Energy Innovations in CEE

How CEE researchers are finding new ways to save and generate energy

What do deep-sea bacteria have in common with your refrigerator? Both are the subject of CEE research efforts concerning energy generation and use, and may become key factors in the way we think about energy. In the face of climate change concerns coupled with a rising demand for power, researchers are striving to develop energy technology that will meet consumers' needs while preserving the health of the environment. By tackling energy challenges from numerous directions, CEE researchers can give communities the tools they need for the sustainable generation and use of energy.

Developing microbial fuel cells for remote power generation

A bacteria-powered fuel cell has been busily running in CEE Associate Professor **Kelvin Gregory**'s office refrigerator for the past six years, but Gregory doesn't seem to mind. Gregory's recent research, done in collaboration with Professor of Mechanical Engineering **Phil LeDuc**, centers on the utilization of electricity-generating bacteria in remote, self-powered electricity generation, and the fuel cell is a testament to the project's success.

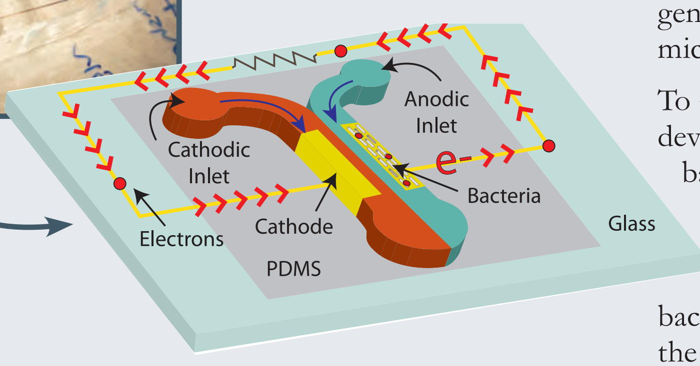


Photo and accompanying diagram of Associate Professor Kelvin Gregory's microbial fuel cell

A fuel cell is a device that physically separates a chemical reaction into fuel production and oxidization, producing an electric current. Gregory studies microfluidic fuel cells, in which the two reactions are separated by fluid moving slowly through small channels. Having researched fuel cells during his post-doctoral work, he decided to pursue the topic further at Carnegie Mellon. He was aware that a particular species of bacteria called Geobacter could produce electricity, and wanted to approach this unique feature from a technological standpoint: could humans combine the electricity generation capabilities of these bacteria with microfluidic fuel cell technology?

To address the question, Gregory set out to develop a tiny fuel cell that could be powered by bacteria. The project was based on previous experimentation with a crude fuel cell composed of a wire half-submerged in ocean floor sediment. As electricity-generating bacteria in the sediment colonized an electrode on the submerged end of the wire, the electricity they produce traveled through the wire to an electrode on the opposing end. Using these "sediment batteries" as a framework, Gregory was able to develop a fuel cell that is only 0.3 microliters in total volume, making it one of the world's smallest fuel cells. (For reference, the average raindrop is over 300 times this size.) "There is an enormous amount of energy that is accessible by bacteria," he explained. "By putting the correct bacteria into a fuel cell, we could ensure a remote source of electricity that would be inexhaustible as long as the cells are alive."

Microbial fuel cell technology is ideal for small-scale electricity generation in environments where using conventional batteries is prohibitively expensive or dangerous. For instance, the cells could power sensing devices that monitor corrosion and pressure levels in deep-sea oil and gas pipelines. And the applications aren't limited to the ocean floor; Gregory envisions microbial fuel cells powering medical devices such as glucose sensors implanted in humans.

Gregory believes microbial fuel cells will play a unique role in energy production. "You won't see microbial fuel cells powering a city," he said. "But when it comes to remote electricity generation in places where humans should not or cannot reach, microbial fuel cells have a huge advantage."

Modeling electromechanical materials for next-generation battery technology

Gregory is one of several CEE researchers who are thinking big by going small. Assistant Professor **Kaushik Dayal** studies the behavior of electromechanical and electrochemical materials, or materials that interact with electricity in fascinating ways. His research group's current work, funded by the Army Research Office, focuses on understanding the physics behind atom-to-atom interactions at the nanoscale level, and has the potential to transform next-generation battery technology.

Dayal and PhD candidate **Jason Marshall** are working to develop a computer method to predict the behavior of electromechanical and electrochemical materials at the nanoscale. This method would provide researchers with valuable information about how these materials behave under electrical loadings. "When you go down to the atomic level, the structures of a material are constantly moving and changing, and you see impurities that you just don't see at larger scales," Marshall explained. "We're working to incorporate those structural defects into a model so researchers can understand more about the structure of materials at the atomic level."

The Dayal group's approach to materials modeling represents the next step in the evolution of multiscale models. Because most current multiscale materials models assume that atoms only engage in short-range interactions with the atoms closest to them, these models are limited in their ability to characterize electromechanical materials, whose atoms interact with every other atom in the system. The Dayal group has successfully incorporated these long-range atom interactions into their model; in addition, they have found a way to run their model in tandem with existing models.

The research being conducted by the Dayal group has numerous applications; in particular, it could transform battery technology for use in hybrid cars and more. "Big batteries are not very efficient," Dayal explained. "The more space between the two ends of a battery, the harder it is to quickly get energy from it. By making a battery about a nanometer long and lining it up with billions of others of its kind, we could theoretically form a larger battery that quickly provides energy." Their work could also have applications in large-scale energy harvesting: systems based on intermittent power sources such as solar power would have the option of storing excess energy in large batteries and utilizing it in times of high demand.

Assistant Professor Kaushik Dayal (right) with PhD candidate Jason Marshall (left)

Dayal framed his group's research as a key step toward energy efficiency, saying, "Batteries are going to be important, and these materials are going to be important for batteries. It is the perfect time to advance these technologies."

Using demand response to manage energy use in buildings

As Dayal and Gregory advance our understanding of energy generation technology, other CEE researchers are designing new ways to regulate energy use in buildings and communities. Assistant Professor **Mario Bergés** is focusing his research efforts on using infrastructure monitoring and machine learning techniques to develop "smart" urban infrastructure—that is, infrastructure that self-regulates in response to changing internal and external conditions. His lab, INFERlab, is currently part of efforts funded by the National Science Foundation, Samsung Electronics, and Hewlett-Packard to make buildings active participants in the power grid through monitoring and control of appliances' energy consumption.

When an appliance draws power from the grid, it leaves a unique electrical signature that can tell engineers how much power it consumes and whether it requires maintenance. The researchers in INFERlab are working to disaggregate a home's total power consumption into individual appliance-level data. These data could then be used to create a central control unit that reduces home energy use in a non-intrusive manner. For instance, some home appliances such as refrigerators can be switched off for short intervals without inconveniencing the user; this results in a small but reliable savings in energy. This concept would then be applied to a collection of appliances across many homes, using them as a single responding unit. Since appliance-level control mechanisms deal with very small amounts of power, they need to take place as a coordinated effort to positively affect the power grid; shutting off a thousand refrigerators for five minutes could make a difference during a power shortage.

Adjusting power demand to fit the supply is known as demand response. Though demand response already occurs on a large scale—utilities offer energy-intensive clients a rebate if they restrict their energy use when demand is high—INFERlab is studying its applicability on a residential scale. "There is a sense that in the near future, there is going to be a more dynamic balancing act between the utilities, who are providing you power, and the consumers," Bergés said. "Both a top-down and bottom-up approach to energy conservation are going to be necessary for that to work."

Anthony Rowe (ECE)

An example of the smart meters used by INFERlab researchers to monitor energy use at the plug level

Bergés' research is happening at the right time. While many renewable power sources such as wind and solar have significant advantages, they are intermittent sources, meaning they are not continuously available. As human reliance on intermittent power sources increases, having the option to instantaneously harvest multiple small energy loads when power supply cannot meet consumer demand will play a key role in energy conservation.

Quantifying the transportation savings of brownfield developments

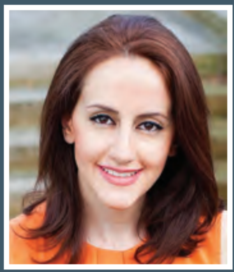
Duquesne Light University Professor **Chris Hendrickson** is also working to characterize consumer energy use, albeit from a slightly different perspective. Hendrickson, Steinbrenner Institute Executive Director **Deborah Lange**, and PhD candidates (now doctors) **Yeganeh Mashayekh** and **Amy Nagengast** recently completed a study of the transportation savings associated with brownfield developments. Brownfields are land that

Tailoring Demand Response to User Preferences

PhD candidate Leneve Ong is working with Bergés to incorporate consumer preferences into building-level demand response. "In demand response, it is difficult for the building operator to prioritize what changes to implement without knowing what's going on inside the building," Ong explained. "If we understand the behavior of different energy-consuming appliances in a particular building, we can estimate the amount of energy that can be saved from that building in times of high demand while respecting the habits of the occupants."

Ong plans to put her methods to the test by outfitting an on-campus computer lab with sensing equipment that gathers data about energy use in the lab. Armed with information about the typical habits of individuals using the lab, Ong can then implement a range of demand response strategies and solicit feedback from the inhabitants. "For example, if we dim the lights at a certain time or reduce the temperature by a few degrees, the people working in the lab can give us information about whether it interfered with their work," she said. "This gives us more active data about the occupants' preferences."

Ong envisions her research leading to a user preference model that uses data from sensors to estimate the extent to which each building in the grid can participate in demand response. This tailored approach to energy use modeling would provide utilities with reliable estimates of their demand response capabilities, while giving customers more control in the demand response process.



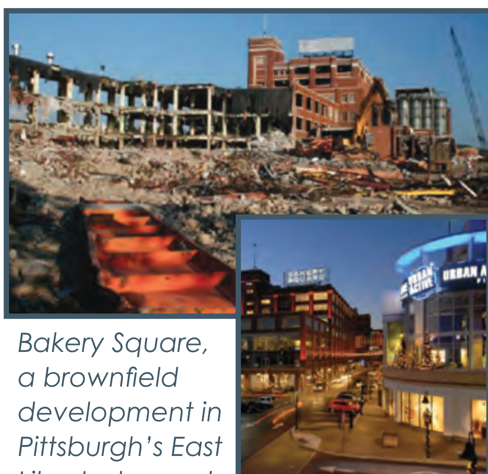
Comparing Strategies for Reducing Vehicular Greenhouse Gas Emissions

Yeganeh Mashayekh, who completed her PhD in Civil Engineering in February, worked with Hendrickson on a project funded by the U.S. Department of Transportation to test the viability of strategies aimed at reducing greenhouse gas (GHG) emissions in light-duty vehicles. She considered a range of strategies, including fuel and vehicle options, low carbon and renewable power technologies, travel demand management, and land use changes. "We wanted to bring these strategies together and see how they interact," Mashayekh explained. "Would we see synergies, or would one strategy limit the effectiveness of another?"

Mashayekh found that while no sole strategy will be sufficient to meet the climate change reduction goals set by the Intergovernmental Panel on Climate Change (IPCC), certain combinations of strategies can bring about significant GHG emission reduction. For instance, travel demand management strategies complement land use changes that encourage high-density development. However, she noted that the public agencies implementing these strategies tend to work independently from each other, thus hampering the development of a more holistic approach to climate change reduction.

Now a post-doctoral fellow at CMU, Mashayekh will be collaborating with public agencies to push for the adoption of more comprehensive policy performance measures. "If we focus only on land use changes, or only on electric vehicles, we won't achieve the climate change goals that have been set for the coming decades," she said. "We must bring these strategies together under one roof in order to meet our goals."

previously housed industrial facilities which left an environmental residue problem—Pittsburgh's Bakery Square development in East Liberty is one example—and the high cost of the initial site cleanup sometimes dissuades developers from investing in them. Despite this disadvantage, the team was curious about the numbers. Because most brownfield developments are urban infill, their inhabitants enjoy a transportation advantage due to their proximity to city centers. Would people living in brownfields incur lower transportation-related costs, and if so, would the savings be sufficient to balance the cost of environmental remediation?



Photos courtesy of Bakery Square

Bakery Square, a brownfield development in Pittsburgh's East Liberty, housed the Nabisco Factory before it was redeveloped in 2006.

With funding from the Environmental Protection Agency, Hendrickson's team compared residential brownfield developments to developments on greenfields, or land that has not been previously developed. Using data gathered from sixteen sites in the U.S., they analyzed the total vehicle kilometers traveled (VKT) and associated travel costs—time, fuel, and external air pollution—of each site's inhabitants. They then compared the calculated costs to the cost of environmental remediation.

Hendrickson's hunch that brownfields would have lower transportation costs than greenfields was correct. The research team found that the VKT, travel time and fuel costs for brownfield residents were less than half of those of greenfield residents, and transportation-related external air pollution dropped by 66%. In total, living in a brownfield development led to annual transportation-related savings of approximately $2,900 per household. Furthermore, they found that the site remediation cost of the brownfields included in the study was offset by transportation-related savings within an average of six years.

These findings on the transportation savings associated with brownfield developments have the potential to inform land use decision-making and policy formation, and may change the way developers and consumers make housing decisions. In addition to reducing travel time and fuel costs for inhabitants, brownfield developments also benefit the surrounding community by ensuring reduced air pollution levels. With the individual and community advantages made clear, policymakers would have reason to incentivize brownfield development by funding all or part of the environmental remediation.

Ultimately, Hendrickson sees the findings as one step closer to energy-efficient development. "We're seeing a resurgence in alternative fuels and energy-efficient forms of transportation, and at the same time there is a growing interest in compact cities," he explained. "Brownfield development is a supply-side change that can help us move toward the idea of a higher-density, energy-aware city."