

Tackling greenhouse gases

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Associate Professor Asegun Henry is researching how to use hot metals like molten tin to store heat from a concentrated solar power system, so it can be used to generate electricity as needed. Credit: Rob Felt/Georgia Tech

The images are ubiquitous: A coastal town decimated by another powerful hurricane, satellite images showing shrinking polar ice caps, a school of dead fish floating on the surface of warming waters, swaths of land burnt by an out-of-control wildfire. These dire portrayals share a common thread—they offer tangible evidence that climate change is affecting every corner of the globe.

According to NASA, Earth's surface temperature has risen 0.9 degrees Celsius since the dawn of the Industrial Revolution. Researchers agree that the rise in temperatures has one primary culprit: increased greenhouse gas emissions.

Greenhouse gases like [carbon](#) dioxide, nitrous oxide, and methane all trap heat in our atmosphere, making them directly responsible for [climate change](#). The occurrence of these gases in our atmosphere has increased exponentially since the late 1800s due to growth in [fossil fuels](#) use across the energy, manufacturing, and transportation industries.

A report from the U.N. Intergovernmental Panel on Climate Change (IPCC), released on Oct. 8, 2018 warned that if the Earth's temperature rises greater than 1.5 C, the effects would be catastrophic. Entire ecosystems could be lost, sea levels would be higher, and extreme weather events would become even more common. According to the IPCC, avoiding this scenario "would require rapid, far-reaching and unprecedented changes in all aspects of society," including a 45 percent decrease in carbon dioxide levels by 2030.

Researchers across MIT are working on a myriad of technologies that reduce greenhouse gas emissions across every industry. Many faculty are looking at [sustainable energy](#). Associate Professor Tonio Buonassisi and his team in the Photovoltaic Research Lab hope to harness the power of the sun, while Professor Alexander Slocum has conducted research in making offshore wind turbines more efficient and economically viable.

In addition to exploring sustainable forms of energy that do not require fossil fuels, a number of faculty members in MIT's Department of Mechanical Engineering are turning to technologies that store, capture, convert, and minimize greenhouse gas emissions using very different approaches.

Improving energy storage with ceramics

For renewable energy technologies like concentrated solar power (CSP) to make sense economically, storage is crucial. Since the sun isn't always shining, solar energy needs to be somehow stored for later use. But CSP plants are currently limited by their steel-based infrastructure.

"Improving energy storage is a critical issue that presents one of the biggest technological hurdles toward minimizing greenhouse gas emissions," explains Asegun Henry, the Noyce Career Development Professor and associate professor of mechanical engineering.

An expert in heat transfer, Henry has turned to an

unlikely class of materials to help increase the efficiency of [thermal storage](#): ceramics.

Currently, CSP plants are limited by the temperature at which they can store heat. Thermal energy from the solar power is currently stored in liquid salt. This liquid salt can't exceed a temperature of 565 C since the steel pipes they flow through will get corroded.

"There has been a ubiquitous assumption that if you're going to build anything with flowing liquid, the pipes and pumps have to be out of metal," says Henry. "We essentially questioned that assumption."

Henry and his team, which recently moved from Georgia Tech, have developed a ceramic pump that allows liquid to flow at much higher temperatures. In January 2017, he was entered into the Guinness Book of World Record for the "highest operating temperature liquid pump." The pump was able to circulate molten tin between 1,200 C and 1,400 C.

"The pump now gives us the ability to make an all-ceramic infrastructure for CSP plants, allowing us to flow and control liquid metal," Henry adds.

Rather than use liquid salt, CSP plants can now store energy in metals, like molten tin, which have a higher temperature range and won't corrode the carefully chosen ceramics. This opens up new avenues for energy storage and generation. "We are trying to turn up the temperature so hot that our ability to turn heat back into electricity gives us options," Henry explains.

One such option, would be to store electricity as glowing white hot heat like that of a light bulb filament. This heat can then be turned into electricity by converting the white glow using photovoltaics—creating a completely greenhouse gas free energy storage system.

"This system can't work if the pipes are temperature limited and have a short lifetime," adds Henry. "That's where we come in, we now have the materials that can make things work at crazy high temperatures."

Henry's record-breaking pump's ability to minimize greenhouse gas emissions goes beyond altering the infrastructure of solar plants. He also hopes to use the pump to change the way hydrogen is produced.

Hydrogen, which is used to make fertilizer, is created by reacting methane with water, producing carbon dioxide. Henry is researching an entirely new hydrogen production method which would involve heating tin hot enough to split methane directly and create hydrogen, without introducing other chemicals or making carbon dioxide. Rather than emit carbon dioxide, solid carbon particles would form and float on the surface of the liquid. This solid carbon is something that could then be sold for a number of purposes.

Converting pollutants into valuable materials

Capturing [greenhouse gases](#) and turning them into something useful is a goal shared by Betar Gallant, assistant professor of mechanical engineering.

The Paris Agreement, which seeks to minimize greenhouse gas emissions on a global scale, stated that participating countries need to consider every greenhouse gas, even those emitted in small quantities. These include fluorinated gases like sulfur hexafluoride and nitrogen trifluoride. Many of these gases are used in semiconductor manufacturing and metallurgical processes like magnesium production.

Fluorinated gases have up to 23,000 times the global warming potential of carbon dioxide and have lifetimes in the thousands of years. "Once we emit these fluorinated gases, they are virtually indestructible," says Gallant.

With no current regulations on these gases, their release could have lasting impact on our ability to curtail global warming. After the ratification of the Paris Agreement, Gallant saw a window of opportunity to use her background in electrochemistry to capture and convert these harmful pollutants.

"I'm looking at mechanisms and reactions to activate and convert harmful pollutants into either

benign storable materials or something that can be recycled and used in a less harmful way," she explains.

Her first target: fluorinated gases. Using voltage and currents along with chemistry, she and her team looked into accessing a new reaction space. Gallant created two systems based on the reaction between these fluorinated gases and lithium. The result was a solid cathode that can be used in batteries.

"We identified one reaction for each of those two fluorinated gases, but we will keep working on that to figure out how these reactions can be modified to handle industrial-scale capture and large volumes of materials," she adds.

Gallant recently used a similar approach for capturing and converting carbon dioxide emissions into carbon cathodes.

"Our central question was: Can we find a way to get more value out of carbon dioxide by incorporating it into an energy storage device?" she says.

In a recent study, Gallant first treated carbon dioxide in a liquid amine solution. This prompted a reaction that created a new ion-containing liquid phase, which fortuitously could also be used as an electrolyte. The electrolyte was then used to assemble a battery along with lithium metal and carbon. By discharging the electrolyte, the carbon dioxide could be converted into a solid carbonate while delivering a power output at about three volts.

As the battery continuously discharges, it eats up all the carbon dioxide and constantly converts it into a solid carbonate that can be stored, removed, or even charged back to the liquid electrolyte for operation as a rechargeable battery. This process has the potential for reducing greenhouse gas emissions and adding economic value by creating a new usable product.

The next step for Gallant is taking the understandings of these reactions and actually designing a system that can be used in industry to capture and convert greenhouse gases.

"Engineers in this field have the know-how to design more efficient devices that either capture or convert greenhouse gas emissions before they get released into the environment," she adds. "We started by building the chemical and electrochemical technology first, but we're really looking forward to pivoting next to the larger scale and seeing how to engineer these reactions into a practical device."

Closing the carbon cycle

Designing systems that capture carbon dioxide and convert it back to something useful has been a driving force in Ahmed Ghoniem's research over the past 15 years. "I have spent my entire career on the environmental impact of energy and power production," says Ghoniem, the Ronald C. Crane Professor of Mechanical Engineering.

In the 1980s and 1990s, the most pressing issue for researchers working in this sphere was creating technologies that minimized the emission of criteria pollutants like nitric oxides. These pollutants produced ozone, particular matter, and smog. Ghoniem worked on new combustion systems that significantly reduced the emission of these pollutants.

Since the turn of the 21st century, his focus shifted from criteria pollutants, which were successfully curbed, to carbon dioxide emissions. The quickest solution would be to stop using fossil fuels. But Ghoniem acknowledges with 80 percent of energy production worldwide coming from fossil fuels, that's not an option: "The big problem really is, how do we continue using fossil fuels without releasing so much carbon dioxide in the environment?"

In recent years, he has worked on methods for capturing carbon dioxide from power plants for underground storage, and more recently for recycling some of the captured carbon dioxide into useful products, like fuels and chemicals. The end goal is to develop systems that efficiently and economically remove carbon dioxide from fossil fuel combustion while producing power.

"My idea is to close the carbon cycle so you can convert carbon dioxide emitted during power

production back into fuel and chemicals," he explains. Solar and other carbon-free energy sources would power the reuse process, making it a closed loop system with no net emissions.

In the first step, Ghoniem's system separates oxygen from air, so fuel can burn in pure oxygen—a process known as oxy-combustion. When this is done, the plant emits pure carbon dioxide that can be captured for storage or reuse. To do this, Ghoniem says, "We've developed ceramic membranes, chemical looping reactors, and catalysts technology, that allow us to do this efficiently."

Using alternative sources of heat, such as solar energy, the reactor temperature is raised to just shy of 1,000 C to drive the separation of oxygen. The membranes Ghoniem's group are developing allow pure oxygen to pass through. The source of this oxygen is air in oxy-combustion applications. When recycled carbon dioxide is used instead of air, the process reduces [carbon dioxide](#) to carbon monoxide that can be used as fuel or to create new hydrocarbon fuels or chemicals, like ethanol which is mixed gasoline to fuel cars. Ghoniem's team also found that if water is used instead of air, it is reduced to hydrogen, another clean fuel.

The next step for Ghoniem's team is scaling up the membrane reactors they've developed from something that is successful in the lab, to something that could be used in industry.

Manufacturing, human behavior, and the so-called "re-bound" effect

While Henry, Gallant, Ghoniem, and a number of other MIT researchers are developing capture and reuse technologies to minimize greenhouse gas emissions, Professor Timothy Gutowski is approaching climate change from a completely different angle: the economics of manufacturing.

Gutowski understands manufacturing. He has worked on both the industry and academic side of manufacturing, was the director of MIT's Laboratory for Manufacturing and Productivity for a decade, and currently leads the Environmentally Benign Manufacturing research group at MIT. His primary

research focus is assessing the environmental impact of manufacturing.

"If you analyze the global manufacturing sector, you see that the making of materials is globally bigger than making products in terms of energy usage and total carbon emitted," Gutowski says.

As economies grow, the need for material increases, further contributing to greenhouse gas emissions. To assess the carbon footprint of a product from material production through to disposal, engineers have turned to life-cycle assessments (LCA). These LCAs suggest ways to boost efficiency and decrease environmental impact. But, according to Gutowski, the approach many engineers take in assessing a product's life-cycle is flawed.

"Many LCAs ignore real human behavior and the economics associated with increased efficiency," Gutowski says.

For example, LED light bulbs save a tremendous amount of energy and money compared to incandescent light bulbs. Rather than use these savings to conserve energy, many use these savings as a rationale to increase the number of light bulbs they use. Sports stadiums in particular capitalize on the cost savings offered by LED light bulbs to wrap entire fields in LED screens. In economics, this phenomenon is known as the "rebound effect."

"When you improve efficiency, the engineer may imagine that the device will be used in the exact same way as before and resources will be conserved," explains Gutowski. But this increase in efficiency often results in an increase in production.

Another example of the rebound effect can be found in airplanes. Using composite materials to build aircrafts instead of using heavier aluminum can make airplanes lighter, thereby saving fuel. Rather than utilize this potential savings in fuel economy to minimize the impact on the environment, however, companies have many other options. They can use this potential weight savings to add other features to the airplane. These could include, increasing the number of seats,

adding entertainment equipment, or carrying more fuel to increase the length of the journey. In the end, there are cases where the composite airplane actually weighs more than the original aluminum airplane.

"Companies often don't think 'I'm going to save fuel'; they think about ways they can economically take advantage of increased efficiency," Gutowski.

Gutowski is working across disciplines and fields to develop a better understanding of how engineers can improve life cycle assessment by taking economics and human behavior into account.

"The goal is to implement policies so engineers can continue to make improvements in efficiency, but these improvements actually result in a benefit to society and reduce greenhouse gas emissions," he explains.

A global problem

The diversity of approaches to tackling climate change is reflective of the size of the problem. No one technology is going to act as a panacea for minimizing greenhouse gas emissions and staying below the crucial 1.5 C global temperature increase threshold outlined by the U.N.

"Remember, global warming is a global problem," says Ghoniem. "No one country can solve it by itself, we must do it together."

In September 2019, the U.N. Climate Summit will convene and challenge nations across the world to throw their political and economic weight behind solving climate change. On a smaller scale, MIT is doing its part to minimize its environmental impact.

Last spring, Gutowski and Julie Newman, director of sustainability at MIT, co-taught a new class entitled 2.S999 (Solving for Carbon Neutrality at MIT). Teams of students proposed realistic scenarios for how MIT can achieve carbon neutrality. "The students were doing real work on finding ways MIT can keep our carbon down," recalls Gutowski.

Whether it's a team of students in class 2.S999 or

the upcoming U.N. Climate Summit, finding ways to minimize [greenhouse gas emissions](#) and curtail climate change is a global responsibility.

"Unless we all agree to work on it, invest resources to develop and scale solutions, and collectively implement these solutions, we will have to live with the negative consequences," Ghoniem says.

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