Penn State Battery & Energy Storage Technology (BEST) Center

Focus

Research on energy storage to enable renewables and vehicle electrification, from materials to cells to systems.

Highlights

- Penn State has led the nation in battery research, including the first EV battery fabrication facility in a US University.
- BEST faculty have successfully competed in almost every DOE program in batteries.
- Other universities are challenging our early lead through strategic hires and infrastructure investment.
- Many grand challenges remain to be solved in energy storage, the first of which is lowering costs.
- A key opportunity area for PSU is to grow our infrastructure and capabilities in grid storage, a rapidly growing field.

Goals

- Increase funding and activities through strategic investment in research in materials, cells, and systems.
- Stimulate research on new battery chemistries with lower cost, higher safety and performance, and longer life.
- Support interdisciplinary work to integrate batteries with renewable energy technologies.
- Leverage recent advances in smart batteries that have built in intelligence, sensing, and actuation.
- Expand work on multifunctional batteries that can carry structural loads, actuate motion, and sense stress while storing electrical energy.

Overview

Balancing the increasing energy demand by society with the need to economically reduce greenhouse emissions is arguably the defining challenge of our time. It is therefore unsurprising that among the 14 Grand-Challenges for Engineering in the 21st century identified in the National Academy of Engineering's 2008 report, 3 address the need to lower humanity's carbon footprint. Moreover, most world energy forecasts show, further, that absent a disruptive intervention that creates cost-effective alternatives to fossil fuel consumption in the transportation, electric power generation, manufacturing, and residential sectors, efforts to balance economic growth and carbon emissions, particularly in the developing world, cannot succeed. This contention is supported by the most recent (2017) report from the Environmental Protection Agency (EPA) reproduced in **Fig. 1**, which shows that energy use in these four economic sectors account for nearly 90% of annualized greenhouse gas emissions in the United States. There is broad consensus that electrical energy storage (EES) systems capable of meeting the complex and differentiated performance, cost, life cycle, environmental, and societal needs in each of these sectors are a requirement for progress. **Currently, there is no cost-effective energy storage solution that can handle the integration of renewable energy resources on a large scale.**

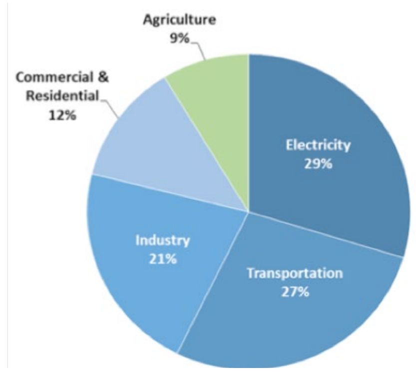


Fig. 1 Major greenhouse gas emissions, by commercial sector. US EPA (2017). Inventory of emissions: 1990-2015

In 2014, electric vehicles (EVs) accounted for less than 1% of total auto sales in all countries except Norway (12.5%), the Netherlands (3.9%), the U.S. (1.5%), and Sweden (1.4%). Today's batteries constitute the major obstacle to EV sales; they increase the price and limit the driving range. In the Nissan Leaf (the best-selling EV) and the Tesla Model S, the battery accounts for about 25% of the weight and 25% of the manufacturing cost of the car. In September 2015, Electric Power Research Institute and the Natural Resources Defense Council stated that if EVs accounted for 50% of the miles traveled by personal vehicles in the U.S., they would reduce the total annual CO_2 from our transportation and electricity sectors by the equivalent of removing 80 million gasoline-powered cars from the road. The President's Council of Advisors on Science and Technology has identified energy storage as a "game changer" for both EVs and solar energy storage.

Energy storage research will help to meet the National Academy of Engineering grand challenge of making solar energy economical. Low cost and long life energy storage is needed to fill the gaps in renewable energy production in homes, microgrids, and the national grid. Batteries are already taking this role with major storage facilities coming on line in California and Australia.

The BEST Center was created with seed funding from across the university to address these challenges. Leveraging this support, BEST faculty have secured large grants from the Department of Energy (DOE), National Science Foundation (NSF), and industry sponsors. Examples include (>$10M in total for these specific projects):

- **CAEBAT** (DOE – Rahn and CY Wang) - PSU was the only academic participant in this DOE program.
- **BATT** (DOE – D. Wang and Hickner) – fundamental research on battery chemistry.
- **Li-S Batteries** (DOE – D. Wang and CY Wang) - PSU leads; subcontracts to Argonne, JCI, and EC Power.
- **Extreme Fast Charging** (DOE – CY Wang and D. Wang) – PSU leads, subcontract to Argonne.
- **Cold-sintered Solid State Batteries** (ARPA-E – E. Gomez, C.Y. Wang, C. Randall)
- **Multifunctional Batteries** (NSF – Rahn, D. Wang, Frecker)
- **High-performance Li Metal Anodes** (DOE – D. Wang) – PSU leads, subcontract to Ashland Corp.

In addition to these specific projects, the BEST Center faculty have substantial funding for their battery work from most major automobile companies (including GM, Ford, Chrysler, JCI, Cummins, Toyota, and Nissan).

Strategic Planning

Low cost solar and wind power are major motivators for increased energy storage. The focus in the BEST center has been at the smaller, vehicle scale, but we aspire to attack these global and large scale problems in the future. A new key activity will therefore be to work with the solar and wind centers to better integrate battery storage into renewable energy production.

The BEST Center will continue to promote and enhance activities in energy storage, at the materials, cell, and systems level and with a new emphasis on large scale storage. Key strategic needs to facilitate this shift are:

- Four faculty hires in the areas of grid storage, battery systems, power electronics, and energy markets;
- Seed grant funding for materials research on high energy density, low cost, safe, and long-life battery chemistries (Four $200K projects);
- Creation of an on-campus fully instrumented and programmable microgrid-scale energy storage system;
- An $1.2M investment in core facilities that include: (i) A new pouch cell fabrication line for cells that are the backbone of grid energy storage systems; (ii) A battery maker space with material preparation equipment, glove boxes, cell fabrication equipment, and electrical testing machines to support the education of the next generation of powertrain and grid engineers.

List of participants

Primary contact: Prof. Chris Rahn, 150A Hammond.

Participants: Chao-Yang Wang (co-director of BEST), Hosam Fathy, Donghai Wang, Adri van Duin, Michael Hickner, Michael Janik, Randy Vander Wal, Serguei Lvov, Joel Anstrom, Tim Cleary, and Arash Khoshkbar-Sadigh, Enrique Gomez, Clive Randall.

Education and Outreach

DOE funded Graduate Automotive Technology Education Program (2008 – 2018) focused in energy storage.

Minor: Electrochemical Engineering

Courses: ME/Emch/Matsc 597K – In Vehicle High Power Energy Storage, ME 442W/443W Advanced Vehicle Design I/II, ME 597G, Electrochemical Engines with Lab, ME 597C, Battery Systems Engineering.

Outreach activities: CAC Legacy of Tour de Sol, EcoCar, Solar Decathlon.

Supplemental information

Website: www.best.psu.edu

Location: EESL (MRL) Co-Directed by Prof. Chris Rahn (150A Hammond) and Chao-Yang Wang (162 EESL).

Bioenergy @ Penn State

Focus: Research on technologies that harness energy from biological sources, from bioenergy feedstock production to conversion and utilization; development of sustainable systems for bioenergy production and carbon capture that enhance the natural environment.

Highlights

- Penn State has strengths in fundamental and applied research related to production, structure, and conversion of plant-based biomass.
- Existing, relevant centers headquartered at Penn State include the Biomass Energy Center, the Northeast Regional Sun Grant Center, the Center for Lignocellulose Structure and Formation, the Center of Excellence in Industrial Biotechnology, and the Center for Excellence in Structural Biology.
- Centers with Penn State co-leadership include the Mid-Atlantic Bioenergy Council, the US DOE Center for Bioenergy Innovation, and the Aviation Sustainability Center
- Penn State is a world leader in research on: bioenergy farming; harvest, storage, and conversion of biomass; hydrogen production from biomass; and plant cell walls.

Goals

- Rebrand the Biomass Energy Center as the **Center for BioRenewables (C4BR)** that will coordinate bioenergy activities across Penn State
- Strategically invest in bioenergy economics, law, policy, business, and education activities
- Enhance and coordinate research on biomass production, harvest, processing, degradation, and conversion technologies
- Develop strategies to leverage biomass accumulation in living organisms for carbon capture and sequestration, achieving drawdown of greenhouse gases from the atmosphere
- Help grow the nascent breeding industry for bioenergy crops into an economically attractive option for farmers in Pennsylvania and beyond
- Facilitate collaboration with industry that leads to new funding for bioenergy research and development

Overview

The current mission of the Biomass Energy Center at Penn State is to coordinate and facilitate research and outreach in bioenergy across the university, building teams to address the complete value chain of biomass energy systems. This value chain can be classified into four categories:

- Improved production of biomass feedstocks;
- Integration of biomass production into sustainable agrosystems;
- Conversion of biomass into energy; and
- Technology transfer to companies, state agencies, NGOs, and citizens throughout the Commonwealth and beyond.

Penn State has significant strengths in each these four focal areas: each have a significant number of faculty involved, with critical masses of researchers emerging in many subtopics.

Current Activities

Funding for bioenergy-related research by Penn State faculty comes from the United States Department of Energy (DOE), the Department of Agriculture (USDA), the National Science Foundation (NSF), and the Federal Aviation Administration (FAA). Current bioenergy research activities at Penn State include:

- Metabolic modeling of biomass accumulation and of biomass-degrading organisms
- Engineering plants that will grow faster or have more easily degradable cell walls
- Characterizing the fundamental structure, assembly, and mechanics of plant cell walls, which form the majority of plant biomass
- Biomass comminution, particulate mechanics, solids storage, flow, handling and densification, pretreatment, and co-treatment
- Mechanistic investigations of biomass-degrading enzymes

- Biological, thermochemical, and catalytic conversion technologies for bioenergy production
- Microbial fuel cell development for electricity production from biomass
- Nutrient recovery from waste streams into plant biomass for use as a bioenergy feedstock
- United States bioenergy-related law and policy

Strategic Planning and Investment

Although Penn State houses a broad constellation of bioenergy-related activities, they are not linked into a coherent vision of a biorenewable future. To remedy, this, strategies and investments with the greatest future impacts include:

- Appoint directors of the Center for BioRenewables (25% teaching release), with the ability to hire 5 faculty with research expertise in bioenergy systems, modeling, and process engineering
- Convene a bioenergy leadership council under the Center for BioRenewables that will guide and coordinate bioenergy activities across Penn State
- Use BioRenewables Seed Grants (4 grants/year, $100k/year total) to bridge the steps in the bioenergy pipeline that are currently being pursued independently by Penn State researchers (e.g., studying the effects of engineering bioenergy crops to improve their digestibility on planting, growth, harvesting, storage, and conversion practices)

These investments will enable Penn State researchers to:

- Enhance our ability to capture, manipulate, transport, and release energy in the carbon-carbon and carbon-hydrogen bonds of biomass, without releasing excess carbon into the environment
- Link environmental remediation (e.g., carbon capture, nutrient recovery) with bioenergy production
- Leverage and engineer photosynthesis to efficiently capture and store energy in assimilated carbon and hydrogen
- Transform the modern agricultural economy into a supplier of food, feed, materials, and energy that will power a sustainable and renewable future
- Build on Pennsylvania's strengths in energy, agriculture, and manufacturing to accelerate the transition to a bioenergy economy
- Elevate Penn State to become the world leader in bioenergy research (current peers include the University of Illinois Urbana-Champaign, Purdue University, the University of Wisconsin-Madison, Michigan State University, Iowa State University, and DOE Bioenergy Research Centers)

Education and Outreach

- *Graduate Program:* BioRenewable Systems Graduate Program (https://abe.psu.edu/graduateprograms/brs)
- *Courses*: ABE 884 & BE 464, Biomass Energy Systems; ABE 885, Biomass Harvesting and Logistics; ABE 888 & BE468, Conversion Technologies for Bioenergy Production; FOR 880, Bioenergy Feedstocks
- *World campus*: Graduate Certificate in Bioenergy (https://www.worldcampus.psu.edu/degrees-and-certificates/bioenergy-certificate/overview)
- Bioenergy short course series
- *Outreach activities*: Energy Days; Ag Progress Days

Participants

Primary contact: Charles T. Anderson, Associate Professor of Biology (cta3@psu.edu).

Participants: Charles T. Anderson, Saurabh Bansal, Rachel Brennan, Nicole Brown, John Carlson, Daniel Ciolkosz, Daniel Cosgrove, Ali Demirci, Lara Fowler, Ying Gu, Michael Jacobson, Armen Kemanian, Seong Kim, Manish Kumar, Joel Landry, Costas Maranas, Judd Michael, Bruce Miller, Tracy Nixon, Jacqueline O'Connor, Virendra Puri, John Regan, Mohammad Rezaee, Tom Richard, Phillip Savage, Paul Smith, Chunshan Song, Ming Tien, Hojae Yi

Supplemental information

Biomass Energy Center Website: bioenergy.psu.edu (will be updated as part of the Energy 2100 Initiative)

Penn State Blue Energy Research & Education

Focus

Research on extracting renewable energy from the natural water cycle (i.e., “blue energy”). Currently, energy extracted from stores of water held back by dams is the single greatest source of renewable electricity globally.

Highlights

- Penn State researchers are working in several areas related to blue energy, such as conventional hydroelectric dams, tidal energy, and salinity gradient energy, but these efforts are currently disconnected.
- Penn State is in a position to lead large scale research efforts related to capturing blue energy from non-traditional sources.

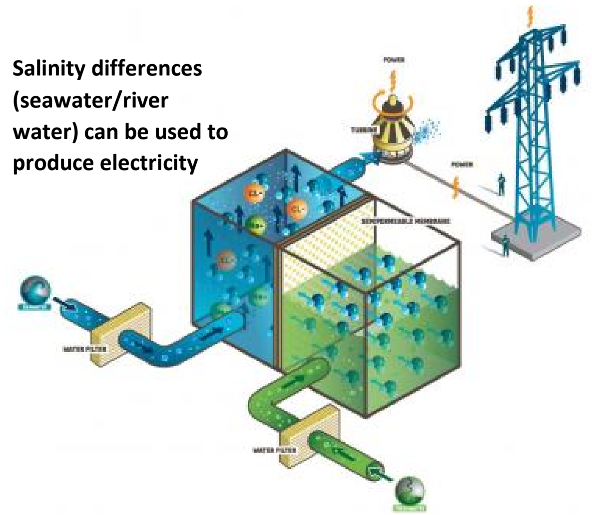
Goals

- Develop a center at the University to centralize researchers from a range of disciplines to tackle large-scale funding opportunities and problems.

Overview

The natural water cycle generates an enormous amount of renewable potential energy that can be converted to electricity. Conventional hydroelectric dams currently produce ~70% of all the renewable electricity created globally (44% in the U.S.). Conventional high-head, hydroelectric power uses turbines within large-scale dams to produce electricity. While conventional hydroelectric dams have been optimized for well over a century, other sources of power from moving water remain less developed (e.g., low-head water flows, wave energy, hydrokinetic energy, and tidal basins).

As funding opportunities emerge for these unconventional hydroelectric sources, a research team with a wide range of expertise is necessary to address relevant problems. For example, generating electricity from oceanic waters requires research on how to remotely service/repair devices, how to optimize performance in dynamic conditions, and how to account for environmental, ecological, and social factors.



Research into water as an energy storage medium is emerging as an important topic. With the introduction of intermittent renewable energy sources into the electrical power grid, energy production and consumption need to be decoupled in time. Presently, 96% of global electricity storage is accomplished by pumping water uphill to store energy, and allowing it to flow through a turbine to produce electricity. Research in this area requires optimization analyses combined with assessment of ecological impacts.

Currently, researchers are working on converting salinity gradients into electricity using electrochemical cells. Natural salinity gradients between freshwater and seawater at coasts contain enough energy to supply ~40% of the global electrical demand. Current work is focusing on maximizing power densities and energy recovery efficiencies.

Current Status of Blue Energy Research at Penn State

To date, research in water-based energy processes has occurred primarily as small, independent efforts across campus. Research at the Applied Research Laboratory (ARL) and in the College of Engineering (COE) include:

1. Turbine hydro device design for increased efficiency
2. Reduction in operation and maintained costs of conventional turbines through reduced manufacturing costs, system health monitoring, and advanced material design
3. Pumped-storage
4. International standards development for design,

testing and characterization of resources and device performance
5. Workforce development through education
6. Evaluation of environmental/ecological impacts of and mitigation measures for dams.
7. Technologies to harvest energy from new sources, such as salinity gradients, using electrochemical systems.
8. Systems modeling to understand macro-level water-energy interdependencies over time and space.

Funding for these projects has come primarily from the Department of Energy, the National Science Foundation, and industries. Forming a center that brings a diverse range of faculty together will be particularly useful in working with industrial partners. Past and current industry partners that have worked with Penn State on water power research include GE, Ecomerit technologies, Verdant Power, ORPC, Cardinal Engineering, and Composite Technology Development, Inc.

Strategic Planning

Penn State is uniquely positioned to serve as a hub of multidisciplinary research in blue energy. Presently, researchers at Penn State are leaders in conventional hydroelectric power, which includes collaborations with several industry partners and the researchers at national labs in the Department of Energy. Penn State also has researchers who are leaders in fields relevant to blue energy, such as material sciences, energy engineering, and ecology. What is needed is a concerted effort to bring these diverse faculty together to address multidisciplinary problems relevant to emerging funding opportunities and industry needs.

To address this need, we propose to draft a new intercollegiate center focused on blue energy research. The vision of this center is to create a hub of faculty to efficiently target large-scale funding opportunities from the Department of Energy and to provide a resource hub for existing and new industry partners. To organize this center, we propose funds ($20k) to write the center proposal.

As a first step towards this vision, a workshop will be organized at the 2019 Energy Days to bring faculty with relevant skillsets together to target large funding opportunities. The workshop will be led by the COE and ARL, Professors John Cimbala and Arnold Fontaine. At the start of the Spring 2019 semester, messages will be sent out to relevant Centers, departments, and faculty to recruit potential collaborators.

List of Participants

Primary Contact: Christopher Gorski
Participants: Arnold Fontaine, John Cimbala, Xiaofeng Liu, Caitlin Grady.

Relevant Courses

ME 400 - Thermodynamics of Propulsion and Power Systems, ME 408 – Energy Systems, ME 422 – Principles of Turbomachinery, EGEE 438 – Wind and Hydropower Energy Conversion.

[Figure from https://www.climatetechwiki.org/technology/jiqweb-ro]

Energy Use & People @ Penn State -- Social Science Research Efforts

Focus

Develop a social science agenda for research related to renewable energy that integrates, broadens, and builds upon current research in the social sciences at PSU and is grounded in the technologies being developed by scientist and engineers at PSU.

Highlights

- Pennsylvania residents have access to a variety of energy sources, including fossil fuels and renewables. However, there are many barriers to acceptance of energy technologies, including economic costs, uncertain futures, experiences with energy suppliers, and the content of intrapersonal, interpersonal, and media coverage that provide information about renewable energy.
- Social science research, including Penn State research, deals with perceptions of energy policies, communicating scientific information to the public, visualization of energy extraction sites, and media narratives contribution to opinions and environmentally relevant civic engagement.
- There is potential for much more research with greater numbers of networked people in the social sciences informed by research done by scientist and engineers.

Goals

- Increase interdisciplinary collaborations and application of social science methodologies to investigate how communities come to understand and talk about energy generation, technologies, and use.
- Obtain funding related to the social and psychological aspects of energy use and public reactions to energy technologies and policies.
- Develop outreach activities around community engagement with renewable energy use.

Overview

People's understandings of energy are likely to be socially constructed—formed from socially shared information about energy generation, technologies,

use, and related policies--perhaps generated from personal experiences with energy use and bills, literature and podcasts about experiences with wind turbines as seen from one's backyard, and snippets of news about benefits and harms of renewable energy generation and policies. The resulting social constructions are likely highly influential because they can amplify or attenuate perceived risks, communicate social norms about energy use, and activate social identities that influence responses to policies and the perceived importance of the topic. Social constructions may exclude important considerations, such as those related to geographic or temporally distal environmental and social justice. The following areas of inquiry would help build a program that contains a strong social science contribution to research on renewable energy at Penn State.

The Stories People Tell About Energy

How do communities talk about energy use and energy technologies? What is the content of their stories? How willing are various types of people to talk about energy, and with whom? How are these conversations influenced by politics? And how do media contribute to or shift the narratives surrounding energy use in different types of communities? These questions underscore the central role of interpersonal and mediated conversations in shaping how people respond to energy use and new energy technologies. Even when concern about climate change, many do not talk about it. Sociologist at PSU have years of experience developing student led and facilitated discussions about difficult topics including climate change. These could be expanded to target discussions about energy. Additionally, research is needed to examine actual community conversations about energy and technology, how to productively facilitate them.

Risk perception
Greater understanding of risk perception as it relates to the development and implementation of renewable energy generation is needed. Although environmental risk perception has been studied for decades, much of this research originated in studying perceived risk from nuclear power. Currently, there is much research on perceived climate change risk perception and its associations with policy support, such as support for funding research on renewable energy. However, support for research is different from support for its implementation as NIMBY considerations highlight: despite general support, some communities resist wind turbines in their "back yards" (NIMBY). Additionally, anticipated benefits and harms of energy policies predicts support for the policies beyond climate change risk perception and political identity. Research is needed to pinpoint how communication (interpersonal and mediated via technology), and the resulting narratives communities construct about energy use, influence perceptions of from renewable energy to be better able to listen do and address community concerns.

Community Impact
Understanding the current, potential, and anticipated impacts of energy use and new energy technologies on communities can prepare residents for shifts in availability, pricing, and community upheaval that may result. While certain communities bear the brunt of environmental and health impacts of fossil fuel extraction and impacts of climate change, these same communities may be most vulnerable to transition costs to renewable energy and least able to make adjustments in their live to take advantage of new technologies. Additionally, perceptions are not static and vary across and within communities; most people value research on the development of renewable energy but, as the actual implementation begins, many become concerned about the visual and ecological impacts of the production of energy. Recognizing that social movements may coalesce around energy use, particularly as it applies to climate change and environmental justice, can provide additional insights as to the role of renewable energy in community life.

Strategic Planning
To facilitate research into the above areas of research, we recommend Faculty hires with expertise in the following areas:
- Perceived risk of renewable energy innovations;
- Social and environmental justice as it relates to the food--energy-water nexus;
- The application of field research, mixed methods, and innovative methods for studying renewable energy and energy policies that involve virtual and immersive reality, analyses of "big data" such as posting on social media, and social network analyses.

Funding is needed to develop collaborative social science-based research teams (with the assistance of staff, post-docs, and course releases) in order to:
- Develop and coalesce on a social science perspective and research questions about renewable energy and technologies;
- Implement and test community outreach programs that could, for example, use augmented reality to provide informed choices about the visual changes that would take place in their communities;
- Train students in interdisciplinary research that crosses social, engineering, and physical sciences with workshops and classes.

Current participants
Janet Swim (Psychology), Jessica Myrick (Media Studies), Alexander Klippel (Geography), Leland Glenna (Rural Sociology)

Education and Outreach
Example Courses: COMM 328; PSYCH 419; CED 417; CED 452:   GEOG 197F: GEOG 560
Outreach activities: TBD, but includes community discussions, working with informal science learning centers, applying new digital technology.

Penn State Electrochemistry Research & Education

Focus

Research and education on electrochemical processes used for producing renewable energy, energy storage, and chemical production and waste gas (e.g., CO_2) conversion. Activities specific to batteries are addressed in the BEST Center plan above.

Highlights

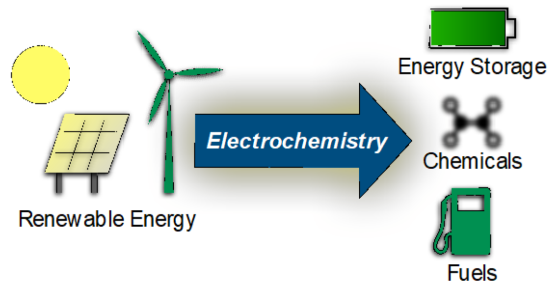
- Penn State has research strengths in electrochemical systems, but we lack a cohesive community and strong leadership.
- Penn State is in a unique strategic position to become a leader in electrochemical conversion and surface electrochemistry with energy applications.

Goals

- Develop intercollegiate leadership for large-scale collaborative efforts.
- Conduct an electrochemistry workshop that brings thought leaders to campus to increase visibility.
- Strategically invest in projects and new people in two collaborative research areas: Electrochemical conversions and surface electrochemistry.

Overview

Electrochemical processes convert electricity into chemical reactions and vice versa. Electrochemical reactions are essential for producing solar energy, converting energy in fuel cells, creating CO_2-neutral fuels, and producing chemicals. In recent years, interest in electrochemical processes has been rapidly expanding. This growth is fueled in part by the introduction of renewable energy sources, such as solar and wind, into the power grid. The electricity created from these sources can be very inexpensive, which opens up new opportunities to use electrochemical processes to produce fuels and chemicals. In an interview in 2017, Steven Chu, the former U.S. Secretary of Energy, emphasized this point:[1] *“Electrochemistry is about to see a real resurgence because if you look over the horizon, electricity’s going to cost three cents, then two cents, and even less per kilowatt hour. At two cents per kilowatt hour, all of a sudden electrochemistry becomes something very real. … That’s very exciting because that means a new world is going to open up.”*



Growing interest in electrochemical processes is currently being demonstrated by new funding opportunities. In 2018, NSF created a new, permanent program in the Division of Chemical, Bioengineering, Environmental and Transport Systems called Electrochemical Systems.[2] The Department of Energy is also heavily investing in electrochemistry research through new programs like ARPA-E’s Duration Addition to electricitY Storage (DAYS) and Renewable Energy to Fuels Through Utilization of Energy-Dense Liquids (REFUEL).

Researchers at Penn State are taking advantage of these opportunities, but there is a sensed lack of broad community or leadership among faculty. This is due in part to the fact that electrochemical processes are cross-disciplinary, with research being conducted in the College of Engineering, the College of Earth and Mineral Sciences, and the College of Science. The BEST Center[3] is focused on battery research but not the broader range of electrochemical technologies for which we have ongoing and growing activities. A consequence of the missing sense of community is perceived inabilities to pursue large, center-level funding opportunities.

Strategic Research Planning

Establishing Penn State as a leading University in the area of renewable energy requires a top-tier electrochemistry community due to the fundamental role electrochemical processes play in transitioning to

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[1] https://www.electrochem.org/redcat-blog/steven-chu-climate-change-energy-solutions/

[2] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505558

[3] http://www.best.psu.edu/

renewables and taking advantage of cheap electricity. To succeed in this area, two issues need to be addressed: the lack of a broad community; and the lack of strategically chosen collaborative research areas. These issues can be addressed through two primary activities.

Create a broad and cohesive electrochemistry community. To accomplish this, we recommend two primary activities:

1. **Obtain support for leadership.** A mid-career or senior level faculty member is needed to lead efforts to coalesce the community. To achieve this, support could be offered for a semester of teaching release to more carefully examine current strengths, weaknesses, collaborative opportunities and venues for funding. This faculty member would develop a website and lead a workshop at *Energy Days* to include external parties in these discussions.
2. **Create an electrochemistry workshop** to bring together Penn State faculty, 5-10 external researchers leaders working in the target research areas discussed below, industry contacts, and program sponsors (e.g., from DoE or NSF). As little as $20k would be needed to support a pilot launch of this workshop, primarily to support site activities and travel for invitees.

Strategically invest in collaborative research areas. Collaborative research efforts should be focused around existing strengths unique to Penn State, notably our strength in materials science. We recommend the two areas to support with new strategic faculty hires and seed funds.

1. **Electrochemical conversions**. Penn State is already a leader in electrocatalysis, but there has been limited success in securing large-scale grants. To increase the probability of success, this new research area requires new combinations of instrumentation that are not currently available on campus. Therefore, we propose a one-year seed project aimed at: (1) developing a new collaborative team on conversions; (2) producing preliminary data that would support an ERC-scale project team proposal; and (3) constructing a differential electrocatalytic flow through reactor ($60k for supplies and student time).
2. **Surface electrochemistry.** Penn State has the potential to become a key player in this field, which leverages our experimental capabilities to enhance computational simulations and discovery. To improve capabilities and increase awareness, we propose seed funds to create a new electronic database of surface electrochemical properties ($60k to partially support a post-doc; $30k to support initial computational infrastructure). The work done with the seed funds would be subsequently leveraged for a large proposal, such as an ERC or DOE center.

Strategic Education Plan

Electrochemistry is becoming an increasingly important component of science and engineering. Currently, the topic is taught to undergraduates in Chemistry and Materials Science, but not in engineering. For example, Chemical Engineering undergrads have no exposure to electrochemistry despite taking fundamental courses related to relevant processes. The undergraduate curricula in relevant departments will be evaluated to look for opportunities for incorporating electrochemistry. This effort will be led by Prof. Michael Janik (Undergraduate Program coordinator for Chemical Engineering).

List of participants

Primary Contact: Christopher Gorski
Participants: Ismaila Dabo, Sergei Lvov, Derek Hall, Bruce Logan, Adri van Duin, Chris Rahn, Mike Hickner, Mike Janik

Education and Outreach

Undergraduate Minor: Electrochemical Engineering; *Graduate Minor*: Electrochemical Science and Engineering

Undergraduate courses: EEGE 420, Hydrogen and Fuel Cells; EGEE 437, Design of Solar Energy Conversion Systems; EGEE 441, Electrochemical Engineering Fundamentals; EME 407, Electrochemical Energy Storage; ESC 455, Electrochemical Methods Engineering and Corrosion Science; MATSE 421, Corrosion Engineering; ME 403, Polymer Electrolyte Fuel Cell Engines; EGEE 442, Electrochemical Methods. *Graduate courses*: EME 541, Electrochemical Science & Engin. Fundamentals; CHEM 524, Electroanalytical Chemistry; ESC 501, Solar Cell Devices; CHE/MATSE 510, Surface Characterization of Materials; CE 556, Environmental Electrochemistry

Penn State Hydrogen Energy (H_2E) Center

Focus

Research on renewable production of hydrogen gas, and advancing development of fuel cell technologies for electrical power generation from hydrogen.

Highlights

- Penn State has historically had presence as a national leader in technologies related to fuel cells.
- A hydrogen fueling station is located on the University Park campus (although currently inactive).
- Penn State is a leader in research on: microbial fuel cells for renewable electricity generation, and microbial electrolysis cells for electrochemical hydrogen production from waste biomass.
- Cutting edge materials research includes developing non-precious metal catalysts using nickel and phosphorus compounds for the catalyzing electrochemical hydrogen production.

Goals

- Increase external funding for research in a variety of electrochemical technologies, especially fuel cells.
- Enhance research on non-precious metal catalysts for water splitting and hydrogen evolution.
- Focus on technologies and processes that can eliminate the use of fossil fuels for H2 production.
- Successfully link solar or wind electricity generation with electrochemical H_2 and ammonia production (two-stage processes).

Overview

Over 50 billion kg of H_2 is used globally, and 20% of that in the US. Nearly all of this H_2 is made from fossil fuels, with more than half produced using natural gas. About 53% of the H_2 produced is used just to make ammonia for fertilizers using the energy-intensive Haber-Bosch process. Changing how we produce and use H_2 can have a profound impact on energy sustainability, agriculture, and global climate change. H_2 can be a focus point in the energy-water-food nexus.

Hydrogen and fuel cell research has increased in the US in recent years, recovering after a large decline in funding over a decade ago, following a shift in the US towards battery research. Globally, the demand for hydrogen and fuel cell technologies has remained strong, as H_2 gas is an environmentally friendly fuel in fuel cell vehicles as it produces only water, and thus it is also an excellent method of energy storage.

The H_2E Center is the focal point at Penn State for all hydrogen and fuel cell research spanning topics related to: hydrogen production, storage, and utilization; and educational activities that include seminars, classes, and participation in professional societies. Launched in 2000, one notable activity of the H_2E Center was “Hydrogen Day”, with the first event held on February 5, 2003, one week after President Bush announced a $1.2 billion investment to fund hydrogen research, education and infrastructure.

Hydrogen fuel cell vehicles and devices continue to have strong global industrial interest. Hydrogen fuel cell cars can travel 300 miles or more without refueling, and most major automotive companies have vehicles for lease or sale. Hydrogen buses and trucks are a growing sector due to their fast refueling times and often limited travel distances from fueling stations. For example, Anheuser-Busch and Nikola Motor Company recently announced an order for up to 800 hydrogen-electric powered semi-trucks. Forklifts powered by fuel cells are one of the fastest growing hydrogen applications due to their short refueling time and ability to operate indoors with no emissions other than water. The industrial growth of hydrogen fueled technologies will drive the need for increased education and research in these areas.

Funding sources for research by members of the H_2E Center include the Department of Energy (DOE), National Renewable Energy Laboratory (NREL), National Science Foundation (NSF), Air Products and Chemicals Inc., KAUST, US Filter, and others. Current research activities at Penn State include:

- High temperature fuel cells
- Proton exchange membranes for hydrogen fuel cells
- Catalysts for hydrogen gas production
- Hydrogen fuel cell demonstrations: fueling station, fuel cell buses, fuel cell performance
- Microbial fuel cells for electricity production from waste biomass
- Bioelectrochemical hydrogen gas production using microbial electrolysis cells, with an emphasis on plant-based feedstocks
- Hydrogen gas for environmental remediation of pollutants
- Electrochemical research that can enable ammonia production without the need for the Haber-Bosch process (or to augment this process)

Strategic Planning

The greatest future impact of the H_2E Center can be through focusing on electrochemical technologies, specifically in renewable hydrogen gas production to reduce carbon dioxide emissions from current methods reliant on fossil fuels. The emergence of cheap solar power at costs of $0.03/kWh (comparable to natural gas, and less expensive than other fossil fuels), and the rapid growth of wind power (~7% of US electricity production) has the potential to radically change the hydrogen market. Inexpensive but intermittent solar power requires efficient energy storage technologies, and producing hydrogen gas using solar power and storing it for use in fuel cells could be an effective solution.

The Penn State H_2E Center should promote and enhance activities in electrochemistry and electrochemical engineering, as foundations for advancing scientific and engineering education and research. Key strategic needs are:

- Faculty hires in the area of electrochemistry and electrochemical engineering (through the Electrochemistry Strategic initiative)
- Fostering collaborative research on solar-to-hydrogen conversion, storage, and use through seed grants and Foundation funding
- Increasing materials research on water splitting and hydrogen evolution catalysts and processes through seed grants
- Building expertise in electrochemistry, particularly in water electrolyzers, hydrogen-evolving catalysts, and hydrogen storage
- Demonstrating H_2 technologies using hydrogen fuel cell vehicles
- Improving our global profile in the hydrogen and fuel cell areas, primarily through building expertise in renewable hydrogen technologies and focusing on the importance of hydrogen in ammonia production
- Emphasizing H2 as a focal point in the water-energy-food nexus.

List of participants

Primary contact: Prof. Bruce Logan, 212 Sackett.
Participants (partial): Joel Anstrom, Moses Chan, John Golbeck, Derek Hall, Michael Hickner, Bruce Logan, Sergei Lvov, Tom Mallouk, Jay Regan, Chunshan Song, Raymond Schaak, Chao-Yang Wang.

Education and Outreach

Minor: Electrochemical Engineering (www.eme.psu.edu/academics/undergraduate/minors-options/elche-minor)
Courses: EGEE 420, Hydrogen and Fuel Cells; EME 570 (MATSE 570), Catalytic materials; ME 403, Polymer electrolyte fuel cell engines; EGEE 441 Electrochemical engineering fundamentals; EME 407, Electrochemical Energy Storage; CHEM 445 Electrochemistry and chromatography; CHEM 524, Electroanalytical chemistry.
World campus: N/A
Outreach activities: Hydrogen Days

Supplemental information

Website: https://www.engr.psu.edu/h2e/index.html
Location (virtual): Directed by Prof. Bruce Logan, 212 Sackett Building.

Penn State Membrane Research & Education

Focus

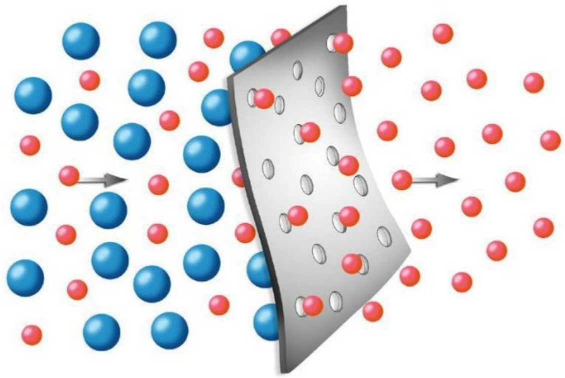
Membranes are integral to many new energy systems, and require collaborations between membrane materials scientists, engineers, and systems researchers. Research and education in membrane processes at Penn State includes fuel cells, electrolyzers, separations, air and water purification, renewable energy, and chemical production (e.g., CO_2 and reduced products)..

Highlights

- Penn State has established national leadership in membranes through a new integrative Center funded by the National Science Foundation Industry–University Cooperative Research Centers Program (I/UCRC), directed by Prof. Andrew Zydney.
- Membranes are being developed for specific applications to enable new device operation regimes, such as high temperatures, alkaline or acidic environments, chemical production, or to withstand fouling and abrasion.
- Penn State has several faculty members studying membranes in detail, but there is a larger pool of researchers using membrane materials for specific applications. These communities – membrane makers and users – need to work together across interdisciplinary fields.
- Membrane cost and performance are key factors in many new renewable energy technologies, including salinity gradient energy, thermal and other advanced batteries, chemical production, and separations.

Goals

- Increase impact in membranes research through additional faculty hires.
- Develop greater industrial connections for funding through I/UCRC that leverages membranes in areas outside of the current main focus (bioprocessing).
- Improve advertising for growing the general knowledge of the importance of membranes, and success of the membrane program at Penn State.
- Develop established courses in membrane processes.



Overview

Membranes are separation materials that are used to purify, concentrate, and recover key ions and molecules during various processes. For instance, membranes serve critical roles in gas purification (e.g. separation of CO_2 from CH_4), chemical separation (in biotechnology applications or for water desalination) in energy technologies such as fuel cells and batteries (as solid electrolytes for ion transport), and many other energy and environmental technologies where a semipermeable barrier is required. Interest and applications of membrane processes has been rapidly expanding due to the importance of themes such as alternative energy, low-energy industrial processing and separations, process intensification, resource recovery, and distributed chemical manufacturing. This growth is complemented by the introduction of renewable energy sources and new concepts in clean energy such as harvesting the energy of salinity gradients. Membrane development is focused in materials science, polymer, and chemical engineering, with the applications of membranes spanning environmental engineering, mining and critical elements separations, green energy, electrochemical technologies, and other applied science and engineering problems

Membranes have played a critical role for a long time in chemical processing, but a key new area of research at Penn State is in purification of new medicines in the bioprocessing industry. The most important membrane activity on campus is the recently-awarded National Science Foundation I/UCRC headed by Prof. Andrew Zydney in Chemical Engineering. This I/UCRC is a node of the MAST center out of University of Colorado.[4] MAST is a broad-based program focusing on the needs of industry.

[4]. http://mastcenter.org

While current activities in the center are focused on our current industrial partners in bioprocessing and membrane characterization, topics are not limited to this area. Thus, as the center builds momentum, the activities at Penn State can expand into other areas under this program.

Membranes are critical to many new areas of energy research. At Penn State, in energy research there is currently a focus on applications in advanced batteries and fuel cells, with large industries that can be served immediately by a robust research and engineering program in membrane materials. There are also developing technologies, for example thermal batteries, electrochemical synthesis, and other types of electrochemical cells which rely upon improved membranes for achieving increased performance. Since membranes support the development of these new technologies, there is continued need for coordination and leadership outside of the MAST program. Because of the interdisciplinary nature of membrane research, sustained teams are needed to seed and to develop robust programming across application areas such as chemical separations, green energy, and novel processing.

Strategic Research Planning

Penn State is well positioned to improve leadership in the area of membranes due to its excellence in material science, as fundamental membrane research (mostly in the areas of structure and transport) relies upon materials development and applications. To further succeed in membranes at Penn State, two issues need to be addressed: the lack of sustained teams and leadership outside of MAST; and the lack of advertising on current membrane work at Penn State.

Create a broad and cohesive membrane community. The present community in membranes at Penn State is too small and isolated, and key researchers in this area are set to leave the university. First, we need to build and diversify the community, by hiring additional membrane-focused faculty. Only two or three new faculty members are needed to cover the main research and application areas related to energy. These faculty could be located in a number of departments, such as engineering disciplines such as Chemical Engineering or Materials Science and Engineering, or Chemistry. Second, we need to better coordinate advertising and outreach. This can be in conjunction with MAST, but the community should strive to nucleate new foci to grow I/UCRC activities.

Strategically invest in collaborative research areas. Collaborative research efforts should be focused around existing areas unique to Penn State, notably our strengths in engineering and materials science. We recommend the two areas to support with new strategic faculty hires and seed funds. We need to focus on membrane materials development. There are many new materials, such as graphene, coming online for advanced membranes. Penn State has some activities in this space, but much of the membrane work at Penn State is focused on polymers, composites, and known materials. There are big opportunities in new 2D materials for membranes and novel membrane chemistry.

Emphasize membranes for new electrochemical processes. Penn State must participate more in membrane research for advanced electrochemical systems. Key areas include: solid-state and advanced batteries, such as thermal and flow batteries; resource recovery and synthesis using electrochemical processes; and hydrogen production and CO_2 conversion through electrolysis. These areas encompass current priority research at the Department of Energy and there will be many opportunities on the horizon in these areas.

Strategic Education Plan

Membranes are becoming an increasingly important component of science and engineering, but there are few formal courses in membranes across the university. We need to explore opportunities for short courses and workforce development.

List of participants

Primary Contact: Michael Hickner
Participants: Andrew Zydney, Bruce Logan, Enrique Gomez, Xueyi Zhang, Mohammad Rezaee, Athanasios Karamalidis.

Education and Outreach

There are few formal courses in membranes at Penn State. These courses are generally offered as electives or as modules in existing courses, but there is little formal coordination across the university.

Supplemental information

Website: https://sites.psu.edu/membranes/

Solar Energy Research and Education

Focus
Research on solar energy technologies for building integration and storage; Education and training of tomorrow's solar workforce.

Highlights
- **Visibility.** University Park is constructing a utility-scale photovoltaic array for power production and hands-on student training.
- **Photovoltaic materials research.** Penn State has strength in thin film photovoltaic materials.
- **Educational programs.** Penn State has solar-related course offerings in multiple departments and online via World Campus.
- **Strong industry ties.** Penn State has connections with many of the leading solar panel manufacturers and installers across the globe.

Goals
- Build strength in building-integrated photovoltaics and solar energy storage research, with a focus on materials that leverages the opportunities through the MRI.
- Establish a nexus between solar energy, battery, and fuel cell research at Penn State.
- Make Penn State a national destination for residential and online solar education and training.
- Provide the foundation needed to compete for center-level funding opportunities in the future.

Overview
Solar energy has passed a tipping point. The installed solar panel capacity worldwide is doubling every two to three years – faster than the early stages of cell phone adoption. In the United States, the cost of solar power has now reached grid parity (i.e. at or below that of fossil fuels) in twenty states and is projected to fall by another factor of two within the next decade. Solar panel installers are correspondingly projected to be the fastest growing occupation during the same time period.

The growing contribution of solar power to the global energy mix over the next two decades is thus coming into focus and will involve large arrays of


MorningStar Solar Home

solar panels installed in fields and on rooftops. This development is already becoming evident at Penn State, with the MorningStar Solar Home on campus, the solar panel array outside the Office of Physical Plant, and the 2 MW utility-scale photovoltaic array currently being constructed next to Beaver Stadium.

Beyond the horizon of 2030, however, new photovoltaic and storage technologies will be required to sustain the growth of solar energy and enable it to truly become a major player in the world energy mix.

This means moving beyond the 'one size fits all' solar panel of today (where the same product is used for urban rooftops and utility-scale solar farms) to solutions that are integrated in the fabric of our infrastructure and transportation. It means being able to store this energy in advanced batteries or in the form of fuels such as hydrogen. From building-integrated photovoltaics needed for 'net-zero' energy buildings to flexible high efficiency cells that recharge and extend the range of electric vehicles, the future of solar energy research lies in integration and storage.

Education is a more immediate need to supply the growing solar workforce over the next decade. **Currently, no university in the US is recognized as the destination for students, industry- and government-sponsored trainees who want to be a part of the solar industry.** Penn State has some of the building blocks to do this, including several residential courses and a graduate certificate in solar energy through the Renewable Energy and Sustainable Systems (RESS) program. However, these offerings are currently too small and too sparse for Penn State to be a major supplier of graduates for the solar workforce.

Strategic Planning

The solar research community at Penn State has a nascent strength in the area of thin film photovoltaic materials and is surrounded by complimentary strengths in battery, hydrogen, and energy-efficient buildings research. However, the community is vulnerable to recent impacts caused by departures of multiple faculty with solar expertise. Thus, there is an acute need for new researchers who can fill these gaps and build the connections between material science, engineering, and architecture that will enable PSU to compete in the translational photovoltaics and storage research areas of the future. To meet this need, we recommend the following actions:

- Hire a senior solar-related faculty member in Chemistry with expertise in solar fuels.
- Create 3 tenure-track faculty lines in a cluster hire targeting a specific opportunity area for PSU such as, e.g. solar fuels or building-integrated solar technologies.
- Support a year-long seminar series under the banner of Energy 2100 to help identify these individuals and determine the hiring focus.
- Provide internal seed funding through IEE for research at the intersection of photovoltaics and electrochemistry to catalyze new collaborations between existing faculty members on solar energy storage.
- Hire 3 teaching faculty to expand residential and online course offerings in solar project planning, finance, manufacturing, hardware, and policy development, with the goal of making PSU a top supplier of graduates that enter the growing solar industry.

List of participants

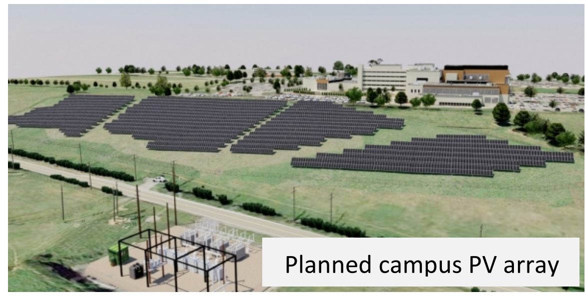
Primary contact: Prof. Chris Giebink, 209H Electrical Engineering West.

Participants: John Asbury, Enrique Gomez, Jeffrey Brownson, David Riley

Education

Courses: EGEE 437, EME 810, EME 812, EME 811, AE 868, AE 878

World campus: RESS program Graduate Certificate in Solar Energy.



Planned campus PV array

Outreach activities: MorningStar Solar Home tours for the public; Engineers Without Borders student trips to install photovoltaic systems.

Sustainability Assessment Modeling of Renewable Energy Systems at Penn State

Focus

Research on the integrated biophysical, socioeconomic, policy, and institutional impacts of new and existing renewable energy technologies, and the tradeoffs, co-benefits, and synergies of alternative technology pathways.

Highlights

- Penn State is an international leader in many of the disciplinary aspects of sustainability assessment such as: complex systems modeling; computable general equilibrium modeling; supply chain analysis; advanced visualizations and immersive technologies; life cycle analysis; political-industrial ecology; socio-ecological systems; and decision-making under uncertainty.
- Despite Penn State's robust interdisciplinary research portfolio, there is a lack of cohesive and sustained training opportunities for systems assessment modeling and decision making in work related to clean technologies, such as renewable energy sources.

Goals

- Establish a new resource/training center for sustainability modeling, data science, and systems assessment related to renewable energy.
- Increase capacity for sustainability assessment-guided research through strategic investment in training for research teams investigating renewable energy pathways, including energy production, storage, and conversion.

Overview

Faculty across Penn State use several different strategies and tools to model complex systems and inform decision making, many which can be applied to the analysis of renewable energy systems, and their interaction with other commodity flows, such as food and water resources (Fig. 1).

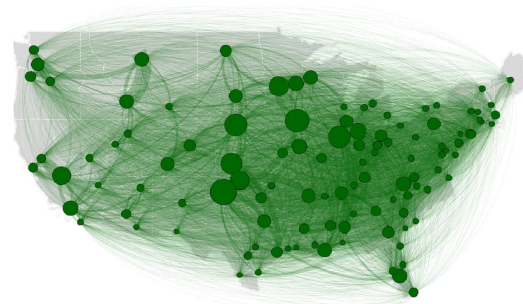


Figure 1: Illustration of the food and energy commodity flow network across the United States. Larger nodes represent increased connectivity.

A large number of sustainability assessment tools have been developed to assist scientists, decision makers, engineers, and designers with analyzing the environmental impacts and tradeoffs of their products and services (ex., energy production and storage), and the role of regulation and market distortions in ameliorating these trade-offs, including:

1. Life cycle analysis, footprint methods, and environmentally-coupled economic analysis;
2. Integrated assessment models;
3. Resilience and vulnerability toolkits;
4. Approaches for decision making under deep uncertainty.

Many of these methodologies suffer greatly from data synthesis issues (i.e., combining data from many different sources), rely on strong assumptions regarding the behavior of economic agents, and are not well integrated with other disciplinary approaches; hence, there are many opportunities for improvement and innovation within the sustainability assessment field. Although a variety of Penn State faculty teams conduct research on these different approaches for sustainability assessment in their areas of interest, few perform LCA modeling, partially due to a lack of available training resources and their interest in using open source software and data to support research reproducibility. However, LCA is particularly useful for assessing the environmental impacts of a product or service through all stages of its life cycle, including raw material acquisition, manufacturing/ production, transportation, use, and end of life. Results from LCA approaches are typically reported in terms of the following impact categories:

1. Global warming potential;
2. Eutrophication potential;
3. Water depletion potential;
4. Human health impact; and
5. Land use impact.

Sensitivity analyses in LCA can help indicate key modifications which can be made to reduce negative environmental impacts of a particular product or service, such as during the production, storage, and conversion of renewable energy technologies.

Current Research

Systems assessment research activities at Penn State have historically been supported by: the National Science Foundation; the U.S. Departments of Agriculture (USDA), Energy (DOE), and Transportation (DOT); as well as the Pennsylvania Department of Environmental Protection (PA DEP). Current research activities related to renewable energy include:

- Quantifying tradeoffs between water, food, and energy consumption across the United States through tracking commodity flows from origin to point of consumption;
- Analyzing systems optimization strategies for growing crops at watershed scales;
- Analyzing life cycle and techno-economic impacts of biofuel feedstock production and processing;
- Examining the non-linearities and uncertainty of sustainability assessment, accounting for coupled uncertainty across economic and environmental systems;
- Understanding the critical importance of alternative public-policy and regulatory regimes on sustainability assessment.

Strategic Planning

A new Center for Sustainability Assessment is proposed to support this effort, ideally administered under the Institutes of Energy and the Environment (IEE) to enable broad, cross-college collaboration. While the center would support the training and computational needs of sustainability assessment modeling for renewable energy systems, it could expand to serve as a resource for sustainability assessment research and development for other applications across the university. The overall mission of the Center would be to:

- Enhance and coordinate research on the formulation, empirical validation, and implementation of new sustainability assessment methods.
- Identify needs for linking sustainability assessment across spatial, temporal, and jurisdictional scales, from local energy production to global supply chains and impacts, spanning decades into the future, and reflecting adjustments across multiple layers of decision-making and regulatory distortions.
- Support data and computational needs required for performing comprehensive sustainability assessment.

To enhance activities in this area, it is proposed that Penn State:

- Hire faculty and post-docs with systems assessment expertise (ex., Industrial Ecology position in ABE)
- Develop new courses (with summer salary support): 200-level GEN ED course on systems assessment modeling and decision making; 400-level course on Industrial Ecology.
- Offer a ~3-wk summer training course on LCA (start by bringing in external training group, which we can then adapt/adopt).
- Provide online training opportunities for students and researchers.
- Coordinate an external speaker seminar series on sustainability assessment (hosted and organized by IEE or other staff).

List of participants

Primary contact: Rachel Brennan, 231-K Sackett (rab44@psu.edu).

Participants: Jennifer Baka; Seth Blumsack; Rachel Brennan; Caitlin Grady; Joel Landry; Alfonso Mejia.

Education and Outreach

Online courses: EME 504, Foundations in Sustainability Systems; EME 805, Renewable Energy and Non-Market Enterprise; EME 807, Technologies for Sustainability Systems

Outreach activities: Energy Days

Renewable Thermal Energy Working Group

Focus

Research focused on identifying and exploiting thermal energy resources for the generation of carbon-free electrical power.

Highlights

- Thermal energy research involves diverse science. Physical scales of interest range from the nanoscale up to geographical scales.
- There are many fields of research at Penn State related to thermal energy, but no unified effort to promote interdisciplinary collaborations.
- Both technology development and robust integration strategies are necessary for future advances in waste heat utilization.

Goals

- Increase funding and activities through strategic investment in research related to thermal energy technologies.
- Make Penn State a leader in thermal-battery research for waste heat recovery and storage.
- Encourage collaboration across Penn State to solve technical and implementation challenges facing thermal energy technologies.

Overview

Thermal energy is both an important primary energy resource and also a byproduct of many industrial processes. Electrical power generation from thermal sources comes primarily from geothermal electricity generation and power conversion from industrial waste heat. Penn State has many thermal experts conducting research in a wide variety of areas, including power production (from geothermal, coal, gas, or nuclear sources), combustion systems, fundamental heat transfer physics, and high-performance materials. The opportunity exists to leverage Penn State's thermal expertise for the development of advanced, carbon-free thermal energy technologies.

Geothermal power generation is the use of natural, high-temperature geothermal resources to generate steam or superheated gas for use in a power generation cycle. Geothermal power generation stations are typically installed where near-surface

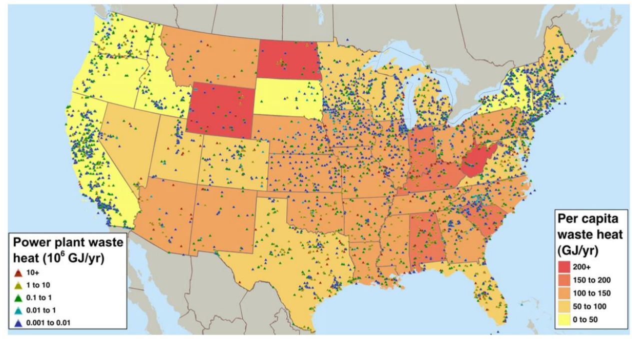


Figure 1. Power plant waste heat in the United States (Rattner, Garimella, 2011)

geothermal resources are abundant. The geothermal power generation capacity worldwide is currently equivalent to about 6 large-scale coal power plants and is projected to increase 40% by the year 2020.

Current research efforts are focused toward extending geothermal power generation to a wider range of geographical sites. Geothermal research activities at Penn State include:

- Simulating enhanced geothermal system implementation and performance
- Enhancing drilling and extraction technologies
- Understanding permeability and induced seismicity from fracturing processes.

Waste heat is thermal energy that is not utilized due to industrial process inefficiencies. Typical efficiencies of large-scale electrical power generation range from 25-44%, while heating systems may achieve efficiencies of over 80%. It is estimated that between 20% and 50% of all energy used by the industrial sector in the United States is lost through waste heat.

Waste heat can be recovered through storage and re-use or through conversion into electricity. The usability of waste heat is determined by its temperature, with sources below 230°C considered low-grade, between 230°C and 650°C considered medium-grade, and above 650°C considered high-grade with the most potential for energy conversion. It is estimated that over 90% of all waste heat is low- to medium-grade.

Technologies to improve waste heat recovery, storage, and re-use have historically seen a consistent level of research activity. Funding has primarily been through the Department of Energy (DOE), the National Science Foundation (NSF, which has a specific Thermal Transport Processes program) and through a variety of industry support. Current research activities at Penn State include:

- High-performance heat exchanger development
- Thermoelectric and pyroelectric materials
- Combined heat-and-power generation
- Building thermal energy storage
- Thermally-chargeable battery development.

Thermal batteries are a particularly important opportunity area for research. They originated at PSU, provide long-term energy storage, and thus far achieve the highest power density for electrochemical low-grade waste heat conversion. With the support measures described below, Penn State can become a leader in this new and rapidly growing area of research.

Strategic Planning

The greatest future impact of renewable thermal energy resources will be achieved by more effectively capturing, storing, and converting low- and medium-grade waste heat and the development of next-generation geothermal power systems. Integrating waste heat storage and conversion systems into future energy-efficient and solar-powered buildings could also deliver an enormous impact.

Penn State should promote activities that enhance technological innovation and improve our understanding of thermal transport phenomena. A focus on the unique integration needs of these technologies should also be targeted. Penn State initiatives should encourage:

- Research on thermal batteries to gain knowledge of how new chemistries and convective transport affect power generation. Penn State can become a leader in this field.
- New material development for building thermal energy storage, including molten salt materials that are cost-effective and non-corrosive.
- Nano-material development that will lead to scalable materials for enhanced solid-state thermal energy scavenging.
- Phase-change system research that improves the efficiency and implementation cost of gas-liquid heat transport technologies.
- Technologies and strategies to minimize the capital cost and physical footprint of geothermal and waste heat recovery technologies.
- Advanced control systems for the integration of renewable and conventional thermal technologies with energy storage systems in cost- and policy-effective ways.
- Exploration of the nexus of solar energy and thermal energy storage for future buildings.
- Regulatory improvements that incentivize implementation of new technologies.

Specifically, Penn State can spur thermal-energy research through:

- Targeted seed grant funding to encourage continued growth in the research areas identified above, while also promoting new collaborative partnerships with industry or government labs.
- Cost-share rewards for successful interdisciplinary external proposals in thermal energy research.
- Uniting the diverse research areas related to thermal energy at Penn State by establishing a University-wide thermal energy research center.
- Leveraging this center to create new outreach programs to develop customized implementation plans for local communities to transition to renewable energy.
- Encourage fundamental-to-applied research activities by investing in large-scale physical test beds for technology demonstration.

List of Participants

Primary contact: Matthew Rau, 301B Reber

Participants: Bruce Logan, Derek Hall, Mark Stutman, Scott Wagner, James Freihaut, Derek Elsworth, Alex Rattner, Susan Stewart, Mike Manahan, Hojong Kim.

Education and Outreach

Departments: Engineering (Mechanical, Electrical, Architectural, Aerospace, Energy and Mineral, Civil), Materials Science and Engineering

Courses: Undergraduate: ME300, ME315, ME410, ME411, ME441. Graduate: ME512 (Conduction Heat Transfer), ME513 (Convection Heat Transfer), ME514 (Radiation Heat Transfer), ME515 (Two-Phase Heat Transfer), ME523 (Numerical Methods in Heat and Mass Transfer), EGEE 497 (Sustainable Energy in New Zealand and Geothermal Energy Engineering)

World campus: see ME500-level courses above

Outreach activities: Potential activities include: DOE Student Geothermal Competition, Home appliance energy efficiency research programs for secondary school students.

Supplemental information

Graphics: (https://psu.box.com/v/Energy2100-Thermal)

Penn State Wind Energy

Focus

Transdisciplinary research addressing pressing wind energy strategic areas such as meteorology, rotor design/structure, manufacturing systems, policy, siting/deployment, finance, system health monitoring and grid integration; and education and outreach efforts to support a growing need for a wind energy workforce.

Highlights

- Established as a leader in modeling aeroacoustics (PSU-WOPWOP wind turbine noise propagation code), and wind turbine design and analysis tool XTurb-PSU
- Internationally recognized research in rotors and blades (e.g. the Vertical lift research center of excellence, VLRCOE) and power systems and controls for advancing wind turbine research and development
- Recognized leader in sensing, analysis and modeling of the atmospheric boundary layer, turbulence, ice & snow physics, as well as forecasting and weather risk via the largest and most established Meteorology department in the country.
- Proficiency with systems design and practical applications through the Applied Research Laboratory (ARL), with expertise in manufacturing analysis design tools, control co-design, and system health monitoring.
- Nascent wind turbines at Sustainability Experience Center
- Established education and impactful outreach activities

Goals

- Enhance collaboration on future research opportunities through engineering, meteorology and ARL through increased interactions between units working in wind related areas at PSU via wind topic meetings and workshops
- Identify opportunities for new funding streams for technology and outreach.
- Elevate current education initiatives to increase enrollment and create linkages to other relevant programs
- Create a sustainable path for outreach efforts, expanding via Repowering Schools and Sustainability Experience Center
- Educate decision makers (e.g. township supervisors)

Overview

Wind energy is a mainstream resource in our electricity supply, representing 30% of all U.S. capacity additions over the last decade and currently rivaling hydropower as the lead renewable energy resource in the United States. Over 90 GW of wind power capacity is currently installed in the United States with another 37.9 GW under construction at the end of the 3rd quarter of 2018[1].

Increased rotor diameters have begun to dramatically increase wind project capacity factors. The average

generating capacity of newly installed wind turbines in the U.S. in 2017 was up 8% over the previous year and up 224% since 1998-1999[2].

The average installed cost of wind projects in 2017 have decreased 33% from a peak in 2009-2010 to $1,611/kW and average levelized long-term pricing from wind power sales agreements has dropped to 2 cents/kWh (dominated by the central U.S. region)**Error! Bookmark not defined.**. U.S. offshore wind is set to greatly increase after the initial 30 MW project off Block Island, RI became operational in January 2017. With this initial experience and investment, future proposed levelized costs have dropped by a factor of about 3 (to ~ 8 cents/kWh). The Block Island project will expand to 400 MW, MA is planning an 800 MW project, and 200 MW are planned in CT. Additionally, several states have made commitments to grow offshore wind capacity in the next couple decades, totaling 25,464 MW of capacity across 13 states[2].

Turbines are also getting taller, with near-future projects deploying progressively taller turbines. A significant portion (>35%) of permit applications to the FAA in early 2018 are for heights over 150 m (to the top of the highest blade)**Error! Bookmark not defined.**.

Funding for research by faculty at Penn State working in wind energy has been provided by Department of Energy (DOE), National Renewable Energy Laboratory (NREL), National Science Foundation (NSF), NASA, and some industry sponsors. Some notable recent research includes:

- Wind energy integration, ABL to power grid
- Wind turbine blade icing
- Distributive cooperative control of wind farms with on-site battery storage
- Wind turbine wake modeling
- Blade manufacturing analysis
- Energy maximization of airborne wind turbines
- Frequency support through MTDC grids with offshore wind farms
- Assessing risk to birds from industrial wind development
- Small wind turbine performance and evaluation
- Modeling and analysis of semi-submersible offshore wind turbines
- Impacts of Clean Power Plan on electricity prices and renewable energy development

Strategic Planning

Penn State is well positioned to make significant impacts in the areas of:

- Icing issues (including prediction, aero performance, and prevention)
- Understanding the marine boundary layer and wind-structure interactions
- Weather risk, for wind operations and construction, onshore and offshore
- Turbulence and blade interactions/wind resource
- Integration of wind/renewable energy into the grid/microgrids

Achieving a more significant national/global leadership position in wind energy research will require:

- Creating a wind energy center with a central theme, and associated administrative support
- Attracting multiple prominent faculty members, ideally in endowed positions, that have strong established research programs and a history of real impact, leadership, and influence on industry practice.
- Seed grants and commitment to cost share to attract existing faculty members to move into this area.
- Leadership of integrative, collaborative activities such as ERC and ARPA-E proposals with internal and external partners. This would require release time, possible additional faculty, and staff support.
- Funding to support a team of grad students (10-20), for example through U.S. Dept of Ed GAANN or NSF IGERT programs, or foundations.
- Pursue ONR DURIP or other instrumentation program to pursue purchase of a Doppler Lidar to support ABL, turbulence, risk and icing studies.

Education and Outreach

The wind industry employed a record 105,500 people across all 50 states in 2017[Error! Bookmark not defined.], the third-largest share of electric power generation employment[3]. Significant growth is projected with scenarios laid out by the U.S. Department of Energy's Wind Vision reports presenting plausible scenarios of 20% wind by 2030 and 35% by 2050.[4] The estimated number of jobs in these scenarios, both direct and indirect, necessary to achieve the proposed levels of wind energy penetration are approximately 350,000 in 2030 and 600,000 by 2050. The U.S. may need more than 50,000 graduate-educated professionals to support 20% wind energy by 2030, four times the current levels.[5]

Thus there has been a focus at Penn State to educate in the area of Wind Energy across all levels of the workforce: outreach, K-12, undergraduate education, as well as graduate level.

- In the outreach and K-12 space, Penn State has been home to the PA Wind for Schools program, funded by the U.S. DOE since 2010. This is being rebranded as PA REpowering Schools, with a fundraising campaign underway to work towards becoming a sustainable, standalone activity. An annual PA KidWind Competition is held at University Park each spring and Teacher Professional Development Workshops are offered a couple of times each year.
- In the undergraduate space, Penn State has been active in the DOE sponsored Collegiate Wind Competition since 2014, placing consistently in the top three and winning three times.
- A DOE sponsored Workforce Development project enabled a Graduate Certificate in Wind Energy, which is currently offered online through the College of Engineering. Penn State is active in the North American Wind Energy Academy (NAWEA) and has an MOU with UMass Amherst, Northern Arizona University and Texas Tech University with a goal of sharing online wind energy courses across institutions.
- A Textbook is under development drawing upon examples using XTurb-PSU wind turbine design & analysis tool

Graduate Certificate in Wind Energy
https://bulletins.psu.edu/graduate/programs/certificates/wind-energy-graduate-credit-certificate-program/

Courses: **EGEE 438**, Wind and Hydropower Energy Conversion; **AERSP 583**[6], Wind Turbine Aerodynamics; **AERSP 880**[6], Wind Turbine Systems; **AERSP 886**[6], Engineering of Wind Project Development**; AERSP 497**, Collegiate Wind Competition; **AERSP 497**, Wind Energy Engineering & Projects

Outreach activities: PA KidWind Competition; STEM Rotor Day; Teacher Professional Development; OLLI Course

List of participants

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Supplemental information

Website: www.wind.psu.edu

Photo resources available from PA KidWind Competitions and DOE Collegiate Wind Competitions