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Energy Futures

WINTER 2024

MIT
ENERGY
INITIATIVE

Nuclear power plants for the future

Identifying materials for new reactor designs **p. 8**

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MITEI awards Seed Fund grants to six innovative energy projects p. 14

Students build and track-test a hydrogen-powered electric motorcycle p. 24

Podcasts at MIT

Wondering where to begin? We've highlighted some great episodes below to get you started! Subscribe in your favorite podcast app, including Apple Podcasts, Google Podcasts, and Spotify.

Energy Reads is a podcast from the MIT Energy Initiative featuring hand-picked audio articles and "footnote" interviews, covering the latest in energy from MIT.

"Footnote: How cities are reducing emissions by retrofitting buildings"
40% of global carbon emissions come from buildings. MIT Professor Christoph Reinhart joins the podcast to discuss how cities are leveraging retrofits to increase building energy efficiency and reduce their carbon emissions.

"Explained: The 1.5 C climate benchmark" by Jennifer Chu
To prevent worsening and potentially irreversible effects of climate change, the world's average temperature should not exceed that of preindustrial times by more than 1.5 degrees Celsius. But why 1.5 degrees C, and how close are we to achieving this goal?

The **Curiosity Unbounded** podcast brings you behind the scenes at MIT through conversations between MIT President Sally Kornbluth and the people working in its labs and in the field. Along the way, Sally and her guests discuss pressing issues, as well as what inspires the people running at the world's toughest challenges at one of the most innovative institutions on the planet.

"How a free-range kid from Maine is helping green-up industrial practices"
MIT President Sally Kornbluth speaks with Desirée Plata, an associate professor of civil and environmental engineering, about her research and what she wishes students knew about their professors.

On the cover
Many promising designs for improved nuclear power reactors use molten salts as fuels or coolants. But a nagging question has been whether radiation inside such a reactor would increase the corrosion damage that salts generally inflict on metals. Using a specially designed experimental setup, Associate Professor Michael Short and Dr. Weiyue Zhou of nuclear science and engineering found that irradiation can actually make some metals more resistant to corrosion. Their results may point to good metals for use in future molten salt–based reactors. Here, Dr. Zhou prepares a sample metal for tests with the proton accelerator that the researchers use to emulate conditions inside a nuclear power reactor. To read more, turn to page 8. Photo: Gretchen Ertl

Energy Futures

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A letter from the director

Dear friends,

We have experienced an exceedingly busy—and inspirational—fall semester at MITEI. As we work to reform our energy system to address climate change—an effort that will require overcoming many challenges—here at MIT, there is hope. You will find that hope in these pages.

In September, MITEI hosted the Women in Clean Energy Education and Empowerment (C3E) Symposium, and it delivered on its topic: "Clearing hurdles to achieve net zero by 2050: Moving quickly, eliminating risks, and leaving no one behind" (see page 36). Also in September, our Annual Research Conference highlighted strategies for large-scale reductions in greenhouse gas emissions. In a keynote address, Jonah Wagner, chief strategist of the U.S. Department of Energy's Loan Programs Office, said, "Most of the technologies that we need to deploy to stay close to the international target of 1.5 degrees Celsius warming are proven and ready to go." Learn more in the article on page 33.

This edition of *Energy Futures* overflows with reporting on ground-breaking research from across the Institute. Our cover story addresses a major concern in designing promising nuclear power reactors based on molten salt—that radiation inside a nuclear reactor may increase the rate at which the salt corrodes and weakens metal components. In a specially designed experimental setup, the researchers found that radiation can *decelerate* corrosion in some metals under some conditions (page 8).

We also explore the development of an online model that enables users to determine the lowest-cost strategy for decarbonizing a selected U.S. regional power grid (page 3). In case studies, the researchers confirmed that the best strategy differs widely from region to region, and they uncovered an unexpected benefit of having both solar and wind resources available.

This year's MITEI Seed Fund Program awarded $900,000 in grants to six novel projects that show promise for high-impact, transformative energy research (page 14). Among the projects is one that will assess the environmental, sustainability, and governance metrics now used by financial institutions to measure the impacts of mining for minerals needed for clean energy technologies. To date, the Seed Fund Program has supported 209 energy-focused projects with grants totaling $28.7 million.

As always, education is a central focus of MITEI and *Energy Futures*. You'll read about fourth-year dual-degree MBA and chemical engineering PhD student Sydney Johnson, who has been modeling and analyzing ways to decarbonize steel manufacturing (page 26). On page 30, learn about a new MITEI series of online courses in sustainable energy, design, transportation, and policy. And don't miss the story about the MIT Electric Vehicle Team's work to build and track-test a hydrogen-powered electric motorcycle—with an eye on a future hydrogen-based transportation system (page 24).

On page 20, we visit with Catherine Wolfram, the William F. Pounds Professor of Energy Economics at MIT Sloan, who is exploring ways to decarbonize global energy systems while also recognizing that energy plays a central role in spurring economic development. While serving in the U.S. Treasury Department from 2021 to 2022, Wolfram played a key role in setting a price cap on Russian natural gas after Russia invaded Ukraine.

The MIT-spinoff energy startup ecosystem also serves as a source of hope. We feature two startups in this edition. Form Energy is leveraging MIT research to manufacture batteries based on iron and air to help incorporate renewables into the grid (page 38). And Antora Energy is commercializing a thermal battery that stores electricity as heat when wind and solar generation is high and delivers either heat or electricity to large-scale manufacturers to reduce their use of fossil fuels (page 40).

MITEI's research, education, and outreach programs are led by Robert Stoner, PhD. Photo: Justin Knight

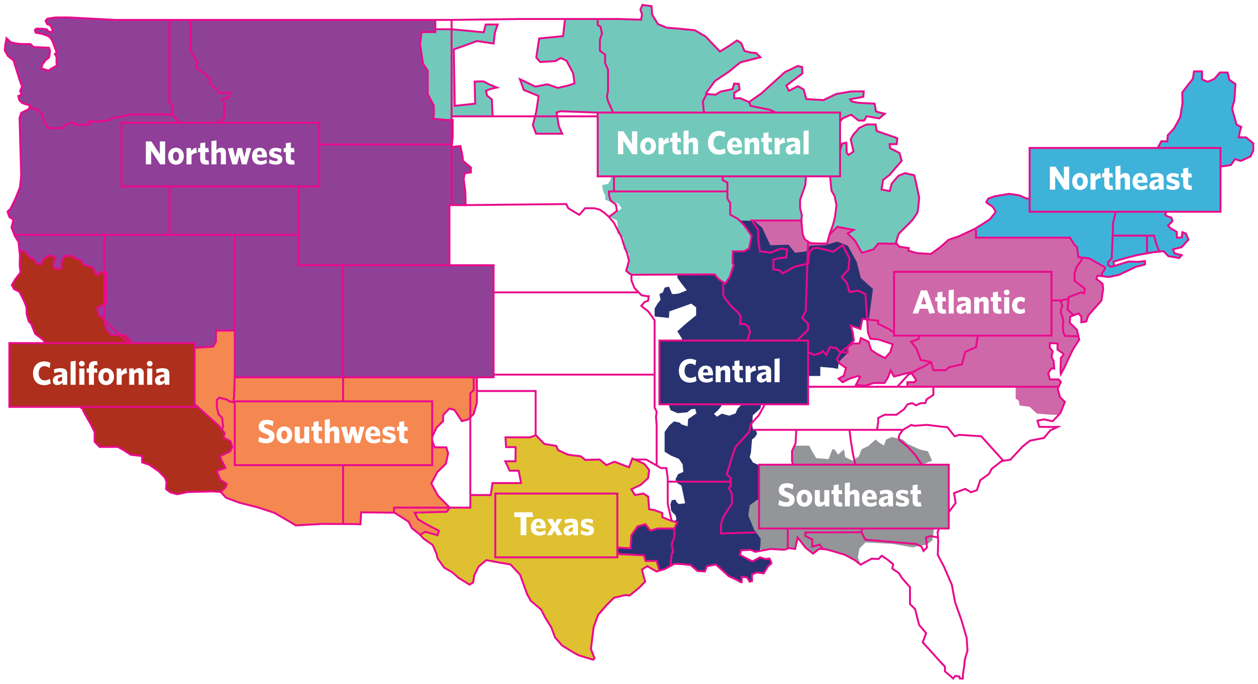
I hope you will enjoy reading more about our work here at MITEI, MIT's hub for energy research, education, and outreach. As we push forward with our urgent efforts to transform the energy system, I thank you for your interest and your support.

With best wishes,

Robert Stoner, PhD
December 2023

Decarbonizing the U.S. power grid

A new MIT online model for regional planning calculates the cost-optimized strategy for specific regions under a variety of constraints and assumptions.



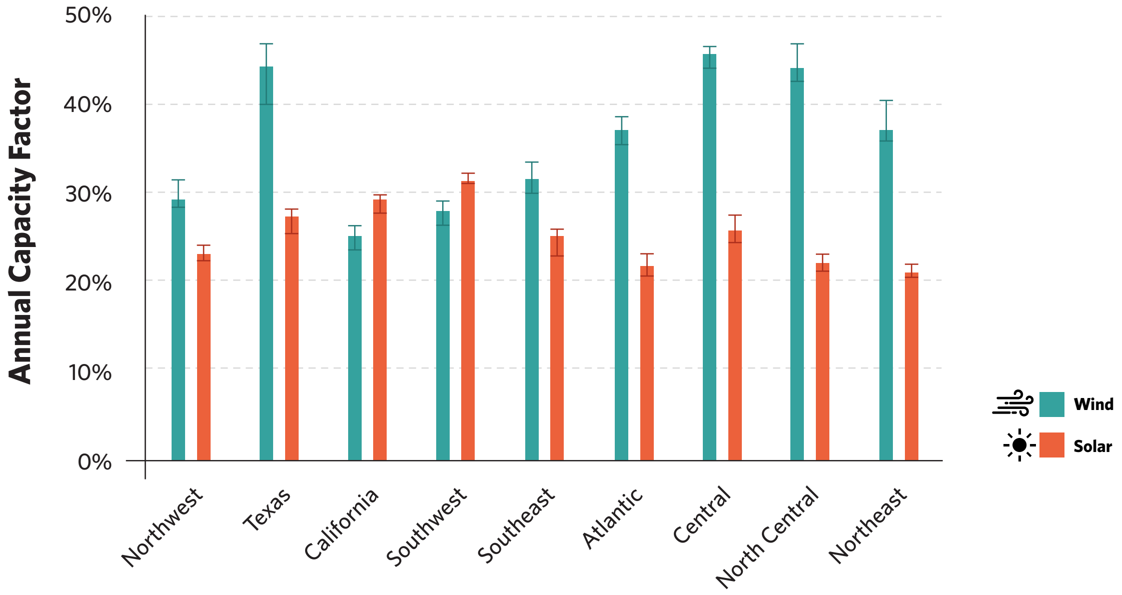
The nine U.S. regional power grids considered in the MIT Energy Initiative (MITEI) analysis. This map shows the boundaries of the nine regions that the MITEI researchers selected for their study of cost-optimized strategies for decarbonizing power grids. They are among the regions recognized by the North American Electric Reliability Corporation (NERC), which oversees all of the interconnected power systems of Canada and the contiguous United States, as well as a portion of Mexico.

IN BRIEF

The need to decarbonize the electric power sector is both urgent and challenging. Now, an online model developed by an MIT Energy Initiative team enables other researchers and operators of U.S. regional grids to explore possible pathways to decarbonization. The MIT researchers have input data for nine regional grids—including electricity demand profiles and available wind and solar resources—plus 10 generating and energy storage technologies. The user enters a targeted carbon emissions cap, and the model calculates the minimum-cost combination of available technologies that will meet that cap. Settings allow the user to test the impact of changing fuel costs, restricting the use of certain generating sources, imposing a range of prices on carbon emissions, and more. In sample analyses, the MIT researchers confirmed that the cost-optimized decarbonization strategy varies widely from region to region. They also found that regions with high wind resources were least expensive to decarbonize, that including the emissions associated with making and installing solar and wind facilities is critical, and that California's current ban on nuclear power plants may limit the regional grid's ability to decarbonize.

To help curb climate change, the United States is working to reduce carbon emissions from all sectors of the energy economy. Much of the current effort involves electrification, for example, switching to electric cars for transportation, electric heat pumps for home heating, and so on. But in the United States, the electric power sector already generates about a quarter of all carbon emissions. "Unless we decarbonize our electric power grids, we'll just be shifting carbon emissions from one source to another," says Amanda Farnsworth, a PhD candidate in chemical engineering and research assistant at the MIT Energy Initiative (MITEI).

But decarbonizing the nation's electric power grids will be challenging. The



A comparison of solar and wind resources in the nine U.S. regions. This bar chart shows the availability of wind and sunlight in each of the nine regions included in the study. "Annual capacity factor" is the ratio between the electricity produced by a generating unit in a year and the electricity that could have been produced if that unit operated continuously at full power for that year.

availability of renewable energy resources such as solar and wind varies in different regions of the country. Likewise, patterns of energy demand differ from region to region. As a result, the least-cost pathway to a decarbonized grid will differ from one region to another.

Over the past two years, Farnsworth and Emre Gençer, a principal research scientist at MITEI, developed a power system model that would allow them to investigate the importance of regional differences—and would enable experts and laypeople alike to explore their own regions and make informed decisions about the best way to decarbonize. "With this modeling capability you can really understand regional resources and patterns of demand, and use them to do a 'bespoke' analysis of the least-cost approach to decarbonizing the grid in your particular region," says Gençer.

To demonstrate the model's capabilities, Gençer and Farnsworth performed a series of case studies. Their analyses confirmed that strategies must be designed for specific regions and that all the costs and carbon emissions associated with manufacturing and installing solar and wind generators must be included for accurate accounting. But the analyses also yielded some unexpected insights, including a correlation between a region's wind energy and the ease of decarbonizing, and the important role of nuclear power in decarbonizing the California grid.

A novel model

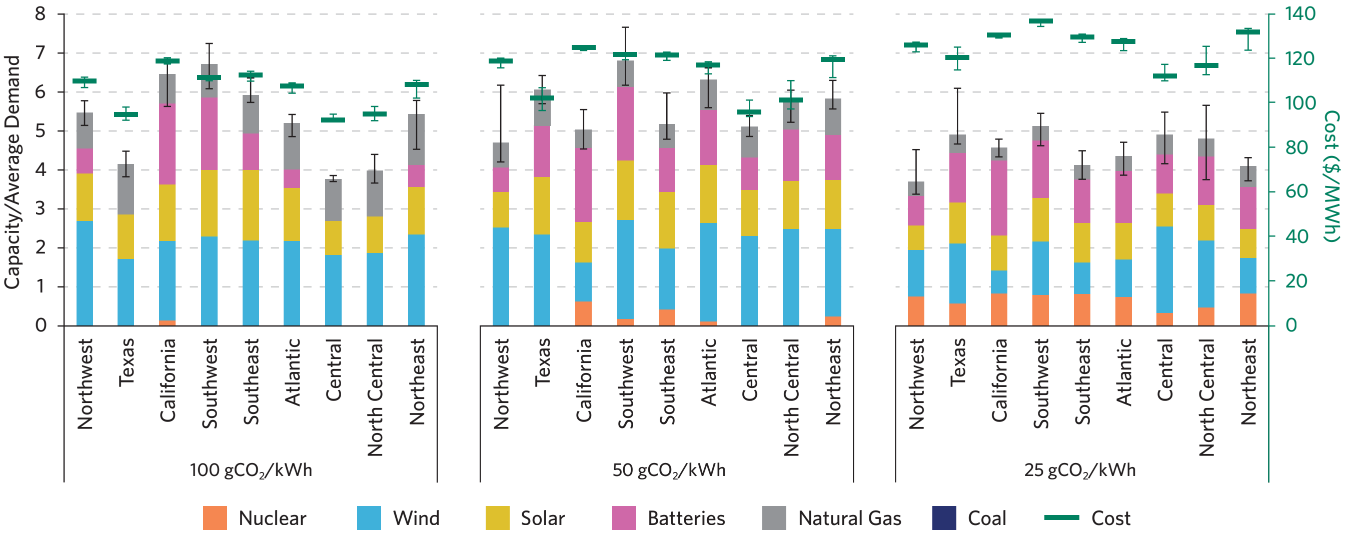
For many decades, researchers have been developing "capacity expansion models" to help electric utility planners tackle the problem of designing power grids that are efficient, reliable, and low cost. More recently, many of those models also factor in the goal of reducing or eliminating carbon emissions. While those models can provide interesting insights relating to decarbonization, Gençer and Farnsworth believe they leave some gaps that need to be addressed.

For example, most focus on conditions and needs in a single U.S. region without highlighting the unique peculiarities of their chosen area of focus. Hardly any consider the carbon emitted in fabricating and installing such "zero-carbon" technologies as wind turbines and solar panels. And finally, most of the models are challenging to use. Even experts in the field must search out and assemble various complex data sets in order to perform a study of interest.

Gençer and Farnsworth's capacity expansion model—called Ideal Grid, or IG—addresses those and other shortcomings. IG is built within the framework of MITEI's Sustainable Energy System Analysis Modeling Environment (SESAME), an energy system modeling platform that Gençer and his colleagues at MITEI have been developing since 2017. SESAME models the levels of greenhouse gas emissions from multiple, interacting energy sectors in future scenarios.

Importantly, SESAME includes both techno-economic analyses and life-cycle assessments of various electricity generation and storage technologies. It thus considers costs and emissions incurred at each stage of the life cycle (manufacture, installation, operation, and retirement) for all generators. Most capacity expansion models only account for emissions from operation of fossil fuel–powered generators. As Farnsworth notes, "While this is a good approximation for our current grid, emissions from the full life cycle of all generating technologies become non-negligible as we transition to a highly renewable grid."

Through its connection with SESAME, the IG model has access to data on costs and emissions associated with many technologies critical to power grid operation. To explore regional differences in the cost-optimized decarbonization



Cost-optimized regional grids under selected CO$_2$ emissions caps. These bar charts show model calculations of the most economic combination of technologies for each region if it limits its total carbon emissions to (from left to right) 100, 50, and 25 grams of CO$_2$ emissions per kWh generated. To permit region-to-region comparisons, the left-hand Y axis represents the required generating capacity divided by the average demand for a particular region. The right-hand Y axis shows generating cost, indicated by the thick green line above each bar. The cost-optimized systems vary in magnitude, composition, and cost from region to region and from one emissions cap to another.

strategies, the IG model also includes conditions within each region, notably details on demand profiles and resource availability.

For their study, Gençer and Farnsworth selected nine of the standard North American Electric Reliability Corporation (NERC) regions, as outlined on the map on page 3. For each region, they incorporated hourly electricity demand into the IG model. Farnsworth also gathered meteorological data for the nine U.S. regions for seven years—2007 to 2013—and calculated hourly power output profiles for the renewable energy sources, including solar and wind, taking into account the geography-limited maximum capacity of each technology.

The availability of wind and solar resources differs widely from region to region, as shown in the bar chart on page 4. To permit a quick comparison, the bar chart shows annual capacity factors, a measure of how much power is produced in a year compared to the amount produced if the generator operated at full capacity continuously. Values for solar power vary between 20% and 30% and for wind between 25% and 45%.

Calculating optimized grids for different regions

For their first case study, Gençer and Farnsworth used the IG model to calculate cost-optimized regional grids to meet defined caps on carbon dioxide (CO$_2$) emissions. The analyses were based on cost and emissions data for 10 technologies: nuclear, wind, solar, three types of natural gas, three types of coal, and energy storage using lithium-ion batteries. Hydroelectric was not considered in this study because there was no comprehensive study outlining potential expansion sites with their respective costs and expected power output levels.

To make region-to-region comparisons easy, the researchers used several simplifying assumptions. Their focus was on electricity generation, so the model calculations assume the same transmission and distribution costs and efficiencies for all regions. Also, the calculations did not consider the generator fleet currently in place. The goal was to investigate what happens if each region were to start from scratch and generate an "ideal" grid.

To begin, Gençer and Farnsworth calculated the most economic strategies for each region to limit its emissions to 100, 50, and 25 grams of CO$_2$ per kilowatt-hour (kWh) generated. For context, the current U.S. average emissions intensity is 386 grams of CO$_2$ emissions per kWh.

Results are presented in the bar chart on this page. Given the wide variation in regional demand, the researchers needed to use a new metric to normalize their results and permit a one-to-one comparison between regions. Accordingly, the Y axis shows the required generating capacity divided by the average demand for a particular region. The required capacity accounts for both the variation in demand and the inability of generating systems—particularly solar and wind—to operate at full capacity all of the time.

The analysis was based on regional demand data for 2021—the most recent data available. And for each region, the model calculated the cost-optimized grid seven times using weather data from seven years. The bars in the figure present mean values, with error bars at the tops indicating the yearly variation in cost and total capacity installed. (Note that the analysis addressed three separate technologies for coal and for natural gas. For clarity, the bars here present total values for both fuels.)

The results confirm that there's a wide variation in the cost-optimized system from one region to another. Most notable is that some regions require a lot of energy storage (pink), while others don't require any at all. A close look at the results hints at the important role played by the availability of wind resources (blue). And it's interesting to track the use of nuclear power (orange). The carbon intensity of nuclear (including uranium mining and transportation) is lower than that of either solar (yellow) or wind, but nuclear is the most expensive technology option, so it's added only when necessary.

Under the most lenient limit on emissions—100 grams of CO_2 per kWh—there's no coal (navy blue) in the mix anywhere. It's the first to go, in general being replaced by the lower-carbon-emitting natural gas (gray). Texas, Central, and North Central—the regions with the most wind—don't need energy storage, while the other six regions do. The regions with the least wind—California and the Southwest—have the highest energy storage requirements. Unlike the other regions modeled, California begins installing nuclear, even at the most lenient limit.

As the model plays out, under the moderate cap—50 grams of CO_2 per kWh—most regions bring in nuclear power. California and the Southeast—regions with low wind capacity factors—rely on nuclear the most. In contrast, wind-rich Texas, Central, and North Central don't incorporate nuclear yet but instead add energy storage—a less-expensive option—to their mix. There's still a bit of natural gas everywhere, in spite of its CO_2 emissions.

Under the most restrictive cap—25 grams of CO_2 per kWh—nuclear is in the mix everywhere. The highest use of nuclear is again correlated with low wind capacity factor. Central and North Central depend on nuclear the least. All regions continue to rely on a little natural gas to keep prices from skyrocketing due to the necessary but costly nuclear component. With nuclear in the mix, the need for storage declines in most regions.

Turning to cost—indicated by the thick green line above each bar—Texas, Central, and North Central all have abundant wind resources, and they can delay incorporating the costly nuclear option, so the cost of their optimized system tends to be lower than costs for the other regions. In addition, their total capacity deployment—that is, the total height of each bar—tends to be lower than for the other regions. California and the Southwest both rely heavily on solar, and in both regions, costs and total deployment are relatively high.

Lessons learned

One unexpected result is the benefit of combining solar and wind resources. The problem with relying on solar alone is obvious: "Solar energy is available only five or six hours a day, so you need to build a lot of other generating sources and abundant storage capacity," says Gençer. But an analysis of unit-by-unit operations at an hourly resolution yielded a less-intuitive trend: While solar installations only produce power in the mid-day hours, wind turbines generate the most power in the nighttime hours. As a result, solar and wind power are complementary. Having both resources available is far more valuable than having either one or the other. And having both impacts the need for storage, says Gençer: "Storage really plays a role either when you're targeting a very low carbon intensity or where your resources are mostly solar and they're not complemented by wind."

Gençer notes that the target for the U.S. electricity grid is to reach net zero by 2035. But the analysis showed that reaching just 100 grams of CO_2 per kWh would require at least 50% of system capacity to be wind and solar. "And we're nowhere near that yet," he says.

Indeed, Gençer and Farnsworth's analysis doesn't even include a zero emissions case. Why not? As Gençer says, "We cannot reach zero." Wind and solar are usually considered to be net zero, but that's not true. Wind, solar, and even storage have embedded carbon emissions due to materials, manufacturing, and so on. "To go to true net zero, you'd need negative emission technologies," explains Gençer, referring to techniques that remove carbon from the air or ocean. That observation confirms the importance of performing life-cycle assessments.

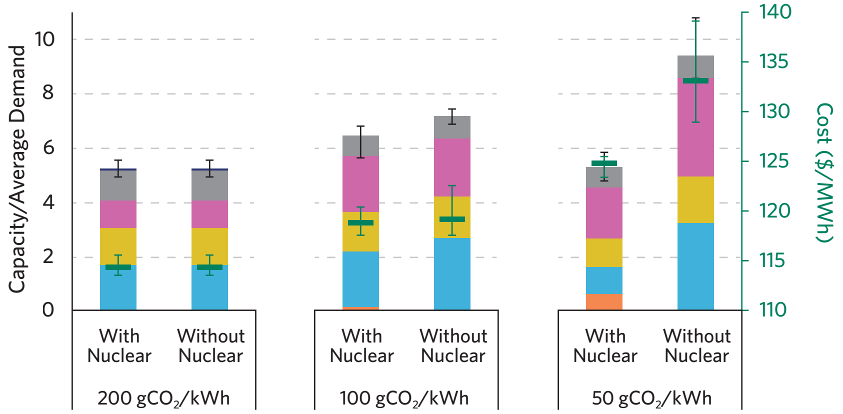
Farnsworth voices another concern: Coal quickly disappears in all regions because natural gas is an easy substitute for coal and has lower carbon emissions. "People say they've decreased their carbon emissions by a lot, but most have done it by transitioning from coal to natural gas power plants," says Farnsworth. "But with that pathway for decarbonization, you hit a wall. Once you've transitioned from coal to natural gas, you've got to do something else. You need a new strategy—a new trajectory to actually reach your decarbonization target, which most likely will involve replacing the newly installed natural gas plants."

Gençer makes one final point: The availability of cheap nuclear—whether fission or fusion—would completely change the picture. In the figure on page 5, when the tighter caps require the use of nuclear, the cost of electricity goes up. "The impact is quite significant," says Gençer. "When we go from 100 grams down to 25 grams of CO_2 per kWh, we see a 20% to 30% increase in the cost of electricity." If it were available, a less-expensive nuclear option would likely be included in the technology mix under more lenient caps, significantly reducing the cost of decarbonizing power grids in all regions.

The special case of California

In another analysis, Gençer and Farnsworth took a closer look at California. In California, about 10% of total demand is now met with nuclear power. Yet current power plants are scheduled for retirement very soon, and a 1976 law forbids the construction of new nuclear plants. (The state recently extended the lifetime of one nuclear plant to prevent the grid from becoming unstable.) "California is very motivated to decarbonize their grid," says Farnsworth. "So how difficult will that be without nuclear power?"

To find out, the researchers performed a series of analyses to investigate the challenge of decarbonizing in California with nuclear power versus without it. Their results appear on page 7. At 200 grams of CO_2 per kWh—about a 50% reduction—the optimized mix and cost look the same with and without nuclear.



Role of nuclear power in decarbonizing the California power grid. This chart shows the cost-optimized system for decarbonizing in California and its cost, with and without nuclear power. At 200 grams of CO_2 per kWh, the optimized mix and cost are comparable. Nuclear is excluded due to its high cost. At 100 grams of CO_2 per kWh, a small amount of nuclear appears, somewhat reducing the total capacity (the height of the bar) but having little impact on cost. At 50 grams of CO_2 per kWh, the ban on nuclear makes a significant difference. Without nuclear, the total system size is significantly larger, and the cost of electricity increases by about 7%.

Nuclear doesn't appear due to its high cost. At 100 grams of CO_2 per kWh—about a 75% reduction—nuclear does appear in the cost-optimized system, reducing the total system capacity while having little impact on the cost.

But at 50 grams of CO_2 per kWh, the ban on nuclear makes a significant difference. "Without nuclear, there's about a 45% increase in total system size, which is really quite substantial," says Farnsworth. "It's a vastly different system, and it's more expensive." Indeed, the cost of electricity would increase by 7%.

Going one step further, the researchers performed an analysis to determine the most decarbonized system possible in California. Without nuclear, the state could reach 40 grams of CO_2 per kWh. "But when you allow for nuclear, you can get all the way down to 16 grams of CO_2 per kWh," says Farnsworth. "We found that California needs nuclear more than any other region due to its poor wind resources."

Impacts of a carbon tax

One more case study examined a policy approach to incentivizing decarbonization. Instead of imposing a ceiling on carbon emissions, this strategy would tax every ton of carbon that's emitted. Proposed taxes range from zero to $100 per ton.

To investigate the effectiveness of different levels of carbon tax, Farnsworth and Gençer used the IG model to calculate the minimum-cost system for each region, assuming a certain cost for emitting each ton of carbon. The analyses show that a low carbon tax—just $10 per ton—significantly reduces emissions in all regions by phasing out all coal generation. In the Northwest region, for example, a carbon tax of $10 per ton decreases system emissions by 65% while increasing system cost by just 2.8% (relative to an untaxed system).

After coal has been phased out of all regions, every increase in the carbon tax brings a slow but steady linear decrease in emissions and a linear increase in cost. But the rates of those changes vary from region to region. For example, the rate of decrease in emissions for each added tax dollar is far lower in the Central region than in the Northwest, largely due to the Central region's already low emissions intensity without a carbon tax. Indeed, the Central region without a carbon tax has a lower emissions intensity than the Northwest region with a tax of $100 per ton.

As Farnsworth summarizes, "A low carbon tax—just $10 per ton—is very effective in quickly incentivizing the replacement of coal with natural gas. After that, it really just incentivizes the replacement of natural gas technologies with more renewables and more energy storage." She concludes, "If you're looking to get rid of coal, I would recommend a carbon tax."

Future extensions of IG

The researchers have already added hydroelectric to the generating options in the IG model, and they are now planning further extensions. For example, they will include additional regions for analysis, add other long-term energy storage options, and make changes that allow analyses to take into account the generating infrastructure that already exists. Also, they will use the model to examine the cost and value of interregional transmission to take advantage of the diversity of available renewable resources.

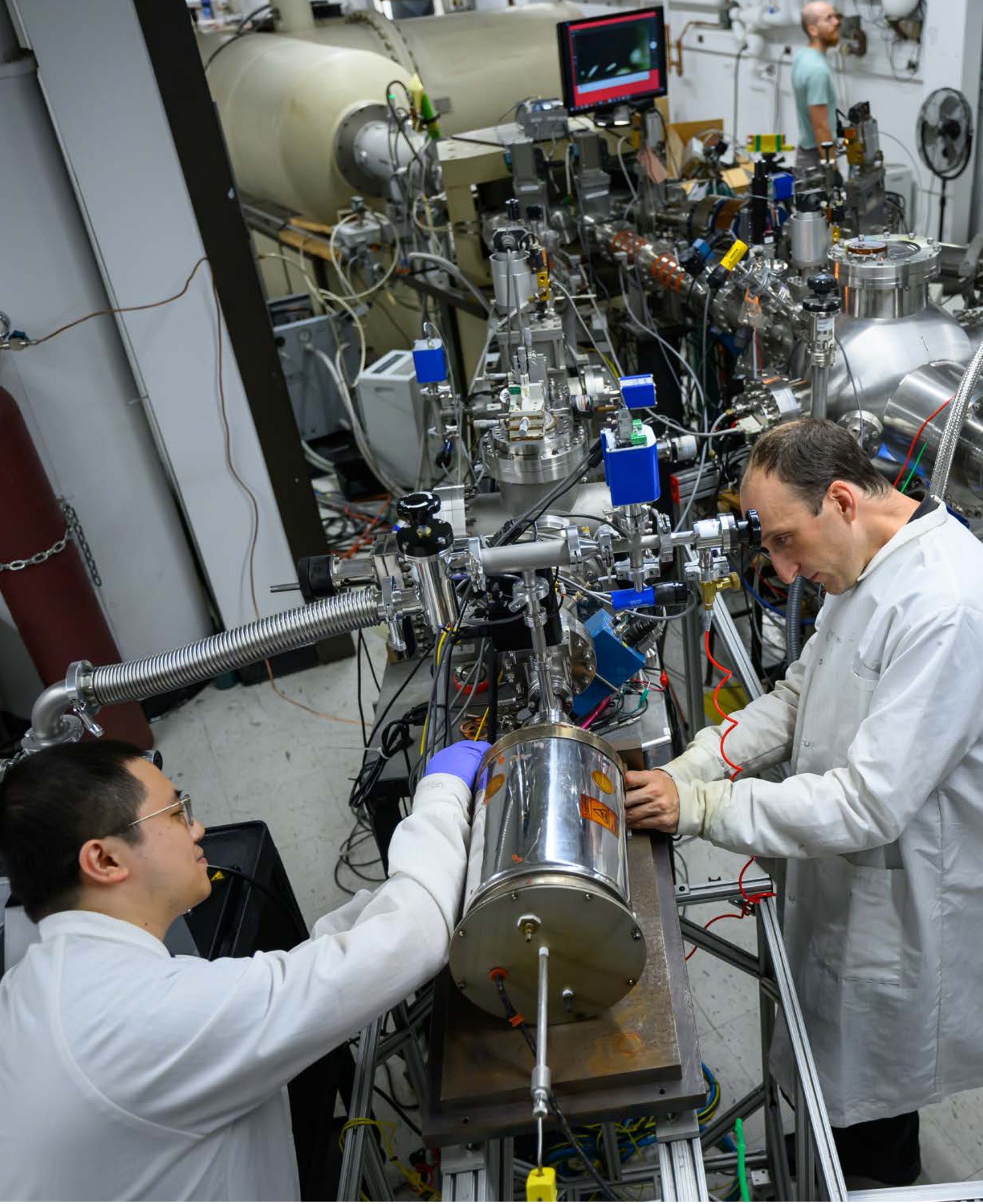
Farnsworth emphasizes that the analyses reported here are just samples of what's possible using the IG model. The model is a web-based tool that includes embedded data covering the whole United States, and the output from an analysis includes an easy-to-understand display of the required installations, hourly operation, and overall techno-economic analysis and life-cycle assessment results. "The user is able to go in and explore a vast number of scenarios with no data collection or pre-processing," she says. "There's no barrier to begin using the tool. You can just hop on and start exploring your options so you can make an informed decision about the best path forward."

Nancy W. Stauffer, MITEI

NOTES

This work was supported by the International Energy Agency Gas & Oil Technology Collaboration Programme (GOT-CP) and the MIT Energy Initiative Low-Carbon Energy Centers. Further information can be found in:

A. Farnsworth and E. Gençer. "Highlighting regional decarbonization challenges with novel capacity expansion model." *Cleaner Energy Systems*, June 4, 2023. Online: doi.org/10.1016/j.cles.2023.100078.



Promising designs for nuclear power reactors using molten salt

Selecting the right metal can alleviate the corrosion problem.

IN BRIEF

Promising new designs for both fission and fusion nuclear power reactors rely on molten salt to play key roles, such as transferring heat out to produce electricity and to keep important metal components cool. But a major concern is corrosion: Will the radiation inside a nuclear reactor speed up the rate at which the salt corrodes and weakens those metal components? MIT researchers have demonstrated that some metal alloys will corrode not *more* but *less* when they're exposed to radiation under some conditions. The team devised and built an experimental setup that emulates conditions inside a molten salt–based nuclear reactor. Tests with various alloys show that certain combinations of elements become more resistant to corrosion when they are also subjected to radiation. The researchers provide simple guidelines for designers and operators to follow when selecting commercial alloys for their molten salt–based nuclear reactors.

Most discussions of how to avert climate change focus on solar and wind generation as key to the transition to a future carbon-free power system. But Michael Short, the Class of '42 Associate Professor of Nuclear Science and Engineering and associate director of the Plasma Science and Fusion Center (PSFC), is impatient with such talk. "We can say we should have only wind and solar someday. But we don't have the luxury of 'someday' anymore, so we can't ignore other helpful ways to combat climate change," he says. "To me, it's an 'all-hands-on-deck' thing. Solar and wind are clearly a big part of the solution. But I think that nuclear power also has a critical role to play."

For decades, researchers have been working on designs for both fission and fusion nuclear reactors using molten salts as fuels or coolants. While those designs promise significant safety and performance advantages, there's a catch: Molten salt and the impurities within them often corrode metals, ultimately causing them to crack, weaken, and fail. Inside a reactor, key metal components will be exposed not only to molten salt but also simultaneously to radiation, which generally has a detrimental effect on materials, making them more brittle and prone to failure. Will irradiation make metal components inside a molten salt–cooled nuclear reactor corrode even more quickly?

Short and Dr. Weiyue Zhou PhD '21, a postdoc in the PSFC, have been investigating that question for eight years. Their experimental findings show that certain alloys will corrode more slowly when they're irradiated—and identifying them among all the available commercial alloys can be straightforward.

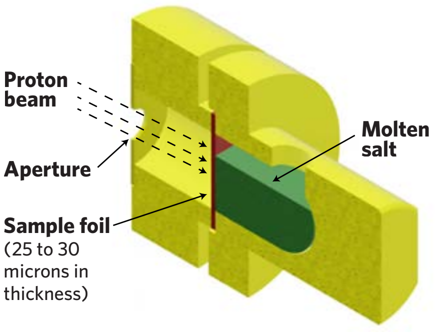
The first challenge—building a test facility

When Short and Zhou began investigating the effect of radiation on corrosion, practically no reliable facilities existed to look at the two effects at once. The standard approach was to examine such mechanisms in sequence: first corrode, then irradiate, then examine the impact on the material. That approach greatly simplifies the task for the researchers but with a major trade-off. "In a reactor, everything is going to be happening at the same time," says Short. "If you separate the two processes, you're not simulating a reactor; you're doing some other experiment that's not as relevant."

So, Short and Zhou took on the challenge of designing and building an experimental setup that could do both at once. Short credits a team at the University of Michigan for paving the way by designing a device that could accomplish that feat in water rather than molten salts. Even so, Zhou notes, it took them three years to come up with a device that would work with molten salts. Both researchers recall failure after failure, but the persistent Zhou ultimately tried a totally new design, and it worked. Short adds that it also took them three years to precisely replicate the salt mixture used by industry—another factor critical to getting a meaningful result. The hardest part was achieving and ensuring that the purity was correct by removing critical impurities such as moisture, oxygen, and certain other metals.

As they were developing and testing their setup, Short and Zhou obtained initial results showing that proton irradiation did not always accelerate corrosion but sometimes actually decelerated it. They and others had hypothesized that possibility, but even so, they were surprised. "We thought we must be doing something wrong," recalls Short. "Maybe we mixed up the samples or something." But they subsequently made similar observations for a variety of conditions,

Facing page: Associate Professor Michael Short (right) and postdoc Dr. Weiyue Zhou attach a novel test chamber containing a metal sample and salt to the end of a proton accelerator. Experiments to date show that proton irradiation decreases the rate of corrosion in certain metal alloys. That's potentially good news for designers and builders of promising nuclear power reactors that rely on molten salts, which tend to be highly corrosive. Photo: Gretchen Ertl



The researchers' experimental setup. This diagram shows the key features of the setup that the researchers designed and built to explore the effect of radiation on corrosion inside a molten salt nuclear reactor. The test chamber appears in yellow. A thin sample of the alloy being tested (at the center, red) is suspended between a bath of molten salt (green) and a beam of protons coming from the other side (dashed lines). With this setup, a single foil sample can be exposed to molten salt over its entire surface and—at the same time—to radiation limited to a circle at its center. Experiments show that the impact of radiation on corrosion damage varies widely from alloy to alloy.

increasing their confidence that their initial observations were not outliers.

The successful setup

Central to their approach is the use of accelerated protons to mimic the impact of the neutrons inside a nuclear reactor. Generating neutrons would be both impractical and prohibitively expensive, and the neutrons would make everything highly radioactive, posing health risks and requiring very long times for an irradiated sample to cool down enough to be examined. Using protons would enable Short and Zhou to examine radiation-altered corrosion both rapidly and safely.

The final design for their experimental setup is illustrated in the diagram on this page. The test chamber is shown in yellow. The bath of molten salt is shown in green. The thin sheet of the metal alloy being tested is at the center (in red), and the beam of protons enters from the left (dashed lines). With this setup, a thin foil sample of the alloy being tested is exposed to molten salt on one side and bombarded with proton radiation on the other side, but the proton beam is restricted to a circle in the middle of the foil sample. "No one can argue with our results then," says Short. "In a single experiment, the whole sample is subjected to corrosion, and only a circle in the center of the sample is simultaneously irradiated by protons. We can see the curvature of the proton beam outline in our results, so we know which region is which."

The results with that arrangement were unchanged from the initial results. They confirmed the researchers' preliminary findings, supporting their controversial hypothesis that rather than accelerating corrosion, radiation would actually decelerate corrosion in some materials under some conditions. Fortunately, they just happen to be the same conditions that will be experienced by metals in molten salt–cooled reactors.

Why is that outcome controversial? A closeup look at the corrosion process will explain. When salt corrodes metal, the salt finds atomic-level openings in the solid, seeps in, and dissolves salt-soluble atoms, pulling them out and leaving a gap in the material—a spot where the material is now weak. "Radiation adds energy to atoms, causing them to be ballistically knocked out of their positions and move very fast," explains Short. So, it makes sense that irradiating a material would cause atoms to move into the salt more quickly, increasing the rate of corrosion. Yet in some of their tests, the researchers found the opposite to be true.

Experiments with "model" alloys

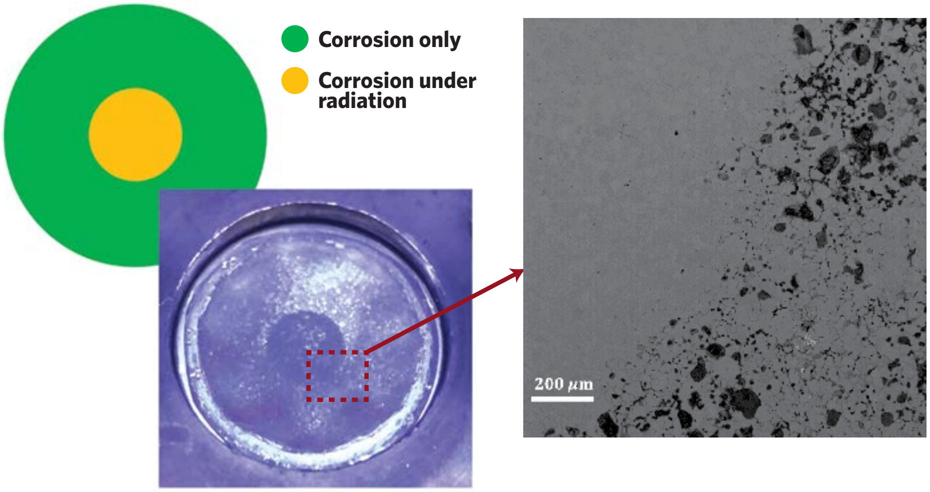
The researchers' first experiments in their novel setup involved "model" alloys consisting of nickel and chromium, a simple combination that would give them a first look at the corrosion process in action. In addition, they added europium fluoride to the salt, a compound known to speed up corrosion. In our world, we often think of corrosion as taking years or decades, but in the more extreme conditions of a molten salt reactor it can noticeably occur in just hours. The researchers used the europium fluoride to speed up corrosion even more without changing the corrosion process. This allowed for more rapid determination of which materials, under which conditions, experienced more or less corrosion with simultaneous proton irradiation.

The use of protons to emulate neutron damage to materials meant that the experimental setup had to be carefully designed and the operating conditions carefully selected and controlled. Protons are hydrogen atoms with an electrical charge; and under some conditions, the hydrogen could chemically react with atoms in the sample foil, altering the corrosion response, or with ions in the salt, making the salt more corrosive. Therefore, the proton beam had to penetrate the foil sample but then stop in the salt as soon as possible. Under these conditions, the researchers found they could deliver a relatively uniform dose of radiation inside the foil layer while also minimizing chemical reactions in both the foil and the salt.

Tests showed that a proton beam accelerated to 3 million electron-volts combined with a foil sample between 25 and 30 microns thick would work well for their nickel-chromium alloys. The temperature and duration of the exposure could be adjusted based on the corrosion susceptibility of the specific materials being tested.

The top figure on page 11 shows sample results. The blue image shows the side of the foil sample facing the proton beam. During the experiment, the entire sample was exposed to molten salt on the opposite side, and the circular region at the center was simultaneously bombarded with protons from this side. The difference in appearance is striking in this optical image. The electron microscope image at the right focuses on the region inside the red rectangle. The area at the right in the image shows dark patches where the salt penetrated all the way through the foil, while the area on the left shows almost no such dark patches. The curvature marking the outside of the radiation beam in the blue image matches the curvature between the damaged and less-damaged regions in the electron microscope image, validating the researchers' experimental approach.

To confirm that the dark patches were due to corrosion, the researchers cut through the foil sample to create cross sections. In them, they could see tunnels that the salt had dug into the sample. "For



Experimental results with model compounds. This figure shows results from tests on a simple alloy consisting of just nickel and chromium. The blue image shows the side of the foil sample facing the proton beam. The whole sample was exposed to molten salt, while only the circle at the center was also subjected to the beam of protons. The boundary between the two areas is clear. The electron microscope image to the right focuses on the region inside the red rectangle. The area at the right in the image shows dark patches where the salt penetrated all the way through the foil, while the area on the left shows almost no such dark patches. The curvature marking the boundary between the damaged and less-damaged regions in the two images is the same, confirming that damage is less extreme where the sample was both corroded and irradiated.

regions not under radiation, we see that the salt tunnels link the one side of the sample to the other side," says Zhou. "For regions under radiation, we see that the salt tunnels stop more or less halfway and rarely reach the other side. So we verified that they didn't penetrate the whole way."

The results "exceeded our wildest expectations," says Short. "In every test we ran, the application of radiation slowed corrosion by a factor of 2 to 3 times."

More experiments, more insights

Subsequent tests with the model alloys provided further insights. To more closely replicate commercially available molten salt, the researchers omitted the additive (europium fluoride) that they had used to speed up corrosion, and they tweaked the temperature for even more realistic conditions. "In carefully monitored tests, we found that by raising the temperature by 100 degrees Celsius, we could get corrosion to happen about 1,000 times faster than it would in a reactor," says Short.

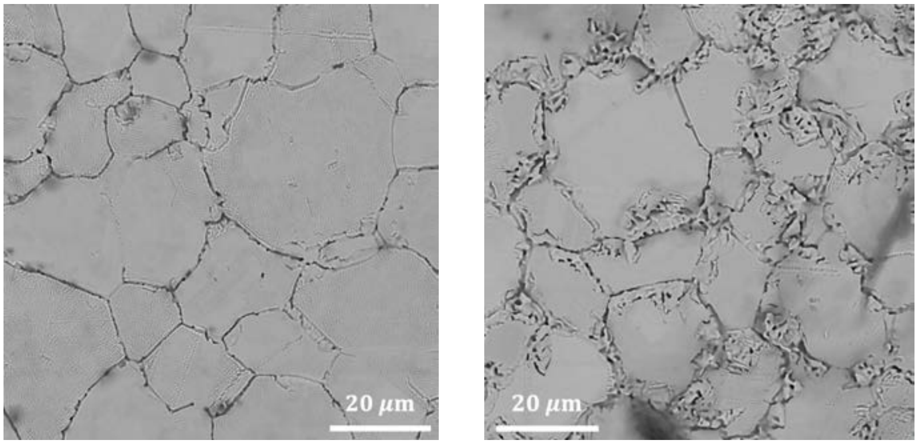
Sample results with the molten salt (without the corrosive additive) plus the nickel-chromium alloy appear in the figure to the right on this page. These images show the salt-facing side of the sample, so the directly corroded side. The image on the left is from the corrosion-only region, while the one on the right is from the region that was also irradiated. The corrosion damage seen in the two regions is distinctly different.

Short explains the observations. Metals are made up of individual grains inside which atoms are lined up in an orderly fashion. Where the grains come together there are areas—called grain boundaries—where the atoms don't line up as well. In the corrosion-only image on the left, dark lines track the grain boundaries. Molten salt has seeped into the grain boundaries and pulled out salt-soluble atoms. In the corrosion-plus-irradiation image on the right, the damage is more general. It's not only the grain boundaries that get attacked but also regions within the grains.

So, when the material is irradiated, the molten salt also removes material from within the grains. Over time, more material comes out of the grains themselves than from the spaces between them. The removal isn't focused on the grain boundaries; it's spread out over the whole surface. As a result, any cracks that form are shallower and more spread out, and the material is less likely to fail.

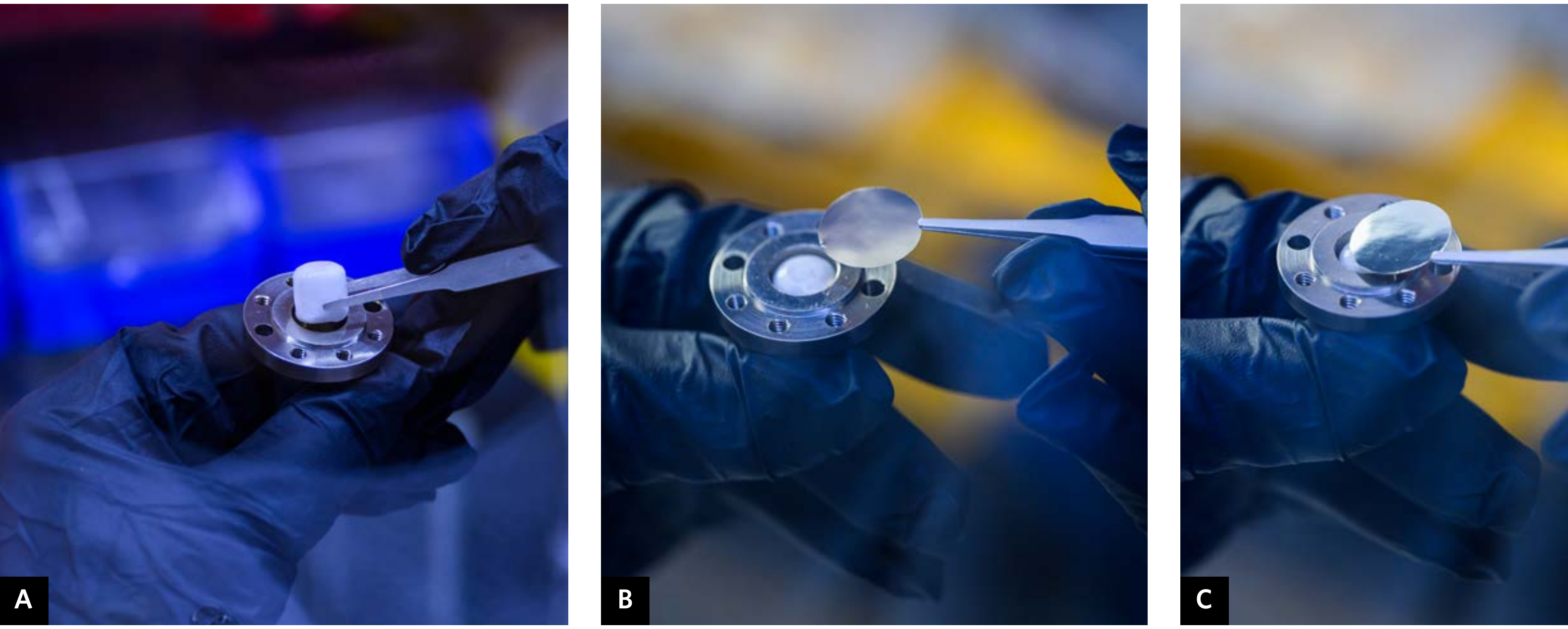
Testing commercial alloys

The experiments described thus far involved model alloys—simple


Corrosion without irradiation

Corrosion plus irradiation

Images showing damage on the salt-facing side of a foil sample. These electron microscope images show the side of the foil of the nickel-chromium alloy sample facing the molten salt. The one on the left shows a section that was only exposed to the molten salt. The corrosion is clearly focused on the weakest part of the structure—the boundaries between the grains in the metal. The image on the right shows a section that was exposed to both the molten salt and the proton beam. Here the corrosion isn't limited to the grain boundaries but is more spread out over the surface. Experimental results show that these cracks are shallower and less likely to cause a key component to break.



Steps involved in setting up the test chamber for an experiment with the proton accelerator. Photos: Gretchen Ertl

A Working inside a glove box, postdoc Weiyue Zhou first drops in a pellet of salt—the key to emulating the corrosive environment inside a molten salt-based nuclear reactor.

B, C Next, he places a sample of the metal being tested on the top of the test chamber, where it will be exposed to the salt pellet beneath it. The metal sample is a foil disc about 21 millimeters in diameter and just 25 to 30 microns thick.

combinations of elements that are good for studying science but would never be used in a reactor. In the next series of experiments, the researchers focused on three commercially available alloys that are composed of nickel, chromium, iron, molybdenum, and other elements in various combinations.

Results from the experiments with the commercial alloys showed a consistent pattern—one that confirmed an idea that the researchers had going in: The higher the concentration of salt-soluble elements in the alloy, the worse the radiation-induced corrosion damage. Radiation will increase the rate at which salt-soluble atoms such as chromium leave the grain boundaries, hastening the corrosion process. However, if there are more not-soluble elements such as nickel present, those atoms will go into the salt more slowly. Over time, they'll accumulate at the grain boundary and form a protective coating that blocks the grain boundary—a "self-healing mechanism that decelerates the rate of corrosion," say the researchers.

Thus, if an alloy consists mostly of atoms that don't dissolve in molten salt, irradiation will cause them to form a protective coating that slows the corrosion process. But if an alloy consists mostly of atoms that dissolve in molten salt, irradiation will make them dissolve faster, speeding up corrosion. As Short summarizes, "In terms of corrosion, irradiation makes a good alloy better and a bad alloy worse."

Real-world relevance plus practical guidelines

Short and Zhou find their results encouraging. In a nuclear reactor made of "good" alloys, the slowdown in corrosion will probably be even more pronounced than what they observed in their proton-based experiments because the neutrons that inflict the damage won't chemically react with the salt to make it more corrosive. As a result, reactor designers could push the envelope more in their operating conditions, allowing them to get more power out of the same nuclear plant without compromising on safety.

However, the researchers stress that there's much work to be done. Many more projects are needed to explore and understand the exact corrosion mechanism in specific alloys under different irradiation conditions. In addition, their findings need to be replicated by groups at other institutions using their own facilities. "What needs to happen now is for other labs to build their own facilities and start verifying whether they get the same results as we did," says Short. To that end, Short and Zhou have made the details of their experimental setup and all of their data freely available online. "We've also been actively communicating with researchers at other institutions who have contacted us," adds Zhou. "When they're planning to visit, we offer to show them demonstration experiments while they're here."

But already their findings provide practical guidance for other researchers and equipment designers. For example, the standard way to quantify corrosion damage is by "mass loss," a measure of how much weight the material has lost. But Short and Zhou consider mass loss a flawed measure of corrosion in molten salts. "If you're a nuclear plant operator, you usually care whether your structural components are going to break," says Short. "Our experiments show that radiation can change how deep the cracks

D Here, Zhou prepares to put the top on the test chamber.

E And here he screws on the top, sealing it shut. The test chamber is now ready to be mounted on the proton accelerator. With this setup, the researchers expose the whole foil sample to the corrosive salt, and—by shielding part of it from the incoming protons—they also subject a limited but well-defined section of it to the proton beam at the same time.

are, when all other things are held constant. The deeper the cracks, the more likely a structural component is to break, leading to a reactor failure."

In addition, the researchers offer a simple rule for identifying good metal alloys for structural components in molten salt reactors. Manufacturers provide extensive lists of available alloys with different compositions, microstructures, and additives. Faced with a list of options for critical structures, the designer of a new nuclear fission or fusion reactor can simply examine the composition of each alloy being offered. The one with the highest content of corrosion-resistant elements such as nickel will be the best choice. Inside a nuclear reactor, that alloy should respond to a bombardment of radiation not by corroding more rapidly but by forming a protective layer that helps block the corrosion process. "That may seem like a trivial result, but the exact threshold where radiation decelerates corrosion depends on the salt chemistry, the density of neutrons in the reactor, their energies, and a few other factors," says Short. "Therefore, the complete guidelines are a bit more complicated. But they're presented in a straightforward way that users can understand and utilize to make a good choice for the molten salt–based reactor they're designing."

Nancy W. Stauffer, MITEI

NOTES

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N. AlMousa, W. Zhou, K.B. Woller, and M.P. Short. "Effects of simultaneous proton irradiation on the corrosion of commercial alloys in molten fluoride salt." *Corrosion Science*, June 2023. Online: doi.org/10.1016/j.corsci.2023.111154.

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Six innovative energy projects received MIT Energy Initiative Seed Fund grants

Annual MITEI awards support research on carbon removal, novel materials for energy storage, improved power system planning, and more.

As part of the 2023 Seed Fund Program, the MIT Energy Initiative (MITEI) has awarded $900,000 in grants to support six novel energy research projects. Each project has been recognized for showing promise for high-impact, transformative energy research, and will receive $150,000 in funding over the span of two years.

"It is important that we keep that pipeline of early-stage research coming," says Robert Stoner, the director of MITEI. "Energy and the way we use energy are central to solving climate change, and MITEI's Seed Fund Program allows us to place bets on potentially game-changing technologies that are often too risky for industry and government sponsors."

To date, the MITEI Seed Fund Program (energy.mit.edu/funding) has supported 209 energy-focused projects through grants totaling $28.7 million. This funding comes primarily from MITEI's Founding and Sustaining Members, supplemented by philanthropic donations.

The 57 proposals submitted this year spanned a breadth of disciplines, hailing from 68 different MIT faculty and researchers across 24 departments, labs, and centers. The projects that were awarded Seed Fund grants range from technologies to remove carbon from industrial wastewater to improved system planning models that account for the complexity and scale of our modern power systems.

Brief descriptions of the six winning projects and their principal investigators (PIs) follow.

Electrochemically stimulated hydrogen desorption

Hydrogen is a clean energy source with the potential to significantly reduce

One of the six novel energy research projects to win an MIT Energy Initiative Seed Fund award will develop improved capacity expansion models that appropriately consider some of the complexities of modern power networks to enable the improved planning of reliable, low-carbon power systems at scale. Image by Tom from Pixabay

carbon emissions from key industrial applications; however, hydrogen can degrade the metallic materials in the piping used for its transport and storage, causing unexpected and catastrophic failures. This project aims to develop a novel electrochemical methodology that will prevent hydrogen damage in existing infrastructure by enabling its removal from structural components during operation. This proposed system will be a scalable, flexible solution for the hydrogen energy industry.

PIs: Ju Li, the Battelle Energy Alliance Professor in Nuclear Engineering and a professor of materials science and engineering; Cem Tasan, an associate professor of materials science and engineering; and Bilge Yildiz, the Breene M. Kerr (1951) Professor

Capturing carbon in industrial wastewater

Industrial wastewater is a massive carbon source, yet while emissions from treatment plants have been recognized, there has been little done to remove the inorganic carbon in waste streams. Each year in the United States alone, more than 90 trillion gallons of industrial wastewater, estimated to contain about 600 Mt/year of dissolved inorganic carbon (DIC), is treated. This project will evaluate the potential of electrochemically mediated carbon capture technology to remove DIC from industrial wastewater, tackling an untapped opportunity for carbon mitigation.

PIs: T. Alan Hatton, the Ralph Landau Professor of Chemical Engineering Practice, and Kripa Varanasi, a professor of mechanical engineering

Measuring the impact of mining

To meet the growing demand for clean energy technologies, critical minerals such as lithium, cobalt, copper, and more will need to be mined in greater volumes. However, mining can cause significant environmental damage and introduce risks to the communities that surround and depend on the mines. This project will assess the controversial environmental, sustainability, and governance (ESG) metrics currently used by financial institutions to measure the impacts of mining and will propose a path for improvement and to make them more effective.

PI: Roberto Rigobon, the Society of Sloan Fellows Professor of Management

Improved planning for reliable, low-carbon power systems

Capacity expansion models (CEMs) are an important tool for system planners, regulators, and utilities to identify best practices for planning and operating power grids, as well as to evaluate the impacts of new technologies and regulations. However, current CEMs do not adequately account for the complexity and scale of our modern power systems. This can result in the loss of billions of dollars per year due to poor planning and dispatch, as well as large-scale outages and loss of lives. This project will develop improved CEMs that appropriately consider some of the complexities of modern power networks (including the nonlinear physics of power grids and the need for robustness against grid failures) to enable the improved planning of low-carbon and reliable power systems at scale.

PIs: Priya Donti, an assistant professor in the Department of Electrical Engineering and Computer Science and the Laboratory for Information and Decision Systems, and Dharik Mallapragada, a principal research scientist at MITEI

Iono-electronic polymer composites for electrochemical energy storage

The demand for batteries continues to grow in a number of applications and electronics. This has made it necessary to introduce novel materials, especially non-mined alternatives, and a rethinking of battery design. This project will investigate iono-electronic polymer composites as a novel class of electrode materials for polymer-based energy storage. This work will help fill an urgent need for alternative material sources, as well as prove significant for investigations into organic batteries, which will be more suitable for many next-generation electronics.

PI: Aristide Gumyusenge, the Merton C. Flemings (1951) Career Development Professor and an assistant professor of materials science and engineering

2D polymer membranes for liquid separations

A growing global population and rapid industrialization have imposed unprecedented strains on the Earth's natural resources, with water and energy demand at the heart of these pressures. Membrane-based separation processes can address these challenges by, for example, helping to produce water from unconventional sources and enabling liquid separations while consuming less energy than classical processes. This project will develop a new class of membrane material—a 2D polyaramid with controllable porosity—that may hold promise as a next-generation permselective membrane material.

PI: Michael Strano, the Carbon P. Dubbs Professor in Chemical Engineering

Kelley Travers, MITEI

Study suggests energy-efficient route to capturing and converting CO_2

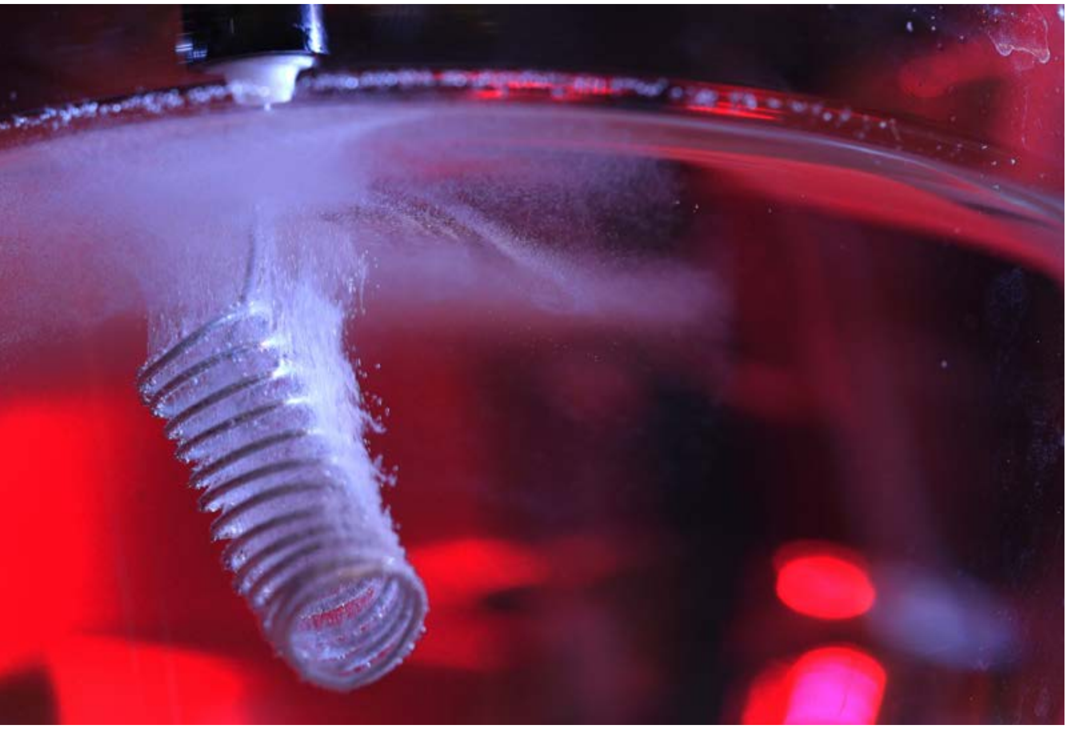
The findings, based on a single electrochemical process, could help cut emissions from the hardest-to-decarbonize industries, such as steel and cement.

In the race to draw down greenhouse gas emissions around the world, scientists at MIT are looking to carbon-capture technologies to decarbonize the most stubborn industrial emitters.

Steel, cement, and chemical manufacturing are especially difficult industries to decarbonize, as carbon and fossil fuels are inherent ingredients in their production. Technologies that can capture carbon emissions and convert them into forms that feed back into the production process could help to reduce the overall emissions from these "hard-to-abate" sectors.

But thus far, experimental technologies that capture and convert carbon dioxide (CO_2) do so as two separate processes that themselves require a huge amount of energy to run. The MIT team is looking to combine the two processes into one integrated and far more energy-efficient system that could potentially run on renewable energy to both capture and convert CO_2 from concentrated, industrial sources.

In a study reported in *ACS Catalysis*, the researchers reveal the hidden functioning of how CO_2 can be both captured and converted through a single electrochemical process. The process involves using an electrode to attract CO_2 released from a sorbent and to convert it into a reduced, reusable form.



Researchers uncovered how carbon dioxide can be both captured and converted through a single electrochemical process in which an electrode, like the one pictured covered in bubbles, is used to attract carbon dioxide released from a sorbent and convert it into carbon-neutral products.
Photo: John Freidah, MIT Department of Mechanical Engineering

Others have reported similar demonstrations, but the mechanisms driving the electrochemical reaction have remained unclear. The MIT team carried out extensive experiments to determine that driver, and found that, in the end, it came down to the partial pressure of CO_2. In other words, the more pure CO_2 that makes contact with the electrode, the more efficiently the electrode can capture and convert the molecule.

Knowledge of this main driver, or "active species," can help scientists tune and optimize similar electrochemical systems to efficiently capture and convert CO_2 in an integrated process.

The study's results imply that, while these electrochemical systems would probably not work for very dilute environments (for instance, to capture and convert carbon emissions directly from the air), they would be well-suited to the highly concentrated emissions generated by industrial processes, particularly those that have no obvious renewable alternative.

"We can and should switch to renewables for electricity production. But deeply decarbonizing industries like cement or steel production is challenging and will take a longer time," says study author Betar Gallant, the Class of 1922 Career Development Associate Professor at MIT. "Even if we get rid of all our power plants, we need some solutions to deal with the emissions from other industries in the shorter term, before we can fully decarbonize them. That's where we see a sweet spot, where something like this system could fit."

The study's MIT co-authors are lead author and postdoc Graham Leverick and graduate student Elizabeth Bernhardt, along with Aisyah Illyani Ismail, Jun Hui Law, Arif Arifutzzaman, and Mohamed Kheireddine Aroua of Sunway University in Malaysia.

Breaking bonds

Carbon-capture technologies are designed to capture emissions, or "flue gas," from the smokestacks of power plants and manufacturing facilities. This is done primarily using large retrofits to funnel emissions into chambers filled with a "capture" solution—a mix of amines, or ammonia-based compounds, that chemically bind with CO_2, producing a stable form that can be separated out from the rest of the flue gas.

High temperatures are then applied, typically in the form of fossil fuel–generated steam, to release the captured CO_2 from its amine bond. In its pure form, the gas can then be pumped into storage tanks or underground, mineralized, or further converted into chemicals or fuels.

"Carbon capture is a mature technology, in that the chemistry has been known for about 100 years, but it requires really large installations and is quite expensive and energy-intensive to run," Gallant notes. "What we want are technologies that are more modular and flexible and can be adapted to more diverse sources of carbon dioxide. Electrochemical systems can help to address that."

Her group at MIT is developing an electrochemical system that both recovers the captured CO_2 and converts it into a reduced, usable product. Such an integrated system, rather than a decoupled one, she says, could be entirely powered with renewable electricity rather than fossil fuel–derived steam.

Their concept centers on an electrode that would fit into existing chambers of carbon-capture solutions. When a voltage is applied to the electrode, electrons flow onto the reactive form of CO_2 and convert it to a product using protons supplied from water. This makes the sorbent available to bind more CO_2, rather than using steam to do the same.

Gallant previously demonstrated this electrochemical process could work to capture and convert CO_2 into a solid carbonate form (see *Energy Futures*, spring 2019, or online at bit.ly/power-plant-exhaust).

"We showed that this electrochemical process was feasible in very early concepts," she says. "Since then, there have been other studies focused on using this process to attempt to produce useful chemicals and fuels. But there's been inconsistent explanations of how these reactions work, under the hood."

Solo CO_2

In the new study, the MIT team took a magnifying glass under the hood to tease out the specific reactions driving the electrochemical process. In the lab, they generated amine solutions that resemble the industrial capture solutions used to extract CO_2 from flue gas. They methodically altered various properties of each solution, such as the pH, concentration, and type of amine, then ran each solution past an electrode made from silver—a metal that is widely used in electrolysis studies and known to efficiently convert CO_2 to carbon monoxide. They then measured the concentration of carbon monoxide that was converted at the end of the reaction, and compared this number against that of every other solution they tested, to see which parameter had the most influence on how much carbon monoxide was produced.

In the end, they found that what mattered most was not the type of amine used to initially capture CO_2, as many have suspected. Instead, it was the concentration of solo, free-floating CO_2 molecules, which avoided bonding with amines but were nevertheless present in the solution. This "solo-CO_2" determined the concentration of carbon monoxide that was ultimately produced.

"We found that it's easier to react this 'solo' CO_2, as compared to CO_2 that has been captured by the amine," Leverick offers. "This tells future researchers that this process could be feasible for industrial streams, where high concentrations of carbon dioxide could efficiently be captured and converted into useful chemicals and fuels."

"This is not a removal technology, and it's important to state that," Gallant stresses. "The value that it does bring is that it allows us to recycle carbon dioxide some number of times while sustaining existing industrial processes, for fewer associated emissions. Ultimately, my dream is that electrochemical systems can be used to facilitate mineralization, and permanent storage of CO_2—a true removal technology. That's a longer-term vision. And a lot of the science we're starting to understand is a first step toward designing those processes."

This research is supported by Sunway University in Malaysia.

Jennifer Chu, MIT News Office

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NOTES

For more information, please see the following:

G. Leverick, E.M. Bernhardt, A.I. Ismail, J.H. Law, A. Arifutzzaman, M.K. Aroua, and B.M. Gallant. "Uncovering the active species in amine-mediated CO_2 reduction to CO on Ag." *ACS Catalysis*, September 5, 2023. Online: doi.org/10.1021/acscatal.3c02500.

To improve solar and other clean energy tech, look beyond hardware

MIT study finds system deployment processes have been slow to improve over time—but must be addressed to lower clean energy costs in the future.

To continue reducing the costs of solar energy and other clean energy technologies, scientists and engineers will likely need to focus, at least in part, on improving technology features that are not based on hardware, according to MIT researchers. They described this finding in the journal *Nature Energy*.

While the cost of installing a solar energy system has dropped by more than 99% since 1980, this new analysis shows that "soft technology" features, such as the codified permitting practices, supply chain management techniques, and system design processes that go into deploying a solar energy plant, contributed only 10% to 15% of total cost declines. Improvements to hardware features were responsible for the lion's share.

But because soft technology is increasingly dominating the total costs of installing solar energy systems, this trend threatens to slow future cost savings and hamper the global transition to clean energy, says the study's senior author, Jessika Trancik, a professor in MIT's Institute for Data, Systems, and Society (IDSS).

Trancik's co-authors include lead author Magdalena M. Klemun, a former IDSS graduate student and postdoc who is now an assistant professor at the Hong Kong University of Science and Technology; Goksin Kavlak, a former IDSS graduate student and postdoc who is now an associate at the Brattle Group; and James McNerney, a former IDSS postdoc and now a senior research fellow at the Harvard Kennedy School.

The team created a quantitative model to analyze the cost evolution of solar energy systems, which captures the contributions of both hardware technology features and soft technology features.

The framework shows that soft technology hasn't improved much over time—and that soft technology features contributed even less to overall cost declines than previously estimated.

The findings indicate that to reverse this trend and accelerate cost declines, engineers could look at making solar energy systems less reliant on soft technology to begin with, or they could tackle the problem directly by improving inefficient deployment processes.

"Really understanding where the efficiencies and inefficiencies are, and how to address those inefficiencies, is critical in supporting the clean energy transition. We are making huge investments of public dollars into this, and soft technology is going to be absolutely essential to making those funds count," says Trancik.

"However," Klemun adds, "we haven't been thinking about soft technology design as systematically as we have for hardware. That needs to change."

The hard truth about soft costs

Researchers have observed that the so-called "soft costs" of building a solar power plant—the costs of designing and installing the plant—are becoming a much larger share of total costs. In fact, the share of soft costs now typically ranges from 35% to 64%.

"We wanted to take a closer look at where these soft costs were coming from and why they weren't coming down over time as quickly as the hardware costs," Trancik says.

In the past, scientists have modeled the change in solar energy costs by dividing total costs into additive components—hardware components and nonhardware components—and then tracking how these components changed over time.

"But if you really want to understand where those rates of change are coming from, you need to go one level deeper to look at the technology features. Then things split out differently," Trancik says.

The researchers developed a quantitative approach that models the change in solar energy costs over time by assigning contributions to the individual technology features, including both hardware features and soft technology features.

For instance, their framework would capture how much of the decline in system installation costs—a soft cost—is due to standardized practices of certified installers—a soft technology feature. It would also capture how that same soft cost is affected by increased photovoltaic module efficiency—a hardware technology feature.

With this approach, the researchers saw that improvements in hardware had the greatest impacts on driving down soft costs in solar energy systems. For example, the efficiency of photovoltaic modules doubled between 1980 and 2017, reducing overall system costs by 17%. But about 40% of that overall decline could be attributed to reductions in soft costs tied to improved module efficiency.

The framework shows that, while hardware technology features tend to improve many cost components, soft technology features affect only a few.

An analysis from MIT researchers reveals that soft technology—the processes to design and deploy a solar energy system—contributed far less to the total cost declines of solar installations than previously estimated. Their quantitative model shows that driving down solar energy costs in the future will likely require either improving soft technology or reducing system dependencies on soft technology features. Image: Jose-Luis Olivares, MIT

"You can see this structural difference even before you collect data on how the technologies have changed over time. That's why mapping out a technology's network of cost dependencies is a useful first step to identify levers of change, for solar PV and for other technologies as well," Klemun notes.

Static soft technology

The researchers used their model to study several countries, since soft costs can vary widely around the world. For instance, solar energy soft costs in Germany are about 50% less than those in the United States.

The fact that hardware technology improvements are often shared globally led to dramatic declines in costs over the past few decades across locations, the analysis showed. Soft technology innovations typically aren't shared across borders. Moreover, the team found that countries with better soft technology performance 20 years ago still have better performance today, while those with worse performance didn't see much improvement.

This country-by-country difference could be driven by regulation and permitting processes, by cultural factors, or by market dynamics such as how firms interact with each other, Trancik says.

"But not all soft technology variables are ones that you would want to change in a cost-reducing direction, like lower wages. So, there are other considerations, beyond just bringing the cost of the technology down, that we need to think about when interpreting these results," she says.

Their analysis points to two strategies for reducing soft costs. For one, scientists could focus on developing hardware improvements that make soft costs more dependent on hardware technology variables and less on soft technology variables, such as by creating simpler, more standardized equipment that could reduce on-site installation time.

Or researchers could directly target soft technology features without changing hardware, perhaps by creating more efficient workflows for system installation or automated permitting platforms.

"In practice, engineers will often pursue both approaches, but separating the two in a formal model makes it easier to target innovation efforts by leveraging specific relationships between technology characteristics and costs," Klemun says.

"Often, when we think about information processing, we are leaving out processes that still happen in a very low-tech way through people communicating with one another. But it is just as important to think about that as a technology as it is to design fancy software," Trancik notes.

In the future, she and her collaborators want to apply their quantitative model to study the soft costs related to other technologies, such as electric vehicle charging and nuclear fission. They are also interested in better understanding the limits of soft technology improvement, and how one could design better soft technology from the outset.

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Adam Zewe, MIT News Office

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NOTES

For more information, please see the following:

M.M. Klemun, G. Kavlak, J. McNerney, and J.E. Trancik. "Mechanisms of hardware and soft technology evolution and the implications for solar energy cost trends." *Nature Energy*, August 17, 2023. Online: doi.org/10.1038/s41560-023-01286-9.

A delicate dance

Economist Catherine Wolfram balances global energy demands and the pressing need for decarbonization.

In early 2022, economist Catherine Wolfram was at her desk in the U.S. Treasury building. She could see the east wing of the White House, just steps away.

Russia had just invaded Ukraine, and Wolfram was thinking about Russia, oil, and sanctions. She and her colleagues had been tasked with figuring out how to restrict the revenues that Russia was using to fuel its brutal war while keeping Russian oil available and affordable to the countries that depended on it.

Now the William F. Pounds Professor of Energy Economics at MIT, Wolfram was on leave from academia to serve as deputy assistant secretary for climate and energy economics.

Working for Treasury Secretary Janet L. Yellen, Wolfram and her colleagues developed dozens of models and forecasts and projections. It struck her, she said later, that "huge decisions [affecting the global economy] would be made on the basis of spreadsheets that I was helping create." Wolfram composed a memo to the Biden administration and hoped her projections would pan out the way she believed they would.

Tackling conundrums that weigh competing, sometimes contradictory, interests has defined much of Wolfram's career.

Wolfram specializes in the economics of energy markets. She looks at ways to decarbonize global energy systems while recognizing that energy drives economic development, especially in the developing world.

"The way we're currently making energy is contributing to climate change. There's a delicate dance we have to do to make sure that we treat this important industry carefully, but also transform it rapidly to a cleaner, decarbonized system," she says.

Professor Catherine Wolfram, an economist in the MIT Sloan School of Management, looks for ways to decarbonize global energy systems while recognizing that energy drives economic development, especially in the developing world. Photo: Tim Correira for Caitlin Cunningham Photography LLC

Economists as influencers

While Wolfram was growing up in a suburb of St. Paul, Minnesota, her father was a law professor and her mother taught English as a second language. Her mother helped spawn Wolfram's interest in other cultures and her love of travel, but it was an experience closer to home that sparked her awareness of the effect of human activities on the state of the planet.

Minnesota's nickname is "land of 10,000 lakes." Wolfram remembers swimming in a nearby lake sometimes covered by a thick sludge of algae. "Thinking back on it, it must've had to do with fertilizer runoff," she says. "That was probably the first thing that made me think about the environment and policy."

In high school, Wolfram liked "the fact that you could use math to understand the world. I also was interested in the types of questions about human behavior that economists were thinking about.

"I definitely think economics is good at sussing out how different actors are likely to react to a particular policy and then designing policies with that in mind."

After receiving a bachelor's degree in economics from Harvard in 1989, Wolfram worked with a Massachusetts agency that governed rate hikes for utilities. Seeing its reliance on research, she says, illuminated the role academics could play in policy setting. It made her think she could make a difference from within academia.

While pursuing a PhD in economics from MIT, Wolfram counted Paul L. Joskow, the Elizabeth and James Killian Professor of Economics and former director of the MIT Center for Energy and Environmental Policy Research, and Nancy L. Rose, the Charles P. Kindleberger Professor of Applied Economics, among her mentors and influencers.

After spending 1996 to 2000 as an assistant professor of economics at Harvard, she joined the faculty at the Haas School of Business at UC Berkeley.

At Berkeley, it struck Wolfram that while she labored over ways to marginally boost the energy efficiency of U.S. power plants, the economies of China and India were growing rapidly, with a corresponding growth in energy use and carbon dioxide emissions. "It hit home that to understand the climate issue, I needed to understand energy demand in the developing world," she says.

The problem was that the developing world didn't always offer up the kind of neatly packaged, comprehensive data economists relied on. She wondered if, by relying on readily accessible data, the field was looking under the lamppost—while losing sight of what the rest of the street looked like.

To make up for a lack of available data on the state of electrification in sub-Saharan Africa, for instance, Wolfram developed and administered surveys to individual, remote rural households using on-the-ground field teams.

Her results suggested that in the world's poorest countries, the challenges involved in expanding the grid in rural areas should be weighed against potentially greater economic and social returns on investments in the transportation, education, or health sectors.

Taking the lead

Within months of Wolfram's memo to the Biden administration, leaders of the intergovernmental political forum Group of Seven (G7) agreed to the price cap. Tankers from coalition countries would only transport Russian crude sold at or below the price cap level, initially set at $60 per barrel.

"A price cap was not something that had ever been done before," Wolfram says. "In some ways, we were making it up out of whole cloth. It was exciting to see that I wrote one of the original memos about it, and then literally three and a half months later, the G7 was making an announcement.

"As economists and as policy makers, we must set the parameters and get the incentives right. The price cap was basically asking developing countries to buy cheap oil, which was consistent with their incentives."

In May 2023, the U.S. Treasury Department reported that despite widespread initial skepticism about the price cap, market participants and geopolitical analysts believe it is accomplishing its goals of restricting Russia's oil revenues while maintaining the supply of Russian oil and keeping energy costs in check for consumers and businesses around the world.

Wolfram held the U.S. Treasury post from March 2021 to October 2022 while on leave from UC Berkeley. In July 2023, she joined MIT Sloan School of Management partly to be geographically closer to the policy makers of the nation's capital. She's also excited about the work taking place elsewhere at the Institute to stay ahead of climate change.

Her time in D.C. was eye opening, particularly in terms of the leadership power of the United States. She worries that the United States is falling prey to "lost opportunities" in terms of addressing climate change. "We were showing real leadership on the price cap, and if we could only do that on climate, I think we could make faster inroads on a global agreement," she says.

Now focused on structuring global agreements in energy policy among developed and developing countries, she's considering how the United States can take advantage of its position as a world leader. "We need to be thinking about how what we do in the U.S. affects the rest of the world from a climate perspective. We can't go it alone.

"The U.S. needs to be more aligned with the European Union, Canada, and Japan to try to find areas where we're taking a common approach to addressing climate change," she says. She will touch on some of those areas in the class she will teach in spring 2024 titled "Climate and Energy in the Global Economy," offered through MIT Sloan.

Looking ahead, she says, "I'm a techno optimist. I believe in human innovation. I'm optimistic that we'll find ways to live with climate change and, hopefully, ways to minimize it."

Deborah Halber, MITEI correspondent

Embracing the future we need

MIT Sloan Professor Andy Sun works to improve the electricity grid so it can better use renewable energy.

When you picture MIT doctoral students taking small PhD courses together, you probably don't imagine them going on class field trips. But it does happen, sometimes, and one of those trips changed Andy Sun's career.

Today, Sun is a faculty member at the MIT Sloan School of Management and a leading global expert on integrating renewable energy into the electric grid. Back in 2007, Sun was an operations research PhD candidate with a diversified academic background: He had studied electrical engineering, quantum computing, and analog computing but was still searching for a doctoral research subject involving energy.

One day, as part of a graduate energy class taught by visiting professor Ignacio J. Pérez Arriaga, the students visited the headquarters of ISO-New England, the organization that operates New England's entire power grid and wholesale electricity market. Suddenly, it hit Sun. His understanding of engineering, used to design and optimize computing systems, could be applied to the grid as a whole, with all its connections, circuitry, and need for efficiency.

"The power grids in the U.S. continent are composed of two major interconnections, the Western Interconnection, the Eastern Interconnection, and one minor interconnection, the Texas grid," Sun says. "Within each interconnection, the power grid is one big machine, essentially. It's connected by tens of thousands of miles of transmission lines, thousands of generators, and consumers, and if anything is not synchronized, the system may collapse. It's one of the most complicated engineering systems."

And just like that, Sun had a subject he was motivated to pursue. "That's how I got into this field," he says. "Taking a field trip."

Sun has barely looked back. He has published dozens of papers about optimizing the flow of intermittent renewable energy through the electricity grid, a major practical issue for grid operators, while also thinking broadly about the future form of the grid and the process of making almost all energy renewable. Sun, who in 2022 rejoined MIT as the Iberdrola-Avangrid Associate Professor in Electric Power Systems, and is also an associate professor of operations research, emphasizes the urgency of rapidly switching to renewables.

"The decarbonization of our energy system is fundamental," Sun says. "It will change a lot of things because it has to. We don't have much time to get there. Two decades, three decades is the window in which we have to get a lot of things done. If you think about how much money will need to be invested, it's not actually that much. We should embrace this future that we have to get to."

Successful operations

Unexpected as it may have been, Sun's journey toward being an electricity grid expert was informed by all the stages of his higher education. Sun grew up in China and received his BA in electronic engineering from Tsinghua University in Beijing in 2003. He then moved to MIT, joining the Media Lab as a graduate student. Sun intended to study quantum computing but instead began working on analog computer circuit design for Professor Neil Gershenfeld, another person whose worldview influenced Sun.

"He had this vision about how optimization is very important in things," Sun says. "I had never heard of optimization before."

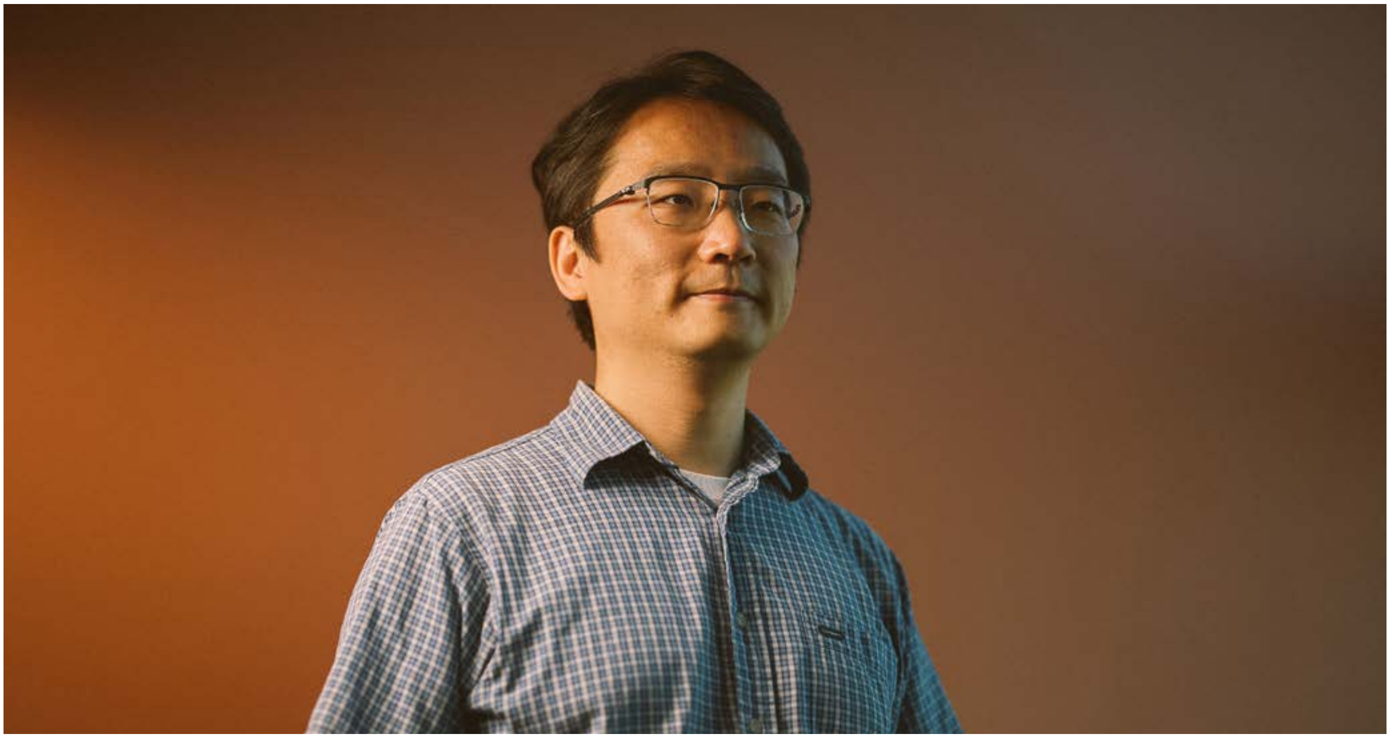
To learn more about it, Sun started taking MIT courses in operations research. "I really enjoyed it, especially the nonlinear optimization course taught by Robert Freund in the Operations Research Center," he recalls.

Sun enjoyed it so much that after a while, he joined MIT's PhD program in operations research, thanks to the guidance of Freund. Later, he started working with MIT Sloan Professor Dimitri Bertsimas, a leading figure in the field. Still, Sun hadn't quite nailed down what he wanted to focus on within operations research. Thinking of Sun's engineering skills, Bertsimas suggested that Sun look for a research topic related to energy.

"He wasn't an expert in energy at that time, but he knew that there are important problems there and encouraged me to go ahead and learn," Sun says.

So it was that Sun found himself in ISO-New England headquarters one day in 2007, finally knowing what he wanted to study and quickly finding opportunities to start learning from the organization's experts on electricity markets. By 2011, Sun had finished his MIT PhD dissertation. Based in part on ISO-New England data, the thesis presented new modeling to more efficiently integrate renewable energy into the grid; built some new modeling tools grid operators could use; and developed a way to add fair short-term energy auctions to an efficient grid system.

The core problem Sun deals with is that, unlike some other sources of electricity, renewables tend to be intermittent, generating power in an uneven pattern over time. That's not an insurmountable problem for grid operators, but it does require some new approaches. Many of the papers Sun has written focus on precisely how to increasingly draw upon intermittent energy sources while ensuring that the grid's current level of functionality remains intact. This is also the focus of his 2021 book, co-authored



"I'm just very excited about the opportunity of being back at MIT," Sun says. "The MIT Energy Initiative is a such a vibrant place, where many people come together to work on energy." Photo: Jared Charney

with Antonio J. Conejo, *Robust Optimization in Electric Energy Systems*.

"A major theme of my research is how to achieve the integration of renewables and still operate the system reliably," Sun says. "You have to keep the balance of supply and demand. This requires many time scales of operation from multidecade planning, to monthly or annual maintenance, to daily operations, down through second-by-second. I work on problems in all these timescales."

"I sit in the interface between power engineering and operations research," Sun says. "I'm not a power engineer, but I sit in this boundary, and I keep the problems in optimization as my motivation."

Culture shift

Sun's presence on the MIT campus represents a homecoming of sorts. After receiving his doctorate from MIT, Sun spent a year as a postdoc at IBM's Thomas J. Watson Research Center, then joined the faculty at Georgia Tech, where he remained for a decade. He returned to the Institute in January of 2022.

"I'm just very excited about the opportunity of being back at MIT," Sun says. "The MIT Energy Initiative is a such a vibrant place, where many people come together to work on energy. I sit in Sloan, but one very strong point of MIT is there are not many barriers, institutionally. I really look forward to working with colleagues from engineering, Sloan, everywhere, moving forward. We're moving in the right direction, with a lot of people coming together to break the traditional academic boundaries."

Still, Sun warns that some people may be underestimating the severity of the challenge ahead and the need to implement changes right now. The assets in power grids have a long lifetime, lasting multiple decades. That means investment decisions made now could affect how much clean power is being used a generation from now.

"We're talking about a short timeline, for changing something as huge as how a society fundamentally powers itself with energy," Sun says. "A lot of that must come from the technology we have today. Renewables are becoming much better and cheaper, so their use has to go up."

And that means more people need to work on issues of how to deploy and integrate renewables into everyday life, in the electric grid, transportation, and more. Sun hopes people will increasingly recognize energy as a huge growth area for research and applied work. For instance, when MIT President Sally Kornbluth gave her inaugural address in May 2023, she emphasized tackling the climate crisis as her highest priority, something Sun noticed and applauded.

"I think the most important thing is the culture," Sun says. "Bring climate up to the front, and create the platform to encourage people to come together and work on this issue."

Peter Dizikes, MIT News Office

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The future of motorcycles could be hydrogen

MIT Electric Vehicle Team builds a unique hydrogen fuel cell-powered electric motorcycle.

Aditya Mehrotra performs a "shakedown" test—running the motorcycle at high speeds to ensure that the mechanical and electrical systems hold up. Photo: Adam Glanzman

MIT's Electric Vehicle Team, which has a long record of building and racing innovative electric vehicles, including cars and motorcycles, in international professional-level competitions, is trying something very different this year: The team is building a hydrogen-powered electric motorcycle, using a fuel cell system, as a testbed for new hydrogen-based transportation.

The motorcycle successfully underwent its first full test-track demonstration in October. It is designed as an open-source platform that should make it possible to swap out and test a variety of different components, and for others to try their own versions based on plans the team is making freely available online.

Aditya Mehrotra, who is spearheading the project, is a graduate student working with mechanical engineering professor Alex Slocum, the Walter M. May (1939) and A. Hazel May Chair in Emerging Technologies. Mehrotra was studying energy systems and happened to also really like motorcycles, he says, "so we came up with the idea of a hydrogen-powered bike. We did an evaluation study, and we thought that this could actually work. We should try to build it."

Team members say that while battery-powered cars are a boon for the environment, they still face limitations in range and have issues associated with the mining of lithium and resulting emissions. So the team was interested in exploring hydrogen-powered vehicles as a clean alternative, allowing for vehicles that could be quickly refilled just like gasoline-powered vehicles.

Unlike past projects by the team, which has been part of MIT since 2005, this vehicle will not be entering races or competitions but will be presented at a variety of conferences. The team, consisting of about a dozen students, has been working on building the prototype since January 2023. In October, they presented the bike at the Hydrogen Americas Summit, and in May, they will travel to the Netherlands to present it at the World Hydrogen Summit. In addition to the two hydrogen summits, the team plans to show its bike at the Consumer Electronics Show in Las Vegas in January 2024.

Mehrotra says that in their presentations at these conferences, "we're hoping to use this project as a chance to start conversations around 'small hydrogen' systems that could increase demand, which could lead to the development of more infrastructure. We hope the project can help find new and creative applications for hydrogen." In addition to these demonstrations and the online information they will provide, he adds, they are also working toward publishing papers in academic journals describing their project and lessons learned from it, in hopes of making "an impact on the energy industry."

The motorcycle took shape over the course of the year piece by piece. "We got a couple of industry sponsors to donate components like the fuel cell and a lot of the major components of the system," he says. They also received support from the MIT Energy Initiative, the departments of Mechanical Engineering and Electrical Engineering and Computer Science, and the MIT Edgerton Center.

Initial tests were conducted on a dynamometer, a kind of instrumented treadmill Mehrotra describes as "basically a mock road." The vehicle used battery power during its development, until the fuel cell, provided by South Korean company Doosan, could be delivered and installed. The space the group has used to design and build the prototype, the home of the Electric Vehicle Team, is in MIT's building N51 and is well set up to do detailed testing of each of the bike's components as it is developed and integrated.

Elizabeth Brennan, a senior in mechanical engineering, says she joined the team in January 2023 because she wanted to gain more electrical engineering experience, "and I really fell in love with it." She says group members "really care and are very excited to be here and work on this bike and believe in the project."

Brennan, who is the team's safety lead, has been learning about the safe handling methods required for the bike's hydrogen fuel, including the special tanks and connectors needed. The team initially used a commercially available electric motor for the prototype but is now working on an improved version, designed from scratch, she says, "which gives us a lot more flexibility."

As part of the project, team members are developing a kind of textbook describing what they did and how they carried out each step in the process of designing and fabricating this hydrogen electric fuel-cell bike. No such motorcycle yet exists as a commercial product, though a few prototypes have been built.

That kind of guidebook to the process "just doesn't exist," Brennan says. She adds that "a lot of the technology development for hydrogen is either done in simulation or is still in the prototype stages, because developing it is expensive, and it's difficult to test these kinds of systems." One of the team's goals for the project is to make everything available as an open-source design, and "we want to provide this bike as a platform for researchers and for education, where researchers can test ideas in both space- and funding-constrained environments," she says.

Unlike a design built as a commercial product, Mehrotra says, "our vehicle is fully designed for research, so you can swap components in and out, and get real hardware data on how good your designs are." That can help people work on implementing their new design ideas and help push the industry forward, he says.

The few prototypes developed previously by some companies were inefficient and expensive, he says. "So far as we know, we are the first fully open-source, rigorously documented, tested and released-as-a-platform, [fuel cell] motorcycle in the world. No one else has made a motorcycle and tested it to the level that we have, and documented to the point that someone might actually be able to take this and scale it in the future, or use it in research."

He adds that "at the moment, this vehicle is affordable for research, but it's not affordable yet for commercial production because the fuel cell is a very big, expensive component." Doosan Fuel Cell, which provided the fuel cell for the prototype bike, produces relatively small and lightweight fuel cells mostly for use in drones. The company also produces hydrogen storage and delivery systems.

The project will continue to evolve, says team member Annika Marschner, a second-year student in mechanical engineering. "It's sort of an ongoing thing, and as we develop it and make changes, make it a stronger, better bike, it will just continue to grow over the years, hopefully," she says.

While the Electric Vehicle Team has until now focused on battery-powered vehicles, Marschner says, "Right now we're looking at hydrogen because it seems like something that's been less explored than other technologies for making sustainable transportation. So, it seemed like an exciting thing for us to offer our time and effort to."

Making it all work has been a long process. The team is using a frame from a 1999 motorcycle, with many custom-made parts added to support the electric motor, the hydrogen tank, the fuel cell, and the drive train. "Making everything fit in the frame of the bike is definitely something we've had to think about a lot because there's such limited space there. So, it required trying to figure out how to mount things in clever ways so that there are not conflicts," she says.

Marschner says, "A lot of people don't really imagine hydrogen energy being something that's out there being used on the roads, but the technology does exist." She points out that Toyota and Hyundai have hydrogen-fueled vehicles on the market, and that some hydrogen fuel stations exist, mostly in California, Japan, and some European countries. But getting access to hydrogen, "for your average consumer on the East Coast, is a huge, huge challenge. Infrastructure is definitely the biggest challenge right now to hydrogen vehicles," she says.

She sees a bright future for hydrogen as a clean fuel to replace fossil fuels over time. "I think it has a huge amount of potential," she says. "I think one of the biggest challenges with moving hydrogen energy forward is getting these demonstration projects actually developed and showing that these things can work and that they can work well. So, we're really excited to bring it along further."

MIT Energy Initiative

Using an on-board logging computer, Electric Vehicle Team members (left to right) Anand John, Rachel Mohammed, and Aditya Mehrotra check data on the bike's performance, battery levels, and hydrogen tank levels to calculate the range of the vehicle. Photo: Adam Glanzman

Moving past the Iron Age

Graduate student Sydney Johnson looks at how to achieve greener steel.

MIT graduate student Sydney Rose Johnson has never seen the steel mills in central India. She's never toured the American Midwest's hulking steel plants or the mini mills dotting the Mississippi River. But in the past year, she's become more familiar with steel production than she ever imagined.

A fourth-year dual degree MBA and PhD candidate in chemical engineering and a graduate research assistant with the MIT Energy Initiative (MITEI) as well as a 2022-2023 Shell Energy Fellow, Johnson looks at ways to reduce carbon dioxide (CO_2) emissions generated by industrial processes in hard-to-abate industries. Those include steel.

Almost every aspect of infrastructure and transportation—buildings, bridges, cars, trains, mass transit—contains steel. The manufacture of steel hasn't changed much since the Iron Age, with some steel plants in the United States and India operating almost continually for more than a century, their massive blast furnaces re-lined periodically with carbon and graphite to keep them going.

According to the World Economic Forum, steel demand is projected to increase 30% by 2050, spurred in part by population growth and economic development in China, India, Africa, and Southeast Asia.

The steel industry is among the three biggest producers of CO_2 worldwide. Every ton of steel produced in 2020 emitted, on average, 1.89 tons of CO_2 into the atmosphere—around 8% of global CO_2 emissions, according to the World Steel Association.

A combination of technical strategies and financial investments, Johnson notes, will be needed to wrestle that 8% figure down to something more planet friendly.

Johnson's thesis focuses on modeling and analyzing ways to decarbonize steel. Using data mined from academic and industry sources, she builds models to calculate emissions, costs, and energy consumption for plant-level production.

"I optimize steel production pathways using emission goals, industry commitments, and cost," she says. Based on the projected growth of India's steel industry, she applies this approach to case studies that predict outcomes for some of the country's thousand-plus factories, which together have a production capacity of 154 million metric tons of steel. For the United States, she looks at the effect of Inflation Reduction Act (IRA) credits. The 2022 IRA provides incentives that could accelerate the steel industry's efforts to minimize its carbon emissions.

Sydney Johnson, an MBA and PhD candidate and researcher in the MIT Energy Initiative, is building models that can calculate the cost and effectiveness of various strategies for cutting carbon dioxide emissions in steel production plants. Her techniques can be applied to many other hard-to-decarbonize industries. Photo: Corban Swain

Johnson compares emissions and costs across different production pathways, asking questions such as: "If we start today, what would a cost-optimal production scenario look like years from now? How would it change if we added in credits? What would have to happen to cut 2005 levels of emissions in half by 2030?"

"My goal is to gain an understanding of how current and emerging decarbonization strategies will be integrated into the industry," Johnson says.

Grappling with industrial problems

Growing up in Marietta, Georgia, outside Atlanta, the closest she ever came to a plant of any kind was through her father, a chemical engineer working in logistics and procuring steel for an aerospace company, and during high school, when she spent a semester working alongside chemical engineers tweaking the pH of an anti-foaming agent.

At Kennesaw Mountain High School, a STEM magnet program in Cobb County, students devote an entire semester of their senior year to an internship and research project.

Johnson chose to work at Kemira Chemicals, Inc., which develops chemical solutions for water-intensive industries with a focus on pulp and paper, water treatment, and energy systems.

"My goal was to understand why a polymer product was falling out of suspension—essentially, why it was less stable," she recalls. She learned how to formulate a lab-scale version of the product and conduct tests to measure its viscosity and acidity. Comparing the lab-scale and regular product results revealed that acidity was an important factor. "Through conversations with my mentor, I learned this was connected with the holding conditions, which led to the product being oxidized," she says. With the anti-foaming agent's problem identified, steps could be taken to fix it.

"I learned how to apply problem-solving. I got to learn more about working in an industrial environment by connecting with the team in quality control as well as with R&D and chemical engineers at the plant site," Johnson says. "This experience confirmed I wanted to pursue engineering in college."

As an undergraduate at Stanford, she learned about the different fields—biotechnology, environmental science, electrochemistry, and energy, among others—open to chemical engineers. "It seemed like a very diverse field and application range," she says. "I was just so intrigued by the different things I saw people doing and all these different sets of issues."

Turning up the heat

At MIT, she turned her attention to how certain industries can offset their detrimental effects on climate.

"I'm interested in the impact of technology on global communities, the environment, and policy. Energy applications affect every field. My goal as a chemical engineer is to have a broad perspective on problem-solving and to find solutions that benefit as many people, especially those under-resourced, as possible," says Johnson, who has served on the MIT Chemical Engineering Graduate Student Advisory Board, the MIT Energy & Climate Club, and is involved with diversity and inclusion initiatives.

The steel industry, Johnson acknowledges, is not what she first imagined when she saw herself working toward mitigating climate change.

"But now, understanding the role the material has in infrastructure development, combined with its heavy use of coal, has illuminated how the sector, along with other hard-to-abate industries, is important in the climate change conversation," Johnson says.

Despite the advanced age of many steel mills, some are quite energy efficient, she notes. Yet these operations, which produce heat upwards of 3,000 degrees Fahrenheit, are still emission intensive.

Steel is made from iron ore, a mixture of iron, oxygen, and other minerals found on virtually every continent, with Brazil and Australia alone exporting millions of metric tons per year. Commonly based on a process dating back to the 19th century, iron is extracted from the ore through smelting—heating the ore with blast furnaces until the metal becomes spongy and its chemical components begin to break down.

A reducing agent is needed to release the oxygen trapped in the ore, transforming it from its raw form to pure iron. That's where most emissions come from, Johnson notes.

"We want to reduce emissions, and we want to make a cleaner and safer environment for everyone," she says. "It's not just the CO_2 emissions. It's also sometimes NO_x and SO_x [nitrogen oxides and sulfur oxides] and air pollution particulate matter at some of these production facilities that can affect people as well."

In 2020, the International Energy Agency (IEA) released a roadmap exploring potential technologies and strategies that would make the iron and steel sector more compatible with the agency's vision of increased sustainability. Emission reductions can be accomplished with more modern technology, the agency suggests, or by substituting the fuels producing the immense heat needed to process ore. Traditionally, the fuels used for iron reduction have been coal and natural gas. Alternative fuels include clean hydrogen, electricity, and biomass.

Using the MITEI Sustainable Energy System Analysis Modeling Environment (SESAME), Johnson analyzes various decarbonization strategies. She considers options such as switching fuel for furnaces to hydrogen with a little bit of natural gas or adding carbon capture devices. The models demonstrate how effective these tactics are likely to be. The answers aren't always encouraging.

"Upstream emissions can determine how effective the strategies are," Johnson says. Charcoal derived from forestry biomass seemed to be a promising alternative fuel, but her models showed that processing the charcoal for use in the blast furnace limited its effectiveness in negating emissions.

Despite the challenges, "there are definitely ways of moving forward," Johnson says. "It's been an intriguing journey in terms of understanding where the industry is at. There's still a long way to go, but it's doable."

Johnson is heartened by the steel industry's efforts to recycle scrap into new steel products and incorporate more emission-friendly technologies and practices, some of which result in significantly lower CO_2 emissions than conventional production.

A major issue is that low-carbon steel can be more than 50% more costly than conventionally produced steel. "There are costs associated with making the transition, but in the context of the environmental implications, I think it's well worth it to adopt these technologies," she says.

After graduation, Johnson plans to continue to work in the energy field. "I definitely want to use a combination of engineering knowledge and business knowledge to work toward mitigating climate change, potentially in the startup space with clean technology or even in a policy context," she says. "I'm interested in connecting the private and public sectors to implement measures for improving our environment and benefitting as many people as possible."

Deborah Halber, MITEI correspondent

Introducing new students to MIT's energy landscape

Pre-orientation program for incoming first-year students provided an overview of energy-related activities and research.

During the Discover Energy FPOP program, students visited Codman Farms in Lincoln, Massachusetts, where they learned about the farm's sustainable farming practices and work to reduce their carbon footprint. Photo: Nicole Klaey, MITEI

Before they even settle into their new life as MIT students, groups of incoming first-years can attend one of several subject-related pre-orientation sessions to learn about courses and research programs in which they might want to participate. Among those offerings, which took place the week before regular first-year orientation, was a weeklong session called "Discover the Energy Transition," sponsored by the MIT Energy Initiative (MITEI). Seventeen students took part in that series of events, which included visits to a wind-turbine-blade testing facility, a nuclear reactor, and a sustainable farm, plus a chance to harness wind power themselves for a sail on the Charles River.

"We look at it as a way to get to know new students," says the program's director, MITEI Senior Academic Administrator Rowan Elowe, "and introduce them to the energy programs, the wealth of resources and labs, faculty members, courses, and of course our Energy Studies Minor program and some of the other education programs we offer at MITEI." Elowe, who directed the 13-year-old program this year for the first time, says, "We're trying to show students MITEI and its many resources in the energy landscape, but also, we really want to show how energy is interconnected across disciplines."

The activities included a welcome barbecue at Kresge Oval, then four days of visits to labs, testing facilities, and real-world energy-related sites. The visits began with a tour of a large facility in Charlestown where wind turbine blades undergo detailed stress testing simulating years of use in a just a few months. This gave the students a chance to see the mammoth scale of today's wind turbines.

"I really enjoyed touring the wind turbine testing facility," says incoming first-year John Dwyer. "It was interesting to see how much work goes into even just testing the structure of a blade, much less the design and construction" of the whole wind farm.

Both kinds of nuclear energy were the subject of back-to-back presentations: a tour of the Plasma Science and Fusion Center, where a new kind of potential fusion power generator was developed and spun off into startup company Commonwealth Fusion Systems, and then a tour of MIT's own fission research reactor.

A student, Trent Lee, presented a summary of work he performed on energy issues last summer through MIT's Undergraduate Research Opportunities Program (UROP). This gave the incoming students a taste of research opportunities in which they might soon be able to partake, but also gave the presenting student practice before he had to present his work at MITEI's Annual Research Conference.

Mike Howland, the Esther and Harold E. Edgerton Assistant Professor of Civil and Environmental Engineering, gave a talk about the benefits of fine-tuning how existing wind farms are operated. His research highlights how adjusting individual turbines to minimize the wind disruption to turbines further downwind increases the facility's overall power output with no change to existing hardware.

"Personally, as someone planning to major in physics, my favorite part [of the week's activities] was learning about modeling the interaction between separate wind turbines to increase their overall efficiency," says first-year student Borna Perković.

The group also traveled to Lincoln, Massachusetts, to tour Codman Farm, which has been implementing a wide variety of methods to reduce its overall carbon footprint, including a large solar array providing most of the farm's power, solar water heaters, and efficient farming methods to reduce waste that can generate greenhouse gases. Perković says that among the students this farm tour was "probably the majority's favorite, because it showed how, with resourcefulness and patience, small steps can go a long way."

Janelle Knox-Hayes, an MIT professor of economic geography and planning, spoke to the group about her research, which includes energy access and indigenous people's rights and stakeholder engagement in the creation of equitable, sustainable energy projects. The program also featured two MIT faculty members who were organizing a discussion about climate change between a faculty member and an MIT alum with differing views on the severity of the problem, but who stress the importance of civil dialog about such important issues and are planning a public debate on the subject.

First order of business for the weeklong Discover Energy FPOP program: The students met with their counselor for introductions, taking the opportunity to get to know each other as well as a little more about MIT. Pictured left to right: Emma Hopkins, Samuel Zhou, Ruoxi Qian, Celestina Pint, Maria Alder. Photo: Charlotte Whittle, MITEI

MIT graduate student Zander Keith (right) gave the FPOP students a tour of the Plasma Science and Fusion Center. Photo: Nicole Klaey, MITEI

Elowe explains that he wanted to have the organizers talk about preparing for that debate so that students could see "how they're planning to facilitate that, what they could expect to see, and how they can navigate these kinds of conversations on their own." He said students were surveyed before the program began and were asked what they worried about most. "A lot of them were worried about the political divide in the United States and the heavily politicized discourse," he says. Because climate change is one of these heavily politicized topics, he says the upcoming program of debates should help to address this concern.

A few events were just for fun, intended to encourage bonding among the group of newly arrived students, along with some faculty and staff members. The group experienced firsthand the power of the wind by sailing some of Community Boating's fleet of small sailboats on the Charles River alongside campus—enjoying one of humanity's oldest forms of sustainable transportation. Participants also spent one afternoon riding bikes on some of the area's bike trails and learning how to rent bikes from the services that provide them and how to maintain their own bikes—another traditional and climate-friendly way to get around.

They also toured a facility where MIT's Electric Vehicle Team, the oldest of its kind in the nation, is in the process of building and testing an innovative hydrogen fuel-cell electric motorbike.

Overall, Elowe says, a survey of the students afterward showed "ultimately everyone was really pleased with the week" and with its balance of lectures and hands-on events and tours. Some of the students have already volunteered to come back next year to help with the tours and events, he says.

"If we can recruit more students to the Energy Studies Minor program, that's wonderful," he says. "The goal of the minor is to have anyone who's working in a field proximate to energy understand how energy is a lever for climate change mitigation and to understand how in whatever role they choose to follow in their profession, they're able to have a positive impact."

Whichever majors or minors these students ultimately choose, he says, just knowing about MITEI and the Energy Studies Minor and having had this introduction to the topics, "I'd be happy to know that they're just keeping it in the back of their minds, how they can positively impact climate change and reduce carbon emissions, in any way they can, in whatever role they work."

Looking back on the week's events, Dwyer says, "Overall, it was an amazing and extremely valuable experience that I am grateful to have had the opportunity to partake in. It got me excited to be a part of the MIT community, and MITEI, too!"

MIT Energy Initiative

Empowering the globe to mitigate climate change through MIT courses

MITx and MIT Energy Initiative launch new series in sustainable energy, design, transportation, and policy.

Avidipto Biswas hoped to work in policy and renewable energy after finishing his master's degree in international energy affairs, but he wanted to gain more knowledge and experience first. He turned to MITx (mitxonline.mit.edu) for a course on sustainable and equitable solutions in urban mobility, calling it "the perfect bridge" between his education and work experience.

"This class is a stepping stone for practitioners starting in the field and looking for hands-on research experience," he says. "The assignments build upon each other to develop a real-life proposal and promote learning by doing."

Biswas took "ENE.001x Transformative Living Labs in Urban Climate Action and Transportation Planning" (bit.ly/mitx-transformative), one of the hundreds of high-quality massive open online courses (MOOCs) adapted from the MIT classroom for learners around the world. A leader in the online learning space since its launch in 2012, the MITx program, part of MIT Open Learning (openlearning.mit.edu), leverages MIT's considerable subject matter expertise and drives best practices in emerging digital and scalable learning environments. MITx also offers sequences, or series, of courses that give learners more robust instruction over three to 18 weeks.

The newest MITx sequence, Future Energy Systems (energy.mit.edu/education/online), is offered by the MIT Energy Initiative (MITEI). The four-course XSeries launched in September 2023 on the edX platform. But MITEI staff have been building toward this release since the debut of their first MITx course, "Sustainable Building Design," in 2020. After working with the MITx team to develop three new courses from the ground up, MITEI now offers "Sustainable Energy," "Energy Economics and Policy," and "Transformative Living Labs in Urban Climate Action and Transportation Planning."

"We always knew we wanted to make a program of courses that, together, represent the interdisciplinary nature of energy studies and focus on energy as the lever for mitigating climate change," says Rowan Elowe, MITEI senior academic administrator.

"XSeries courses are designed to work together as a group," explains Sarah Davis, MITx project administrator. "When a learner completes the four courses, they should be able to see the connections and have a fuller, deeper understanding of energy and the climate crisis."

The MITx teams work with MIT faculty to translate their research and on-campus courses into online courses. MOOCs are carefully planned. Courses can include lectures filmed in the MITx studio, contributions from external collaborators, access to a digital library of supplemental learning materials like interactive problem sets, and a discussion board where learners can communicate in real time.

"For our residential and online courses, our goal is for students to consider how they can engage systems thinking to reduce carbon emissions and mitigate climate change, regardless of the profession they have in mind," says Elowe. "For the MITx series, we took the research, tools, and knowledge at MIT and made it openly accessible for global audiences to expedite the transition to sustainable energy."

"MITx courses are just as rigorous as on-campus courses, but the people enrolled in them are not full-time students," Davis says. "By narrowing the focus in these courses, we can maintain the level of academic rigor and make it sustainable. That means there are some concepts that require multiple MITx courses in order to have a strong foundation. In creating a series, we build a path for learners."

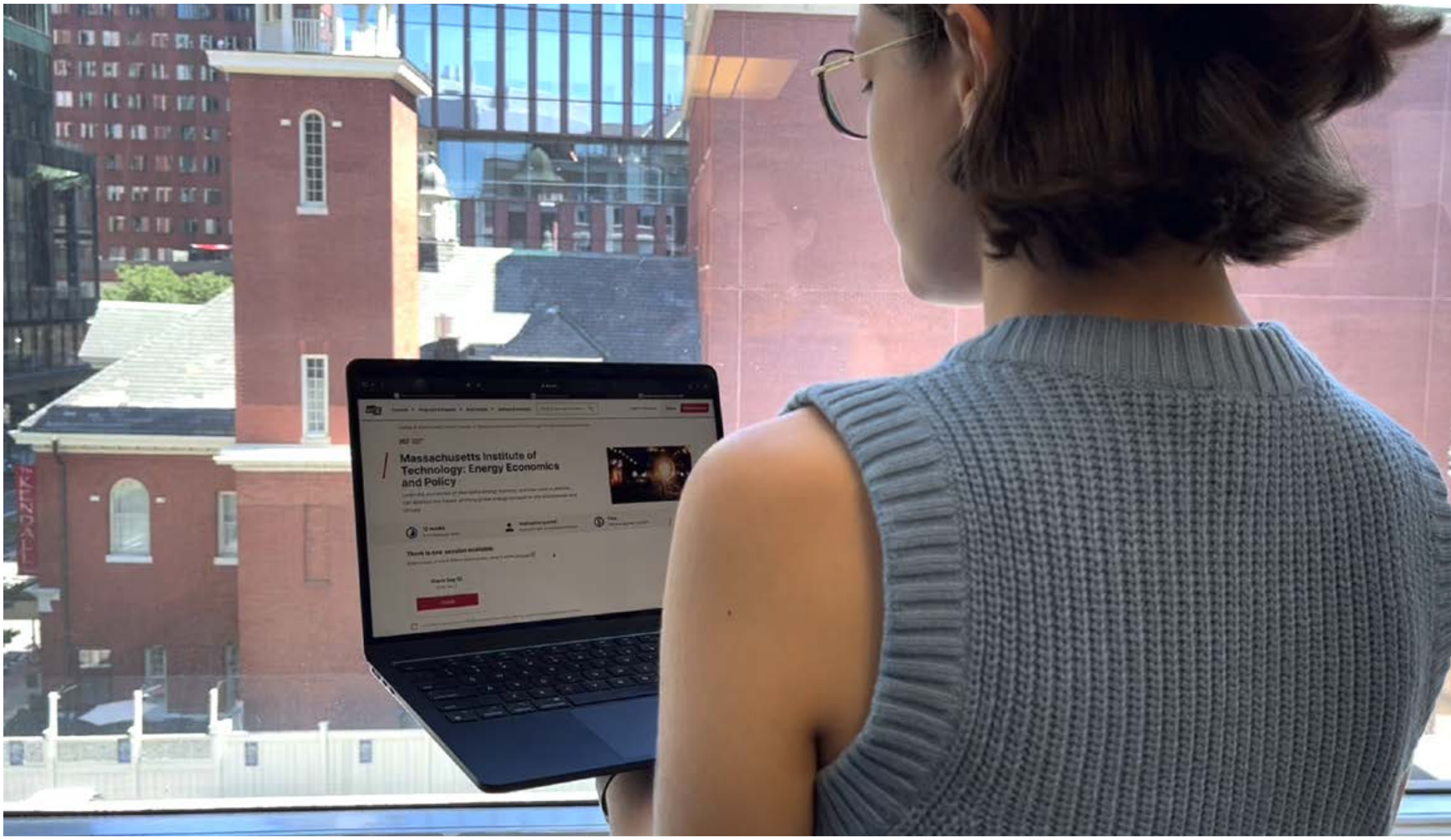
Addressing the greatest scientific and societal challenge of the ages

The Future Energy System XSeries launched at a moment when MIT is focused on climate change research. In her inaugural address, MIT President Sally Kornbluth said climate change was "the greatest scientific and societal challenge of this or any age" and called upon the MIT community to bring all their expertise to bear on the problem.

The first two courses launched in this XSeries—"Sustainable Energy" and "Energy Economics and Policy"—have enrolled more than 7,000 learners. In addition to the course content, learners have access to discussion boards where they can share ideas and ask questions of teaching assistants (TAs).

"Students in these courses come from a variety of backgrounds and levels of experience in the energy sector," says Elowe, who coordinates and supports TAs across courses. "TAs can point students to additional resources, like a crash course video on thermodynamics, if they are having trouble wrapping their heads around a concept. The courses attract learners who may not be native English speakers, so we are on hand to assist with any issues of translation and ensuring that all learners understand the assignments and expectations."

Photo courtesy of the MIT Energy Initiative



Listia Khairunnisa, MITEI graduate education program assistant, adds that being a TA gives her insight into the different motivations people have for enrolling in the courses. "I'm moderating the course on sustainable energy and observing learners who have shifted their careers to focus on energy," she says. "They enrolled to gain a deeper understanding of renewable energy."

Testimonials from learners who have enrolled in MITx courses from MITEI since 2020 show that the experience can benefit people at all stages of their careers and across a variety of industries.

Claude Gerstle SB '68, a climate activist and retired ophthalmologist who enrolled in a class on transportation planning, says, "I'm always looking for ways to make myself useful in the energy transition. This course is so well-organized, and I especially liked the way the homework was arranged and assisted by having templates you could fill in to organize your answers. Peer reviewing each other's submissions demonstrated the very high-level understanding of the other students."

Gerstle, who is also an MIT Open Learning supporter, adds that his course project on a cable car linking the New Jersey Palisades with New York City assisted him in preparing for a meeting with his state senator.

Claire Gotham, an executive with years of experience in the energy industry, found that there is always more to learn. "I particularly enjoyed the real work applicability of the course materials and assignments. Even after so many years of being hands-on in the energy space, I learned an enormous amount during the [Sustainable Energy] course that I expect to leverage and build on for years to come."

Elowe is pleased to see the latest XSeries up and running. "At MITEI, we want to amplify all of the efforts happening here on campus," he says. "Climate change is an immediate challenge. By making this content available globally we can enable and empower people to better engage with these questions and challenges."

Davis emphasizes that learners can audit all MITx courses for no fee. "At MITx, we really believe that everyone should be able to have access to these big ideas," she says. There are no applications, no required prerequisite courses or travel. All learners have to do is hit enroll.

Lauren Rebecca Thacker, MIT Open Learning

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Energy Fellows, 2023–2024

Photo: Jake Belcher

The Society of Energy Fellows at MIT welcomed 9 new members in fall 2023. Their fellowships were made possible through the generous support of four MITEI Member companies.

Chevron

Landon Schofield
Chemical Engineering

Eni S.p.A.

Yehoon Lee
Mechanical Engineering

ExxonMobil

Caolan John
Physics

Santosh Singh, PhD
Chemistry

YuJou Wang, PhD
Nuclear Science and Engineering

Duhan Zhang, PhD
Materials Science and Engineering

Shell

Tali Dotan, PhD
Chemical Engineering

Nathaniel Hickok
Economics

Rashmi Ravishankar
Aeronautics and Astronautics

How to decarbonize the world, at scale

The MIT Energy Initiative's Annual Research Conference highlights strategies for implementing large-scale reductions in the world's greenhouse gas emissions.

The world in recent years has largely been moving on from debates about the need to curb carbon emissions and focusing more on action—the development, implementation, and deployment of the technological, economic, and policy measures to spur the scale of reductions needed by mid-century. That was the message Robert Stoner, the director of the MIT Energy Initiative (MITEI), gave in his opening remarks at MITEI's Annual Research Conference, held on September 13-14, 2023.

Attendees at the two-day conference included faculty members, researchers, industry and financial leaders, government officials, and students, as well as more than 50 online participants from around the world.

"We are at an extraordinary inflection point. We have this narrow window in time to mitigate the worst effects of climate change by transforming our entire energy system and economy," said Jonah Wagner, the chief strategist of the U.S. Department of Energy's (DOE) Loan Programs Office, in one of the conference's keynote speeches.

Vice Provost Anne White (left) presented a keynote on the role of the research university before joining MITEI Director Robert Stoner to address audience questions. Photo: Kelley Travers, MITEI

Yet the solutions exist, he said. "Most of the technologies that we need to deploy to stay close to the international target of 1.5 degrees Celsius warming are proven and ready to go," he said. "We have over 80 percent of the technologies we will need through 2030 and at least half of the technologies we will need through 2050."

For example, Wagner pointed to the newly commissioned advanced nuclear power plant near Augusta, Georgia—the first new nuclear reactor built in the United States in a generation, partly funded through DOE loans. "It will be the largest source of clean power in America," he said. Though implementing all the needed technologies in the United States through mid-century will cost an estimated $10 trillion, or about $300 billion a year, most of that money will come from the private sector, he said.

As the United States faces what he describes as "a tsunami of distributed energy production," one key example of the strategy that's needed going forward, he said, is encouraging the development of Virtual Power Plants (VPPs). The U.S. power grid is growing, he said, and will add 200 gigawatts of peak demand by 2030. But rather than building new, large power plants to satisfy that need, much of the increase can be accommodated by VPPs, he said—which are "aggregations of distributed energy resources like rooftop solar with batteries, like electric vehicles (EVs) and chargers, like smart appliances, commercial and industrial loads on the grid that can be used together to help balance supply and demand just like a traditional power plant." For example, by shifting the time of demand for some applications where the timing is not critical, such as recharging EVs late at night instead of right after getting home from work when demand may be peaking, the need for extra peak power can be alleviated.

Such programs "offer a broad range of benefits," including affordability, reliability and resilience, decarbonization, and emissions reductions. But implementing such systems on a wide scale requires some up-front help, he explained. Payment for consumers to enroll in programs that allow such time adjustments "is the majority of the cost" of establishing VPPs, he says, "and that means most of the money spent on VPPs goes back into the pockets of American consumers." But to make that happen, there is a need for standardization of VPP operations "so that we are not recreating the wheel every single time we deploy a pilot or an effort with a utility."

The conference's other keynote speaker, Anne White, the vice provost and associate vice president for research administration at MIT, cited devastating recent floods, wildfires, and many other extreme weather-related crises around the world that have been exacerbated by climate change. "We saw in myriad ways that energy concerns and climate concerns are one and the same," she said. "So, we must urgently develop and scale low-carbon and zero-carbon solutions to prevent future warming. And we must do this with a practical systems-based approach that considers efficiency, affordability, equity, and sustainability for how the world will meet its energy needs."

White added that at MIT, "we are mobilizing everything." People at MIT feel a strong sense of responsibility for dealing with these global issues, she said, "and I think it's because we believe we have tools that can really make a difference."

Among the specific promising technologies that have sprung from MIT's labs, she pointed out, is the rapid development of fusion technology that led to MIT spinoff company Commonwealth Fusion Systems, which aims to build a demonstration unit of a practical fusion power reactor by the decade's end. That's an outcome of decades of research, she emphasized—the kinds of early-stage risky work that only academic labs, with help from government grants, can carry out.

For example, she pointed to the more than 200 projects that MITEI has provided seed funds of $150,000 each for two years, totaling over $28 million to date. Such early support is "a key part of producing the kind of transformative innovation we know we all need." In addition, MIT's The Engine has also helped launch not only Commonwealth Fusion Systems, but also Form Energy, a company building a plant in West Virginia to manufacture advanced iron-air batteries for renewable energy storage, and many others.

Following that theme of supporting early innovation, the conference featured two panels that served to highlight the work of students and alums and their energy-related startup companies. First, a startup showcase, moderated by Catarina Madeira, the director of MIT's Startup Exchange, featured presentations about seven recent spinoff companies that are developing cutting-edge technologies that emerged from MIT research. These included:

- Aeroshield, developing a new kind of highly insulated window using a unique aerogel material;
- Sublime, which is developing a low-emissions concrete;
- Found Energy, developing a way to use recycled aluminum as a fuel;
- Veir, developing superconducting power lines;
- Emvolom, developing inexpensive green fuels from waste gases;
- Boston Metal, developing low-emissions production processes for steel and other metals;
- Transaera, with a new kind of efficient air conditioning; and
- Carbon Recycling International, producing cheap hydrogen fuel and syngas.

Later in the conference, a "student slam competition" featured presentations by 11 students who described results of energy projects they had been working on over the summer. The projects were as diverse as analyzing opposition to wind farms in Maine, how best to allocate EV charging stations, optimizing bioenergy production, recycling the lithium from batteries, encouraging adoption of heat pumps, and conflict analysis about energy project siting. Attendees voted on the quality of the student presentations, and electrical engineering and computer science student Tori Hagenlocker was declared first-place winner for her talk on heat pump adoption.

In his keynote address, Jonah Wagner, the chief strategist of the U.S. Department of Energy's Loan Programs Office, discussed how to enable commercial liftoff for clean energy technologies. Photo: Jake Belcher

Students were also featured in a first-time addition to the conference: a panel discussion among five current or recent students, giving their perspective on today's energy issues and priorities, and how they are working toward trying to make a difference. Andres Alvarez, a recent graduate in nuclear engineering, described his work with a startup focused on identifying and supporting early-stage ideas that have potential. Graduate student Dyanna Jaye of urban studies and planning spoke about her work helping to launch a group called the Sunrise Movement to try to drive climate change as a top priority for the country, and her work helping to develop the Green New Deal.

Peter Scott, a graduate student in mechanical engineering who is studying green hydrogen production, spoke of the need for a "very drastic and rapid phaseout of current, existing fossil fuels" and a halt on developing new sources. Amar Dayal, an MBA candidate at the MIT Sloan School of Management, talked about the interplay between technology and policy, and the crucial role that legislation like the Inflation Reduction Act can have in enabling new energy technology to make the climb to commercialization. And Shreyaa Raghavan, a doctoral student in the Institute of Data, Systems, and Society, talked about the importance of multidisciplinary approaches to climate issues, including the important role of computer science. She added that MIT does well on this compared to other institutions, and "sustainability and decarbonization is a pillar in a lot of the different departments and programs that exist here."

Some recent recipients of MITEI's Seed Fund grants reported on their progress in a panel discussion moderated by MITEI Executive Director Martha Broad. Seed grant recipient Ariel Furst, a professor of chemical engineering, pointed out that access to electricity is very much concentrated in the global North and that, overall, one in ten people worldwide lacks access to electricity and some 2.5 billion people "rely on dirty fuels to heat their homes and cook their food," with impacts on both health and climate. The solution her project is developing involves using

Institute Professor Suzanne Berger spoke on a panel that explored the geopolitical implications of the energy transition at mid-century. Photo: Kelley Travers, MITEI

DNA molecules combined with catalysts to passively convert captured carbon dioxide into ethylene, a widely used chemical feedstock and fuel. Kerri Cahoy, a professor of aeronautics and astronautics, described her work on a system for monitoring methane emissions and powerline conditions by using satellite-based sensors. She and her team found that powerlines often begin emitting detectable broadband radio frequencies long before they actually fail in a way that could spark fires.

Admir Masic, an associate professor of civil and environmental engineering, described work on mining the ocean for minerals such as magnesium hydroxide to be used for carbon capture. The process can turn carbon dioxide into solid material that is stable over geological times and potentially usable as a construction material. Kripa Varanasi, a professor of mechanical engineering, said that over the years MITEI seed funding helped some of his projects that "went on to become startup companies, and some of them are thriving." He described ongoing work on a new kind of electrolyzer for green hydrogen production. He developed a system using bubble-attracting surfaces to increase the efficiency of bioreactors that generate hydrogen fuel.

A series of panel discussions over the two days covered a range of topics related to technologies and policies that could make a difference in combating climate change. On the technological side, one panel led by Randall Field, the executive director of MITEI's Future Energy Systems Center, looked at large, hard-to-decarbonize industrial processes. Antoine Allanore, a professor of metallurgy, described progress in developing innovative processes for producing iron and steel, among the world's most used commodities, in a way that drastically reduces greenhouse gas emissions. Greg Wilson of JERA Americas described the potential for ammonia produced from renewable sources to substitute for natural gas in power plants, greatly reducing emissions. Yet-Ming Chiang, a professor in materials science and engineering, described ways to decarbonize cement production using a novel low-temperature process. And Guiyan Zang, a research scientist at MITEI, spoke of efforts to reduce the carbon footprint of producing ethylene, a major industrial chemical, by using an electrochemical process.

Another panel, led by Jacopo Buongiorno, professor of nuclear science and engineering, explored the brightening future for expansion of nuclear power, including new, small, modular reactors that are finally emerging into commercial demonstration. "There is for the first time truly here in the U.S. in at least a decade and a half, a lot of excitement, a lot of attention towards nuclear," Buongiorno said. Nuclear power currently produces 45% to 50% of the nation's carbon-free electricity, the panelists said, and with the first new nuclear power plant in decades now in operation, the stage is set for significant growth.

Carbon capture and sequestration was the subject of a panel led by David Babson, the executive director of MIT's Climate Grand Challenges program. MIT professors Betar Gallant and Kripa Varanasi and industry representatives Elisabeth Birkeland from Equinor and Luc Huyse from Chevron Technology Ventures described significant progress in various approaches to recovering carbon dioxide from power plant emissions, from the air, and from the ocean, and converting it into fuels, construction materials, or other valuable commodities.

Some panel discussions also addressed the financial and policy side of the climate issue. A panel on geopolitical implications of the energy transition was moderated by MITEI Deputy Director of Policy Christopher Knittel, who said, "Energy has always been synonymous with geopolitics." He said that as concerns shift from where to find the oil and gas to where is the cobalt and nickel and other elements that will be needed, "not only are we worried about where the deposits of natural resources are, but we're going to be more and more worried about how governments are incentivizing the transition" to developing this new mix of natural resources. Panelist Suzanne Berger, an Institute Professor, said that "we're now at a moment of unique openness and opportunity for creating a new American production system," one that is much more efficient and less carbon-producing.

One panel dealt with the investor's perspective on the possibilities and pitfalls of emerging energy technologies. Moderator Jacquelyn Pless, an assistant professor in MIT Sloan, said that "there's a lot of momentum now in this space. It's a really ripe time for investing," but the risks are real. "Tons of investment is needed in some very big and uncertain technologies."

The role that large, established companies can play in leading a transition to cleaner energy was addressed by another panel. Moderator J.J. Laukatis, MITEI's director of member services, said that "the scale of this transformation is massive, and it will also be very different from anything we've seen in the past. We're going to have to scale up complex new technologies and systems across the board, from hydrogen to EVs to the electrical grid, at rates we haven't done before." And doing so will require a concerted effort that includes industry as well as government and academia.

MIT Energy Initiative

No time to spare

At Clean Energy Education and Empowerment (C3E) symposium, women rally to beat the clock on climate change.

"There's so much work ahead of us and so many obstacles in the way," said Raisa Lee, director of project development with Clearway Energy Group, an independent clean power producer. But, added Lee, "It's most important to focus on finding spaces and people so we can foster growth and support each other—the power of belonging!"

These sentiments captured the spirit of the 12th annual Women in Clean Energy Education and Empowerment (C3E) Symposium and Awards, held at MIT on September 27 and 28, 2023. The conference is part of the C3E Initiative, which aims to connect women in clean energy, recognize the accomplishments of leaders across different fields, and engage more women in the enterprise of decarbonization.

The conference topic, "Clearing hurdles to achieve net zero by 2050: Moving quickly, eliminating risks, and leaving no one behind," spoke to the shared sense of urgency and commitment to community building among the several hundred participants attending in person and online.

As symposium speakers attested, the task of saving the world doesn't seem as daunting when someone has your back.

Melinda Baglio, chief investment officer and general counsel of the renewable energy finance firm CleanCapital, said, "I have several groups of women in my life…and whenever I am doing something really difficult, I like to close my eyes for a minute and imagine their hands right on my shoulders and just giving me that support and pushing me forward to do the thing that I need to do."

The C3E symposium was hosted by the MIT Energy Initiative (MITEI), which partners in the C3E Initiative with the U.S. Department of Energy (DOE), Stanford University's Precourt Institute for Energy, and the Texas A&M Energy Institute.

Gender diversity and emissions

"Time is not on our side in the race to achieve net zero by 2050," said Martha Broad, executive director of MITEI, in her opening remarks. "However, by increasing the gender diversity of the energy sector, we're putting our best team forward to tackle this challenge."

Closing a pronounced gender gap in corporate leadership and legislative bodies would also help, she said. Research has demonstrated that improving gender diversity in the energy sector leads to stronger climate governance and innovation. In addition, Broad noted, a recent study showed that increasing gender diversity in legislative bodies results in stronger climate policy and "hence lowers CO_2 emissions."

There was wide agreement that beating the clock on climate change means recruiting, training, and retaining a vast and diverse workforce. In talks and panels, symposium participants described their wide-ranging roles as leaders in this enterprise.

"This is a very exciting time to be working in clean energy, and an exciting time to be doubling down on the work that C3E does, because clean energy technologies are ready," said Kathleen Hogan, principal undersecretary for infrastructure at DOE. In her keynote address, Hogan highlighted "the amazing, historic funding through the bipartisan infrastructure law and Inflation Reduction Act, where we are putting ultimately trillions of dollars into clean energy." This presents a "tremendous opportunity to grow the clean energy workforce…to pull in the next generation of women to advance this field of work, and to figure out how to deliver the maximum impact."

Gina McCarthy, who received the C3E lifetime achievement award, rallied symposium participants to remain hopeful and engaged. "It's all about a world of new possibilities, new partnerships we can create together," said the former White House national climate advisor and Environmental Protection Agency administrator. "Use each milestone as an opportunity to pat ourselves on the back and be more passionate than ever before—that is how change happens."

"You belong"

Other speakers provided ample evidence of passion and persistence in their pursuit of clean energy goals.

C3E advocacy award winner and climate justice policy leader Jameka Hodnett works to ensure that historically underfunded Black communities benefit from decarbonization programs. Not all of her community contacts share her concerns about climate change or recognize the necessity of an energy transition. "This is difficult work, where I must be willing to stick my neck out and build relationships with others across differences," she said.

Remote and often marginalized communities in the United States and around the world pose other kinds of challenges. Wahleah Johns, director of DOE's Office of Indian Energy Policy and Programs, described the loss of jobs on tribal lands as fossil fuel companies shut down, and the problem of developing trust with local groups. She believes energy justice in these communities must draw "on indigenous, traditional knowledge of design, building, and planning" and demonstrate "value for future generations."

Evangelina Galvan Shreeve, daughter of immigrant farmworkers, is tapping the talent of diverse communities to build the next generation's clean energy workforce. The C3E education award winner, chief diversity officer, and director of STEM education at the Pacific Northwest

National Laboratory, tells young people: "You are worthy of joining places you dream about, you are brilliant, and we need both to pursue the clean energy future. You belong."

Reducing the carbon budget

In her keynote address, Sally M. Benson, Precourt Family Professor of Energy Science Engineering at Stanford University's School of Earth, Energy, and Environmental Sciences, warned of the hazards of not acting quickly to reduce the global carbon budget. "It's starting to cost us lots of money: In some years we are getting half a trillion dollars in damage," she said. "We need all hands on deck, and to do that we need to align people's views to give us the speed and scale to beat incredibly short timelines."

Benson's strategies include generating community- and city-scale rather than individual-scale actions; streamlining the process for approving renewable energy projects; and advancing technological innovations based on "which would have the largest, transformational impact, the kind that could meet our 2050 [net-zero carbon emissions] goals."

The symposium offered examples of innovations that could play out at the scale and speed that Benson recommends.

Elise Strobach SM '17, PhD '20 developed a nanoporous nanogel coating for windows that can cut energy losses—estimated at $40 billion a year—in half. Her spinout company, AeroShield Materials, Inc., aims to make windows light, thin, and affordable.

Claire Woo's startup employer, Form Energy, has designed an iron-air battery that could bolster the electric grid as renewable sources such as sun and wind fuel more of the world's energy needs. Stacked like so many blocks in giant arrays, the batteries provide 100-hour energy backup for multi-day power outages due to storms or other emergencies.

Grids and energy equity

Panelists discussed the requirements for resilient electric grids in the clean energy transition. Peggy Heeg, a corporate board member of the Electric Reliability Council of Texas (ERCOT), celebrated her state's top-ranked status in solar and wind production but cautioned that "the shift is creating some real problems with our operations of the grid." She believes that, currently, the only viable backup when heat or storms cause demand peaks is natural gas generation.

Caroline Choi, the senior vice president of corporate affairs at Edison International and Southern California Edison, described "unprecedented grid expansion" under way in California, as more solar and wind suppliers plug in. This will require "a significant acceleration in the pace of deployment of transmission systems," said Julie Mulvaney Kemp, a research scientist at Lawrence Berkeley National Laboratory. Such expansion is complicated by fragmented regional planning, high costs, and local siting issues.

Not all power systems are supersized. "I flew in small bush planes with my baby daughter in order to shadow Alaska microgrid operators," said Piper Foster Wilder, founder and CEO of 60Hertz Energy and the C3E entrepreneurship award winner. Her software enables energy suppliers in even the most inaccessible places to monitor and protect utilities and infrastructure.

"Given the fundamental aspects of energy for life, the widely entrenched nature of the energy system, and the intersecting challenges with other priorities, everyone has a vital role to play," said Kathleen Araújo, a professor of sustainable energy systems, innovation, and policy at Boise State University. In a panel devoted to energy justice, speakers hammered home the centrality of historically marginalized groups in achieving a global energy transition.

In the United States, communities must play a vital role in shaping their clean energy futures, whether former mining counties in Pennsylvania, Indian tribes whose lands have been exploited for fossil fuel production, or diesel-importing regions in Alaska, said Araújo. "Inclusive engagement, knowledge sharing, and other forms of collaboration can strengthen the legitimacy and [lead to] more enduring outcomes."

Paula R. Glover, the president of Alliance to Save Energy and a C3E ambassador, speaks on a panel discussing how to strengthen existing policies and implement new ones to accelerate decarbonization. Photo: Gretchen Ertl

Worldwide, 675 million people lack access to electricity, and 590 million of them live in sub-Saharan Africa, according to Rhonda Jordan Antoine, a senior energy specialist at The World Bank. The bank is committed to providing the populace of this vast region with reliable, renewable energy sources, customizing solutions to specific countries and communities. "Africa's not just about connecting households to power but also supporting activities, agricultural productivity, and provision of essential services such as healthcare and education," she said.

Whether confronting environmental injustice, supply chain gridlock, financing difficulties, or communities resistant to addressing decarbonization, symposium participants candidly shared their challenges and frustrations. "I personally find this is really hard work," Sally Benson acknowledged. "It took us 100 years or more to build the energy system that we have today, and now we're saying that we want to change it in the next 20 years."

But the words of Gina McCarthy were invoked repeatedly over the two-day conference, lifting spirits in the room: "I am hugely optimistic," she said. "The clean energy future isn't just around, it isn't just possible, it is already under way. And it is the opportunity of a lifetime."

Leda Zimmerman, MITEI correspondent

Power when the sun doesn't shine

With batteries based on iron and air, Form Energy leverages MIT research to incorporate renewables into the grid.

In 2016, at the huge Houston energy conference CERAWeek, MIT materials scientist Yet-Ming Chiang found himself talking to a Tesla executive about a thorny problem: how to store the output of solar panels and wind turbines for long durations.

Chiang, the Kyocera Professor of Materials Science and Engineering, and Mateo Jaramillo, a vice president at Tesla, knew that utilities lacked a cost-effective way to store renewable energy to cover peak levels of demand and to bridge the gaps during windless and cloudy days. They also knew that the scarcity of raw materials used in conventional energy storage devices needed to be addressed if renewables were ever going to displace fossil fuels on the grid at scale.

Energy storage technologies can facilitate access to renewable energy sources, boost the stability and reliability of power grids, and ultimately accelerate grid decarbonization. The global market for these systems—essentially large batteries—is expected to grow tremendously in the coming years. A study by the nonprofit LDES (Long Duration Energy Storage) Council pegs the long-duration energy storage market at between 80 and 140 terawatt-hours by 2040. "That's a really big number," Chiang notes. "Every ten people on the planet will need access to the equivalent of one EV [electric vehicle] battery to support their energy needs."

In 2017, one year after they met in Houston, Chiang and Jaramillo joined forces to co-found Form Energy in Somerville, Massachusetts, with MIT graduates Marco Ferrara SM '06, PhD '08 and William Woodford PhD '13, and energy storage veteran Ted Wiley.

"There is a burgeoning market for electrical energy storage because we want to achieve decarbonization as fast and as cost effectively as possible," says Ferrara, Form's senior vice president in charge of software and analytics.

Investors agreed. Over the next six years, Form Energy would raise more than $800 million in venture capital.

Form Energy's battery modules are grouped together in environmentally protected enclosures. Hundreds of these enclosures are grouped together in modular megawatt-scale power blocks. Depending on the system size, tens to hundreds of these power blocks will be connected to the electricity grid. For scale, in its least dense configuration, a 1-megawatt system comprises half an acre of land. Higher density configurations would achieve more than 3 megawatts per acre. This rendering shows a 56-megawatt Form Energy battery system. Image courtesy of Form Energy

Bridging gaps

The simplest battery consists of an anode, a cathode, and an electrolyte. During discharge, with the help of the electrolyte, electrons flow from the negative anode to the positive cathode. During charge, external voltage reverses the process. The anode becomes the positive terminal, the cathode becomes the negative terminal, and electrons move back to where they started. Materials used for the anode, cathode, and electrolyte determine the battery's weight, power, and cost "entitlement," which is the total cost at the component level.

During the 1980s and 1990s, the use of lithium revolutionized batteries, making them smaller, lighter, and able to hold a charge for longer. The storage devices Form Energy has devised are rechargeable batteries based on iron, which has several advantages over lithium. A big one is cost.

Chiang once declared to the MIT Club of Northern California, "I love lithium-ion." Two of the four MIT spinoffs Chiang founded center on innovative lithium-ion batteries. But at hundreds of dollars a kilowatt-hour and with a storage capacity typically measured in hours, lithium-ion was ill-suited for the use he now had in mind.

The approach Chiang envisioned had to be cost-effective enough to boost the attractiveness of renewables. Making solar and wind energy reliable enough for millions of customers meant storing it long enough to fill the gaps created by extreme weather conditions, grid outages, and when there is a lull in the wind or a few days of clouds.

To be competitive with legacy power plants, Chiang's method had to come in at around $20 per kilowatt-hour of stored energy—one-tenth the cost of lithium-ion battery storage.

But how to transition from expensive batteries that store and discharge over a couple of hours to some as-yet-undefined, cheap, longer-duration technology?

"One big ball of iron"

That's where Ferrara comes in. Ferrara has a PhD in nuclear engineering from MIT and a PhD in electrical engineering and computer science from the University of L'Aquila in his native Italy. In 2017, as a research affiliate at the MIT Department of Materials Science and Engineering, he worked with Chiang to model the grid's need to manage renewables' intermittency.

How intermittent depends on where you are. In the United States, for instance, there's the windy Great Plains; the sun-drenched, relatively low-wind deserts of Arizona, New Mexico, and Nevada; and the often-cloudy Pacific Northwest.

Ferrara, in collaboration with Professor Jessika Trancik of MIT's Institute for Data, Systems, and Society and her MIT team, modeled four representative locations in the United States and concluded that energy storage with capacity costs below roughly $20/kilowatt-hour and discharge durations of multiple days would allow a wind-solar mix to provide cost-competitive, firm electricity in resource-abundant locations.

Now that they had a time frame, they turned their attention to materials. At the price point Form Energy was aiming for, lithium was out of the question. Chiang looked at plentiful and cheap sulfur. But a sulfur, sodium, water, and air battery had technical challenges.

Thomas Edison once used iron as an electrode, and iron-air batteries were first studied in the 1960s. They were too heavy to make good transportation batteries. But this time, Chiang and team were looking at a battery that sat on the ground, so weight didn't matter. Their priorities were cost and availability.

"Iron is produced, mined, and processed on every continent," Chiang says. "The Earth is one big ball of iron. We wouldn't ever have to worry about even the most ambitious projections of how much storage that the world might use by mid-century." If Form ever moves into the residential market, "it'll be the safest battery you've ever parked at your house," Chiang laughs. "Just iron, air, and water."

Scientists call it reversible rusting. While discharging, the battery takes in oxygen and converts iron to rust. Applying an electrical current converts the rusty pellets back to iron, and the battery "breathes out" oxygen as it charges. "In chemical terms, you have iron, and it becomes iron hydroxide," Chiang says. "That means electrons were extracted. You get those electrons to go through the external circuit, and now you have a battery."

Form Energy's battery modules are approximately the size of a washer and drier unit. They are stacked in 40-foot containers, and several containers are electrically connected with power conversion systems to build storage plants that can cover several acres.

The right place at the right time

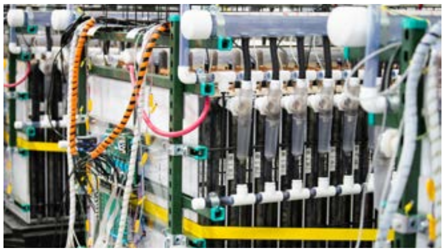
The modules don't look or act like anything utilities have contracted for before.

That's one of Form's key challenges. "There is not widespread knowledge of needing these new tools for decarbonized grids," Ferrara says. "That's not the way utilities have typically planned. They're looking at all the tools in the toolkit that exist today, which may not contemplate a multi-day energy storage asset."

Form Energy's customers are largely traditional power companies seeking to expand their portfolios of renewable electricity. Some are in the process of decommissioning coal plants and shifting to renewables.

Ferrara's research pinpointing the need for very low-cost multi-day storage provides key data for power suppliers seeking to determine the most cost-effective way to integrate more renewable energy.

Using the same modeling techniques, Ferrara and team show potential customers how the technology fits in with their existing system, how it competes with other technologies, and how, in some cases, it can operate synergistically with other storage technologies.



Form Energy operates a 54,000-square-foot campus in the heart of the Bay Area where its full-scale battery systems are designed and tested at scale. Working in close collaboration with Form's R&D team in Somerville, Massachusetts, and Advanced Manufacturing team in Eighty Four, Pennsylvania, Form's Berkeley team ensures that the iron-air batteries are designed and validated to be manufactured at the system level. This photo shows a battery module being tested in Form's Berkeley lab. Image courtesy of Form Energy

"They may need a portfolio of storage technologies to fully balance renewables on different timescales of intermittency," he says. But other than the technology developed at Form, "there isn't much out there, certainly not within the cost entitlement of what we're bringing to market." Thanks to Chiang and Jaramillo's chance encounter in Houston, Form has a several-year lead on other companies working to address this challenge.

In June 2023, Form Energy closed its biggest deal to date for a single project: Georgia Power's order for a 15-megawatt/1,500-megawatt-hour system. That order brings Form's total amount of energy storage under contracts with utility customers to 40 megawatts/4 gigawatt-hours. To meet the demand, Form is building a new commercial-scale battery manufacturing facility in West Virginia.

The fact that Form Energy is creating jobs in an area that lost more than ten thousand steel jobs over the past decade is not lost on Chiang. "And these new jobs are in clean tech. It's super exciting to me personally to be doing something that benefits communities outside of our traditional technology centers.

"This is the right time for so many reasons," Chiang says. He says he and his Form Energy co-founders feel "tremendous urgency to get these batteries out into the world."

Deborah Halber, MITEI correspondent

MIT alumnus' thermal battery helps industry eliminate fossil fuels

Antora Energy is commercializing a thermal battery that lets manufacturers use renewable energy around the clock.

The explosion of renewable energy projects around the globe is leading to a saturation problem. As more renewable power contributes to the grid, the value of electricity is plummeting during the times of day when wind and solar hit peak productivity. The problem is limiting renewable energy investments in some of the sunniest and windiest places in the world.

Now Antora Energy, co-founded by David Bierman SM '14, PhD '17, is addressing the intermittent nature of wind and solar with a low-cost, highly efficient thermal battery that stores electricity as heat to allow manufacturers and other energy-hungry businesses to eliminate their use of fossil fuels.

"We take electricity when it's cheapest, meaning when wind gusts are strongest and the sun is shining brightest," Bierman explains. "We run that electricity through a resistive heater to drive up the temperature of a very inexpensive material—we use carbon blocks, which are extremely stable, produced at incredible scales, and are some of the cheapest materials on Earth. When you need to pull energy from the battery, you open a large shutter to extract thermal radiation, which is used to generate process heat or power using our thermophotovoltaic, or TPV, technology. The end result is a zero-carbon, flexible, combined heat and power system for industry."

Antora's battery could dramatically expand the application of renewable energy by enabling its use in industry, a sector of the U.S. economy that accounted for nearly a quarter of all greenhouse gas emissions in 2021, according to the U.S. Environmental Protection Agency.

Antora says it is able to deliver on the long-sought promise of heat-to-power TPV technology because it has achieved new levels of efficiency and scalability with its cells. Earlier this year, Antora opened a new manufacturing facility that will be capable of producing 2 megawatts of its TPV cells each year—which the company says makes it the largest TPV production facility in the world.

Antora's thermal battery manufacturing facilities and demonstration unit are located in sun-soaked California, where renewables make up close to a third of all electricity. But Antora's team says its technology holds promise in other regions as increasingly large renewable projects connect to grids across the globe.

"We see places today [with high renewables] as a sign of where things are going," Bierman says. "If you look at the tailwinds we have in the renewable industry, there's a sense of inevitability about solar and wind, which will need to be deployed at incredible scales to avoid a climate catastrophe. We'll see terawatts and terawatts of new additions of these renewables, so what you see today in California or Texas or Kansas, with significant periods of renewable overproduction, is just the tip of the iceberg."

Bierman has been working on thermal energy storage and thermophotovoltaics since his time at MIT, and Antora's ties to MIT are especially strong because its progress is the result of two MIT startups becoming one.

Alumni join forces

Bierman did his master's and doctoral work in MIT's Department of Mechanical Engineering, where he worked on solid-state solar thermal energy conversion systems. In 2016, while taking course 15.366 (Climate and Energy Ventures), he met Jordan Kearns SM '17, then a graduate student in the Technology and Policy Program and the Department of Nuclear Science and Engineering. The two were studying renewable energy when they began to think about the intermittent nature of wind and solar as an opportunity rather than a problem.

"There are already places in the U.S. where we have more wind and solar at times than we know what to do with," Kearns says. "That is an opportunity for not only emissions reductions but also for reducing energy costs. What's the application? I don't think the overproduction of energy was being talked about as much as the intermittency problem."

Kearns did research through the MIT Energy Initiative, and the researchers received support from MIT's Venture Mentoring Service and the MIT Sandbox Innovation Fund to further explore ways to capitalize on fluctuating power prices.

Kearns officially founded a company called Medley Thermal in 2017 to help companies that use natural gas switch to energy produced by renewables when the price was right. To accomplish that, he combined an off-the-shelf electric boiler with novel control software so the companies could switch energy sources seamlessly from fossil fuel to electricity at especially windy or sunny times. Medley went on to become a finalist for the MIT Clean Energy Prize, and Kearns wanted Bierman to join him as a co-founder, but Bierman had received a fellowship to commercialize a thermal energy storage solution and decided to pursue that after graduation.

The split ended up working out for both alumni. In the ensuing years, Kearns led Medley Thermal through a number of projects in which gradually larger companies switched from relying on

Antora Energy has developed a low-cost, highly efficient thermal battery that stores electricity produced by wind and solar generators as heat, allowing manufacturers and other energy-hungry businesses to eliminate their use of fossil fuels. Above: Antora installs its first commercial-scale unit at an industrial site near Fresno, California. Photo courtesy of Antora Energy

natural gas or propane sources to renewable electricity from the grid. The work culminated in an installment at the Jay Peak resort in Vermont that Kearns says is one of the largest projects in the United States using renewable energy to produce heat. The project is expected to reduce about 2,500 tons of carbon dioxide per year.

Bierman, meanwhile, further developed a thermal energy storage solution for industrial decarbonization, which works by using renewable electricity to heat blocks of carbon, which are stored in insulation to retain energy for long periods of time. The heat from those blocks can then be used to deliver electricity or heat to customers at temperatures that can exceed 1,500 C. When Antora raised a $50 million Series A funding round last year, Bierman asked Kearns if he could buy out Medley's team, and the researchers finally became co-workers.

"Antora and Medley Thermal have a similar value prop: There's low-cost electricity, and we want to connect that to the industrial sector," Kearns explains. "But whereas Medley used renewables on an as-available basis, and then when the winds stop we went back to burning fossil fuel with a boiler, Antora has a thermal battery that takes in the electricity, converts it to heat, but also stores it as heat so even when the wind stops blowing we have a reservoir of heat that we can continue to pull from to make steam or power or whatever the facility needs. So, we can now further reduce energy costs by offsetting more fuel and offer a 100 percent clean energy solution."

United we scale

Today, Kearns runs the project development arm of Antora.

"There are other, much larger projects in the pipeline," Kearns says. "The Jay Peak project is about 3 megawatts of power, but some of the ones we're working on now are 30, 60 megawatt projects. Those are more industrial focused, and they're located in places where we have a strong industrial base and an abundance of renewables, everywhere from Texas to Kansas to the Dakotas—that heart of the country that our team lovingly calls the Wind Belt."

Antora's future projects will be with companies in the chemicals, mining, food and beverage, and oil and gas industries. Some of those projects are expected to come online as early as 2025.

The company's scaling strategy is centered on the inexpensive production process for its batteries.

"We constantly ask ourselves, 'What is the best product we can make here?'" Bierman says. "We landed on a compact, containerized, modular system that gets shipped to sites and is easily integrated into industrial processes. It means we don't have huge construction projects, timelines, and budget overruns. Instead, it's all about scaling up the factory that builds these thermal batteries and just churning them out."

It was a winding journey for Kearns and Bierman, but they now believe they're positioned to help huge companies become carbon-free while promoting the growth of the solar and wind industries.

"The more I dig into this, the more shocked I am at how important a piece of the decarbonization puzzle this is today," Bierman says. "The need has become super real since we first started talking about this in 2016. The economic opportunity has grown, but more importantly, the awareness from industries that they need to decarbonize is totally different. Antora can help with that, so we're scaling up as rapidly as possible to meet the demand we see in the market."

Zach Winn, MIT News Office

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3 Questions: How are cities managing record-setting temperatures?

Professor of urban and environmental planning David Hsu explains what municipal governments are doing as climate change accelerates.

MIT Associate Professor David Hsu is an expert in city policies concerning climate change. Following record-setting heat in the summer of 2023, he describes what cities are now doing in response, and the possibilities for new policy measures. Image: iStock

July 2023 was the hottest month globally since humans began keeping records. People all over the United States experienced punishingly high temperatures last summer. In Phoenix, there were a record-setting 31 consecutive days with a high temperature of 110 degrees Fahrenheit or more. July was the hottest month on record in Miami. A scan of high temperatures around the country often yielded some startlingly high numbers: Dallas, 110 F; Reno, 108 F; Salt Lake City, 106 F; Portland, 105 F.

Climate change is a global and national crisis that cannot be solved by city governments alone, but cities suffering from it can try to enact new policies reducing emissions and adapting its effects. MIT's David Hsu, an associate professor of urban and environmental planning, is an expert on metropolitan and regional climate policy. In a 2017 paper in the Journal of Planning Education and Research, *Hsu and some colleagues estimated how 11 major U.S. cities could best reduce their carbon dioxide emissions, through energy-efficient home construction and retrofitting, improvements in vehicle gas mileage, more housing density, robust transit systems, and more. As we neared the end of this historically hot summer, MIT News talked to Hsu about what cities are now doing in response to record heat, and the possibilities for new policy measures.*

Q We've had record-setting temperatures in many cities across the U.S. this summer. Dealing with climate change certainly isn't just the responsibility of those cities, but what have they been doing to make a difference, to the extent they can?

A I think this is a very top-of-mind question because even ten or fifteen years ago, we talked about adapting to a changed climate future, which seemed further off. But literally every week this summer we can refer to [dramatic] things that are already happening, clearly linked to climate change, and are going to get worse. We had wildfire smoke in the Northeast and throughout the Eastern Seaboard in June, this tragic wildfire in Hawaii that led to more deaths than any other wildfire in the U.S., [plus record high temperatures]. A lot of city leaders face climate challenges they thought were maybe 20 or 30 years in the future, and didn't expect to see happen with this severity and intensity.

One thing you're seeing is changes in governance. A lot of cities have recently appointed a chief heat officer. Miami and Phoenix have them now, and this is someone responsible for coordinating response to heat waves, which turn out to be one of the biggest killers among climatological effects. There is an increasing realization not only among local governments, but insurance companies and the building industry, that flooding is going to affect many places. We have already seen flooding in the Seaport area in Boston, the most recently built part of our city. In some sense just the realization among local governments, insurers, building owners, and residents, that some risks are here and now, already is changing how people think about those risks.

Q To what extent does a city being active about climate change at least signal to everyone, at the state or national level, that we have to do more? At the same time, some states are reacting against cities that are trying to institute climate initiatives and trying to prevent clean energy advances. What is possible at this point?

A We have this very large, heterogeneous, and polarized country, and we have differences between states and within states in how they're approaching climate change. You've got some cities trying to enact things like natural gas bans, or trying to limit greenhouse gas emissions, with some state governments trying to preempt them entirely. I think cities have a role in showing leadership. But one thing I harp on, having worked in city government myself, is that sometimes in cities we can be complacent. While we pride ourselves on being centers of innovation and less per-capita emissions—we're using less than rural areas, and you'll see people celebrating New York City as the greenest in the world—cities are responsible for consumption that produces a majority of emissions in most countries. If we're going to decarbonize society, we have to get to zero altogether, and that requires cities to act much more aggressively.

There is not only a pessimistic narrative. With the Inflation Reduction Act, which is rapidly accelerating the production of renewable energy, you see many of those subsidies going to build new manufacturing in red states. There's a possibility people will see there are plenty of better paying, less dangerous jobs in [clean energy]. People don't like monopolies wherever they live, so even places people consider fairly conservative would like local control [of energy], and that might mean greener jobs and lower prices. Yes, there is a doomscrolling loop of thinking polarization is insurmountable, but I feel surprisingly optimistic sometimes.

Large parts of the Midwest, even in places people think of as being more conservative, have chosen to build a lot of wind energy, partly because it's profitable. Historically, some farmers were self-reliant and had wind power before the electrical grid came. Even now in some places where people don't want to address climate change, they're more than happy to have wind power.

Q You've published work on which cities can pursue which policies to reduce emissions the most: better housing construction, more transit, more fuel-efficient vehicles, possibly higher housing density, and more. The exact recipe varies from place to place. But what are the common threads people can think about?

A It's important to think about what the status quo is, and what we should be preparing for. The status quo simply doesn't serve large parts of the population right now. Heat risk, flooding, and wildfires all disproportionately affect populations that are already vulnerable. If you're elderly, or lack access to mobility, information, or warnings, you probably have a higher risk of dying in a wildfire. Many people do not have high-quality housing and may be more exposed to heat or smoke. We know the climate has already changed, and is going to change more, but we have failed to prepare for foreseeable changes that are already here. Lots of things that are climate-related but not only about climate change, like affordable housing, transportation, energy access for everyone so they can have services like cooking and the internet—those are things that we can change going forward. The hopeful message is: Cities are always changing and being built, so we should make them better. The urgent message is: We shouldn't accept the status quo.

Peter Dizikes, MIT News Office

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Student poster session at MIT Energy Initiative (MITEI) Annual Research Conference

At MITEI's 2023 Annual Research Conference, graduate students were invited to share their energy-related research with attendees during an afternoon poster session. Wan-Ni Wu (left), a PhD candidate in the Department of Chemical Engineering, presented a poster on her work designing microporous polymer-based composite membranes for organic solvent nanofiltration. Here she discusses her work with MITEI Director of Education Antje Danielson. To find out more about the Annual Research Conference, turn to page 33. Photo: Kelley Travers, MITEI