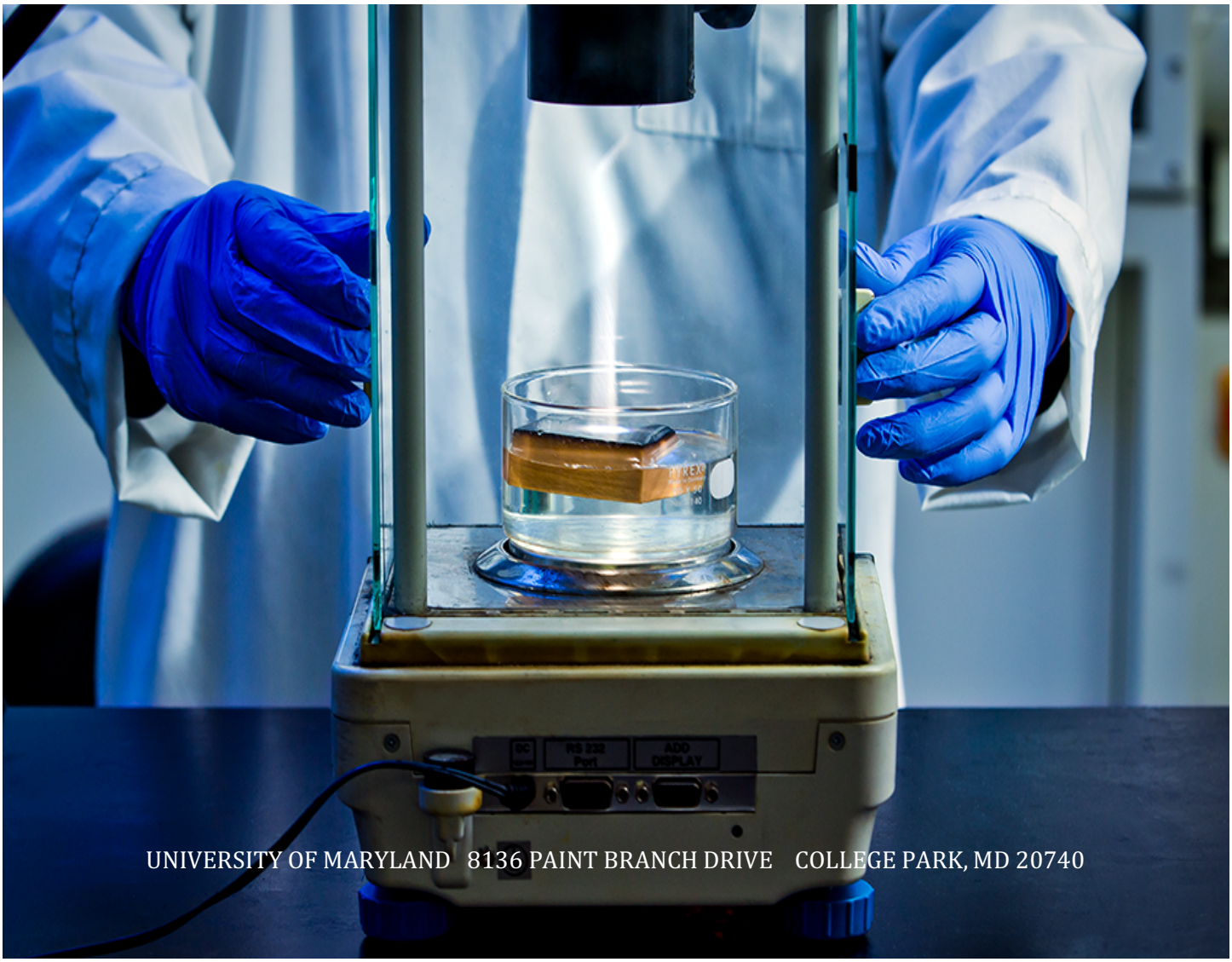
MARYLAND ENERGY INNOVATION INSTITUTE

Annual Report FY 2019



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 a reality.

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MARYLAND ENERGY INNOVATION INSTITUTE

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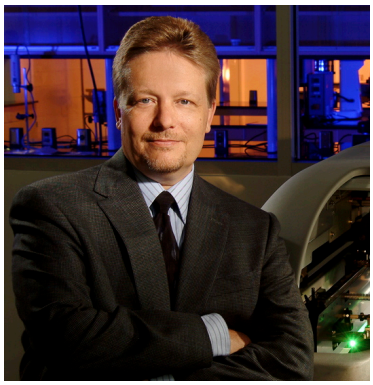
Message from the Director

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 of the University of Maryland 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. Both battery technologies would be beneficial to the defense and aerospace industry, consumer electronics, commercial grid storage and the biomedical industry. 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 and environmental research 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 2019 the Legislature passed the Clean Energy Jobs Act creating a goal of 50% of electric power generation coming from renewable energy sources such as wind and solar by 2030. Only nine states and the District of Columbia have such lofty goals. Moreover, Governor Hogan laid out his strategy to put Maryland on a path to 100% clean electricity by 2040. The Clean and Renewable Energy Standard (CARES) Act supports clean energy solutions and green energy jobs. The CARES Act calls for investment in increasing the strategic use of zero- and low-carbon clean and renewable energy sources, extending to additional sources of power such as nuclear, hydropower, emerging technology for carbon capture and storage, and utilizing the role of energy-efficient combined heat and power.

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, resulting in the growth of clean tech companies in the state of Maryland and thereby contributing towards economic growth within the State. As such, MEI^2 is the innovation catalyst necessary to create the technology push needed for Maryland to generate the jobs created in the state by its market pull policies.

MEI^2 early stage innovation technology investments have paid off in terms of a tremendous increase in federally funded energy 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 participated in 20 projects, leading 17 of those projects. To date, ARPA-E has awarded 20 UMD participating teams over $55M leading to the formation of 7 Maryland based spinoff companies thus far. At the 2018 ARPA-E technology showcase, three UMD ARPA-E awards were highlighted and demonstrated their products on the technology stage.

UMD's and MEI^2 stature in Battery science and technology continues to grow in both DOE Basic Energy Science (BES) and DOE Energy Efficiency & Renewable Energy (EERE). Under BES, UMD is in its final year of leading the $29M Energy Frontier Research Center (EFRC) "Nanostructures for Electrical Energy Storage (NEES)". During 2019 an additional $3M in EERE (Battery 500) awards were received for innovative battery technologies that could have large payoffs and grow into significant energy storage solutions. MEI^2 also received numerous other energy research awards in 2019 including ~$3M in EERE awards for advanced building technologies and systems that will serve as a foundation for future technological developments and reductions in building energy consumption and a $3.6M ARPA-E award to advance "Super Wood" as a low carbon replacement for steel in automotive construction.

Finally, Dr. Paul Albertus joined UMD in December 2018 as the MEI^2 Associate Director. He will, among other things, focus on engaging the faculty and student population at UMD with MEI^2 and expand the bandwidth to pursue large center proposals. With regard to the

latter, during FY2019 MEI^2 applied for a $25M NSF Science and Technology Center entitled, "Center for Ionic Transport in Solids" and $20M for the BIRD Foundation's Energy Center funding opportunity for U.S. – Israel cooperation in energy and water technologies.

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.

FY2019 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)*
Joseph Dominquez
Senior Vice-President, Exelon Corporation
Abigail Hopper
President & CEO, Solar Energy Industries Association
Geoff Oxnam
Chair of the board for MCEC
CEO, American Microgrid Solutions
Philip Perconti
Director, U.S. Army Research Laboratory
Jigar Shah
Founder, Generate Capital and SunEdison
Mary Beth Tung
Director, Maryland Energy Administration

In the spring of 2019, Jigar Shah, Founder of Generate Capital, stepped down from the MEI^2 Advisory Board and was replaced by Dr. Steven Freilich. Dr. Freilich recently retired as the Director of Materials Science at DuPont Central Research and Development and was previously Chief Technology Officer for Dupont Electronics and Communications. In those roles he was responsible for developing and implementing technology growth strategies in such rapidly moving areas as solar energy, energy storage, materials for displays, biomaterials, and electronic materials. Prior to his Director role, Dr. Freilich led research organizations in the fields of thin film physics, materials for information storage, organic photochemistry, scientific computing, and particle science. He also serves as Vice Chair of the Advisory Committee for the Clean Energy Manufacturing Analysis Center at the National Renewable Energy Laboratory.

Additional changes to the Advisory Board include Scott Dupcak replacing Joseph Dominguez, who's corporate responsibility transitioned to Director of ComEd, an Exelon company. Dupcak is Managing Director of Constellation Technology Ventures (CTV), the venture capital investing arm of Exelon Corp. In this role, he oversees the CTV investing strategy, the management of the CTV portfolio and the commercialization of new energy technologies within the Exelon commercial platform.

The MEI^2 Advisory Board convened on August 27, 2018 for a full day of presentations articulating the resources and success of MEI^2, as well as the progress of near-term goals including results from the first round of energy seed grant funding, 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. Identifying relevant key performance indicators as metrics against the program goals remains an ongoing effort.

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

- Solicit a second round of a state-wide call for Transformative Energy Innovation Seed Grants with an increased focus on market assessment and future funding plans
- Stand up an Incubator at UMD and assist start-ups with common support services and find ways to reduce initial start-up costs
- If approved by MCEC Board, advise on effectively investing capital in Maryland start-up companies using MCEC financial resources
- 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.

The Board also discussed a range of approaches to producing the State legislatively mandated 2019 report to the General Assembly and Governor on the availability and efficiency of funds for the development and deployment of clean energy technologies in Maryland. The Board thanked Professor Ellen Williams for agreeing to take the lead in preparing this report and noted that her experience as former director of ARPA-E makes her uniquely qualified to undertake this endeavor. This report has the potential to make a major impact on Maryland's energy economy and will require significant resources in this next fiscal year. As such, MEI^2 was encouraged to maximize its scope and impact.

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 forecast 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.

This report is due to the Governor and State Legislature in December 2019.

To begin evaluating the needs for future economic growth in the clean energy technology space, MEI^2 held an Energy Grid Storage Workshop on March 20, 2019 seeking input from

external stakeholders including technology providers, regulators, representatives of utilities and state government agencies, researchers, and others. Discussions centered on energy innovation within the State, including appropriate amounts and forms of support for early stage developments in universities and young companies.

Energy storage is a revealing example of the potential for energy innovation due to 1) its diversity of applications including stationary and vehicle storage; defense, aerospace, and biomedical uses; and growing opportunities in the internet-of-things, 2) the economic importance to Maryland of leadership in the modernization of the electric power system, and 3) the rapid technical advances that are underway in improving performance and decreasing cost of energy storage.

2019 Workshop Attendees

Adam Murray, *SAFT*
Cathy Stephens, *MEI²*
Charles Hernick, *Citizens for Responsible Energy Solutions*
Chris Rice, *MEA*
Cynthia Lundgren, *Army Research Laboratory*
Ellen D. Williams, *University of Maryland*
Eric Wachsman, *MEI²*
James Herbermann, *SAFT*
Jennifer Hammaker, *TEDCO*
Joey Chen, *Maryland Public Service Commission*
Kathy Magruder, *MCEC*
Kavita Surana, *University of Maryland – School of Public Policy*
Mark Alberding, *Lockheed Martin*
Paul Albertus, *MEI²*
Paul Spies, *Maryland Department of Commerce*
Sachi Jayasuriya, *Det Norske Veritas Group*
Shetty Subing (Tom), *PEPCO*
Stephen Sunderhauf, *PEPCO*

Many significant points, goals, and recommendations emerged from the discussion:

1. Energy storage provides growing commercial opportunities. Maryland's combination of industrial investments, government laboratories, military installations and University expertise in this area positions the state to capture the benefits of in-state commercialization.
    a. The Army Research Laboratory, SAFT and Lockheed Martin have active programs in batteries for energy storage, and offer opportunities for collaborative engagement with University and small-business activities in developing, evaluating and demonstrating expanded opportunities.
    b. Coordination of such efforts, possibly led by the MEA, could be designed to bring down costs and support expansion of in-state supply chains, workforce and manufacturing capabilities.
    c. The impact of federal funding at Universities and small companies in this area can be expanded by using seed grants, mentoring and testing opportunities to drive down development risk and thus make follow-on venture investment more attractive.
    d. State support for early stage technology developers provides a mechanism to retain in-state talent and develop a company base that is more likely to remain in-state.
2. Stationary energy storage for the electric power grid represents serious policy as well as technology issues. The demands on the grid are changing rapidly due to concerns for resiliency under extreme weather events. (including the high-value, in-state industries such as data servers used for cybersecurity), Maryland's renewable portfolio standards (RPS) (recently expanded to 50% renewables by 2030), expected growth in

off-shore wind productions, grid congestion in the northeastern part of the state, and economic interest in reducing Maryland's dependence on out-of-state renewable energy credits (RECs) to meet RPS goals.

a. State utilities need clear regulatory guidelines before investing in expanded energy storage, including clarification of ownership models.
b. The Public Utilities Commission must do due-diligence in evaluating energy storage as a potential consumer benefit that could be supported under EmPower. Utilities are willing to help with such evaluations. Both MEA and the Department of Commerce (DOC) can support such assessments by providing support for demonstrations, test and early deployment.
c. Early technology demonstrations should be supported in collaboration with users that have stringent requirements for uninterrupted power, and thus less restrictive cost-points.
d. The DOC should evaluate the benefits of state-incentives for energy storage in the context of attracting to the state businesses that have a strong commitment to reduced emissions and/or use of renewable power.
e. Demonstrations of energy storage at the transmission level can be costly, but are needed for sound decision making. State support to encourage cooperative provision of test opportunities involving PJM, the utilities and technology developers is needed.

3. Numerous states have either committed to, or are evaluating a shift to carbon-free electricity in the time frame of 2040-2050, including Maryland's recent expansion of the RPS to 50% by 2030, and the CARES Act goal of achieving 100% carbon-free electricity by 2040. Reaching such aggressive goals, especially if renewables provided the majority of the carbon-free electricity, may require fundamentally different types of energy storage than are being deployed today. This means the development of new stationary storage technologies, especially those that can storage electricity for days, weeks, or longer represent a substantial research development and deployment opportunity that MEI^2 and Maryland should pursue.

ADVANCING THE MARYLAND ENERGY INNOVATION ECOSYSTEM

MEI^2 continues to drive Maryland energy innovations in partnership with Mtech, the MCEC and the Maryland DOC. MEI^2 has been extremely active in mentoring UMD ARPA-E award winners in technology commercialization from proposal stage to post award results, examples of which include Ion Storage Systems (ISS), Mobile Comfort, and InventWood below.

INVENTWOOD

Inventwood is developing wood technologies for sustainability including strong wood, transparent wood, thermal insulating wood, battery wood and water desalination wood. The firm is part of a $3.6M ARPA-E award for scaling up and commercialization. It has also received ~ $1.25M SBIR funding from USDA and the DOE Building Technology Office.

Super Strong Wood
- ~ 5 times lighter than steel
- Similar to carbon fiber but > 10X cheaper

Transparent Wood
- > 90% transparency
- Better insulation than glass

Transparent Nanopaper
- 50X stronger than paper
- Replace plastic and completely biodegradable
- 100% paper material

Wood+Water Batteries
- High energy density
- Completely biodegradable

Solar Desalination Wood
- High solar desalination efficiency
- No salt accumulation

Ion Storage Systems

ISS is focused on developing the most energy dense and safest batteries that can be deployed in any environment. The batteries are nonflammable, smaller and lighter than current lithium ion batteries with 10X the capacity of current batteries. They also have 2-3X higher energy density than existing batteries.

- To date has received ~$13M in funding from U.S. Department of Energy ARPA-E and EERE, NASA, and Lockheed Martin.
- One of 7 finalists from 129 applications across 27 countries to compete in the LG Chem Battery Challenge, finishing 3rd overall in the competition at LG HQ in Seoul, Korea.
- Recipient of $5K at the Maryland Clean Energy Center's summit and Innovation Showcase.
- Received $8M in financing from Alsop Louie Partners, a San Francisco based risk-oriented venture capital firm.
- Moving into MEI^2 Incubator and hiring ~20 employees in coming year.

MOBILE COMFORT

RoCo is the world's first personal air conditioner. Designed at the University of Maryland with a $2.6M DOE ARPA-E grant, Mobile Comfort was established to bring the technology to market. Industry Partners include Daikin Industries, Optimized Thermal Systems, Alliance Material Handling and Harbor Designs and Manufacturing.

- Cordless and portable
- 8-hour battery life; 4 hours to recharge
- No ventilation required
- Facial recognition to track the user
- $1.5M in private investment to develop a residential version

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 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. In the first round, 10 proposals were received from three different academic institutions in Maryland.

FY2019 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
Jigar Shah
Founder, Generate Capital and SunEdison
Neil Davis
Director, Entrepreneurial Development, TEDCO

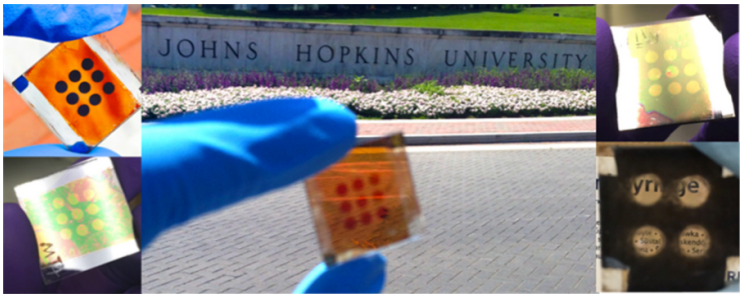
First Round Seed Grant Results and Future Development

In January 2018, MEI^2 awarded four $100K Seed Grants for Energy Innovation. Their final reports were received in the spring/summer of 2019 and their final written reports were delivered in the spring of 2019 and presentations were given at the 2019 annual board meeting in July.

- **Biogas Enhancement and Ammonia Extraction for Increased Revenue in Waste-to-Energy Systems**; Lead PI: Stephanie Lansing, Associate Professor, Department of Environmental Science & Technology, University of Maryland College Park, Partnering Company: Planet Found Energy Systems, LLC

The MEI^2 seed grant allowed Dr. Lansing and her corporate partner to build a full-scale anaerobic digestor in Pokomoke City, Maryland for testing. The digester extracts nutrients from solid waste and scrubs impurities from biogas. The process creates non-intermittent, renewable energy (electricity and natural gas), reduces methane and emissions and reduces pollution, pathogens, and odors from manure and food waste. The group modeled the flow and treatment conditions and were able to create a market plan based on analysis of the operating system. A lifecycle assessment (LCA) was also performed of the nutrients, energy, and carbon flows. Consumer agriculture and horticulture markets within a 150-mile radius were identified (Norfolk, VA, Baltimore/Washington, Wilmington, DE and Philadelphia, PA). Future plans call for the initial product to be market tested as part of Planet Found Energy System's Element Soil® product line. The product will be sold as horticultural fertilizer to establish local market price points. The group plans to continue technology refinement and improved process engineering while further developing a market strategy. Their goal is to have licensing and contracts in place by 2020 with an initial product revenue stream. Additionally, a DOE proposal for $1.15M entitled "High Solids Poultry Litter Digestion with Ammonia Harvesting" was submitted.

- **Large Area Quantum Dot Solar Cells for Building Integrated Photovoltaics**; Lead PI: Susanna Thon, Department of Electrical and Computer Engineering, Johns Hopkins University; Partnering Company: NanoDirect LLC



Dr. Thon in collaboration with NanoDirect LLC has built transparent conductors for quantum dot solar cells that can be used for building-integrated photovoltaics (BIPV). These allow for light-weight systems that can be incorporated into building facades, providing a solution to limited real estate for generating solar energy in high power consumption areas. Key advances due to the seed grant award include improved lab-scale-are colloidal quantum dot (CQD) solar cell device performance, demonstration of large-area CQD solar cell performance, construction and optimization of a scalable spray-cast deposition for large-area devices, and formulation of a silver nanowire electrode material necessary for high-performing, flexible devices. The group has identified over 100 potential customers for the materials, established a new laboratory and manufacturing site in Baltimore, liaised with corporate customers (LG, DuPont Microcircuit Electronics, SunChemical and VFP Ink) in preparation for shipping test materials, and produced a business plan specific to the silver nanowire and transparent conductor development. The

group will seek additional grant funding through NSF SBIR and DOE SBIR in 2019. By 2020, their goal is to fully launch in commercial space.

- **Prototype Study of One-Step Membrane Reactor for Stranded Natural Gas to Liquids**; Lead PI: Dongxia Liu, Assistant Professor, Department of Chemical & Biomolecular Engineering, University of Maryland College Park; Partnering Company: Protonic Membranes

With the sustained low price of natural gas in the United States, Dr. Liu, with the aid of the MEI^2 seed grant, has developed a bench-scale prototype system for a high performance, low cost, energy-efficient method of methane conversion into alternative fuels. Current methods cause global environmental problems, transporting the gases is not economical, and the gas-to-liquid (GTL) technologies are currently expensive. The new one step membrane reactor eliminates all three issues. The project holds multiple patent applications for devices and catalysts for methane conversion, and has filed a new disclosure on oxygen-containing (H_2O and air) sweep gases with the UMD OTC office. The group is collaborating with Shell and Praxair on Federal funding opportunities. The work was invited for an NSF highlight and is currently being exhibited at the Baltimore Museum of Industry.

- **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 Handling

At the conclusion of the Phase I seed grant, the project designed and built a new RoCo prototype for forklift application which is ready for performance testing. A novel IR based tracking approach was developed to lower the prototype cost and in-house software was developed to support the IR tracking system. Additionally, the initial RoCo prototype was upgraded with lower cost and mass-production-ready designs. Work began with Harbor Design to standardize the RoCo design and fabrication process. The group is working with local industry leaders in the electric truck and small utility vehicle markets. Forklift, golf cart, and tractor dealers in Maryland are participating with the team to design and test comfort systems. Mobile Comfort Inc. has also received $1.5M in private funding to develop a residential version of RoCo.

Second Round FY2019 Seed Grants

In March 2019, two Phase I seed grants were each awarded $100K and one Phase II award for $200K was awarded. The MEI^2 Investment Committee mandates that Phase II awards must also include progress made on the technical and business aspects of the previous proposal as well as a more complete business plan towards commercialization. The Investment Committee is also placing a stronger focus on business plans, technical and

financial milestones and confirmed support from partner companies on upcoming proposal calls. The following awards were given:

- **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 Handling

The Phase II Mobile Comfort and UMD team are continuing the development of RoCo with the goal of making a viable consumer product for sale. Focus will be on three new technical areas: a hot climate version of RoCo, indoor unconditioned workspace in industrial locations, and grid-independent RoCo operation. Updated prototypes at a reduced cost are being produced and sent out for beta testing in 2019. Transitioning the device from the laboratory to a manufacturable product is technically challenging. Current prototypes were hand built, but modularization of components and subassemblies allow for cost-effective manufacturing and future maintenance and servicing. Much of the Phase II budget will be spent on large scale manufacturing and market 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 project aims to experimentally investigate and commercialize a new infinitely variable transmission (IVT) for tidal current turbines. Tidal current energy is a clean and local source of renewable energy, but current tidal turbines are costly and inefficient. The project will test a new IVT based on a two scotch-yoke system and a noncircular gear pair which could potentially lower the cut-in speed and harvest more tidal current energy in all speed regions. The total tidal current energy resource along the US continental shelf edge is estimated to meet about 56% of the US existing electricity demand if harvested efficiently. The proposed IVT would directly convert irregular low-speed tidal current motion to regular high-speed rotation of a doubly-fed induction generator, which has a lower cost that a permanent magnet generator.

Assessment of Energy Production Potential from Tidal Streams in the United States, DOE, 2011

- **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

Seed grant funding for this project is to develop needed packaging for new solid-state batteries. Proper packaging is essential in obtaining strategic partners investment and transition the technology to a marketable product. Battery packaging will enable the delivery and testing of samples by potential customers. A custom rigid shell to encase one to four trilayer garnet cells wired in parallel, series or both is proposed. Protection from flexural, tensile, shear, and compressive forces will be incorporated. Vibration dampening layers are also needed. The seed grant will support "first generation" packaging for testing of samples, but as the cells are integrated into specific systems, packaging thresholds will become application specific – mechanical protection for launch into orbit is significantly different that mechanical protection required for stationary grid storage. Strategic testing partners such as ARL and Lockheed Martin, have already been identified.

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.

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 2018, the CREB Biannual Fall Meeting focused on a tentative ARL funded challenge program to develop a safe, nonflammable, contoured battery to wear on a soldier platform. Speakers included Soldier Warrior (SWAR), Maneuver Center of Excellence (MCOE-Protection) and industry (Cuberg, SAFT). The 2019 Biannual Spring meeting focused on electric flight batteries. Speakers included those from ARPA-E, Joint Center for Energy Storage Research (JCESR), SAFT, NASA JPL, and ARL. New battery chemistries as well as storage for transportation and flight were discussed.

Corporate Partnerships

MEI^2 is looking to further increase its economic impact through corporate partnerships. Exelon Corporate Strategy recently completed a visit to MEI^2 at which numerous presentations on research and commercialization activities on campus were made, and subsequently confirmed their interest in having UMD become one of their university research partners. The terms of a Master Research Agreement between Exelon and UMD are under negotiation. Exelon's other university partnership are with MIT (through the MIT Energy Initiative), Northwestern, and University of Illinois.

Maryland Energy Innovation Accelerator (MEIA)

MEIA was established in partnership with MEI^2 and MCEC to assist start-up companies achieve commercial success. MEIA will surround inventors with professionals from a wide variety of disciplines who are committed to creating a new, impactful company. MEIA will provide services for Startups including legal, intellectual property, accounting, finance, market research, branding, customer discovery, and more. They will also provide a project manager to keep efforts moving forward. These services are crucial to ensure a company

is formed correctly and is on solid footing for growth. MEIA supports solar, wind, batteries, energy efficiency, grid modernization, carbon capture utilization and storage (CCUS), and any other technology that reduces greenhouse gas emissions or provides negative emissions benefits in the electric, oil and gas, residential, commercial or industrial sectors.

MEI² – Daegu Gyeongbuk Institute of Science & Technology Partnership

In July 2018, MEI² and the Daegu Gyeongbuk Institute of Science & Technology (DGIST) announced a five-year partnership to accelerate research and development of energy technologies. The Institutes will cooperate and develop joint projects in fields of common interest including electrochemical energy conversion and storage and advanced materials design. The agreement allows for exchange of faculty and students for research; joint research activities and the exchange of scholars for meetings; and the exchange of scholarly publications and information. DGIST is an institute of science and technology founded by the Korean government to benefit society through development and advancement of science and engineering. The institute contributes to a national and global economy through translational research and development programs, technology commercialization and the growth of an innovation and entrepreneurship program. The Energy Science and Engineering department is working on the improvement of new renewable energies such as solar energy conversion, bio-fuels, fuel cells, secondary batteries for a more efficient use, geothermal energy, and on low-carbon gas energy production.

Eric Wachsman (MEI²) and Jong-Sung Yu (DGIST) sign MOU

U.S. – German Energy Storage Collaboration

The U.S. DOE and corresponding German energy agency (BMBF) are collaborating on pre-competitive energy storage technology through a consortia of universities and national laboratories in their respective countries. The MEI² Director, Dr. Wachsman, has been asked to be the U.S. Thrust Lead on Solid-Electrolyte/Solid-Cathode Interfaces and will be coordinating the university and national lab research activities with his German counterpart on this topic.

NSF Science and Technology Center Preliminary Proposal

In June, 2019, UMD submitted (as the lead organization) a preliminary proposal to the National Science Foundation (NSF) for a Science and Technology Center, which are funded at a level of $25M over 5 years and available for one five-year renewal. As described by the NSF, "The Science and Technology Centers (STC): Integrative Partnerships program supports exceptionally innovative, complex research and education projects that require large-scale, long-term awards. STCs focus on creating new scientific paradigms, establishing entirely new scientific disciplines and developing transformative technologies which have the potential for broad scientific or societal impact." The title of the UMD-led proposal is "Center for Ionic Transport in Solids," and includes researchers

from MIT, Northwestern, NIST, and Argonne National Laboratory. The proposal is focused on solid materials that conduct ions, where science and technology breakthroughs would have impacts in advanced energy storage and conversion, gas separation and sensing, fuel cells, the development of memristors for advanced neuromorphic computing, and other areas. Many of the areas that would be impacted by this center are related to energy technologies and energy innovations. The proposal also includes a strong focus on educational and workforce development activities at UMD and partner institutions. A notification of an invitation to submit a full proposal is expected in late October, 2019.

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

MEI^2 researchers were contacted in summer, 2019, by Bar Ilan University, and invited to be the U.S. lead on a full proposal to the U.S.-Israel Binational Industrial Research and Development (BIRD) Foundation Energy Center. The proposal was submitted in September, 2019. The BIRD Foundation funds joint research and development activities between US and Israeli organizations, with the Energy Center call the first time the BIRD Foundation is specifically seeking to engage with universities (historically the focus has been on companies). The Energy Center proposal is led by the UMD for the US, with Forge Nano and Saft as US partners. On the Israeli side are Bar Ilan University, (lead) Tel Aviv University, 3D Battery, and Materials Zone. The project team therefore includes leading academic groups as well as companies. The BIRD Foundation Energy Centers are funded at a level of $20M over five years, and the proposed UMD share is $5.5M. Building on its strength in batteries and energy storage, and the connections with CREB, the Energy Center proposal 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. Selections are expected by the end of 2019.

RESEARCH FUNDING AWARD HIGHLIGHTS

Significant financial support of research into new energy technologies was obtained in FY19. Examples of this include three UMD projects received funding from the DOE Building Technologies Office, two DOE Vehicle Technology Office Phase II Battery 500 awards, and another ARPA-E award were received.

DOE BENEFIT Program

The Building Technologies Office invested $19.5 million in 19 projects that will drive innovation in early-stage research and development for advanced building technologies and systems that will serve as a foundation for future technological developments and reductions in building energy consumption. These technologies will improve the efficiency of our nation's buildings and will help American consumers and businesses save energy and money on their utility bills. UMD was the **only** university to receive **three** of these awards.

FY2019 Major Awards

- DOE ARPA-E Award "Super Wood" - $3.6M
- Three DOE Building Technology Awards ~$3M
- Two DOE Battery 500 Awards - ~$3M

The BENEFIT awards were distributed among six research topic areas, which include technologies that can significantly improve building energy efficiency in heating, ventilation, and air conditioning (HVAC), water heating, and appliances, and building envelope applications; developing highly insulating building envelope materials and windows, novel approaches to building energy modeling and sensors and controls; testing next-generation building systems and equipment in real-world conditions; and significantly improving the energy efficiency of natural gas and other fuel-driven equipment. Two UMD projects received funding in the Advanced Separation Technologies for Building Energy Efficiency:

- "Highly-Efficient Micro-Emulsion-Based Absorption Chillers for HVAC Application." The research team will develop a waste-heat absorption cooling system that can be used in highly energy-efficient chillers, which are used to cool fluids or dehumidify air in commercial and industrial facilities. Dr. Bao Yang, UMD Professor and Director of Laboratory of Micro/Nanoscale Heat Transfer and Energy Conversion is the PI on the project.
- "Electrohydrodynamic Enabled Electrochemical Membrane Dehumidifier for Separate Sensible and Latent Cooling." The research team will develop a novel electrochemical dehumidification device for separate sensible and latent cooling that will increase the energy efficiency of air conditioners significantly. Dr. Yunho Hwang, Professor and Associate Director for the UMD Center for Environmental Energy Engineering, and Dr. Chunsheng Wang, UMD Professor in the Department of Chemical and Biomolecular Engineering and Robert Franklin and Frances Riggs Wright Distinguished Chair, are the co-PIs of this project. Their research will reduce the energy consumption of air conditioners by 22% and save 836 TBtu for the US in every year. Dr. Hwang hopes to expand the research for improving air conditioning system's energy efficiency by developing novel membrane technology.

In addition, UMD received another award in the High-Performance Windows Project:

- "Low-Cost Vacuum Insulated Glass (VIG) for Retrofit of Single Pane Windows." The research team will develop a new approach to producing vacuum insulated glass; the approach uses small vacuum cells that can be cut to size on site, avoiding custom manufacturing of windows, making it economically attractive.

Battery 500 Awards

In 2016, the US Department of Energy (DOE) Pacific Northwest National Laboratory (PNNL), announced its intention to develop lithium-metal batteries with a specific energy of 500 Wh/kg, compared to the 170-200 Wh/kg per kilogram in today's typical electric vehicle (EV) battery. The Battery500 consortium "Seedling" program involves new, potentially risky battery technologies that could pay off big and grow into significant energy storage solutions. UMD was awarded three of these Battery 500 seedling grants in 2016. Now, two of those projects were selected in 2019 to receive a phase II award. These phase II awards come with an additional $890K in funding. UMD is the **only** university to receive multiple (3) initial Battery 500 awards and the **only** institute to advance two awards to the phase II level.

The first phase II award is, "3D Printed, Low Tortuosity Garnet Framework for Beyond 500 Wh/kg Batteries" from Dr. Eric Wachsman, Director of the Maryland Energy Innovation Institute (MEI^2) and William L. Crentz Centennial Chair in Energy Research, and Dr. Liangbing Hu, UMD Associate Professor in Materials Science and Engineering (MSE). The 3D printing method enables ordered low tortuosity and higher porosity (~85%) garnet structures, such as columns, stacked arrays, or more complex patterns. The resulting enhanced charge transport and ease of electrode infiltration will allow a dramatic increase in electrode thickness with an optimized structure and obtain even higher energy density far exceeding 500 Wh/kg.

The second UMD phase II award is "Advanced Electrolyte Supporting 500 Wh/kg Li-C/NMC Batteries" from Dr. Chunsheng Wang, UMD Wright Distinguished Chair in Chemical and Biomolecular Engineering. The objective of Wang's project is to research, develop, and demonstrate a Bi@graphite/NMC811 and Bi@graphite/$LiNiO_2$battery capable of achieving an energy density ≥ 500 Wh/Kg while achieving a life of ≥ 1,000 cycles using super fluorinated electrolyte.

ARPA-E Award

Dr. Liangbing Hu (the PI), University of Maryland Associate Professor of Material Sciences and Engineering and the Maryland Energy Innovation Institute (MEI^2), and Dr. Teng Li (a Co-PI), Professor in Mechanical Engineering at UMD received one of the OPEN 2018 awards for their work in "Super-strong, Low-cost Wood for Lightweight Vehicles". The research grant of $3.6M will support the further improvement, manufacturing and commercialization effort of their super-strong, low-cost wood technology (also called mettlewood). The team including Inventwood LLC will further develop their "super wood" approach to providing an alternative to steel and carbon fiber in the automotive industry. Over three years, the project will improve super wood's properties to achieve the ability to withstand pressure of 1 gigapascal (or 145,038 pounds per square inch) and meet the requirements of a low-cost automotive structural material. This material could cut vehicle manufacturing costs by 10-20% and reduce the energy used in the manufacturing process by up to 80% on a component level and by about 28% on a vehicle level. In addition, Hu's "Super Wood" is also a recent recipient of the 56th annual R&D 100 Awards, an international competition that recognizes the 100 most exceptional innovations in science and technology from the past year. The R&D 100 Awards have long been considered the most globally prestigious recognition of invention and innovation. With the addition of this award, UMD now receives close to $55M in ARPA-E awards.

RESEARCH HIGHLIGHTS

Significant and impactful research progress was also made in FY19. Multiple papers were published in high profile journals such as *Science, Nature,* and *Proceedings of the National Academy*. A few results are highlighted below.

Battery Technology

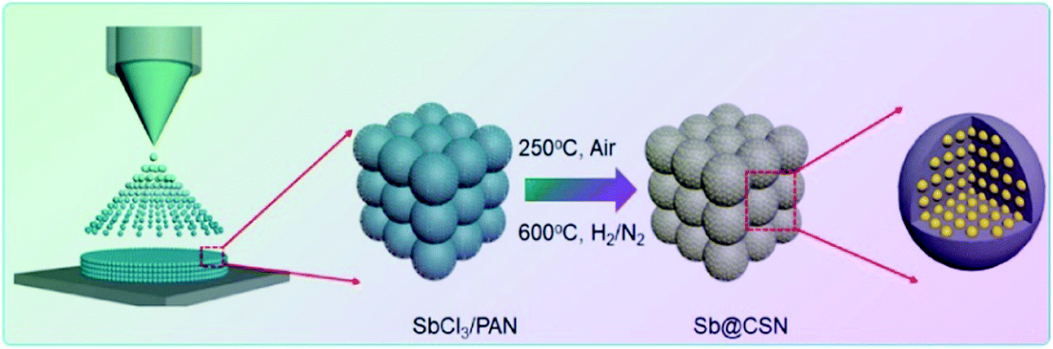
Aqueous Li-ion battery enabled by halogen conversion–intercalation chemistry in graphite, Yang, C., Chen, J., Ji, X., Pollard, T. P., Lü, X., Sun, C.-J., Hou, S., Liu, Q., Liu, C., Qing, T., Wang, Y., Borodin, O., Ren, Y., Xu, K., and Wang, C., *Nature*, 2019 Vol. 569, No. 7755.

Dr. Chunsheng Wang and his research group have invented a water-in-salt (WIS) electrolyte. The WIS electrolyte enables Zn-air batteries and transition metal-free $LiBr_{0.5}Cl_{0.5}$-Graphite cathodes to achieve high energy density and cycle life. The team demonstrated a novel WIS electrolyte that enables aqueous rechargeable Li-ion batteries to provide 170 Wh/Kg and operates even after cutting and exposure to air and water. The group also demonstrated a flexible aqueous Li-ion battery that continuously drives a fan during cutting in air and in water. The WIS electrolyte replaces the need for cobalt in Li-battery cathodes. Professor Jeffrey Dahn, Tesla Chair at Dalhousie University in Canada, one of the world's leading experts in battery technology state that Wang's research "has produced the most creative new battery chemistry I've seen in at least 10 years." Wang's work was demonstrated at the Technology Showcase during the 2019 ARPA-E summit.

Dr. Chunsheng Wang presents at the 2019 ARPA-E Technology Showcase

Extremely stable antimony–carbon composite anodes for potassium-ion batteries, Zheng, J., Yang, Y., Fan, X., Ji, G., Ji, X., Wang, H., Hou, S., Zachariah, M., and Wang, *C., Energy Environ. Sci.*, 2019.

Dr. Wang's group found that loading the metal antimony as nanoparticles into carbon could make a good anode match for potassium's larger size and slower reactions. Potassium is much more abundant on earth than its counterpart, lithium, and would be cheaper to use in large-scale batteries. They sprayed a precursor containing the carbon and antinomy sources to create small spheres of carbon holding even tinier nanoparticles of antimony. This proved to be an effective way to mix carbon and metal to take advantage of both carbon's compatibility and metal's ability to hold electrical charge. One of the reasons this combination works is that a "crust" of a new material is formed where the carbon-antimony



Schematic illustration of the electrospray-assisted strategy for fabricating the material.

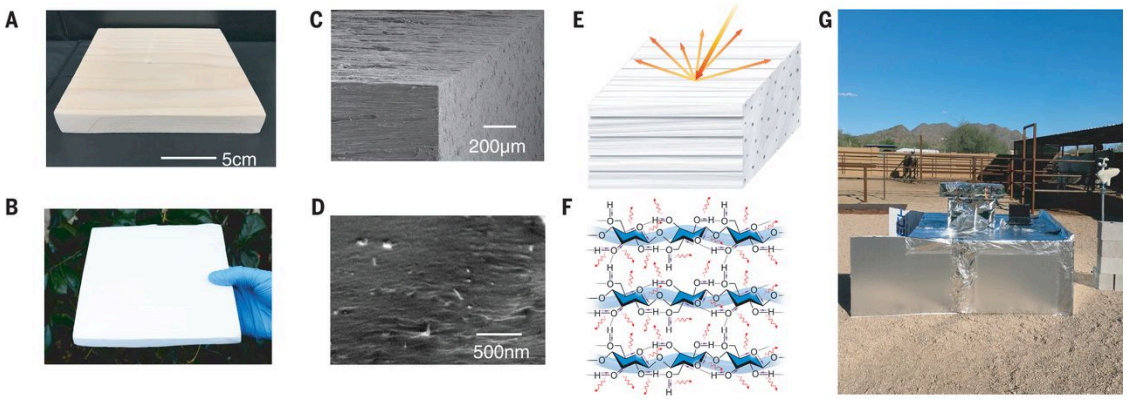
structure meets the potassium. This interface of the two materials makes a layer of antimony-potassium that protects each surrounding material from the energetic effects of its partner. The new battery, which is still in the testing phases, has a long cycle life and can hold large amounts of charge for its weight. Potential applications include energy storage on a very large scale, such as a citywide grid.

Fluorinated solid electrolyte interphase enables highly reversible solid-state Li metal battery, Fan, X., Ji, X., Han, F., Yue, J., Chen, J., Chen, L., Deng, T., Jiang, J., Wang, C., *Sci. Adv*., Dec. 2018.
Dr. Chunsheng Wang and his research group have created a high energy-dense solid-state battery that can effectively suppress Li dendrite growth. With the addition of fluorine, they were able to form a "crust" between the charge-carrying electrolyte and the Li anodes. This prevented Li dendrite from growing into the battery. The "crust" (known to scientists as a "solid-electrolyte interface") protected the solid-state electrolyte from forming Li dendrite and produced a battery with record high current density (2 mA per square centimeter, twice the best reported current density for the Li metal solid state batteries. It was also more efficient in keeping the stored charge available and not losing it through Li dendrite formation (98% efficiency with fluorine, compared to 88% efficiency without). The new battery is a small test device, not yet scaled up to be a vehicle battery. However, the research work provided an effective way to manufacture solid-state Li metal batteries at high rate and long cycle. The principle of Li dendrite suppression in solid state electrolytes will accelerate the commercialization of solid-state batteries.

High electronic conductivity as the origin of lithium dendrite formation within solid electrolytes. Han, F., Westover, A.S., Yue, J., Fan, X., Wang, F., Chi, M., Leonard, D.N., Dudney, N.J., Wang, H., and Wang, C. (2019). *Nature Energy*
Dr. Chunsheng Wang and collaborators determined the use of a lithium metal anode in rechargeable batteries could significantly increase the energy density of conventional batteries, but combined with solid electrolytes (SEs) presents a challenge due to the formation of dendrites. Dendrites – a mass of crystal resembling a crown of broccoli – form inside electrolytes, causing batteries to fail. They discovered that high electronic conductivity of solid electrolytes is the root cause of dendrite formation in solid-state batteries. If the electronic conductivity can be reduced, dendrites are less likely to form, boosting the battery's longevity. The Wang Group found that dendrites start to grow *inside* the bulk solid electrolyte, due to the fact that sulfide and oxide electrolytes have a much higher electronic conductivity than those of liquid electrolytes and LiPON. Future research should focus on developing methods to reduce the electronic conductivity while simultaneously increasing, or at least, maintaining, the ionic conductivity of SEs. The results will aid in the development of safe, high-performance solid-state batteries, which can be utilized for clean energy storage in portable electronic devices (e.g., mobile phones and laptops) and electric vehicles.

Materials Innovation
A radiative cooling structural material, Li, T., Zhai, Y., He, S., Gan, W., Wei, Z., Heidarinejad, M., Dalgo, D., Mi, R., Zhao, X., Song, J., Dai, J., Chen, C., Aili, A., Vellore, A., Martini, A., Yang, R., Srebric, J., Yin, X., Hu, L., *Science*, 24 May 2019.

Dr. Liangbing Hu, MEI[2] Researcher and UMD Professor of Materials Science and Engineering, has harnessed nature's nanotechnology to help solve the problem of finding a passive way for buildings to dump heat that is sustainable and strong. It is a dramatic improvement in roof cooling using renewable resources. Using tiny structures found in wood – cellulose nanofibers and the natural chambers that grow to pass water and nutrients up and down inside a living tree - that specially processed wood has optical properties that radiate heat away. By removing the lignin, the part of the wood that makes it brown and strong, the UMD researchers created a very pale wood made of cellulose nanofibers. They



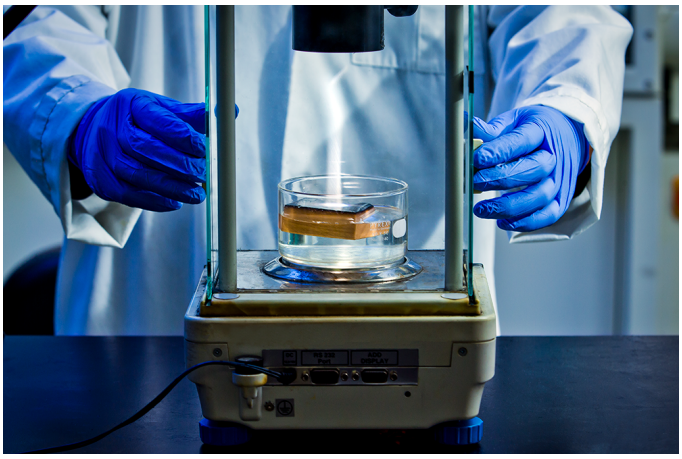
Cooling wood demonstrates passive daytime radiative cooling. A) natural wood B) cooling wood C) SEM image of the cooling wood showing aligned wood channels D) SEM image partially aligned cellulose nanofibers E) schematic of wood structure strongly scattering solar irradiance F) schematic of infrared emission by molecular vibration of cellulose G) Setup of real-time measurement of subambiant cooling performance.

then compressed the wood to restore its strength. To make it water repellent, they added a super hydrophobic compound that helps protect the wood. The result: a bright white building material that could be used for roofs to push away heat from inside the building. The mechanical strength per weight of this wood is also stronger than steel, which makes it a great choice for building materials. It is ten times stronger than natural wood and beats steel's strength, reaching 334 MPa·cm3/g (compared to 110 MPa·cm3/g for steel). It also damages less easily and can bear more weight than natural wood. To see how much energy the wood saves, they calculated how much heat is used by typical apartment buildings in cities across the US in all climate zones. Hot cities like Phoenix and Honolulu would save the most energy, especially if older buildings had their siding and roofs replaced with cooling wood. Buildings across the US that were built after 2004, or now, would save on average 20% of cooling costs.

Bioinspired Solar-Heated Carbon Absorbent for Efficient Cleanup of Highly Viscous Crude Oil**,** Kuang, Y., Chen, C., Chen, G., Pei, Y., Pastel, G., Jia, C., Song, J., Mi, R., Yang, B., Das, S., Hu, L., *Adv. Functional Materials* (2019)

Dr. Hu and his research team demonstrated a successful prototype of one critical component for affordable small-scale desalination: an inexpensive solar evaporator, made of wood. The evaporator generates steam with high efficiency and minimal need for maintenance. The design employs a technique known as interfacial evaporation, which shows great potential in response to global water scarcity because of its high solar-to-vapor

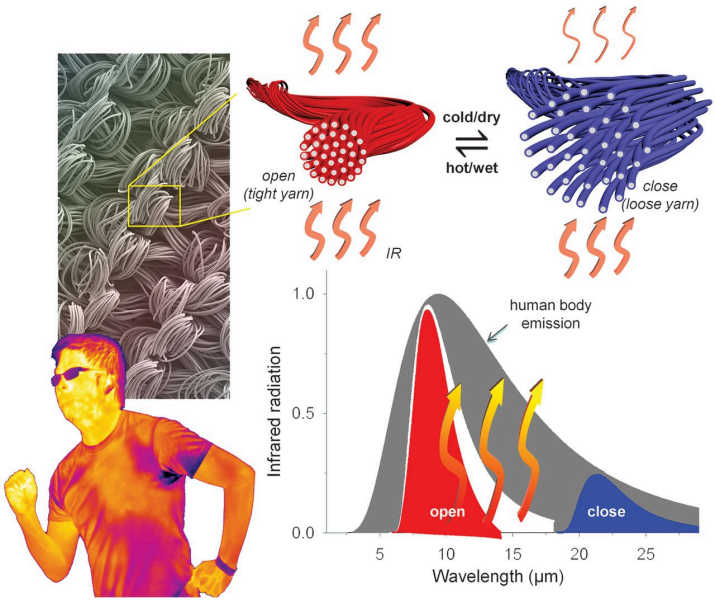
efficiency, low environmental impact, and portable device design with low cost. These features make it suitable for off-grid water generation and purification, especially for low-income countries. Hu and his colleagues minimized the need for this maintenance with a device made out of basswood that exploits the wood's natural structure of the micron-wide channels that carry water and nutrients up the tree. The researchers supplement these natural channels by drilling a second array of millimeter-wide channels through a thin cross-section of the wood. The investigators then briefly expose the top surface to high heat, which carbonizes the surface for greater solar absorption. Hu's lab also recently developed another solar-heated prototype device that takes advantage of carbonized wood's ability to absorb and distribute solar energy—this one created to help clean up spills of hard-to-collect heavy oils. Low tortuosity of the porous structure together with the efficient color-thermal conversion enable the device to absorb viscous crude oil 10 times faster than previous results.



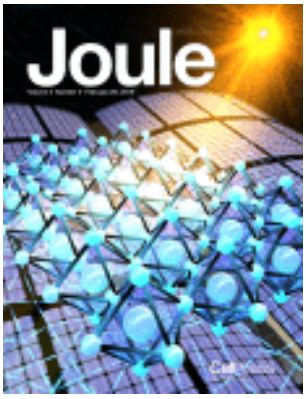
Cellulose ionic conductors with high differential thermal voltage for low-grade heat harvesting, Li, T., Zhang, X., Lacey, S.D., Mi, R., Zhao, X., Jiang, F., Song, J., Liu, Z., Chen, G., Dai, J., Yao, Y., Das, S., Yang, R., Briber, R., and Hu, L., *Nature Materials* 2019. Dr. Liangbing Hu and Dr. Robert Briber of the UMD Department of Materials Science, and Siddhartha Das of mechanical engineering, transformed a piece of wood into a flexible membrane that generates energy from the same type of electric current (ions) that the human body runs on. This energy is generated using charged channel walls and other unique properties of the wood's natural nanostructures. With this new wood-based technology, they can use a small temperature differential to efficiently generate ionic voltage. They have demonstrated their proof-of-concept device to harvest low-grade heat using nano-ionic behavior of processed wood nanostructures. The researchers used basswood, which is a fast-growing tree with low environmental impact. They treated the wood and removed two components – lignin, that makes the wood brown and adds strength, and hemicellulose, which winds around the layers of cells binding them together. This gives the remaining cellulose its signature flexibility. This process also converts the structure of the cellulose from type I to type II which is a key to enhancing ion conductivity. The charged channel walls can establish an electrical field that appears on the nanofibers and thus help effectively regulate ion movement under a thermal gradient,

Dynamic gating of infrared radiation in a textile, Zhang, X., Yu, S., Xu, B., Li, M., Peng, Z., Wang, Y., Deng, S., Wu, X., Wu, Z., Ouyang, M., Wang, Y.-H., *Science*, 2019.

UMD researchers have created a fabric that can automatically regulate the amount of heat that passes through it. When conditions are warm and moist, such as those near a sweating body, the fabric allows infrared radiation (heat) to pass through. When conditions become cooler and drier, the fabric reduces the heat that escapes. The fabric is specially engineered from yarn coated with a conductive metal. Under hot, humid conditions, the strands of yarn compact and activate the coating, which changes the way the fabric interacts with infrared radiation. They refer to the action as "gating" of infrared radiation, which acts as a tunable blind to transmit or block heat. The base yarn for this new textile is created with fibers made of two different synthetic materials—one absorbs water and the other repels it. The strands are coated with carbon nanotubes, a special class of lightweight, carbon-based, conductive metal. Because materials in the fibers both resist and absorb water, the fibers warp when exposed to humidity such as that surrounding a sweating body. That distortion brings the strands of yarn closer together, which does two things. First, it opens the pores in the fabric. This has a small cooling effect because it allows heat to escape. Second, and most importantly, it modifies the electromagnetic coupling between the carbon nanotubes in the coating. Depending on the tuning, the fabric either blocks infrared radiation or allows it to pass through. The reaction is almost instant, so before people realize they're getting hot, the garment could already be cooling them down. On the flip side, as a body cools down, the dynamic gating mechanism works in reverse to trap in heat. More work is needed before the fabric can be commercialized, but according to the researchers, materials used for the base fiber are readily available and the carbon coating can be easily added during standard dying process.



Machine Learning for Perovskites' Reap-Rest-Recovery Cycle, Howard, J., Tennyson, E., Neves, B., and Leite, M., *Joule*, (cover 2019)



Marina Leite, UMD Assistant Professor in Materials Science and Engineering, and her team of researchers graced the cover of the February 20th issue of *Joule* magazine for their pioneering work on artificial intelligence solutions using solar cell materials. Hybrid organic-inorganic perovskite (HOIP) photovoltaic (PV) devices are an emerging technology with record power conversion efficiency. But the effects of water and oxygen as well as temperature and light can often hinder the efficiency. The research team believes that identifying, understanding, and controlling the influence of each one of

these factors (as well as their combined effects) toward the stability of HOIPs from the macro- to the nanoscale will continue to be a major thrust in the research community. More importantly, these tools will allow the scientific community to identify the most influential environmental parameters, as well as the cutoff between recovery and degradation. Using this information, advanced computational frameworks based on ML could be quickly developed that maximize overall long-term power output, minimizing material degradation. AI strategies facilitating rapid knowledge transfer could ultimately enable reliable perovskite solar cells. First author and UMD Materials Science student, John Howard, is a Harry K. Wells fellowship recipient, awarded by MEI^2. His research is focused on identifying degradation mechanisms in perovskite solar cells.

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.

Hulka and Wells Graduate Fellowships

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 2019-20 Wells recipients are: Tristan Deppe (Electrical and Computer Engineering) and Pattanun Chanpiwat (Mechanical Engineering). Deppe's project includes developing a nighttime solar cell that employs thermoradiative photovoltaics and advancing the field of radiative cooling. The device harvest energy from the net radiative heat loss from the earth to space in order to generate power both day and night. Chanpiwat will be using his knowledge of machine learning, statistical and optimization modeling of demand response incorporating storage aspects of power. He hopes to deliver predictive modeling of renewable energy supply and use the demand response modeling in renewable energy generation and storage.

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, Hulka fellowship recipient, Kiran Burra, is focusing his efforts on developing an efficient pathway for the conversion of CO_2 to CO and its subsequent conversion to downstream value-added products such as fuels, energy and plastics. The primary objective includes the development of high temperature resilient, catalytic oxygen carrier materials in the form of mixed metal oxides for the production of CO through redox reaction with sustainability over multiple cycles in a lab-scale.

Engineering Sustainability Day 2019

The 9th annual Engineering Sustainability Day, April 22, 2019 entitled "Towards Zero Emissions and Beyond" focused on innovative energy technologies to reduce greenhouse gas emissions and even produce "negative" emissions. The workshop brought together leading academic researchers, modelers, investors, and policymakers to examine how to combine technical and policy perspectives of clean energy innovation to accelerate climate change mitigation.

Dr. Ross Salawitch, UMD Professor of Chemistry and Biochemistry, kicked off the meeting by discussing the overarching issues of greenhouse gases (GHGs) and the urgency of reducing GHG emissions from a climate perspective. David Hart, Senior Fellow of the Information Technology & Innovation Foundation at George Mason University followed with a presentation on an innovation agenda for deep carbonization and the current gaps in research and development. Sam Gomberg of the Union of Concerned Scientists highlighted another complication of current carbon capture reality. A significant force behind the push for federal carbon capture legislation is the oil/gas industry which uses CO_2 for enhanced oil recovery. On a more local level, Paul Spies, director of the Energy program at the Maryland Department of Commerce, provided a state-wide jobs and business perspective on clean energy technology deployment within Maryland. Graduate students from the University System of Maryland competed in a student poster contest regarding their innovative clean energy technologies.

Paul Spies, Maryland Department of Commerce, speaks during Engineering Sustainability Day 2019.

Maryland Day 2019

Each year the University of Maryland (UMD) welcomes thousands of visitors for one day to celebrate learning and discovery. The event, on April 27, showcased scientific demonstrations, exhibitions and performances. MEI^2 students and faculty demonstrated new battery technologies and Dr. Hu's diverse uses for wood including transparent wood, super strong wood, and wood batteries.

Electrochemical Society Student Chapter

The University of Maryland chapter of the Electrochemical Society (ECS) spent a number of resources in the 2018-2019 school year dedicated to community outreach. They reached out to young students to encourage their curiosity and develop an appreciation for science and engineering. The group designed two lesson plans based on electrochemistry and material science principles with the help of Adventures in Science. On October 20th, 2018, ECS presented the first lesson based on electrochemistry at the University of Maryland Adventures in Science where the students built and measured their own batteries made

from zinc and copper electrodes and a lemon slice electrolyte. On December 15th, 2018 the led the second electrochemistry lesson at the NIST campus. The last Adventures in Science lesson was held on February 23rd, 2019 in which they taught a lesson on the general materials science concept of phase transitions where the students experimented with liquid nitrogen and the appropriate safety equipment necessary to watch materials undergo various temperature dependent transitions. These lesson plans are a great foundation to build on for future Adventures in Science. Dr. Wachsman is the faculty advisor for the student ECS chapter.

Association of Energy Engineers Student Chapter

Founded in 2018, the new student chapter at UMD is devoted to engaging students in energy engineering and leveraging their role in promoting renewable energy and next-generation energy systems. The student chapter hosts brown bag lunches on various topics including this year's topics on microgrids, the solar decathlon, and a panel on the energy industry. The panelists discussed the different energy sectors and how each promote and develop projects. These events are free for all AEE UMD registered students. Dr. Farah Singer, faculty research associate for the Center for Environmental Energy Engineering, is the faculty sponsor of the group.

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. Early stage energy innovation technology investments have paid off as evidenced from the Energy Seed Grant Program. Moreover, local start-up companies such as Ion Storage Systems, InventWood, and Mobile Comfort have received multi-$M ARPA-E and other federal awards, raised private investment capital, and are moving into commercial space within the State, creating new job opportunities and economic impact for Maryland through manufacturing and commercialization of their new energy saving products.

MEI^2 is working with MCEC to establish 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.

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. MOUs were signed with the Korean Electronics Technology Institute (KETI) and the Daegu Gyeongbuk Institute of Science and Technology (DGIST). Research collaborations began with General Technical Services, LLC, ManTech, and the Regional Manufacturing Institute of Maryland.

MEI^2 has demonstrated, through the establishment of the Center for Research in Extreme Batteries (CREB), how Maryland can provide developmental support through partnerships with local federal laboratories and industry, in this case to advance clean energy innovation.

Further progress in developing a clean energy innovation support infrastructure is possible by building on Maryland's system of biotechnology-focused infrastructure and mentoring approaches.

With the MEI^2 mandated report on the availability and efficiency of use of funds for the development and deployment of clean energy technology in the State and the commercialization of that technology due December 2019 to the Maryland State Legislature and Governor Hogan, MEI^2 held an Energy Grid Storage Workshop on seeking input from external stakeholders in several specific technological and application areas to discuss the case for innovation, including appropriate amounts and forms of support for early stage developments in universities and companies. A vast array of energy storage applications, including stationary and vehicle storage, defense, aerospace, and biomedical were considered. On the application side, an emphasis was placed on innovation opportunities for stationary electricity storage for a post-2040 Maryland electricity system, which is likely to be far different than the present system. Additional by in for the report has been garnered from the Maryland Commerce Department, Maryland Energy Administration, the Public Service Commission, TEDCO, and other State industrial partners.

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.

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

September 27, 2018

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

Dear Dr. Wachsman,

Following the August 27, 2018 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 results from the first round of energy seed grant funding, the Advisory Board sees 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.

The Advisory Board was impressed by MEI^2's progress in research as well as the number of awards funded by the Department of Energy's Energy Efficiency & Renewable Energy (EERE) and Advanced Research Projects Agency - Energy (ARPA-E) programs, the latter continuing to be more than any other university in the U.S. The Advisory Board was also pleased with the outreach and engagement by MEI^2 and the number of energy partnerships established or under development, ranging from industry, such as discussions initiated by Exelon Corp. for University of Maryland (UMD) to be one of its academic research partners, to international, such as the MOU with the Korean Electronics Technology Institute (KETI) and subsequent joint proposal to the Korean Ministry of Trade, and Industry, and Energy (MOTIE).

The Advisory Board is pleased with the selection and progress of the four energy seed grants that were awarded in January, 2018. A major focus of these seed grants is supporting the progression of research to marketable technologies, and the Advisory Board can see that the 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. As discussed, 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 is pleased that an associate director has been hired and will begin in December 2018. The associate director will assist in leveraging incubator programs currently at UMD and help develop the Industry Research Program at MEI^2. The Advisory Board also encourages developing a state-matching fund for faculty members pursuing federal and other energy grants. MEI^2 was encouraged in this endeavor to continue to explore opportunities for federally funded centers such as the DOE Advanced Manufacturing Office and NIST Manufacturing Hubs.

The Board also reviewed the proposed budget plan for the coming fiscal year and agreed with the level of funding for Energy Seed Grants. This past year four - $100,000 USD grants were awarded. It is possible that fewer awards could be funded in the coming years, or follow on awards could be made to current recipients while reserving $100K in assisting start-ups in the incubator space. The MEI^2 Investment Committee will take this under advisement before the next call for proposals in December 2018.

In examining the Institute as a whole, the board encouraged looking at potential funding and investment opportunities through MCEC capabilities. As MCEC has bonding authority and can make advancements to advance clean energy solutions, the Board suggested MEI^2 explore and socialize opportunities for MCEC to go beyond financing energy technology deployment. The Advisory Board discussed finding ways for small companies to have a guaranteed first market and support services including human resource, marketing and accounting assistance. The MEI^2 Investment Committee could potentially evaluate risks of start-ups based on patents filed and other metrics and then suggest to MCEC where to effectively invest if approved by MCEC Board of Directors.

In addition, the Board heard a range of potential approaches to producing a 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 Board thanks Professor Ellen Williams for agreeing to take the lead in preparing this report and notes that her experience as former director of ARPA-E makes her uniquely qualified to undertake this endeavor. This report has the potential to make a major impact on Maryland's energy economy and will require significant resources in this next fiscal year. As such, MEI^2 should endeavor to obtain additional resources to maximize its scope and impact.

With respect to Advisory Board recommendations from the prior meeting, MEI^2 has made excellent progress in implementing those recommendations. Identifying relevant key performance indicators as metrics against the program goals remains an ongoing effort.

The Advisory Board, therefore, makes the following recommendations with the aim of MEI^2 achieving its full transformative, scholarly, and financial potential:

- 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

- Stand up the Incubator at UMD and assist start-ups with common support services and find ways to reduce initial start-up costs
- If approved by MCEC Board, advise on effectively investing capital in Maryland start-up companies
- 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.

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.

Sincerely,

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)

Joseph Dominguez
Sr. Vice-President, Exelon Corporation

Abigail Hopper
CEO, Solar Energy Industry Association
Director, US Bureau of Ocean Energy Management
Director, Maryland Energy Administration

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

Philip Perconti
Director, Army Research Laboratory

Jigar Shah
CEO, Generate Capital

Mary Beth Tung
Director, Maryland Energy Administration

APPENDIX 2. MEI^2 FY19 Budget

	Budget	Actual	Difference
Salaries/ Benefits	$192,980.00	149,173.00	43,807.00
Seed Grants	$400,000.00	400,000.00	0.0
Events/ Outreach	$13,500.00	15,074.00	-1,574.00
Legislative Report	$0.0	3600.00	-3,600.00
Equipment/ Supplies	$5,786.00	7,240.00	-1,454.00
Totals	**$612,266.00**	**$575,087.00**	**$37,179.00**