MARYLAND ENERGY INNOVATION INSTITUTE

Annual Report FY 2020

UNIVERSITY OF MARYLAND 8136 PAINT BRANCH DRIVE. COLLEGE PARK, MD 20740

The Maryland Energy Innovation Institute brings together science, industry, government and economic leaders to develop new energy technologies and facilitate the transfer of technology ideas into commercial reality.

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MARYLAND ENERGY INNOVATION INSTITUTE

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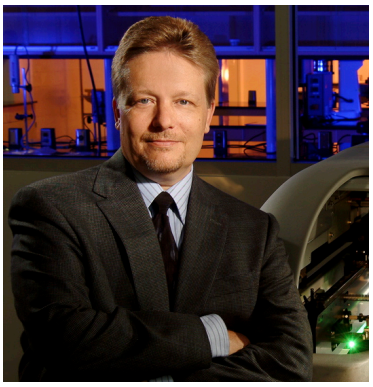
Message from the Director

Achieving a healthy cleantech innovation system in Maryland requires a balance of all components of the commercial value chain including research, development, demonstration and deployment, along with market potential and policies that support demand. As such an effective innovation system must include mechanisms to move emerging technologies along the different stages from discovery to commercialization. At the earliest stage, Maryland's strong University System provides a natural source of clean energy innovation opportunities for environmentally sustainable economic growth.

The Maryland Energy Innovation Institute (MEI^2) is committed to catalyzing and advancing Maryland university developed clean energy technologies and assisting in the transitioning of these technologies into marketable products and services through Maryland based entrepreneurial ventures. These energy innovations have tremendous potential to both grow the State of Maryland economy and have a positive impact on addressing global energy needs in a sustainable manner.

Examples of a few Maryland university based energy innovations being developed in partnership with local spinoff companies include game changing solid state batteries that are intrinsically safe and high performing as well as aqueous lithium ion batteries with increased efficiency and longevity. These advanced battery technologies would be beneficial to early adopter defense and aerospace industries, and ultimately larger consumer electronics, commercial grid storage, and automotive markets. Energy saving technologies for building heating/cooling systems and personal heating/cooling devices for consumer use, as well as advanced photovoltaics and the conversion of agricultural waste and natural gas to value added chemicals are also under development.

MEI^2 continues to increase the visibility of Maryland's energy research and innovation while providing a centralized Institute for the needs of the State Government with respect to energy expertise.



Dr. Eric D. Wachsman
Director, Maryland Energy Innovation Institute
William L. Crentz Centennial Chair in Energy Research
University of Maryland

INTRODUCTION

Maryland has continued to demonstrate its commitment to more sustainable sources and use of energy. In December 2019, Governor Hogan laid out his strategy to put Maryland on a path toward 50% renewable energy requirements by 2030 and 100% by 2040. The Clean and Renewable Energy Standard (CARES) Act supports clean energy solutions and green energy jobs. The Governor's CARES Act calls for investment in increasing the strategic use of zero- and low-carbon clean and renewable energy sources. New Clean Energy Resource Credits would now be available only to facilities in Maryland that generate electricity through new nuclear power, combined heat and power, natural gas or biomass, such as wood or manure. Natural gas and biomass plants would have to use technology that captures carbon dioxide emissions to be eligible.

The State Legislature similarly worked to advance sustainable energy policy by introduction of a number of targeted bills including the Clean Energy Cars Act of 2020, Clean Building Jobs Act, and several other bills to expand on clean and renewable energy use and production. The Clean Energy Cars Act expands on the initiative to promote the use of electric vehicles. The legislation extends the Electric Vehicle Recharging Equipment Rebate Program and the tax credit for purchase of electric vehicles. House Bill 1545 establishes a timetable for phasing out coal burning and providing support to impacted workers and communities. The Clean Building Jobs Act requires greenhouse gas monitoring and reporting of buildings, and mandates energy performance targets be met.

The Maryland Energy Innovation Institute (MEI^2) is actively engaged in helping the State attain these goals and continues to invest and coordinate interdisciplinary energy R&D across the University System of Maryland (USM) in these areas. In support of these efforts, Senate Bill 739 and House Bill 1426 "Advanced Clean Energy and Clean Energy Innovation Investments and Initiatives" were introduced in February 2020 by Senator Feldman, and Delegates Qi, Korman, Barve, Brooks, Crosby, Fraser-Hidalgo, Lierman, Queen, Rogers, and Walker, respectively. These bills call for altering the definition of "clean energy" to "advanced clean energy" in order to support development of clean energy industries in the State; requiring the Maryland Technology Development Corporation and MEI^2 to coordinate with each other in supporting certain technology companies; requiring the MEI^2 and MCEC to implement an accelerator program and to consult with certain State agencies; and altering the purposes of the Maryland Strategic Energy Investment Fund (SEIF) to include providing continued funding each fiscal year to the Maryland Energy Innovation Fund (MEIF).

Senate Bill 739 and House Bill 1426 were largely the result of the findings of MEI^2's mandated mid-term report to Governor Hogan and the State Legislature on the present status and future potential of Maryland's clean energy innovation system. The report offered multiple suggestions for strategically leveraging clean energy technology innovations that foster economic growth in the State, and is discussed in further detail below.

MEI^2 early stage innovation technology investments have paid off in terms of a tremendous increase in federally funded energy research for the State of Maryland as well as the spinoff

of companies created based on the technological breakthroughs from that federally funded research. The United State Department of Energy (DOE) Advanced Research Projects Agency - Energy (ARPA-E) was formed in 2009 to specifically advance U.S. energy innovation. Since its inception in 2009, the University of Maryland (UMD) has received and/or participated in 24 projects, taking the lead on 20. To date, ARPA-E has awarded UMD participating teams over $60M in funding [1] leading the nation among U.S. universities in ARPA-E awards.

UMD's and MEI^2's stature in energy science and technology continues to also grow in the DOE office of Energy Efficiency & Renewable Energy (EERE). During FY2020 an additional $3M from the DOE Building Technology Office (BTO) awards were received for two new projects under the topics *Flexible Building Technologies* and *Heating, Ventilation and Air Conditioning*. UMD was the only university to receive multiple awards from this solicitation. Likewise, UMD received two additional awards from the DOE Vehicle Technology Office (VTO) in the *Advanced Battery* category. To date, UMD has received more funding from VTO than any other university and is the only one to receive multiple awards in this category. It is also one of only two universities to receive two awards overall in all categories during this solicitation.

MEI^2 continues to develop international and domestic research partnerships to pursue advances in scientific understanding and technical innovation that will lead to commercialization for a wide range of societally relevant applications including renewable energy generation and storage and the effective use of energy (i.e., advanced batteries, fuel cells, ultrafast high temperature sintering, and the optimization of energy use). MEI^2 will co-lead (with Bar Ilan University) the new U.S. - Israel Bilateral Industrial Research and Development (BIRD) Foundation Energy Storage Consortium and has been instrumental in adding industrial and research partners to the Center for Research in Extreme Batteries (CREB).

Since its inception in 2017, MEI^2 has leveraged the State's investment (MEI^2 portion of the MEIF to date is $1.8M) to obtain over $40M in federal funding, a factor of >20X return to the Maryland economy.

MEI^2 ADVISORY BOARD

The MEI^2 Advisory Board is composed of nine members including: (1) the Director of the Maryland Energy Administration (MEA) and the Chair of the board of directors of the Maryland Clean Energy Center (MCEC); and (2) seven members selected based on expertise in energy technology commercialization, the clean energy industry, venture capital financing and energy research.

[1] As of September 2020, two additional ARPA-E awards were received, bringing the total to 26 awards and over $65M in funding.

In the fall of 2019, Dr. David Rapaport, Head of Siemens Technology Research Collaboration Management, joined the MEI^2 Advisory Board, replacing Dr. Phillip Perconti, who stepped down from his seat due to his change in position at the Army Research Lab (ARL). One Advisory Board position remains open and a new member search began.

FY2020 Advisory Board

Victor Der, Board Chair
Assistant Secretary of Fossil Energy, U.S. DOE (retired)
Ellen Williams, Vice-Chair *University of Maryland Distinguished University Professor, Former Director, ARPA-E (DOE)*
Scott Dupcak
Managing Director, Constellation Technology Ventures
Steven Freilich
Head, Dupont Central Research and Development (retired)
Abigail Hopper
President & CEO, Solar Energy Industry Association
Geoff Oxnam
Chair of the Board, Maryland Clean Energy Center
CEO, American Microgrid Solutions
David Rapaport
Head, Research Collaboration Management, Siemens Technology
Mary Beth Tung
Director, Maryland Energy Administration

The MEI^2 Advisory Board convened on July 2019 for a full day of presentations articulating the resources and success of MEI^2, as well as the progress of near-term goals including final results from the first round of energy seed grant funding and introductions to the second round of seed grants. The Advisory Board confirmed in their letter (Appendix 1) that MEI^2 has catalyzed significant advancement in research and innovation of advanced clean energy technology toward greater economic growth in the state of Maryland. As stated in their letter the Advisory Board was impressed by MEI^2's progress in research and its excellent progress in implementing the Advisory Board's recommendations from the previous year while identifying relevant key performance indicators as metrics against the program goals remains an ongoing effort.

The Advisory Board made the following recommendations for FY2020 year with the aim of MEI^2 achieving its full transformative, scholarly, and financial potential:

1. Continue engagement on the topic of advising the Maryland Clean Energy Center (MCEC) on effectively investing capital in Maryland start-ups
2. Support the MEI^2 report recommendations for increased funding, prepare operational models and budget options for the Institute's strategically planned programs
3. Work with MCEC and MTECH to complete the initial planning phase for the Maryland Energy Innovation Accelerator (MEIA), and develop a proposal for a fully operational service at different possible funding levels
4. At a level consistent with the possible number of Seed Grant projects, examine a process for improving the socialization and notifications of Seed Grant opportunities to encourage more proposal submissions from universities statewide

5. Conduct an impact/benefits analysis to inform a decision regarding the potential use of Seed Grant funds for participation in the U.S. – Israel Energy Center Funding Opportunity which leverages matching funds.

Outcomes and results from these recommendations will be discussed further in this report.

CLEAN ENERGY TECHNOLOGY DEVELOPMENT AND DEPLOYMENT IN MARYLAND

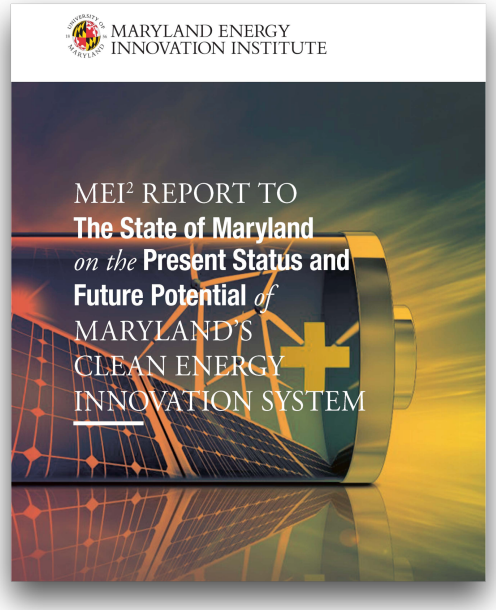
In accordance with 2-1246 of the Senate Bill 313 which established MEI[2], the Institute was charged with studying and evaluating:

(i) The availability and efficiency of the use of funds for the development and deployment of clean energy technology in the State and the commercialization of that technology, including funds from the Strategic Energy Investment Fund (SEIF) and other practical forms of financing;

(ii) The forecasted need, if any, for additional funding or financing options for these purposes; and

(iii) Appropriate sources and levels of funding and financing options for these purposes.

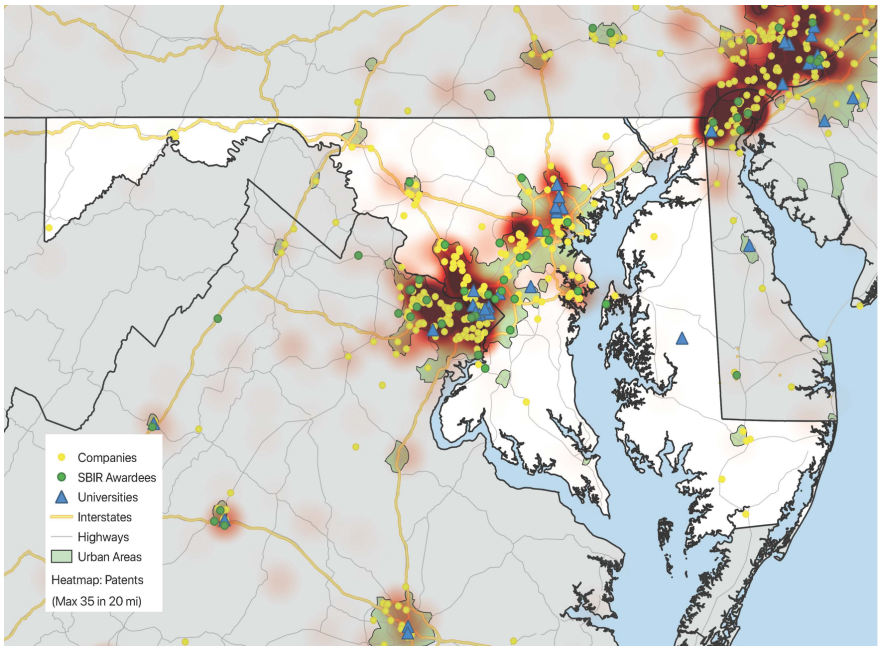
On November 24, 2019, MEI[2] delivered the report [2] to Governor Hogan and the State Legislature. Many interviews and stakeholder discussions were used to inform the contents of the report and are listed in Appendix F of the report. In summary, Maryland's future economic success depends largely on the ability of its companies and institutions to innovate, creating a competitive advantage in new areas that provide opportunities for its companies and residents. The State has previously invested systematically and strategically in commercial development based on in-state discoveries and intellectual property in the field of biotechnology and cybersecurity. Maryland's innovation in clean energy technologies would provide another pathway for the State to diversify and build a strong economic future.



Maryland is a leader in clean energy innovation, currently ranking 5th nationally, and has a strong foundation of research and development (R&D) capabilities, ranking 2nd among

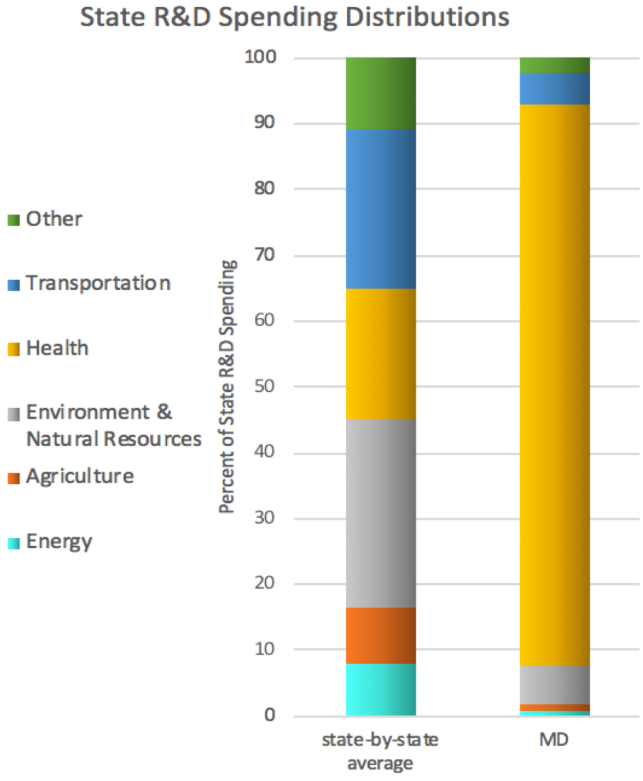
[2] https://energy.umd.edu/publications

states in annual per capita R&D expenditures and 1st in per capita university R&D expenditures. Even though Maryland has not previously focused on clean energy as an economic development opportunity, it now has over 150 clean technology firms engaged in development and in-state manufacturing, illustrated in the figure below. Among these firms are a growing number that have taken advantage of new types of Federal support designed to accelerate commercialization of innovative clean energy technologies.



Distribution of Maryland firms (bright yellow dots) involved in development, commercialization and manufacturing of innovative clean energy technologies and heatmap (dark red) of energy patents.

Though Maryland has clear assets and capabilities, the state has under-performed in creating new economic opportunities that leverage the state's strong commitment to clean energy and reduction of greenhouse gas emissions. Maryland has not previously focused on clean energy technology as a strategic approach to economic development with in-state commercial R&D and manufacturing. Instead, Maryland has focused more narrowly than other states on a single area, health care-related technologies as illustrated to right. In fact, *Maryland is last in the nation in the diversity of its state R&D expenditures* with 85% dedicated to healthcare. While this positions Maryland to take



advantage of one research strength, it disregards a broader set of opportunities for its citizens. Across the fifty states, technology focus is widely distributed. Median state spending is $5.93 per capita. Maryland has placed a strong strategic focus on health-related R&D, which has crowded out support in other areas. Maryland's reported R&D spending is $4.66 per capita. The report concludes that given the evidence regarding support and outcomes in states similar to Maryland, the State could accomplish a ten-year goal of doubling the rate of formation of clean energy firms each year while cutting in half the rate at which firms fail. Spending for early innovation stages, rather than just deployment of innovation, along with investment to provide developmental support to clean energy firms would enhance economic growth along with additional societal benefits in using clean energy technologies.

To address both Maryland's societal and economic goals for clean energy, the following high-level and financial recommendations were reached in the report:

1. The state of Maryland should diversify its strategic economic development priorities to include multiple technology pillars, beginning by specifically mandating a Clean Energy Innovation System that supports innovation, development, and in-state manufacturing of clean energy technologies. The goals for the Clean Energy Innovation System should align with the state's societal commitment to energy efficiency, clean energy and the environment, including reduction of greenhouse gas emissions.
2. Future legislative language regarding Maryland's Clean Energy Innovation System should reinforce a broad definition of clean energy to ensure that Maryland has the flexibility to support development of cutting-edge new approaches to meet the state's clean energy and greenhouse gas reduction goals.
3. The state should designate a responsible agency to provide coordination among the agencies that need to be involved in delivering the outcomes expected of the state's Clean Energy Innovation System: Department of Commerce, Public Service Commission (PSC), Maryland Energy Administration (MEA), Maryland Energy Innovation Institute, Maryland Clean Energy Center (MCEC), and the Maryland Technology Development Corporation (TEDCO).
4. As part of the state's Clean Energy Innovation System, the Maryland Energy Innovation Institute should be tasked and funded to deliver developmental support in the form of additional infrastructure and mentoring specifically tailored to the needs of early-stage clean energy firms, using partnerships with MCEC, TEDCO and university venture programs.
5. As part of the state's Clean Energy Innovation System, the Maryland Energy Innovation Institute should be tasked and funded to expand early-stage innovation funding for clean energy firms to a per-capita funding level intermediate between Colorado and New York and should coordinate this program with TECO, MIPS, and university venture programs.

6. The program to create a thriving Clean Energy Innovation System in Maryland should be managed in 5-year stages and assessed against quantitative metrics including growth in firm number, Federal and private sector funding per company, and rate and extent of commercial maturation.
7. Given Maryland's unusually low level of support for early deployment of new clean energy technologies, compared with support for mature technologies, the state should require an assessment of the potential for reallocating some EmPOWER funds for emerging clean energy technologies that may provide expanded consumer benefits.
8. The state should require an assessment of the potential for expanded impact of EmPOWER funds by using green finance mechanisms for market growth of established clean technologies.
9. The state should modify its present Investment Incentive Tax Credits and associated TEDCO Investment Funds to support investments in clean energy technologies. DOC, TEDCO and MEI^2 should be jointly responsible for delivery of Maryland's Clean Energy Innovation System goals through these programs.
10. The state should modify the present allocation of the SEIF to include a specific allocation of up to 10% of the fund's budget to support the Maryland Clean Energy Innovation System, with a renewed authorization considered in 5 years based on demonstrated progress toward goals. Of the reallocated funds, $4.5M/yr should be allocated to the MEIF. Of the requested allocation from SEIF to MEIF, $2M/yr should be designated for expanded direct support of innovative clean energy firms; $1M/yr should be designated for developmental support of Maryland clean energy firms through and innovation acceleration program; and $1.5M/yr should be designated support for MCEC outreach programs and for use of MCEC's financing and bonding authority to leverage stage 3 deployment of Maryland developed clean energy technologies.

Following publication of the report, Legislative testimony was provided, and meetings were held with State Legislators regarding potential implementation garnering significant support for the report recommendations. As a result, House Bill 1426 and Senate Bill 739 were introduced by Delegates Qi, Korman, Barve, Brooks, Crosby, Fraser-Hidalgo, Lierman, Queen, Rogers, and Walker and Senator Feldman. The Bills are titled Economic Development – *Advanced Clean Energy and Clean Energy Innovation Investments and Initiatives*. The Bills identify energy as a strong economic opportunity and broaden the definition of included energy technologies. They also remove the sunset of MEI^2 funding and increase Institute funding consistent with report recommendations. However, positive legislative action for HB1426 and SB729 were unable to come to a full vote due to legislative shutdown related to COVID-19. Strong support remains to reintroduce these Bills during the next legislative session.

ADVANCING THE MARYLAND ENERGY INNOVATION ECOSYSTEM

MEI^2 continues to drive Maryland energy innovations in partnership with Mtech, TEDCO, UM Ventures, the MCEC and the Maryland Department of Commerce. MEI^2 has been

extremely active in mentoring UMD ARPA-E applicants and award winners in technology commercialization, from the proposal stage to post award results. Furthermore, with the assistance of MCEC, the Maryland Energy Innovation Accelerator (MEIA) is fully staffed and operational.

FY2020 Investment Committee

Ellen Williams, Vice-Chair *University of Maryland Distinguished University, Former Director, ARPA-E (DOE)*
Robert Briber
Associate Dean for Research, UMD A. James Clark School of Engineering
Eric Chapman
UMD Assistant Vice-President for Research and Development
Julie Lenzer
Associate Vice President of Innovation and Economic Development and Co-Director of UM Ventures
Arti Santhanam
Executive Director, Maryland Innovation Initiative, Maryland Technology Development Corporation (TEDCO)

Energy Innovation Seed Grant Program

In its inaugural year, MEI^2 initiated a seed grant program to bridge the gap between academic transformative laboratory research results and the prototype demonstrations necessary to obtain investor interest. This call was for multiple seed grant awards with a maximum award ceiling of $100,000 USD. All full-time tenured or tenure track faculty members at any Maryland state academic institution or Maryland companies affiliated with and commercializing inventions created by those faculty are eligible to apply. It is expected that the seed grant projects advance energy technology and economic growth in Maryland in partnership with a local university faculty or student led company. The device or process should have appropriate intellectual property protection (invention disclosure, patent application, or patent) filed with the applicant institution. At the end of the one-year project, a report that describes work done and includes a commercialization plan are required. The plan should include a clear market assessment and strategy; a viable revenue model; and a strategy for financing the plan.

The MEI^2 Investment Committee was created to independently oversee the solicitation and review of the Energy Innovation Seed Grants and other activities that support the Energy Investment Fund. Projects are reviewed for: 1) the likelihood of attracting outside funding, 2) innovative and scholarly merit, and 3) potential for commercial readiness. In addition, if approved by the MCEC Board, the Investment Committee could advise MCEC on effectively investing capital in Maryland start-up companies.

Advancing Commercialization

Ion Storage Systems (ISS) is a company that has grown significantly, garnering an $8M investment round led by Alsop Louie Partners. On Thursday, July 30, 2019, MEI^2 officially launched its first start-up company, ISS, into incubator space at the UMD Technology Ventures Building. Dr. Laurie Locascio, UMD Vice-President of Research, kicked off the event by noting that MEI^2 is catalyzing energy research and innovation while providing the technology push necessary for Maryland to generate jobs and positively impact the state economy. She further noted that ISS is a perfect example of MEI^2's commitment to creating an energy business ecosystem as the company has hired 20 employees this year and is

focused on developing the most energy dense and safest batteries that can be deployed in any environment.

Maryland Secretary of Commerce, Kelly Schulz, then presented Dr. Eric Wachsman, Acting CEO of ISS, and Dr. Greg Hitz, CTO of ISS, with the Secretary's Citation for "development of noncombustible, high-performance solid-state batteries in recognition of the broad application of these batteries … in appreciation for your commitment to doing business in Maryland; and with sincere best wishes for success…"

Ribbon Cutting for Ion Storage Systems. From left to right: Maryland State Delegate Kumar Barve, UMD VP of Research Laurie Locascio, Maryland Secretary of Commerce, Kelly Schulz, Dr. Eric Wachsman, and ISS CTO Dr. Greg Hitz.

A reception was held following the ribbon cutting ceremony at the Ion Storage Systems incubator space. In attendance, in addition to VPR Locascio and Secretary Schulz, were Maryland Delegate Kumar Barve, chair of the Environment and Transportation Committee, Mr. Tom Sadowski, the University System of Maryland's Vice-Chancellor for Economic Development, the MEI^2 Advisory Board, UMD faculty and others.

An original MEI^2 Energy Seed Grant recipient, Dr. Susanna Thon, Johns Hopkins University, in partnership with NanoDirect, led by Stephen Farias, has contributed significantly to the COVID-19 response efforts this year. They have converted their nanofabrication equipment in the new facility to make filtration materials for PPE masks. This effort is in partnership with DiPole Materials which is also part of Early Charm and co-located with NanoDirect. In all, the partnership has hired 18 engineers and rapidly increased production from about 3 square feet of material per day at the end of March to about 200 square feet per day by mid-April with 24/7 operation.

Second Round Seed Grant Results and Future Development

In March 2019, MEI^2 awarded two $100K Seed Grants for Energy Innovation and one Phase II Seed Grant. Their mid-term reports were delivered in November 2019, and initial overviews of the projects were presented to the Advisory Board in August 2019. Final reports were delivered in May 2020 and results presented during the July 2020 Advisory Board meeting. The second round Seed Grants include:

- **RoCo (the Roving Comforter)**; Lead PI: Reinhard Radermacher, Professor and Director Center for Environmental Energy Engineering, University of Maryland College Park; Partnering Companies: Mobile Comfort, Daikin and Alliance Material

  RoCo is a Roving Personal Comfort device, which provides personal thermal management for people in inadequately or un-conditioned environments. It is a robotic unit that includes an on-board cooling unit and can either remain stationary or follow a user through an environment using computer vision technology. Most air conditioning systems are designed to cool rooms or entire buildings. RoCo is designed to keep an individual user comfortable and in control. This is achieved with a "smart nozzle" that tracks the movement of the user and delivers a cool stream of air directly on the person in control. It provides 12% to 30% energy savings compared with typical conditioned building systems, and better thermal and mobile comfort to occupants. Initially designed with a $2.6M DOE ARPA-E grant, Mobile Comfort, an energy start-up company, was established to bring the prototype to market.

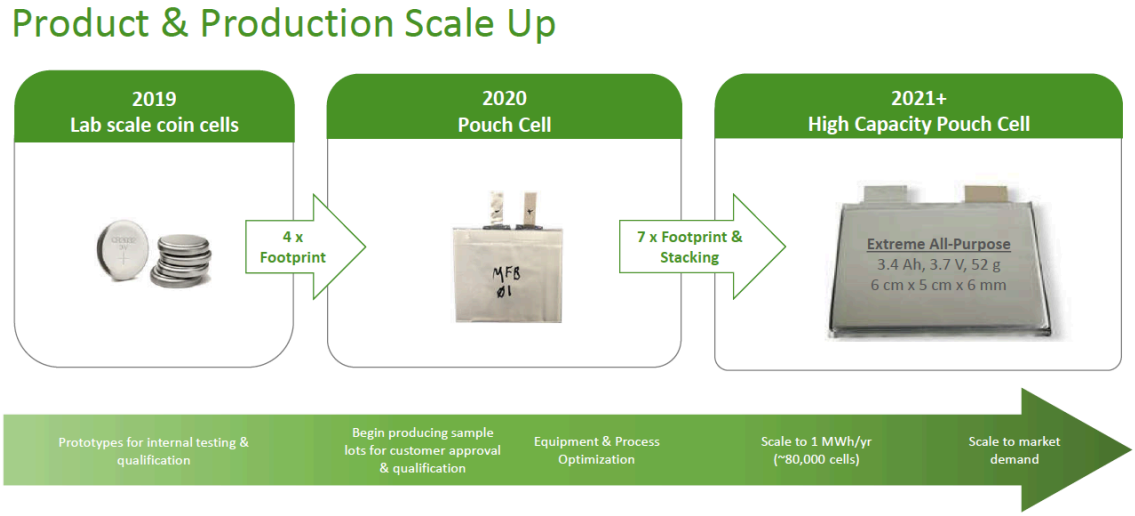
Through Phase II MEI[2] seed grant funding, the RoCo team were able to accomplish the following tasks:

- Develop the RoCo for forklift applications, where an operator may work in an unconditioned space and no air conditioning of any form is currently available.
- Fabricate 25 RoCos for field tests.
- Develop RoCo for an indoor unconditioned environment.
- Develop the RoCo for high temperature climate.
- Develop the RoCo so that it can operate independently of the grid (Solar RoCo).

The RoCo devices that were sent for field tests on forklifts and other personal consumer use managed to thrive during field test use and abuse. The current Solar RoCo is deployed on the roof of Glenn Martin Building in College Park, MD and fixed to roof anchors. Initial testing indicated that the controller charges and discharges batteries as expected. Future tasks include solar system data logging and connecting and operating RoCo in the CEEE office at UMD. RoCo tracking software has also been updated. Improved algorithms were developed and deployed. Furthermore, seed grant funding enabled RoCo to be patented in the European Union and United States. Patents are pending in Canada and Japan. In addition to the initial residential applications, the forklift application has garnered interest from the farm tractor, heavy construction equipment and golf cart dealers. Supply chain explorations are underway.

- **Packaging of Solid-State Batteries for Strategic Partner Testing and Product Integration**; Lead PI: Greg Hitz, CTO Ion Storage Systems, LLC; University Collaborator: Eric Wachsman, Professor Materials Science Engineering, University of Maryland College Park

Ion Storage Systems (ISS) is commercializing a patented next generation solid-state battery technology developed at UMD under ~$12M in federal and industry awards. Through the seed grant funding, ISS made significant progress towards refining the packaging requirements necessary to successfully ship and test cells at partner's sites, completed an assessment of the Harbor Designs packaging prototype, developed an alternative packaging strategy within ISS that can meet the requirements, and is in discussions with strategic partners for such testing as was envisioned at the start of this project.



ISS as a company has grown significantly garnering an $8M investment round lead by Alsop Louie Partners, and currently has 20 employees. In August 2019, ISS moved into 2,000 square feet of incubator space in the MEI^2 Battery Incubator at the Technology Ventures Building and is capable of a full manufacturing process from materials synthesis to testing.

- **A Novel Geared Infinitely Variable Transmission for Tidal Current Energy Harvesting**; Lead PI: Weidong Zhu, Professor Mechanical Engineering, University of Maryland Baltimore County; Partnering Company: Talos Industry Corporation

  The main goal of the project is to experimentally investigate and commercially promote a new infinitely variable transmission (IVT) for tidal current energy harvesting. The value of an IVT lies in its ability to accept variable mechanical input (from waves) and produce a fixed-rate output that can be easily fed to the grid, while maintaining high

  efficiency at all speed ratios. The IVT in this project can achieve a continuously variable speed ratio, reduce failures and operation and maintenance costs, and increase the amount of tidal current energy that is obtained. Current activities include work on a noncircular design, IVT prototype improvements, and power flow and dynamic modeling of the IVT to enable the creation of a control system. Experimental tests for speed ratio control were combined with an integral time-delay feedback control to validate the average input-to-output speed ratio. Minimal errors were detected.

IVT prototype at the Hydrokinetic Energy Corporation

Flume flow tests, consisting of power tests and control tests were planned for the water tunnel at the Hydrokinetic Energy Corporation. The tidal energy device with the IVT prototype was to be tested in environments that can produce similar conditions to those in real water to assess energy harvesting performance with different turbines. The team is also working with the Maryland Energy Innovation Accelerator on a business plan. *Due to COVID-19 and travel restrictions, the third seed grant was granted an extension to complete their field tests in Florida when possible.*

FY2020 Energy Innovation Seed Grants

Following the Advisory Board's recommendation to examine a process for improving the socialization and notifications of Seed Grant opportunities to encourage more proposal submissions from universities statewide, a concerted effort was made to individually communicate to all department chairs and deans involved in energy research across the

University of Maryland State System as well as Johns Hopkins. The third-round request for energy seed grant proposals garnered 18 proposals (3 times the amount from the previous year) from 7 different academic institutions. The Investment Committee awarded $387K to the six projects described below. The MEI^2 Investment Committee developed a partnership with Maryland Industrial Partnerships (MIPS) and MTECH during the year, and thus two MEI^2 seed grant proposals, unable to be funded by MEI^2, were forwarded to the MIPS proposal solicitation for MIPS program review. If either proposal is successful, the Investment Committee reserved $13K to help support these two seed grants.

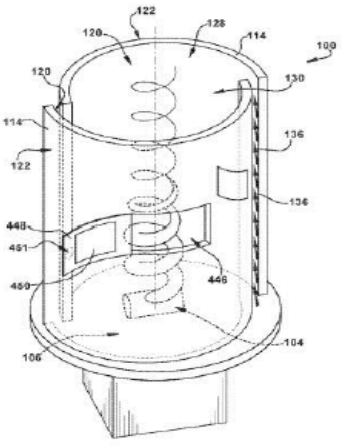
The following six awards were made in March 2020:

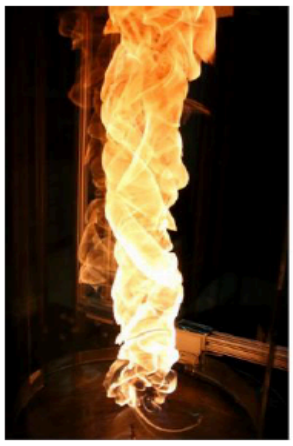
- **Multi-Winding Planar Transformer for Energy Router in Smart Homes**; Lead PI: Alireza Khaligh, Professor of Electrical and Computer Engineering, University of Maryland College Park; Partnering Company: AmpX Technologies, Inc.

  The purpose of the project is to initiate a disruptive approach to manufacture magnetic components for electrical circuit boards. Power electronics are an enabling technology for efficient conversion, transfer, control, and conservation of electrical energy. Power electronic circuits enable power from wind, sun, ocean, and fuel cells to be converted efficiently to useful electricity. A multi-winding planar transformer would be a preferred enabling component of an energy router to integrate different power stages in the smart residential buildings. Thus, the smart building power electronic system can be more compact, efficient, and scalable using a single multi-port interface, instead of utilization of discrete converters sharing the common DC bus with multiple transformers.

- **Swirl Stove: Swirling combustion for efficient wood burning**; Lead PI: Taylor Myers; Partnering Company: MF Fire Inc**.**

  MF Fire is transforming wood heat into clean energy to solve the primary environment and health issues that result from burning wood. The technologies and products are



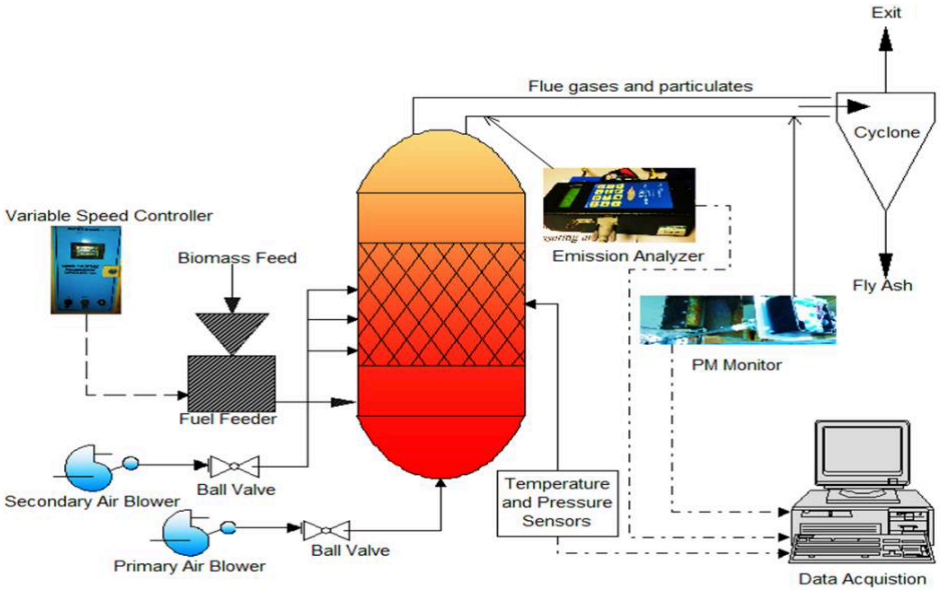



Proposed Swirl Stove Design

designed to help the 50 million Americans who rely on wood for heat and 500 million people worldwide. At full deployment, the solutions can reduce 40% of particulate emissions in the US. The primary goal of the Swirl Stove is to successfully incorporate swirling combustion into a wood stove design. Swirling combustion is used for mixing combustion air with fuel gasification products to achieve a more complete burn, thereby reducing emissions and increasing efficiency. The proposed technology targets reducing particulate emissions production to below 0.5 g/hr, a 75% reduction of MF Fire's current firebox design, and increasing efficiency to 85%, a 15% increase over the current firebox design.

- **Utilizing Industrial Hemp Biomass for High Throughput Biofuel Production in Maryland**; Lead PIs: Jurgen Schwarz, Professor and Chair, and Sadanand Dhekney, Professor, Agriculture, Food and Resource Science, University of Maryland Eastern Shore; Partnering Company: Atlantic Biomass Company

  While a large acreage in Maryland is currently focused on cannabinoid production from flowers, the remaining biomass (e.g., the stalk and roots) remains unutilized. Hemp biomass that is left over following cannabinoid extraction has great potential to be converted into biofuel, in addition to being primarily grown for conversion into fuels. The goal of this study is to utilize hemp waste as a substrate for bioethanol production with dilute acid pretreatment prior to microbial fermentation; and to maximize the production of bioethanol via the engineered strain. The hypothesis is that the presence of cellulose/hemicellulose in the hemp stem and fiber and their depolymerization into monomeric sugars using enzyme catalysts are able to enhance the production of fermentable sugars. Establishment of hemp as a biofuel crop would be beneficial to the



Schematic of proposed biofuel production.

industry by increasing demand for hurd and fiber. Hemp biomass not used for nutrient input would be a good residual biomass for biofuels/bioproducts because of its current low value.

- **Poultry Litter to Energy**; Lead PI: Seong Lee, Industrial and Systems Engineering, Morgan State University; Partnering Company: Cykloburn Technologies, LLC

  The project proposes to address two key societal needs: managing environmentally damaging poultry litter pollution and generating energy from renewable resources. Poultry litter is high is phosphorous and when traditionally used as a crop fertilizer, the run-off contributes to environmental damage to the waterways. Nowhere is that problem more acutely felt than in the Chesapeake Bay region. In addition to the energy savings, replacing the currently used propane heating with a lower moisture radiator heating system from Cykloburn will lead to lower ammonia concentrations, improved bird health, and improved feed conversion ratios. The goal of this project is to advance the current pilot system into an automated prototype by updating primary air system and optimizing the overall combustion system while demonstrating that the system can repeatably operate on multiple farms and a range of environmental conditions.

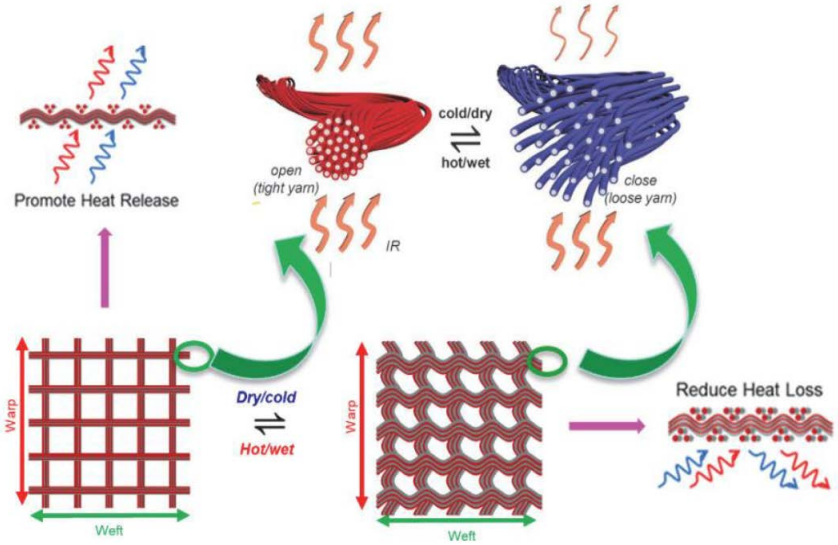
- **Thermohalt Li-Ion Battery Management System Development and Customer Test**; Lead PI: Rengaswamy Srinivasan, Lead Scientist, Johns Hopkins Applied Physics Lab; Partnering Company: Thermohalt Technology, LLC

  Thermohalt has developed the first and only patent protected electrochemical impedance spectroscopy (EIS) solution to apply impedance measurements to improve quality control in the Li-Ion battery manufacturing process and to prevent thermal runaway in operation. This technology will allow customers to maximize quality by detecting and eliminating cells with hidden manufacturing defects, and to maximize performance by measuring cell characteristics and prescribing matching bins. Seed grant funding will be used for testing the prototype product with three key prospective customers, each of which has a requirement that is believed to be common amongst other firms in the industry. In support of these customer tests, Thermohalt will enhance their electronics and interfaces and enhance existing or develop new software to optimize the value provided to the customer.

- **Mind Your Feet – Knitting Meta-Cool into Socks**; Lead PI: YuHuang Wang, Professor of Chemistry and Biochemistry, University of Maryland College Park; Partnering Company: Coolwave Dynamics, LLC

  The project proposes the production of thermoregulating socks as a prototype to demonstrate the technology value of the invention through a close collaboration between the university lab and Coolwave Dynamics, LLC, a spinoff from UMD that is dedicated to bring this energy-saving technology to the market. Because feet present an efficient spot for heat exchange and the cost of manufacturing will be reasonable even at this early stage of the technology development, this thermoregulating sock will serve as a highly demonstrable prototype to advance Meta-Cool technology. The PIs

will produce meta-fibers and knit them into the proposed thermoregulating socks and quantify their adaptive thermoregulating properties in response to the body's local environment. The goal is to showcase the capability of Meta-Cool technology in controlling heat exchange to maintain the wearer's personal thermal comfort through feet. Success in knitting meta-cool technology into socks will significantly enhance the commercial viability, setting a milestone toward the commercialization of Meta-Cool technology as an energy saver for indoor thermo-management.



Schematic of the self-regulative IR gating effect of meta-fibers in response to environmental changes.

PARTNERSHIPS AND COLLABORATIONS

Throughout the past fiscal year, MEI[2] has developed many local, national and international partnerships and contracts in support of the Institute's Research and Innovation foci.

U.S.-Israel Binational Industrial Research and Development Foundation Energy Center

On March 6, 2020, U.S. Secretary of Energy Dan Brouillette and Israel's Minister of Energy, Dr. Yuval Steinitz, announced three winners under the U.S.-Israel Energy Center competitive funding opportunity. Three consortia, comprised of U.S. and Israeli organizations, will undertake five years of research, development, and commercialization of innovative energy technologies each with a different energy-sector focus, fossil energy, energy-water nexus, and the UMD will co-lead (with Bar Ilan University) the consortia focused on energy storage. [3]

[3] https://us-isr-energycenter.org/

MEI^2 will lead the U.S. side of a $18.4M, five-year program, managed by the Binational Industrial Research and Development (BIRD) Foundation. The goal of the U.S.-Israel Energy Center is to promote energy security and economic development through the research and development of innovative energy technologies. Building on MEI^2's strength in batteries and energy storage, the Energy Center is focused on solid-state batteries using sodium or lithium metal anodes, with an initial development focus on applications such as unmanned vehicles (air or underwater), soldier power, and biomedical. Solid-state batteries can offer a breakthrough in terms of energy per unit mass and volume at the cell level, lower cost, improved safety, and an ability to serve numerous end-use sectors including specialized applications such as aerospace, as well as larger markets in transportation and stationary storage. The cooperative project will focus on advancing the science and development of solid-state batteries, including work on advanced coatings, cell components, cells, and materials informatics software, for both Na and Li metal batteries.

The innovations will result from the combination of the diverse set of skills of the center partners. Teams will specialize in (1) development of new solid electrolytes, both ceramic and polymeric, (2) interfacial coatings that facilitate interphases with desirable properties, (3) unique modeling and Artificial Intelligence capabilities for active material screening/choice, and (4) assembly of battery cells for performance assessment.

This partnership with two leading universities (Bar Ilan and Tel Aviv) and two start-up companies (Materials Zone and 3DB) in Israel reflect the international reputation and impact of MEI^2 researchers, along with the three U.S. companies that are part of the U.S. side of the consortia, among which Saft and Ion Storage Systems are Maryland based.

Center for Research in Extreme Batteries

The Center for Research in Extreme Batteries (CREB) aims to foster and accelerate collaborative research in advanced battery materials and technologies and characterization techniques. CREB's focus is on batteries for extreme performance, environments and applications (for example: defense, space, biomedical applications). Participation in CREB is open to national and defense labs, universities, and industry. CREB is a cooperative research and development agreement between UMD and the Army Research Laboratory (ARL). In December 2019, the CREB Biannual Fall Meeting focused on space batteries. Industry leaders from SAFT, Lockheed and NASA's Jet Propulsion Laboratory discussed improvements in materials and technology for satellite batteries and ultra-low temperature batteries for space missions such as Titan.

The CREB Consortium was established in 2017 by an agreement between UMD and ARL, as a separate entity affiliated with CREB in order to provide a mechanism for extended collaborations. Effective the summer of 2020 the consortium was joined by the National Institute of Science and Technology (NIST). Thus, CREB which is focused on battery technologies for Maryland's major defense, aerospace, and biomedical industries, is led by three of its major research institutions across the state UMD, ARL, and NIST, in partnership with leading edge U.S. battery research including Argonne National Laboratory, New York Battery and Energy Storage Technology Consortium, and Stony Brook University/Brookhaven National Laboratory.

Moreover, in the FY2020 US Defense Appropriations Act $10M was appropriated for battery research led by UMD through ARL and its CREB partners. Details of this major federally funded research program are currently under negotiation.

Maryland Energy Innovation Accelerator (MEIA)

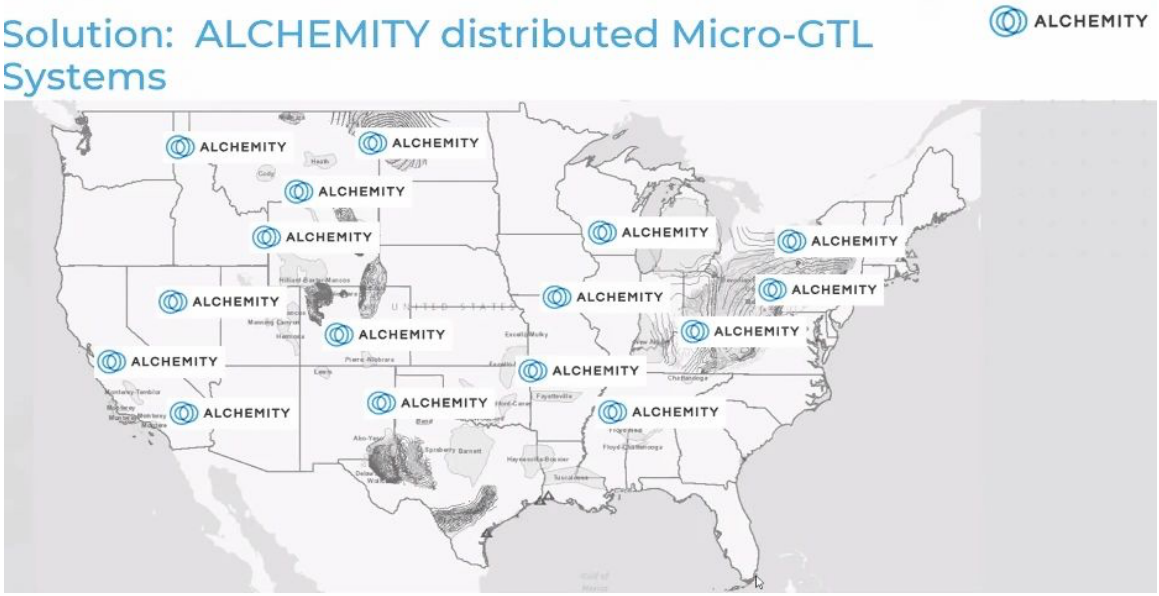
In FY2020 MEIA was launched in partnership with MEI^2 and MCEC to assist start-up companies achieve commercial success. MEIA surrounds inventors with professionals from a wide variety of disciplines who are committed to creating a new, impactful company. MEIA also provides services for Startups including legal, intellectual property, accounting, finance, market research, branding, customer discovery, and more. These services are crucial to ensure a company is formed correctly and is on solid footing for growth.

Through the new business acceleration program, MEIA launched its inaugural cohort of five companies in January 2020. MEIA's first cohort includes technologies from a wide range of clean energy industries that demonstrate the diversity of Maryland's clean energy research and development activities. Four of the five technologies relate to work performed at MEI^2 at the University of Maryland. Two technologies are from UMD, and two technologies are from the University of Maryland Baltimore County (UMBC). The fifth technology was created by University of Maryland alumni and UMD Engineering Hall of Fame member Emilio Fernandez to provide energy savings opportunities to buildings where tenants do not pay individual utility bills.

MEIA is focusing on building out the founding team and the accelerator provides a risk-free way for companies to work with a team of great business executives to determine how to take new technologies forward. Corporate Sponsors for MEIA include Exelon Corporation, Banner Witcoff, Nelson Mullens, Snyder Cohn, and Paley Rothman. Over a six-month time period, teams of inventors and business experts will follow the Lean Startup methodology to determine whether businesses from the cohort should be created. Hopefully, the teams will advance and found technology businesses in Maryland.

The MEIA Program culminates in an Investor Pitch Event where each team will pitch investors for seed round funding. The winner of the Pitch Event in the inaugural cohort was Alchemity, a UMD Startup, who was awarded $1000 from the Maryland Department of Commerce. Alchemity is revolutionizing the $60 billion gas-to-liquids (GTL) processing through a novel one-step non-oxidative membrane reactor. This reactor represents a step change in process intensification over the existing technology developed 95 years ago by combining three conventional processes into a single step, thereby eliminating much of the massive capital requirements to build new GTL plants. The reactor is also more efficient and modular, the latter enabling new GTL plants to be sited much closer to end users. The reactor can also be used to capture methane gas that is currently flared or vented at drilling sites and natural gas processing plants. By capturing flared and

vented gas, and reducing the energy intensity of GTL processing, Alchemity will substantially reduce carbon emissions currently produced by the oil & gas industry.



Examples of potential Alchemity reactor sites across the U.S.

RESEARCH FUNDING AWARD HIGHLIGHTS

Significant financial support of research into new energy technologies was obtained in FY20. In addition to another 3 DOE ARPA-E awards received, UMD won two Vehicle Technology Office and two Building Technology Office awards. The Center for Materials Innovation was established, as was the joint U.S. – Israel Center for Energy Storage.

ARPA-E Awards

In FY20, UMD was the recipient of three additional DOE-ARPA-E awards. In the Breakthroughs Enabling Thermonuclear-fusion Energy (BETHE) category, a team from University of Baltimore County and UMD will lead a project entitled: Centrifugal Mirror Fusion Experiment. The goal is to advance the performance of the centrifugal mirror (CM) fusion concept, which has previously demonstrated stable plasmas with temperatures above 100 eV. The CM has a simple, axisymmetric geometry and provides a potential low-cost pathway to a breakeven experiment. The team will azimuthally rotate a mirror-shaped magnetized plasma to supersonic speeds using high-voltage biasing between a central rod and outer electrode rings. The rotation will stabilize, heat, and centrifugally confine the plasma, potentially eliminating the need for costly auxiliary heating systems requiring high recirculating power, which would degrade the economics of a fusion power plant. The project aims to overcome engineering challenges of the high-voltage biasing, and scientific challenges of achieving good stability and confinement while pushing into higher-temperature regimes. The project aims to achieve a triple product exceeding 1017 keV s/m^3.

UMD also received an award in the Rapid Encapsulation of Pipelines Avoiding Intensive Replacement (REPAIR) program. REPAIR seeks to eliminate the highest pipe

rehabilitation cost components, excavation, and restoration, by repairing pipes without their removal. The selected REPAIR teams are developing smart coatings, robotic systems to line the inside of pipes, inspection tools to verify the integrity of the pipes, and mapping tools to enable 3D renderings of pipes and adjacent underground infrastructure. Dr. Liangbing Hu, MSE, and Dr. Paul Albertus, MEI^2 Associate Director, will lead the project which proposes a multifaceted and integrated approach to develop a smart alloy coating for use in pipe-in-pipe configurations with UMD's patented high-temperature sintering process. A novel smart alloy coating is rapidly sintered with a high-temperature Joule heating bar directly from the alloy powders in approximately 10 seconds. The coating can be scaled to meet commercial market demands due to its high sintering density, mechanical strength, and self-healing properties. UMD's technology is targeted to be capable of generating new steel pipe to replace older infrastructure at a lower cost for gas service and with improved mechanical strength and corrosion resistance on a 50-year lifetime.

The final ARPA-E award in FY20 is from the High Intensity Thermal Exchange through Materials and Manufacturing Processes (HITEMMP) program. Dr. JC Zhou at UMD will lead the project entitled: Additively Manufactured High Efficiency and Low-Cost SCO_2 Heat Exchangers. The project will design, manufacture, and test high-performance, compact heat exchangers for supercritical CO_2 power cycles. Two innovative additive manufacturing processes will enable high performance. One facilitates up to 100 times higher deposition rate compared with regular laser powder additive manufacturing. The other enables crack-free additive manufacturing of an advanced nickel-based superalloy and has the potential to print features as fine as 20 micrometers. These developments could halve the fabrication cost and enable heat exchanger operations above 800°C (1472°F) and 80bar (1160 psi). These systems could be applied to high-efficiency fossil energy, concentrating solar power, and small modular nuclear energy.

With the addition of these awards, UMD has now received over $60M in ARPA-E funding.

DOE Vehicle Technology Office (VTO) Program

The DOE-VTO program focuses on battery and electric drive systems, co-optimized engine and fuel technologies, and alternative fuels and new energy efficient mobility system. Researchers at MEI^2 received two of these awards in the advanced battery category. These projects will accelerate the development of lithium-metal solid state batteries. UMD received more funding than any other university and is the only one to receive multiple awards in this category. It is also one of only two universities to receive two awards overall in all categories.

Dr. Eric Wachsman was awarded $1M for his work on "Low Impedance Cathode/Electrolyte Interfaces for High Energy Density Solid-State Batteries". The project will research, develop, and test lithium metal-based batteries that implement solid lithium-ion conductors equipped with nickel manganese cobalt cathodes integrated into the lithium-metal tri-layer architecture. Performance targets for the batteries include a 15-year calendar

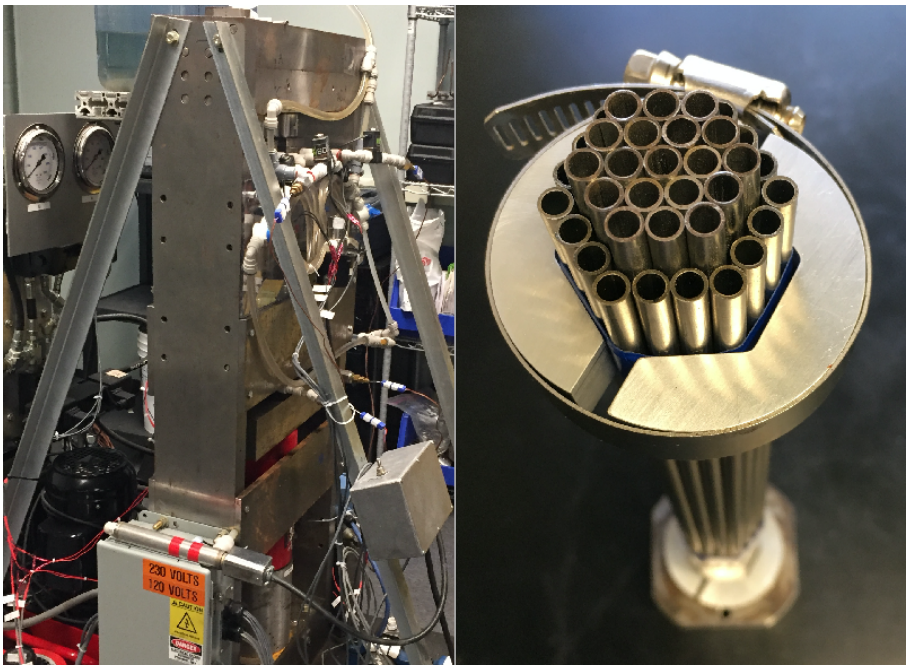
life, cycle life of 1,000 with less than 20% performance degradation, and a specific energy greater than 350 Wh/kg.

Dr. Chunsheng Wang also received $1M in funding for his research in "Lithium Dendrite-Free Solid Electrolytes for High Energy Lithium Batteries". His work will focus on optimizing the next generation, high-energy lithium ion batteries.

DOE Building Technology Office (BTO) program

BTO research is focused on reducing energy intensity with the most opportunity for energy savings, while balancing the need to maintain occupant comfort and productivity, and product performance. This includes both new and existing buildings, both residential and commercial, including their energy-consuming and labor-saving equipment. In the latest round of funding, BTO awarded $47.7 million to 23 projects, two of which come from UMD.

Under BTO's second topic **Heating, Ventilation and Air Conditioning**, UMD Professors Dr. Ichiro Takeuchi and Dr. Reinhard Radermacher's project will develop thermoelastic active regenerators to advance the state of the art of thermoelastic cooling technology, a potentially more sustainable and efficient alternative to vapor compression cooling technology. The goal of the proposed project is to demonstrate for the first time thermoelastic active regenerators with hitherto unattainable system ΔT using cascade active regeneration schemes implemented to increase temperature gradient across thermoelastic refrigerants. Building on their original ARPA-E project, this project is based on an invention at UMD. It integrates fatigue-free compression-based mechanism with heat exchanger/recovery subsystems for a 400 W prototype.



Under the topic of **Flexible Building Technologies**, UMD Professor Aute's project: *A Novel Framework for Performance Evaluation and Design Optimization of PCM Embedded Heat Exchangers for the Built Environment* will create a solid-state energy storage composite phase change material and heat exchanger. The team at the UMD Center for Environmental Energy Engineering (CEEE), in collaboration with Heat Transfer

Technologies LLC (HTT), will develop and validate a novel framework for performance evaluation and design optimization of phase change material (PCM) embedded heat exchangers (HX). These heat exchangers, when integrated with building HVAC&R equipment and envelope, provide thermal storage capabilities leading to reduction in peak energy demand. One of the deliverables of this research is an online PCM-HX design tool to assist researchers/engineers/designers in evaluating commonly used PCM-HX geometries. The framework will allow design of novel PCM-embedded heat exchangers and integrate their performance with other system/building energy simulation tools to evaluate building level impact on the demand, energy, and cost savings. The novel designs will be fabricated by HTT and then tested at CEEE labs.

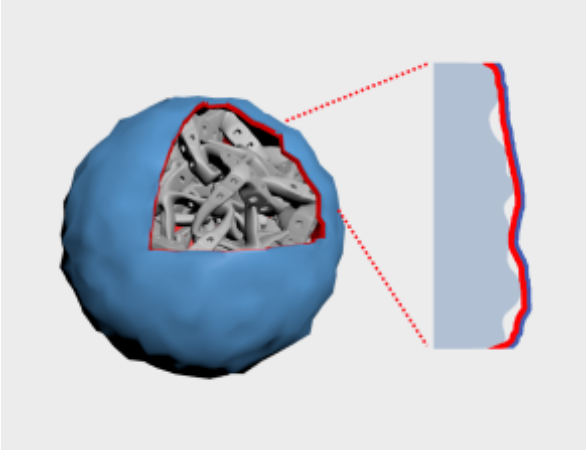
RESEARCH HIGHLIGHTS

Significant and impactful research progress was made in FY20. Multiple papers were published and garnered the cover in high profile journals such as *Science, Nature,* and *Proceedings of the National Academy*. A few results are highlighted below.

Battery Technology

Electrolyte design for LiF-rich solid–electrolyte interfaces to enable high-performance microsized alloy anodes for batteries. Chen, J., Fan, X., Li, Q. et al., *Nature Energy* 5, 386–397 (2020).

The current generation of lithium ion batteries (LIBs) uses graphite as an anode, which has a relatively low capacity, and could be replaced with a silicon anode with high capacity, allowing a lighter-weight and smaller battery. This is a highly promising direction for research -- yet elusive, as batteries with silicon anodes with a large particle size tend to have short cycle life, generally less than 50 cycles. When researchers tried using nanoparticles of silicon, aluminum, and bismuth, they found that these nano-sized alloy anodes still suffer short cycle life and high cost. Dr. Chunsheng Wang and his colleagues may have found a new direction for fixing this degradation problem: the electrolyte.



Nanoparticles of silicon in a battery as the anode are protected by a layer forming naturally from a newly-designed electrolyte to protect silicon nanoparticles used to store energy in a battery.

The team from the University of Maryland and the Army Research Laboratory have made an electrolyte that forms a protective layer on silicon; the layer is stable and resists the swelling that naturally occurs in silicon anode particles as they are cycled. The new

electrolyte – rationally designed using underlying chemical principles –allows the Si anode particles to swell inside the protected layer. The research proves that it is practical and possible to stably cycle (with >100 cycles demonstrated) silicon, aluminum, and bismuth particles as lithium ion battery anodes, offering a pathway to higher energy batteries.

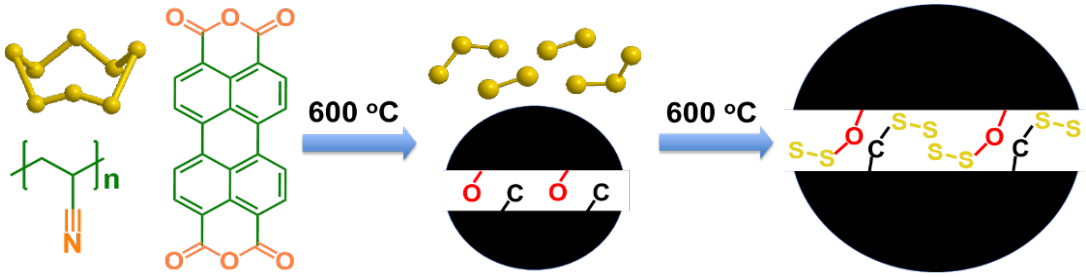
All-temperature batteries enabled by fluorinated electrolytes with non-polar solvents. Fan, X., Ji, X., Chen, L. et al., *Nature Energy* 4, 882–890 (2019).

Despite ongoing research efforts, one of the main problems with battery chemistries to operate over a wide temperature range (e.g., -95ºC to 70ºC) that they reduce energy and power density, and often sacrifice safety. Li-ion battteriess currently on the market can only operate between about -20 and 50ºC due to the strong bond between solvents and Li-ions, which is required for high ionic conductivity. Dr. Chunsheng Wang has developed a method of breaking the bond between solvents and Li-ions by dissolving the fluorinated carbonate electrolytes (e.g., LiFSI-FEC/FEMC) into non-polar solvents.

The result of this chemistry is a safe (i.e., non-flammable) electrolyte boasting superior electrochemical stability that can function under a wide variety of temperatures, all while maintaining a high energy output. This 'super electrolyte' has an operational temperature range from -95ºC/-139ºF to 70ºC/158ºF, creating the first highly reversible battery capable of operating anywhere on Earth — from Antarctica to Death Valley, California. The key is the all-fluorinated electrolyte, which was dissolved in a non-polar fluorine 'bath,' thereby deactivating the link between the fluorinated polar solvent and the ions.

This process increases the energy output of the battery, while bolstering safety, voltage (up to 5.6V) and temperature range. Moreover, it is cost effective and simple to manufacture as the electrolyte is still a liquid, making it an attractive alternative to other LIBs currently on the market.

A chemically stabilized sulfur cathode for lean electrolyte lithium sulfur batteries, Chao Luo, Enyuan Hu, Karen J. Gaskell, Xiulin Fan, Tao Gao, Chunyu Cui, Sanjit Ghose, Xiao-Qing Yang, Chunsheng Wang, *Proceedings of the National Academy of Sciences* Jun 2020, 117 (26) 14712-14720; DOI: 10.1073/pnas.2006301117
Lithium-sulfur batteries have attracted the attention of academic researchers and industry professionals alike due to their high energy density, low cost, abundance, nontoxicity and sustainability. However, Li-sulfur batteries tend to have poor cycle life and low energy density due to the low conductivity of sulfur and dissolution of lithium polysulfide intermediates in the electrolytes, which are generated when pure sulfur reacts with Li^+-ions and electrons. To circumvent these challenges, a multi-institutional research team led by Dr. Chunsheng Wang has developed a new chemistry for a sulfur cathode, which offers increased stability and higher energy for Li-sulfur batteries.



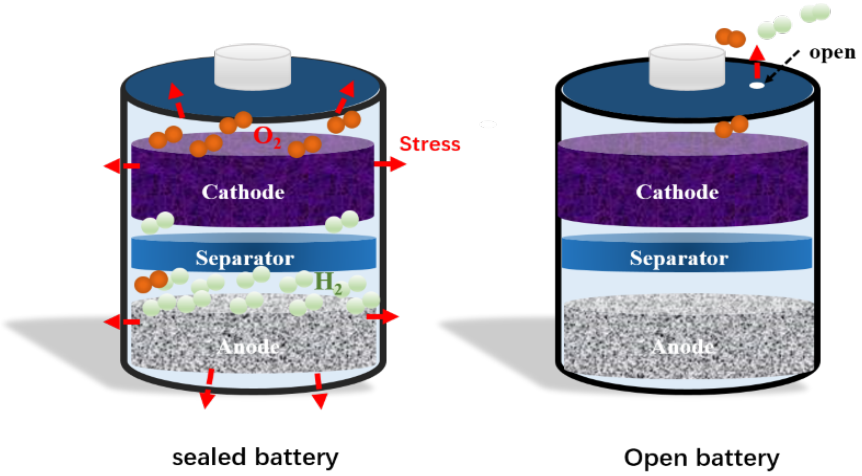
A schematic illustration of the formation of a chemically bonded, stabilized carbon-small sulfur composite (provided by C. Luo).

Numerous conductive materials such as graphene, carbon nanotubes, porous carbon and expanded graphite have been used to prevent the dissolution of polysulfides and increase the electrical conductivity of sulfur cathodes. The challenge here is encapsulating the nano-scale sulfur in a conductive carbon matrix with a high sulfur content to avoid the formation of polysulfides. Chemical bonding between sulfur and oxygen/carbon was used to stabilize the sulfur. This included a high temperature treatment to vaporize the 'pristine' sulfur and carbonize the oxygen-rich organic compound in a vacuum glass tube to form a dense oxygen-stabilized sulfur/carbon composite with a high sulfur content. Scanning electron microscopy (SEM), transmission electron microscopy (TEM) instruments, X-ray photoelectron spectroscopy (XPS) and pair distribution functions (PDF) were used to illustrate the reaction mechanism of the electrodes.

The formation of a solid electrolyte interphase (SEI) during the activation cycles completely seals the sulfur in a carbon matrix, offering superior electrochemical performance under lean electrolyte conditions. Because of their high energy content and low-cost materials, Li-sulfur batteries may have many practical applications in portable electronics, electric vehicles, and large-scale energy storage devices.

Enabling safe aqueous lithium ion open batteries by suppressing oxygen reduction reaction, Chen, Long and Cao, Longsheng and Ji, Xiao and Hou, Singyuk and Li, Qin and Chen, Ji and Yang, Chongyin and Eidson, Nico and Wang, Chunsheng, 2020, *Nature Communications*, Vol 11, No 1.
One critical challenge for non-aqueous batteries is safety issues stemming from thermal runaway, a situation in which the temperature of a battery increases rapidly, which may result in damage to the other cells and surroundings. Although aqueous (i.e., water-based) batteries have a non-flammable electrolyte, they are not immune to rapid heating, for example due to overcharging, external short-circuiting, or crushing (e.g., during shipping). In this work, UMD scientists have made improvements to the battery chemistry to enable open operation, with a particular focus on reducing the rate of reaction of oxygen from air at the anode of the batteries, which would lead to degradation.

The 'open' battery configuration is achieved by placing a hole at the top of the cell to allow heat and pressure to dissipate in the event of misuse or damage to the battery. To circumvent the challenges presented by oxygen entering the cell, large amounts of salt are used. By using a high concentration of the water-in-salt electrolyte (WiSE), the team was able to reduce the oxygen solubility and oxygen reduction reaction (ORR) kinetics. A high salt concentration can also prevent water evaporation, thus preventing dry out of the battery's electrolyte. These characteristics can help this open, water-based Li-ion battery operate stably, with over 1000 cycles demonstrated.



Materials Innovation

A general method to synthesize and sinter bulk ceramics in seconds, Wang., C., Ping, W., Bai, Q., Cui, H., Hensleigh, R., Wang, R., Brozena, A., Xu, Z., Dai, J., Pei, Y., Zheng, C., Pastel, G., Gao, J., Wang, X., Wang, H., Zhao, J.C., Yang, B., Zheng, X., Luo, J., Mo, Y., Dunn, B. and Hu, L., *Science*, 01 May 2020. **(cover)**

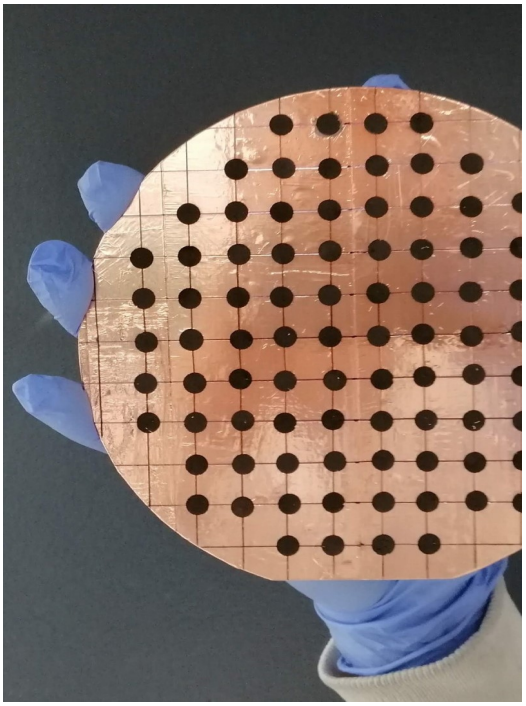
Ceramics are widely used in batteries, electronics, and extreme environments—but conventional ceramic sintering (the firing process used in the manufacture of ceramic objects) often requires hours of processing time. To overcome this challenge, a Maryland research team has invented an ultrafast high-temperature sintering method that both meets the needs of modern ceramics and fosters the discovery of new material innovations. The research, from a team led by Dr. Liangbing Hu, was published on the cover of *Science* 1 May 2020.

Conventional sintering techniques require a long processing time—it takes hours for a furnace to heat up, then several hours more to 'bake' the ceramic material—which is particularly problematic in the development of electrolytes for solid-state batteries because Li can vaporize at high temperatures and the resulting structure thereby have low performance. Alternative sintering technologies (such as microwave-assisted sintering, spark plasma sintering, and flash sintering) have a variety of limitations, including being material-specific and/or expensive.

The Maryland team's new method of ultrafast high-temperature sintering offers high heating and cooling rates, an even temperature distribution, and sintering temperatures of up to 3,000ºC. By using radiation and conduction from a carbon bar, high heat fluxes and temperatures can be achieved, resulting in less than 10 seconds of total processing time—more than 1,000 times faster than the traditional furnace approach for sintering.

With this invention, a pressed green pellet of ceramic precursor powders were "sandwiched" between two strips of carbon that quickly heated the pellet through radiation and conduction, creating a consistent high-temperature environment that forced the ceramic powder to solidify quickly. The temperature is high enough to sinter basically any ceramic material. This patented process can be extended to other membranes beyond ceramics. The rapid sintering technology is being commercialized through HighT-Tech LLC, a UMD spinoff company with a focus on a range of high temperature technologies.

High-throughput, combinatorial synthesis of multimetallic nanoclusters, Y.Yao, Z. Huang, T. Li, H. Wang, Y. Liu, H. S. Stein, Y. Mao, J. Gao, M. Jiao, Q. Dong, J. Dai, P. Xie, H. Xie, S. D. Lacey, I. Takeuchi, J. M. Gregoire, R. Jiang, C. Wang, A. D. Taylor, R. Shahbazian-Yassar, L. Hu, *Proceedings of the National Academy of Sciences* Mar 2020, 117 (12) 6316-6322; DOI: 10.1073/ pnas.1903721117



The nanoparticles located on this wafer are ready for testing for clean energy applications.

A research team led by Dr. Liangbing Hu has developed a process that makes multi-material nanoparticles, which may be used in catalyzing reactions for fuel cells and clean energy reactions. The process is high-throughput and combinatorial, allowing exploration of compositions with a range of elements including platinum, rhodium, palladium, rubidium, iridium, iron, cobalt and nickel, all near neighbors on the periodic table. The process is also rapid, allowing the production of nanoparticles within seconds. While the platinum-group metals are especially good catalysts for important reactions in fuel cells and other clean-energy applications, they are also expensive and rare, motivating the need to find mixtures of the platinum-group metals with other elements that are much more abundant and lower cost (e.g., nickel), but do not significantly reduce catalytic activity.

Fatigue-resistant high-performance elastocaloric materials made by additive manufacturing, H. Hou, E. Simsek, T. Ma, N. S. Johnson, S. Qian, C. Cisse, D. Stasak, N. Al-Hasan, L. Zhou, Y. Hwang, R. Radermacher, V. I. Levitas, M. J. Kramer, M. Asle Zaeem, A. P. Steber, R. Ott, J. Cui, I. Takeuchi, *Science* 29 November 2019: 1116-1121.
UMD scientists have developed a novel elastocaloric cooling material, comprised of a nickel (Ni)-titanium (Ti) alloy and sculpted using additive manufacturing technology, that is highly efficient, eco-friendly and easily scaled-up for commercial use. Cooling technology, used in refrigeration and HVAC systems around the globe, is a multi-billion dollar business. Vapor compression cooling, which has dominated the market for over 150 years, has an efficiency that has plateaued, and also uses chemical refrigerants with high global-warming potential (GWP). Solid-state elastocaloric cooling, where stress is applied to materials to release and absorb (latent) heat, has been under development for the last decade and is a front-runner in among alternative cooling technologies. Shape-memory alloys (SMAs) have been found to display a significant elastocaloric cooling effect; however, the presence of hysteresis – work lost in each cycle that causes material fatigue and eventual failure – remains a challenge.

Dr. Ichiro Takeuchi and his team have developed an improved elastocaloric cooling material using a blend of nickel and titanium metals, forged using a 3D printer, that is only potentially more efficient than current technology, but is completely 'green' in that it does release any gases with a GWP. Moreover, it can be quickly scaled up for use in larger devices. The need for additive technology, otherwise known as 3D printing, in this field is particularly acute because these materials also act as heat exchangers, delivering cooling to a medium such as water. The key to this innovation is the ability of the material to avoid fatigue, a key issue as people expect their refrigerators to last for a decade or longer. The team intensively tested their material over a four-month period, and it did not undergo performance degradation, even after one million cycles.

OUTREACH AND EDUCATION

MEI^2 is actively engaged across campus, the state and nation in educational and outreach efforts. MEI^2 also issues a quarterly newsletter to over 600 faculty, as well as government and industry leaders/researchers. Unfortunately, our regular outreach events such as Maryland Day 2020 and Engineering Sustainability Day 2020 were cancelled this year due to COVID-19 and the university shutdown. Therefore, we are developing virtual outreach programs and engagement given the apparent new normal that may be with us for a while.

Web of Science Highly Cited Researchers

Two MEI^2 research scientists, Dr. Liangbing Hu and Dr. Chunsheng Wang, were identified by the Web of Science Group in their list of the world's most influential researchers in 2019. Each year the Web of Science Group recognizes the select few who have been most frequently cited by their peers over the last decade. In 2019, 6,216 or 0.1% of the world's researchers across 21 fields earned this distinction. Papers surveyed include those published and cited during 2008-2018, and which at the end of 2018 ranked in the top 1% by citation per field. Hu and Wang were both acknowledged for their work in the area of Materials Science. According to the Web of Science Group, these researchers "have contributed disproportionately to extending the frontiers of knowledge and gaining for

society innovations that make the world healthier, richer, more sustainable, and more secure.

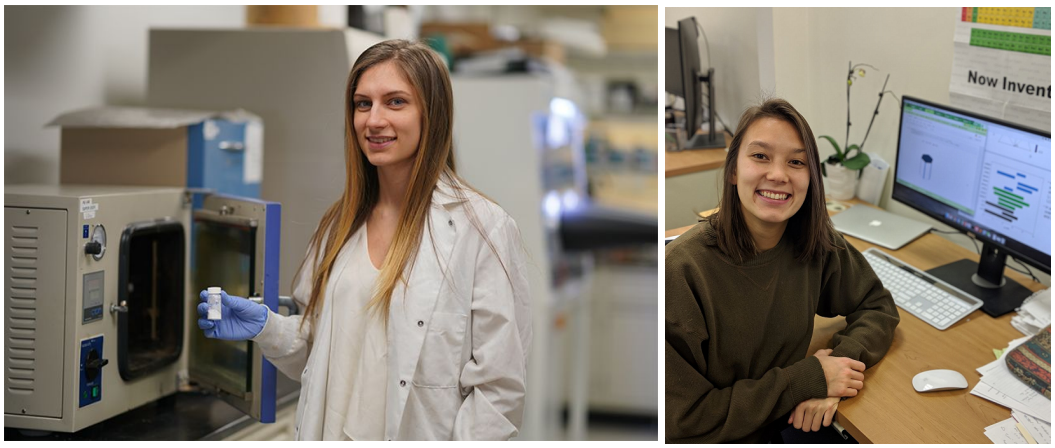
For this period, Hu has 329 publications and was cited 33,174 times. His most highly cited papers include: "Stable cycling of double-walled silicon nanotube battery anodes through solid-electrolyte interphase control", published in *Nature Nanotechnology* in 2012 (1491 citations) and "Emerging Transparent Electrodes Based on Thin Films of Carbon Nanotubes, Graphene, and Metallic Nanostructures", published in *Advanced Materials* on February 15, 2011 (1376 citations).

Wang has 231 publications and was cited 18,210 times during this past decade. His most cited papers were: "Nano- and bulk-silicon-based insertion anodes for lithium-ion secondary cells, published in *Journal of Power Sources* (1698 citations) and "Sulfur-Impregnated Disordered Carbon Nanotubes Cathode for Lithium–Sulfur Batteries", published in *Nano Letters* on October 12, 2011.

MEI^2 Graduate Students in the Spotlight

Several outstanding current and former graduate students were honored and recognized this year not only by UMD, but nationally as well. Emily Hitz, UMD Department of Materials Science and Engineering (MSE), has been named as one of five emerging stars in the field of materials science by the journal, *Nature*. Hitz, whose background is in the development of solid-state batteries, is currently investigating applications for this technology on the moon as part of her three-year NASA fellowship.

Adelaide Nolan, UMD Department of Materials Science and Engineering, is the recent recipient of the 2020-2021 Harry K. Wells Energy Fellowship as well as the recipient of the 2019 Engie North America Chuck Edwards Memorial Fellowship. She also received an Honorable Mention for the National Science Foundation (NSF) Graduate Research Fellowship, in addition to second runner up in the Best Student Paper Competition at the Clearwater Clean Energy Conference in 2019.



Emily Hitz (left) and Adelaide Nolan (right)

Ashley Ruth, 2015 PhD, UMD Department of Materials Science and Engineering, is the recipient of the 2019 Presidential Early Career Award for Scientists and Engineers (PECASE), the highest honor offered by the U.S. government for outstanding scientists and engineers who show exceptional promise early in their careers. Her PhD research was on SOFCs with Dr. Wachsman and her current research is on rechargeable batteries in the Tactical Power Branch at Army DEVCON.

MEI^2 offers the Harry K. Wells Fellowship annually. Mr. Harry K. Wells established an endowment to support engineering graduate student research in energy at UMD. With the fellowship, graduate student(s) are encouraged pursue new research in the field of sustainable energy generation and/or storage**.** The 2020-21 recipients are Adelaide Nolan (Materials Science) and Eric Carmona (Chemical Engineering).

Nolan proposes to develop a theoretical understanding of LLZO cathode interfaces for more efficient and safer energy storage. She will assess and understand the LLZO-cathode interface by conducting (1) data-driven thermodynamic analyses of coatings for the LLZO–cathode interface, and (2) first-principles analyses of Li transport within coating layers. These projects will contribute to understanding of the materials needed to stabilize LLZO and the cathode and set forth rational design guidelines for solid-solid interfaces.

Carmona will focus on the development of a quantitative 2D and/or 3D electro-chemo-mechanical model of lithium dendrite initiation and propagation. The model will couple electrochemistry with relevant mechanical processes (e.g., the influence of stress on current distribution, fracture mechanics) and be validated experimentally. The validated model will be used to assess what lithium properties, electrolyte properties, and operating conditions dictate lithium plating and stripping stability to provide foundational scientific knowledge to guide future applied efforts for lithium metal battery (LMB) design.

Since 2008, Ms. Barbara Hulka has provided the Hulka Energy Research Fellowship to support graduate student research in selected alternative energy fields at MEI^2. Students should pursue new research in one of the following research areas: Advanced solar energy conversion; Fuels and power from sustainable biological processes; Renewable wind energy; or Ocean, thermal or wave energy or geothermal energy conversion. Lu Liu (Chemical and Biomolecular Engineering) is this year's Hulka fellowship recipient. Liu will focus her research on sustainable bioethanol production enabled by renewable polymer-derived carbon membranes. She will develop densification-induced ultra-thin Carbon molecular sieve (CMS) hollow fiber membranes using low-cost renewable cellulose acetate-based precursors, which are promising membrane materials for gas separations. She proposes to address the following challenges to make CMS membranes suitable for algae-based bioethanol production. Membrane cost must be reduced for large-scale production; and membrane CO2 permeance must be significantly improved to provide economical CO_2 productivity using NPFG feed with low-CO_2 concentration.

SUMMARY

MEI^2 continues to catalyze clean energy innovation in Maryland and to contribute to the State's economic growth through new clean technology companies and job creation. Recommendations were made to Maryland Governor Hogan and the State Legislature regarding new economic opportunities to leverage the state's strong commitment to clean energy and greenhouse gas reduction. These recommendations included diversification of strategic economic development priorities by specifically supporting clean energy innovation in conjunction with the biomedical and cyber initiatives already in place.

MEI^2 and MCEC jointly established an innovation accelerator to provide support services for small companies in the form of marketing, accounting, and human resource assistance. The accelerator combines the expertise of Maryland inventors, researchers, founders, and entrepreneurs with strategic partners, local business executives, and service providers to further advance their technology and create new, investible clean energy businesses. The first cohort of start-ups engaged with industry leaders over the winter/spring 2020 with tremendous success. Through engagement with MEIA, companies such as Baltimore based ACTIVEcharge received a $25K strategic partnership award from Exelon for wind energy innovation and UMD start-up Alchemity received a $1K award from the Maryland Department of Commerce and was named the "Most Investible Startup".

Throughout the past two fiscal years, MEI^2 has developed many local, national and international partnerships and contracts in support of the Institute's Research and Innovation foci. In FY2020, NIST joined the CREB Consortium, and MEI^2 was selected to co-lead an $18.4M U.S.-Israel joint energy storage center focusing on the advancing the science and development of solid-state batteries, cell components and material informatics software.

MEI^2 continues to be successful in mentoring ARPA-E award winners and Energy Seed Grant recipients in technology commercialization. UMD continues a strong showing among all U.S. universities with active ARPA-E awards, garnering 3 more awards this fiscal year for a total of an additional $9M in funding. Two additional Vehicle Technology awards as well as two Building Technology Awards, receiving more awards than any other U.S. university. As such MEI^2 is poised to lead the energy innovation ecosystem for the State of Maryland and help establish a competitive advantage in the energy sector for the State's companies and citizens.

Finally, MEI^2 continues to excel in capturing innovations from State universities and focus them towards the growth of in-state clean energy development and manufacturing firms and keeping them within the State of Maryland. Additional early-stage innovation funding would expand the number of clean energy firms and further develop a thriving clean energy innovation ecosystem. This additional funding could capitalize on the success of current start-ups such as Ion Storage Systems and NanoDirect.

APPENDIX 1. Letter from MEI^2 Advisory Board

MARYLAND ENERGY INNOVATION INSTITUTE

MEI^2 Advisory Board
Engineering Lab Building
College Park, MD 20742
Tel: 301-405-9378; Fax: 301-405-8514
www.energy.umd.edu

August 30, 2019

Dr. Eric Wachsman
Director, Maryland Energy Innovation Institute
University of Maryland
1202 Engineering Lab Building
College Park, MD 20742

Dear Dr. Wachsman,

Following the July 30, 2019 meeting of the Maryland Energy Innovation Institute (MEI^2) Advisory Board, this letter was drafted on behalf of MEI^2's Advisory Board members and contains recommendations for the success and growth of MEI^2. After a full day of presentations articulating the resources and success of MEI^2, as well as the progress of near term goals including the second round of energy seed grant awards, the Advisory Board sees MEI^2 as an ongoing catalyst for significant advancement in research and innovation of advanced clean energy and related technologies leading to greater economic growth in the state of Maryland.

As this is the first time the Advisory Board has been formally introduced to Dr. Paul Albertus as the first associate director of MEI^2, it formally welcomes Dr. Albertus and wish him much success. Given Dr. Albertus' distinguished and diverse background in clean energy the Advisory Board looks forward to his contributions as part of the MEI^2 leadership team.

Overall, the Advisory Board remains very impressed by MEI^2's progress in research as well with its effective prioritization of its resources for the key programs in the Institute's strategic planning. In the past year MEI^2 has funded Entrepreneurship Seed Grant activity and has also worked with the University of Maryland and MCEC to establish the Energy Innovation Incubator, which is now active. The Advisory Board is also extremely pleased with the collaborative work of MEI^2 and the Maryland Clean Energy Center (MCEC) in taking the first steps to establish the Maryland Energy Innovation Accelerator (MEIA) The Accelerator is planned to deliver strategic value by providing entrepreneurial support services to assist startup companies in achieving commercial success. Additionally, the Advisory Board commends their broader engagement regarding opportunities and resources across the spectrum of innovation (incubation, acceleration, transition) for emerging technologies.

Further, MEI^2 is to be commended for its active participation and leadership in several energy partnerships both internationally (the U.S. Israel Energy Center Funding Opportunity for Cooperation in Energy and Water Technologies) and domestically including the Center for Research in Extreme Batteries as well as several ongoing and potential corporate research partnerships in clean energy. These activities demonstrate the potential impact for two of the Institute's planned strategic programs, the MEI^2 Industry Research Program and the MEI^2 Matching Fund Program.

MEI^2 continues to impress with its number of awards funded by the Department of Energy's Energy Efficiency & Renewable Energy (EERE) in the Buildings Energy Efficiency Frontiers & Innovation Technologies (BENEFIT) program and in the Battery 500 awards. The Advisory Board is particularly enamored with the continued range of high-quality research in batteries and materials innovation. In addition, MEI^2 continues to support the development of game-changing technology products aimed at advancing the Maryland energy innovation ecosystem and driving economic development. In particular, Ion Storage Systems, a successful start-up which recently secured venture capital funding and is the first occupant of MEI^2's new incubator space, was recognized with a ribbon-cutting ceremony and a citation presentation from the State of Maryland's Secretary of Commerce.

The Advisory Board is pleased with the selection and progress of the three energy Seed Grants for 2019 out of seven proposals received. A major focus of these Seed Grants is supporting the progression of research to marketable technologies. The Advisory Board notes that these grants have been used to expand research from lab scale to field scale in an applied system and scale-up prototype development for market testing of other technologies.

The Advisory Board also reviewed MEI^2's proposed budget plan for the coming fiscal year 2020 and agreed that it is moving on a path in keeping with the mandated mission and goals. The Advisory Board reiterates as it has in prior years that it is possible fewer Seed Grant awards could be funded in the coming years to enable larger impact funding levels, or follow-on awards could be made to current recipients depending on the most efficient use of available funds. An option to be further explored is the use of some Seed Grant funds to propose research under the aforementioned U.S. Israel Energy Center Funding Opportunity in which 50/50 matching funds are required. This will require further consideration based on the benefits versus the impacts to the Seed Grant program whose current annual funding is limited. It is noted, however, fewer proposals were submitted for this round of the Seed Grant solicitation than in the previous year. In keeping with its current practice, the MEI^2 Investment Committee will review the terms of the Seed Grant opportunity before the next solicitation to ensure that the grants include a clear market assessment and strategy and a viable revenue plan for progression towards a marketable product. The Advisory Board also continues to encourage developing

a state-matching fund for faculty members pursuing federal and other energy grants.

The Advisory Board continues to be pleased with the outreach and engagement by MEI^2 especially at the 2019 ARPA-E Summit in which a premier MEI^2 startup, Ion Storage Systems, was showcased in an ARPA-E video. The Advisory Board encourages MEI^2's continued engagement in outreach events such as Engineering Sustainability Day and Maryland Day.

The Advisory Board received a first draft of the 2019 report to the General Assembly and Governor on availability and efficiency of funds for the development and deployment of clean energy technologies in Maryland as mandated in the MEI^2 enabling legislation. The Advisory Board thanks and commends Professor Ellen Williams for her leadership in preparing this comprehensive draft report and presenting the highlights for discussion.

The Advisory Board members will review and provide feedback expeditiously on the draft. The Advisory Board recognizes the potential of clean energy and related technology innovations to make a major impact on Maryland's economy. Therefore, the report should cite the importance of enhancing the priority of clean energy and technology innovation in the State's strategic economic development portfolio. The Advisory Board also recognizes the need for significant resources in the next fiscal year. As such, MEI^2 should continue to endeavor to obtain additional resources to maximize its scope and impact. Additionally, MEI^2 should consider further leveraging partner resources, including beyond the UMD campus, to expand space and capabilities for further innovation, such as scale up, concept validation and prototype demonstrations.

With respect to the status of Advisory Board recommendations from the prior meeting, MEI^2 has made excellent progress in their implementation. It has completed three of the four Board recommendations while one remains an ongoing process. The status of these recommendations is as follows:

- Solicit a second round of an open state-wide call for Transformative Energy Innovation Seed Grants with an increased focus on market assessment and future funding plans – *implemented*
- Stand up the Incubator at UMD and assist start-ups with common support services and find ways to reduce initial start-up costs- *implemented*
- If approved by the MCEC Board, advise on effectively investing capital in Maryland start-up companies – *continuing ongoing discussions*
- Examine key performance indicators in the state of Maryland on the impact of MEI^2 going forward including gathering information on clean energy jobs and number of clean energy companies established as part of the 2019 report requirement. – *To be included in 2019 report to the General Assembly and Governor.*

With the aim of continuous improvement for MEI^2 to achieve its full transformative, scholarly, and financial potential, the Advisory Board makes the following recommendations to MEI^2:

- Continue its engagement on the topic of advising MCEC on effectively investing capital in Maryland start-ups.
- To support the MEI^2 report recommendations for increased funding, prepare operational models and budget options for the Institute's strategically planned programs.
- Work with MCEC and MTECH to complete the initial planning phase for the MEIA and develop a proposal for a fully operational service at different possible funding levels.
- At a level consistent with the possible numbers of SEED grant projects, examine a process for improving the socialization and notifications of SEED Grant opportunities to encourage more proposal submissions from universities statewide.
- Conduct an impact/benefits analysis to inform a decision regarding the potential use of Seed Grant funds (up to $150,000/yr) for participation in U.S.- Israel Energy Center Funding Opportunity which leverages matching funding.

The Advisory Board remains fully committed to participating in the development and alignment of MEI^2 priorities with the UMD College Park, the University System of Maryland, and the State of Maryland. The tactical gains already being realized since the relatively recent inception of MEI^2 bode well for significant strategic impact in making the state of MD a national leader in advanced clean energy technology.

Sincerely,

On Behalf of the Advisory Board

Victor Der
Chair, Maryland Energy Innovation Institute
Assistant Secretary of Fossil Energy, US DOE (Retired)

Ellen Williams
Vice-Chair, Maryland Energy Innovation Institute
Distinguished University Professor UMD
Director, Advanced Research Projects Agency-Energy (ARPA-E)

Scott Dupcak
Managing Director, Constellation Technology Ventures

Steven Freilich
Science Director, Dupont (retired)

Abigail Hopper
CEO, Solar Energy Industry Association

Geoff Oxnam
Founder & CEO, American Microgrid Solutions, LLC Chair of the Board, Maryland Clean Energy Center

Philip Perconti
Director, Army Research Laboratory

Mary Beth Tung
Director, Maryland Energy Administration

APPENDIX 2. MEI^2 FY20 Budget

	Budget	Actual	Difference
Salaries	$190,000	$161,830	$28,170
Seed Grants	$400,000	$387,000	$13,000 *Held for potential MIPS grant support
Events/Outreach	$13,000	$5,567	$7,433 ** events cancelled due to COVID
Reporting	$16,650	$16,650	$0
Equipment/Supplies	$5,000	$4,225	$775
Totals	$624,650	$575,272	$49,378 *($36,378)