes exhibiting very high breakdown voltages (1700 - 4000 V) and figures-of-merit (V_B^2/R_{ON}) greater than 3 GW/cm².^{30,31} The SWITCHES sponsored researchers demonstrated that vertical GaN devices are avalanche capable³² indicating the ruggedness of such devices in breakdown, a critical requirement for power switching and rectifying applications. The pathway towards achieving $\phi 10/A$ for GaN devices was shown to be promising. Projects funded by SWITCHES have demonstrated 80% process yield for 100A, 1200V p-n junctions. With the current cost of 4" GaN wafers and a die size of 12-16 mm² for a 100A, 1200V device, vertical GaN devices should be capable of reaching the price range of $\phi 5/A$ to $\phi 7/A$.

Normally-off vertical transistor devices have been more challenging to fabricate compared to diodes, especially at high current levels, due to the requirement of selective area doping in many vertical device architectures. Attempts at selective area doping in vertical GaN devices in the SWITCHES program resulted in devices with large junction leakage currents, lower than breakdown voltages expected, and avalanche breakdown ruggedness not demonstrated. This is the major challenge faced by the SWITCHES projects with vertical GaN architectures. To overcome the selective area doping limitation in GaN two SWITCHES projects have investigated unique vertical GaN device designs that reduce or eliminate the need for selective area doping. The University of California, Santa Barbara demonstrated one such novel vertical GaN devices to achieve both low on-resistance (R_{ON}) and enhancement mode operation in a vertical GaN device called an "in-situ oxide, GaN interlayer-based vertical trench MOSFET" or OG-FET. In the traditional trench MOSFET structure, a dielectric is deposited on an n-p-n trenched structure and the channel forms via p-GaN inversion at the dielectric/p-GaN interface. However, this results in a relatively high R_{ON} due to poor electron mobility in the channel. By changing the structure to include a metal-organic chemical vapor deposition regrown un-intentionally doped GaN interlayer followed by an in-situ, Al₂O₃ dielectric cap on the n-p-n trenched structure, a pathway (channel) for enhanced electron mobility is created, resulting in reduced resistance. The normally-on OG-FETs fabricated by UCSB demonstrated a threshold voltage of 2V, breakdown voltages of 990 V ($E_{BR} \sim 1.6$ MV/cm), and an R_{ON} of 2.6 m Ω -cm².³³

The SWITCHES project led by Columbia University "High-performance, low-cost vertical GaN devices through smaller devices and GaN substrate re-use" demonstrated a GaN vertical fin power field-effect-transistor structure (VFET) on bulk GaN substrates that addresses the selective area doping limitation of conventional power vertical GaN transistor device structures. The VFET, shown in Figure 5, consists of fin-shaped channels etched into an 8- μ m-thick n- doped GaN drift layer using a combined dry/wet etching technology to achieve smooth fin vertical sidewalls.³⁴ The current flows vertically from the backside drain contact to source contacts deposited on top of

29 E. Zanoni, M. Meneghini, A. Chini, D. Marcon, and G. Meneghesso, "AlGaIn/GaN-based HEMTs failure physics and reliability: Mechanisms affecting gate edge and Schottky junction," *IEEE Trans. Electron Devices*, vol. 60, no. 10, pp. 3119–3131, Nov. 2013, DOI: 10.1109/TED.2013.2271954.

30 I. C. Kizilyalli, A. P. Edwards, H. Nie, D. Disney, and D. Bour, "High voltage vertical GaN p-n diodes with avalanche capability", *IEEE Trans. Electron Devices*, vol. 60, no. 10, pp. 3067-3070, 2013, DOI: 10.1109/TED.2013.2266664

31 K. Nomoto, B. Song, Z. Hu, M. Zhu, M. Qi, N. Kaneda, T. Mishima, T. Nakamura, D. Jena, and H.G. Xing, "1.7-kV and 0.55- m Ω -cm² GaN p-n Diodes on Bulk GaN Substrates With Avalanche Capability", *IEEE Electron Device Letters*, vol. 37, no. 2, pp 161-164, 2016, DOI: 10.1109/LED.2015.2506638

32 O. Aktas, and I. Kizilyalli, "Avalanche capability of vertical GaN pn junctions on bulk GaN substrates." *IEEE Electron Device Letters*, vol. 36, no. 9, pp 890-892, 2015, DOI: 10.1109/LED.2015.2456914

33 C. Gupta, C. Lund, S. Chan, A. Agarwal, J. Liu, Y. Enatsu, S. Keller, and U. Mishra, "In Situ Oxide, GaN Interlayer-Based Vertical Trench MOSFET (OG-FET) on Bulk GaN substrates" *IEEE Electron Device Letters*, vol: 38, no. 3, pp. 353-355, 2017, DOI: 10.1109/LED.2017.2649599

34 M. Sun, Y. Zhang, S. Bedell, J. Barth, D. Sadana, K. Shepard, X. Gao and T. Palacios, "Vertical GaN Power Transistors Using Controlled Spalling for Substrate Heterogeneity" Presented at 3rd Annual SWITCHES Review Meeting, Philadelphia, PA, March 2017

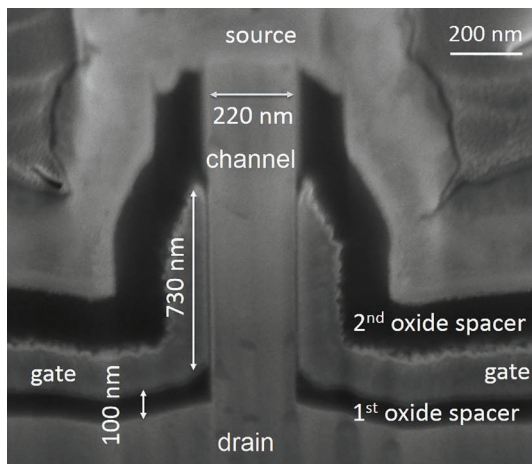


Figure 5: Scanning electron microscope cross sectional view of a fabricated GaN VFET (from ref 34).

GaN wafers by epitaxial liftoff and spalling without damage to the lifted off layer. The MicroLink Devices project “High-performance, low-cost vertical GaN devices through smaller devices and GaN substrate re-use” demonstrated wafer-scale epitaxial lift-off (ELO) using an InGaN release layer and a bandgap-selective photo-enhanced wet etching to fully released a GaN foil from 2-inch bulk GaN substrate as shown in Figure 6.³⁸ Perforations spaced at 1mm apart were used to allow for the wet chemical etch access to the InGaN release layer. The leakage current in both reverse and low-forward-bias regimes for thin-film Schottky diodes was reduced after ELO processing. This is potentially due to the elimination of leakage paths through the underlying n+ buffer layer that is removed in the ELO process.³⁹

On the bulk (free standing) GaN substrate development side, Soraa Inc. developed, in their OPEN 2009 and SWITCHES projects, a large diameter ammono-thermal reactor capable of more than 600°C operation and a pressure

the fins. The sub-micron fin channels are surrounded by metal gate pads which, below the threshold voltage, pinch-off the channel. In this vertical transistor design only n-GaN layers are needed, no material regrowth or p-GaN layer is required.³⁵ Fabricated VFETs demonstrated specific on-resistance of 0.2 mΩ-cm², threshold voltage of 1 V, and a breakdown voltage >1200 V with high ON current (>25 kA/cm²) and low OFF current at 1200 V (<10⁻⁴ A/cm²). This amounts to a figure-of-merit (V_B^2/R_{ON}) of ~7.2 GW/cm². Large devices demonstrated high current up to 10 A and breakdown voltage >800 V.^{36, 37}

Additionally, the SWITCHES program has made advances in the area of epitaxial lift-off of GaN materials. Two SWITCHES projects by the MicroLink Devices and Columbia University teams focused on GaN substrate re-use and thinning. These projects demonstrated large area (>2”) layers released from bulk

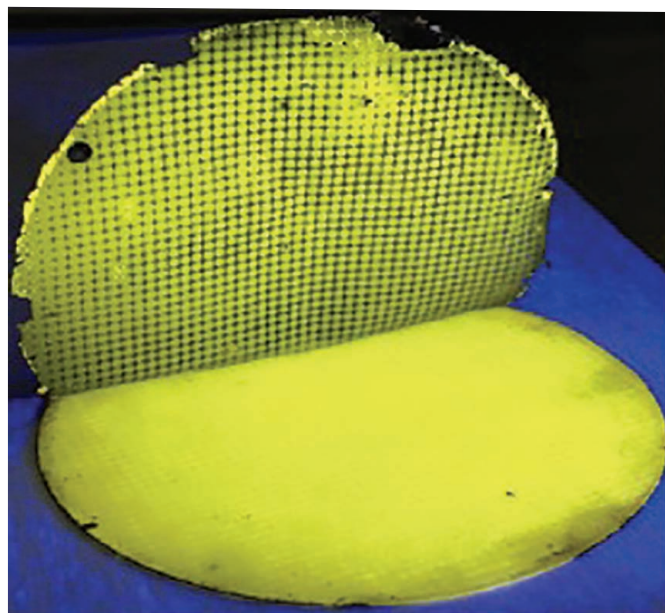


Figure 6: A 5-micron-thick GaN epitaxial film released from a 4-inch sapphire substrate using perforations on a 1-mm pitch. The yellow luminescence of the nitrogen face of the released film is visible under ultraviolet illumination (from ref 39).

35 M. Sun, M. Pan, X. Gao, and T. Palacios, “Vertical GaN power FET on bulk GaN substrate” Paper presented at 2016 74th Device Research Conference (DRC), Newark, DE, June 2016, DOI: 10.1109/DRC.2016.7548467

36 M. Sun, Y. Zhang, X. Gao, and T. Palacios, “High-Performance GaN Vertical Fin Power Transistors on Bulk GaN Substrates” *IEEE Electron Device Letters*, vol: 38, no. 4, pp509-512, 2017, DOI: 10.1109/LED.2017.2670925

37 Y. Zhang, M. Sun, D. Piedra, J. Hu, Z. Liu, Y. Lin, X. Gao, K. Shepard, and T. Palacios, “1200 V GaN Vertical Fin Power Field-Effect Transistors” Presented at IEEE International Electron Device Meeting, San Francisco, CA, December 2017

38 C. Youtsey, R. McCarthy, R. Reddy, K. Forghani, A. Xie, E. Beam, J. Wang, P. Fay, T. Ciarkowski, E. Carlson, and L. Guido, “Wafer-scale epitaxial lift-off of GaN using bandgap-selective photoenhanced wet etching” *Phys. Status Solidi B*, vol: 254, no. 8, pp 1600774, 2017, DOI 10.1002/pssb.201600774

39 J. Wang, C. Youtsey, R. McCarthy, R. Reddy, N. Allen, L. Guido, J. Xie, E. Beam, and P. Fay, “Thin-film GaN Schottky diodes formed by epitaxial lift-off” *Applied Physics Letters*, vol: 110, pp 173503, 2017, DOI: 10.1063/1.4982250

greater than 3,000 atmospheres in order to grow bulk GaN crystals.⁴⁰ The ammonothermal GaN crystal growth method is adapted from the hydrothermal method used to grow quartz crystals, which are very inexpensive and represent the second-largest market for single crystals for electronic applications (after silicon). Soraa successfully demonstrated growth of GaN crystals that are over two inches in diameter at a rate of at least 10 microns per hour, and the fabrication of 2 inch GaN wafers from the crystals (Figure 7).⁴¹ The wafers met Soraa's target specifications for LED crystal quality, dopant levels, dislocation density, miscut, and surface roughness. Soraa has also shown that with additional processing steps, they have the ability to make wafers with a dislocation density less than $1 \times 10^4 \text{ cm}^{-2}$, a breakthrough that will enable higher-performing power electronics devices with a breakdown field greater than 3 MV/cm for GaN.

In the SWITCHES program advances were similarly achieved in the UWBG material diamond. SWITCHES projects focusing on diamond by Arizona State University and Michigan State University have demonstrated thick ($>1\text{mm}$) diamond growth by CVD and doping of diamond with $>10^{20} \text{ cm}^{-3}$ boron and phosphorous for p+ and n+ layers, respectively. Using the advances in diamond growth Schottky and p-n diodes with $>1000\text{V}$ blocking and $100\text{-}500 \text{ A/cm}^2$ forward current were demonstrated.^{42 43} These achievements have yet to reach program targets, but are nonetheless foundational in the pursuit of ultra-wide-bandgap semiconductor devices.

The projects in the SWITCHES program have made tremendous advances in materials development, vertical device architecture, and low cost device fabrication. The SWITCHES program set out to achieve three key aggressive targets: 1200V breakdown, 100A single-die current, and cost of packaged discrete device of no more than $\text{\$}10/\text{A}$. The program is drawing to a close by the end of 2017 and while no project has yet to achieve all the targets of the program, the portfolio of projects are well underway to achieving these targets communally.



Figure 7: 2 inch GaN crystal and wafer fabricated by Soraa's process (from ref 44)

40 R. McCarthy, "High-Power Vertical-Junction Field-Effect Transistors Fabricated on Low-Dislocation Dislocation GaN by Epitaxial Lift-Off" Presented at 3rd Annual SWITCHES Review Meeting, Philadelphia, PA, March 2017

41 "Lower Cost GaN for Lighting and Electronics Efficiency" Advanced Research Projects Agency – Energy Project Impact Sheet, (March 2016) https://arpa-e.energy.gov/sites/default/files/documents/files/Soraa_Open2009_ExternalImpactSheet_FINAL.pdf

42 M. Dutta, F. Koeck, W. Li, R. Nemanich, and S. Chowdhury, "High Voltage Diodes in Diamond Using (100)- and (111)- Substrates", *IEEE Electron Device Letters*, vol. 38, no. 5, pp. 600-603, 2017, DOI: 10.1109/LED.2017.2681058

43 S. Nicley, S. Zajac, R. Rechenberg, M. Becker, A. Hardy, T. Schuelke, and T. Grotjohn, "Fabrication and characterization of a corner architecture Schottky barrier diode structure" *Phys. Status Solidi A*, vol: 212, no. 11, pp 2410-2417, 2015, DOI 10.1002/pssa.201532220

ADDRESSING MATERIAL CHALLENGES - PN DIODES

Many SWITCHES project teams experienced a major obstacle in fabricating vertical GaN power electronic devices specifically the lack of viable GaN selective area doping or selective area epitaxial regrowth processes that yields material of sufficiently high quality to enable defect-free p-n junctions on patterned GaN surfaces. An example is shown in Figure 8. In GaN selective area p-type doping has proved elusive, because the most obvious approaches, such as laterally patterned ion implantation with activation or selective area diffusion of p-type dopants (e.g. Mg, Be, Zn), have not produced p-type regions or satisfactory p-n junctions. Furthermore, selective area etch and regrowth approaches have resulted in poor electrical performance not sufficient to be useful in power electronic applications. A breakthrough is needed to enable high performance vertical GaN transistors. This specific remaining challenge to the SWITCHES program prompted the announcement in late 2016 of the Power Nitride Doping Innovation Offers Devices Enabling SWITCHES (PN DIODES) program. The PN DIODES program aims to develop transformational advances and mechanistic understanding in the process of selective area doping in the III-Nitride wide-bandgap semiconductor material system. The expectation is this will lead to the demonstration of arbitrarily placed, reliable, contactable, and generally useable p-n junction regions that enable high-performance and reliable vertical power semiconductor devices.

Seven projects were selected for funding as part of the PN DIODES program. The project teams will work to develop transformational advances and mechanistic understanding in the process of selective area doping for GaN using innovative technologies. Projects led by Arizona State University, Sandia National Laboratories, and Yale University, will focus on selective area doping using patterned etch and regrowth technology. They will attempt to obtain a deep understanding of the process, including various etching methods, interface impurity control, and the effect of crystal growth direction. Projects led by Adroit Materials, JR2J, and State University of New York Polytechnic Institute, will focus on selective area doping using ion implantation and innovative annealing, or heat treatment. This will include processes such as laser spike and Gyrotron annealing to remove implantation damage and activate the dopants. The remaining project led by the University of Missouri will focus on the development of neutron transmutation doping, exposing GaN wafers to neutron radiation to create a stable network of dopants within, to fabricate a uniformly doped n-type GaN wafer to achieve low resistance substrates.

The Department of Energy and Department of Defense have identified power electronics based on wide-bandgap semiconductors as a major area of concern for energy efficiency and the reduction in size and weight, as well as improvement in the reliability of power conversion systems. Success in the PN DIODES program would offer innovative options to help drive research, development, and commercialization of vertical GaN power electronic devices.

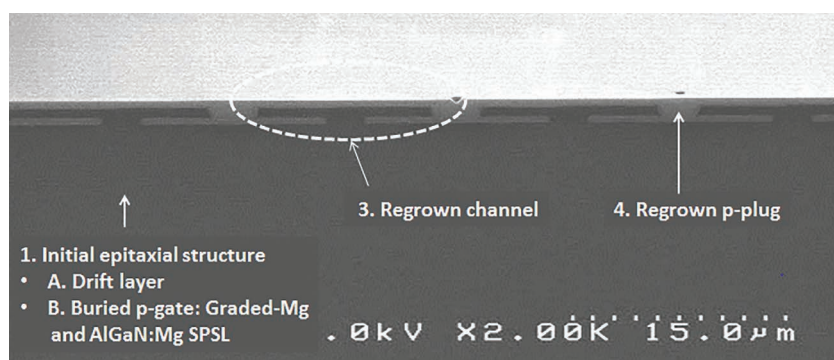


Figure 8 GaN Selective Area Doping example

SYSTEM-LEVEL ADVANCES - CIRCUITS

Previous efforts by ARPA-E have primarily focused on WBG material and device development without focused consideration and redesign of the circuit topology. Such solutions do not fully exploit the potential performance improvements enabled by this new class of power semiconductor devices. The circuit design is critical to the large-scale implementation of more efficient WBG power systems as a result of their ability to operate at high voltage, high frequency, and high temperature. For WBG power electronics devices, their benefits will not be fully realized if they are treated as drop-in replacements for Si devices. Instead, new circuit topologies and designs are needed that take full advantage of the attributes of the WBG semiconductor devices, resulting in minimization of form factor, cooling systems, and auxiliary circuit components. The Creating Innovative and Reliable Circuits Using Inventive Topologies and Semiconductors (CIRCUITS) funding opportunity announcement released in early 2017 seeks to accelerate the development and deployment of a whole new class of efficient, lightweight, and reliable power converters based on WBG semiconductors. The program will drive transformational system-level advances that enable effective operation at high switching frequency, high temperature, and low loss. With an explicit focus on novel circuit topologies, advanced control and drive electronics, as well as innovative packaging, CIRCUITS aims to catalyze disruptive improvements for power electronics afforded by cutting edge materials such as WBG semiconductors. Such technological breakthroughs would catalyze the adoption of higher performance power converters in various critical applications such as motor drives, automotive, power supplies, data centers, aerospace, ship propulsion, rail, distributed energy, and the grid. This will enable significant direct and indirect energy savings and emissions reductions across electricity generation, transmission and distribution, and load-side consumption.

Twenty-one innovative projects were selected for funding as part of the CIRCUITS program. The project teams will accelerate the development and deployment of a new class of circuit topologies optimally designed for WBG semiconductors to maximize system performance that will save energy and give the United States a critical technological advantage in an increasingly electrified economy. CIRCUITS projects will establish the building blocks of this class of power converter by advancing higher efficiency designs that exhibit enhanced reliability and superior total cost of ownership. In addition, a reduced form factor (size and weight) will drive adoption of higher performance and more efficient power converters relative to today's state-of-the-art systems. Some examples of the projects include:

The Eaton Corporation will develop and validate a wireless-power-based computer server supply that enables distribution of medium voltage (AC or DC) throughout a data center and converts it to the 48 VDC used by computer servers. The Eaton team has targeted the data center sector, as it is quickly becoming a major consumer of electricity in the United States. If successful, project developments will reduce U.S. data center energy consumption and operating cost while creating a high-volume commercial market for SiC-based power converters.

Marquette University will develop a small, compact, lightweight, and efficient 1 MW battery charger for electric vehicles with a switching frequency of 1Mhz. The team aims to use state-of-the-art MOSFET switches based on SiC to ensure the device runs efficiently while handling very large amounts of power in a small package. This project endeavors to triple the current state-of-the-art in power density and double specific power of chargers today. If successful, such a device could help to dramatically reduce charging times for big batteries, like those in electric vehicles, to a matter of minutes.

University of Arkansas will develop a 2 by 250 kW power inverter system for use in the electrification of heavy equipment and other higher volume transportation applications (e.g., trucks, buses, cars). The team will leverage SiC power electronics devices to achieve high levels of efficiency while greatly increasing the volumetric and gravimetric power density of its system over existing ones. If successful, the team will achieve an improvement of four times the power density and reduce converter cost by 50% compared to today's technology.

IMPACTS

ARPA-E's sustained exploration in WBG-based power electronics has helped foster a vibrant ecosystem in WBG R&D. Prior to ARPA-E PE programs, the Department of Defense⁴⁴ spearheaded R&D efforts in WBG semiconductors for defense applications. For civilian applications, several DOE offices, including the Energy Efficiency and Renewable Energy (EERE), Advanced Manufacturing Office⁴⁵ (AMO), the Office of Electricity Delivery and Energy Reliability⁴⁶, and the Vehicle Technologies Program⁴⁷, are now also working to bring WBG devices closer to widespread adoption. As of February 2017, ARPA-E has awarded 57 projects related to power electronics, totaling almost \$155 million in federal funding. Together, ARPA-E power electronics projects have published 141 peer reviewed technical papers that have been cited 2,204 times, and have been awarded 26 patents. Nine teams have cumulatively raised almost \$386 million in publically reported funding from the private sector to bring their technologies into commercial applications.

ARPA-E's focus is for transformational change within technology to bridge the gap between the laboratory and follow on funding from private investment companies. Often, follow on funding will come from other DOE Program Offices when the next phase of development still has some risk associated with it. For example, two programs associated with the EERE SunShot Initiative that include PV power electronics development to enhance energy efficiency are the 2011 program Solar Energy Grid Integration Systems - Advanced Concepts, \$25.9M, and the 2015 program, Sustainable and Holistic Integration of Energy Storage and Solar PV (SHINES), \$15M. Both program FOAs reference ARPA-E and its associated projects in the field of power electronics as influencing the aim and scope of the activities.

In 2014, the AMO set up Power America as a manufacturing innovation institute to accelerate the development of next generation of energy-efficient, high-power electronic devices using wide-bandgap semiconductor technologies. One of the active members Power America was X-FAB Inc. X-FAB has established a 150mm Silicon Carbide foundry line in Lubbock, Texas with the support from the PowerAmerica Institute. X-FAB's goal is to accelerate the commercialization of SiC power devices by leveraging the economies of scale that have been established in its silicon wafer fabrication line. In parallel, Monolith Semiconductors Inc., of Round Rock, Texas received funding from ARPA-E through the SWITCHES program to design their next generation SiC diodes and MOSFETs. By partnering with X-Fab Inc., they were able to establish a pathway to manufacture their devices adopting a "fab-less" production model. In March 2017, Littelfuse Inc., a leading manufacturer of electrical circuit protection equipment based in the USA, made an incremental \$15M investment in Monolith Semiconductors Inc., which gave it a majority ownership position in the company.

In 2015, AMO launched the Next Generation Electric Machines: Megawatt Class Motors programs, and awarded \$22M to five projects aimed at emerging WBG technologies focused on advancements in large-scale motor control to increase efficiency in high-energy consuming industries. Previous ARPA-E awardee GE is one of the award recipients in this program. To build capability in the field of WBG power electronics, AMO also launched a \$6M program in 2015 to improve capability in the US workforce, the DOE Traineeship in Power Engineering; Leveraging Wide-Bandgap Power Electronics⁴⁸.

44 "DARPA Sets Tough Goals For The Wide-Bandgap Community," *Compound Semiconductor*, November 8, 2002

45 Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, "Wide Bandgap Semiconductor for Clean Energy Workshop: Summary Report," (Washington, DC: U.S. Department of Energy, 2012)

46 Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, "Wide Bandgap Semiconductor for Clean Energy Workshop: Summary Report," (Washington, DC: U.S. Department of Energy, 2012)

47 Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Program, *Multi-Year Program Plan 2011-2015*, December 2010 (Washington, DC: U.S. Department of Energy)

48 Conversations with P Gradzki of AMO and EERE website

CONCLUSIONS

Despite the remarkable advancements in WBG semiconductors, significant work still remains to realize the full potential of WBG materials in improving energy efficiency. As mentioned above, fundamental research into material properties and processing, and continued development up the power electronics value chain into circuits and systems, are vital steps in ensuring that America can maintain its technological lead in these promising materials, and reap the energy benefits through wide-ranging applications.

APPENDIX: ARPA-E POWER ELECTRONICS PROJECTS

Table 1 ARPA-E Power Electronics Projects and Their Innovation Approaches

Program	Organization	Concept	Material	Device / Packaging	Module / System
Open 2009	Delphi Automotive Systems, LLC	Power converters using GaN-on-Si power transistor and double side cooling modules.	x	x	
Open 2009	Soraa, Inc.	2-inch GaN substrates wafers by am-mono thermal for high quality, low cost.	x		
Open 2009	FastCAP Systems Corp.	Aligned carbon nanotubes ultracapacitors for increased efficiency and energy density	x		
ADEPT	Virginia Polytechnic Institute and State University	Small 3D chip integrating GaN-on-Si and high-frequency soft magnetic material for power conversion.		x	x
ADEPT	General Electric	Lower cost and size, vapor deposited magnetic films.	x		
ADEPT	HRL Laboratories, LLC	Low cost, lighter weight bidirectional EV charger using GaN based power transistors		x	x
ADEPT	Cree, Inc.	High voltage (15kV) SiC power transistors that are 50% more energy efficient.		x	
ADEPT	Teledyne Scientific & Imaging, LLC	Integrated single chip power converter for LEDs using iron magnetic alloys and GaN-on-Si devices.	x	x	x
ADEPT	Virginia Polytechnic Institute and State University	Efficient power converter integrating high-density capacitors, new magnetic materials, high-frequency integrated circuits, and a constant-flux transformer.	x	x	x
ADEPT	Georgia Tech Research Corporation	Utility-scale power router that uses an enhanced transformer to more efficiently direct power on the grid			x
ADEPT	GeneSiC Semiconductor	Unique SiC device structure for better performance		x	
ADEPT	Arkansas Power Electronics International, Inc.	10 times smaller EV charger using SiC based power transistors.		x	x
ADEPT	Massachusetts Institute of Technology	More efficient power circuits for LEDs using GaN-on-Si, new magnetic materials, and new circuit designs.	x	x	x
ADEPT	Georgia Tech Research Corporation	Compact power converters using low-cost stacked iron alloys as magnetic cores.	x		
ADEPT	Transphorm, Inc.	GaN-on-Si transistors for power converters		x	

Program	Organization	Concept	Material	Device / Packaging	Module / System
ADEPT	Case Western Reserve University	Smaller and lighter capacitors using titanium that can store 300% more energy.	x		
ADEPT	City University of New York (CUNY)	Lower cost, smaller, and more efficient power converters for LED lights using nanoscale material capacitors.	x	x	x
Solar ADEPT	Carnegie Mellon University	New nanoscale magnetic material for lower size, weight, and cost power conversion.	x		
Solar ADEPT	Cree, Inc.	Transformer-less power conversion device to directly connect solar power to the grid.			x
Solar ADEPT	University of Colorado, Boulder	Microconverters that can be integrated into individual solar panels.			x
Solar ADEPT	Transphorm, Inc.	Bidirectional GaN-on-Si transistors for more compact and reliable power converters.		x	
Solar ADEPT	SiCLAB, Rutgers University, NJ	Unique high voltage (15kV) SiC power transistors for better performance.		x	
Solar ADEPT	SolarBridge Technologies, Inc.	New power conversion technique to efficiently and cost-effectively improve the energy output of PV power plants.			x
Solar ADEPT	Ideal Power, Inc.	Bi-directional silicon power switches for reduced size, weight, and cost PV inverter.		x	x
Open 2012	Silicon Power Corporation	High-power and high-voltage optically triggered bi-directional SiC transistor switch.		x	
Open 2012	Rensselaer Polytechnic Institute	High-Voltage, Bi-Directional MOS-Grated SiC Power Switches for Smart Grid Utility Applications.		x	
Open 2012	RamGoss, Inc.	Innovative GaN device design for utility-scale electronic switches.	x	x	
Open 2012	Hexatech Inc.	High-voltage AlN devices for use in high-power electronics.	x	x	
Open 2012	Georgia Tech Research Corporation	Graphene based supercapacitor for increased energy density.	x		
Open 2012	General Electric	High Voltage, High Power Gas Tube Technology and Impact Assessment for HVDC Transmission.			x
SWITCHES	Columbia University	High-performance, low-cost vertical GaN devices thru smaller devices and GaN substrate re-use.	x	x	
SWITCHES	SixPoint Materials, Inc.	High-quality, low-cost GaN substrates produced via ammonothermal growth.	x		

Program	Organization	Concept	Material	Device / Packaging	Module / System
SWITCHES	Monolith Semiconductor, Inc.	Lower cost SiC manufacturing using existing low-cost, high-volume silicon manufacturing.		x	
SWITCHES	MicroLink Devices	High-performance, low-cost vertical GaN devices thru smaller devices and GaN substrate re-use.	x		
SWITCHES	Cornell University	Unique GaN device structure for significantly smaller size and higher performance.		x	
SWITCHES	Kyma Technologies, Inc.	High-rate large area GaN substrate growth	x		
SWITCHES	Michigan State University	High-voltage diamond devices for use in high-power electronics.	x	x	
SWITCHES	Avogy, Inc.	High yielding vertical GaN transistor for lower cost.		x	
SWITCHES	Arizona State University	Low-cost, vertical, diamond bipolar device for use in high-power electronics.	x	x	
SWITCHES	iBeam Materials, Inc.	Low-cost GaN LEDs on flexible metal foils.	x	x	
SWITCHES	Soraa, Inc.	Follow-on to OPEN2009 project. Large-area, high-quality, low cost GaN substrates	x		
SWITCHES	HRL Laboratories, LLC	High-performance, low-cost vertical GaN devices at higher power levels than lateral devices.		x	
SWITCHES	Fairfield Crystal Technology, LLC	Unique high-rate GaN boule growth for lower cost GaN wafers.	x		
SWITCHES	University of California, Santa Barbara	High-performance, low-cost vertical GaN devices at higher power levels than lateral devices.		x	
Open 2015	General Electric	High-voltage, solid-state SiC field-effect transistor charge-balanced device.		x	
Open 2015	Tibbar Technologies	Plasma-based 3-phase AC to DC converter.			x
IDEAS	GeneSiC Semiconductor	High-power and voltage vertical GaN bipolar junction transistor.		x	
IDEAS	University of Nebraska, Lincoln	Electromagnetic induction-based static power converter for efficient low cost AC to AC electrical conversions.			x
IDEAS	Northeastern University	Innovative universal power converter using SiC based devices for decreased size.			x
IDEAS	Quora Technology, Inc.	Reliable, high-power and voltage, innovative lateral GaN transistor.		x	

Program	Organization	Concept	Material	Device / Packaging	Module / System
IDEAS	Sandia National Laboratory	High-voltage, high-power density, hybrid switched-capacitor DC-DC power converter using SiC and vertical GaN devices.			x
IDEAS	University of Colorado, Boulder	Capacitive wireless power transfer architecture to dynamically charge EVs.			x
IDEAS	Sandia National Laboratory	MVDC/HVDC Power Conversion with Optically-Controlled GaN Switches.		x	x
IDEAS	Harvard University	Transistor-less Power Supply Technology Based on UWBG Nonlinear Transmission Line.			x
PNDIODES	Adriot Materials Inc.	Selective Area Doping for Nitride Power Devices.	x		
PNDIODES	Arizona State University	Effective selective area doping for GaN Vertical Power Transistors Enabled by Innovative Materials Engineering.	x		
PNDIODES	JR2J	Laser spike anneal technology for the activation of implanted dopants in Gallium Nitride.	x		
PNDIODES	Sandia National Laboratory	High voltage re-grown GaN P-N Diodes enabled by defect and doping control.	x		
PNDIODES	The Research Foundation for State University of New York	Demonstration of PN-junctions by implant and growth techniques for GaN.	x		
PNDIODES	University of Missouri	High quality GaN FETs through transmutation doping and low temperature processing.	x		
PNDIODES	Yale University	Regrrowth and selective area growth of GaN for vertical power electronics.	x		

DESCRIPTIONS OF ARPA-E'S PROGRAMS

Acronym	Title	Year	Brief Description
ADEPT	Agile Delivery of Electric Power Technology	2010	Power Conversion Efficiency: Wide-bandgap semiconductors for high-power, high-current applications
ALPHA	Accelerating Low-Cost Plasma Heating and Assembly	2014	Fusion energy, focused on intermediate density regime, reducing the cost of experimental tests for fusion energy
AMPED	Advanced Management and Protection of Energy Storage Devices	2012	Battery storage, primarily for EV. Addressing efficiency from perspective of the overall battery pack with new approaches to the battery management system. Strong DoD engagement
ARID	Advanced Research in Dry-Cooling	2015	Developing technology to protect power plant efficiency under water constraints - More efficient 'dry-cooling'
BEEST	Batteries for Electric Energy Storage in Transportation	2010	All aspects of battery design and materials, supporting a large amount of alternative battery chemistry work (supplemented by project awards under OPEN 2009 and 2012)
BEETIT	Building Energy Efficiency Through Innovative Thermodevices	2010	Lower energy approaches to heating, ventilation and air conditioning (HVAC). Some projects funded by DoD
CHARGES	Cycling Hardware to Analyze and Ready Grid-Scale Electricity Storage	2014	Two test sites to allow grid-scale batteries to be validated under realistic grid operation conditions
CIRCUITS	Creating Innovative and Reliable Circuits Using Inventive Technologies and Semiconductors	2017	Development and deployment of a new class of efficient, lightweight, and reliable power converters, based on wide-bandgap (WBG) semiconductors
DELTA	Delivering Efficient Local Thermal Amenities	2014	Local thermal management for comfort of individuals, goal to reduce overall AC costs by allocating less stringent building-wide AC
ELECTROFUELS	Microorganisms for Liquid Transportation Fuel	2010	Exploratory development of fuel productions by organisms that directly use electric charge as an energy source
ENLITENED	Energy-Efficient Light-Wave Integrated Technology Enabling Networks that Enhance Datacenters	2016	Integrated photonic interconnects and novel switching networks for more energy efficient manipulation and movement of data
FOCUS	Full Spectrum Optimized Conversion and Utilization of Sunlight	2014	Solar energy approaches that capture both PV and thermal energy, including spectrum splitting to different collectors and development of PV cells that can work at the high T of thermal collection
GENI	Green Electricity Network Integration	2011	Electric power network - Power flow controllers & software to allow more effective integration of renewables
GENSETS	Generators for Small Electrical and Thermal Systems	2015	Distributed power generation - Low-cost, small scale generators for combined heat and power
GRIDS	Grid Scale Rampable Intermittent Dispatchable Storage	2010	Stationary storage, including grid-scale batteries, flow-batteries, and other approaches such as flywheels. Battery portfolio supplemented through OPEN 2009 and 2012 projects

Acronym	Title	Year	Brief Description
GRID DATA	Generating Realistic Information for the Development of Distribution and Transmission Algorithms	2015	Development of realistic, open-source models of transmission and distribution grids to support advanced work on optimization and control algorithms
HEATS	High Energy Advanced Thermal Storage	2011	High Energy Advanced Thermal Storage
IDEAS	Innovative Development in Energy-Related Applied Science		Rapid support of early-stage applied research to explore pioneering new concepts with the potential for transformational and disruptive changes in energy technology
IMPACCT	Innovative Materials and Process for Advanced Carbon Capture Technologies	2010	Carbon capture for emissions from coal plants, supplemented by project awards under OPEN 2009 and 2012
INTEGRATE	Innovative Natural-gas Technologies for Efficiency Gain in Reliable and Affordable Thermochemical Electricity-generation	2018	Develop natural gas fueled, distributed, ultra-high efficiency electrical generation systems.
IONICS	Integration and Optimization of Novel Ion Conducting Solids	2016	Improving the properties of solid ion conductors for batteries, fuel cells, and other electrochemical devices
MARINER	Macroalgae Research Inspiring Novel Energy Resources	2017	Develop the tools to enable the United States to become a global leader in the production of marine biomass
MEITNER	Modeling-Enhanced Innovations Trailblazing Nuclear Energy Reinvigoration	2018	Identify and develop innovative technologies that can enable designs for lower cost, safer advanced nuclear reactors
METALS	Modern Electro/Thermochemical Advances in Light Metal Systems	2013	Efficient production and recycling of Al, Mg, Ti - Lower cost and energy use to support vehicle light-weighting
MONITOR	Methane Observation Networks with Innovative Technology to Obtain Reductions	2014	Sensing methane and localizing the leak point(s) economically enough for routine use by producers
MOSAIC	Micro-Scale Optimized Solar-Cell Arrays with Integrated Concentration	2015	Developing compact solar concentration onto high-efficiency cells while also maintaining capture of diffuse sunlight
MOVE	Methane Opportunities for Vehicular Energy	2012	New forms of storage for natural gas that will reduce volume of tanks or allow them to be integrated into the body of the vehicle
NEXTCAR	Next-Generation Energy Technologies for Connected and Automated On-Road Vehicles	2016	Vehicle and powertrain control technologies to reduce automotive energy use
NODES	Network Optimized Distributed Energy Systems	2015	Developing control algorithms to create effective grid storage through distributed demand response, e.g. water heaters

Acronym	Title	Year	Brief Description
OPEN	Open Funding Solicitation 2009, 2012, 2015 and 2018		ARPA-E's open funding opportunities are designed to catalyze transformational breakthroughs across the entire spectrum of energy technologies.
PETRO	Plants Engineered to Replace Oil	2011	Modification of plants to directly product fuel-ready hydrocarbons
PNDIODES	Power Nitride Doping Innovation Offers Devices Enabling SWITCH-ES	2017	Develop transformational advances in the process of selective area doping in the wide-bandgap (WBG) semiconductor, gallium nitride (GaN), and its alloys
RANGE	Robust Affordable Next-Generation Storage Systems	2013	Battery designs that improve the overall energy density and cost effectiveness of the battery system by using safer materials
REACT	Rare Earth Alternatives in Critical Technologies	2011	Materials and motor design approaches that provide options for continued high-efficiency in the event of rare-earth shortages
REBELS	Reliable Electricity Based on Electrochemical Systems	2014	Fuel cells designed for use in distributed power generation (down to residential scale)
REFUEL	Renewable Energy to Fuels through Utilization of Energy-Dense Liquids	2016	Energy-dense liquid fuels from water and CO ₂ and/or N ₂ from air powered by renewable electricity.
REMOTE	Reducing Emissions using Methanotrophic Organisms for Transportation Energy	2013	Biological conversion of methane to fuels
ROOTS	Rhizosphere Observations Optimizing Terrestrial Sequestration	2016	Biofuel plant root phenotyping for improved growth properties and atmospheric carbon sequestration
SENSOR	Saving Energy Nationwide in Structures with Occupancy Recognition	2018	Develop user-transparent sensor systems that accurately quantify human presence to dramatically reduce energy use in commercial and residential buildings
SHIELD	Single-Pane Highly Insulating Efficient Lucid Designs	2016	Insulating window materials with excellent optical quality which prevent condensation, for cost-effective retrofits or replacements
SOLAR ADEPT	Solar Agile Delivery of Electrical Power Technology	2011	Improved electrical interconnects for integrating solar power with the grid
SWITCHES	Strategies for Wide Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems	2013	Devices to improve Energy Efficiency for electric motors
TERRA	Transportation Energy Resources from Renewable Agriculture	2015	More rapid development of sustainable biofuels crops through sensing, robotics, informatics and genetics for advanced phenotyping of energy crops
TRANSNET	Traveler Response Architecture using Novel Signaling for Networking Efficiency in Transportation	2015	Control architectures and traveler incentives for energy optimization of urban networks.

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