
# Latest Research Developments by the National Renewable Energy Laboratory - Part 1

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*This course was adapted from the National Renewable Energy Laboratory (NREL), "Recent Developments in Renewable Energy Research at NREL Part 1", which is in the public domain.*

**Introduction.** The National Renewable Energy Laboratory (NREL) is the U.S. Department of Energy's primary national laboratory for renewable energy and energy efficiency research and development. NREL is operated for the Energy Department by the Alliance for Sustainable Energy LLC, a partnership between Battelle and MRIGlobal.

NREL's mission is to advance the science and engineering of energy efficiency, sustainable transportation, and renewable power technologies and provide the knowledge to integrate and optimize energy systems.

Every year in addition to publishing technical articles and reports, NREL publishes dozens of NREL News & Feature Stories that take an in-depth, behind-the-scenes look at the latest news and research breakthroughs.

The present course is Part 1 of a three-part series of courses based on excerpts of recently published News & Feature Stories. In general, all three courses should be of interest to anyone wanting to keep up with recent developments from a laboratory regularly recognized for national and global leadership in energy efficiency and renewable energy research and development.

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# Chapter 1. Reducing Wind Turbine Wakes Could Save Wind Farms Millions

## Researchers Are Collecting the Most Comprehensive Data on How Winds Move Through Wind Power Plants To Help Design More Efficient Plants and Reduce Wind Energy Costs

### Jan. 21, 2022

“Windmills,” Bob Kerr said, “don’t eat.”

Through years of drought, Kerr, an Oklahoma cattle rancher and wheat farmer, watched the ponds on his farmland disappear into caked earth. Without water, his wheat and cattle would never survive. And if they did not survive, the farm might not either.

So, after 43 years, Kerr decided to farm something entirely different: wind. He leased his dried-up land to a wind farm. "This is steady, dependable income,” he told National Public Radio. “I don’t have to worry about feeding them, I don’t have to worry about breaking ice for them in the wintertime, I don’t have to worry about these windmills getting out on the road. It’s just a no-worry deal.”

That deal could soon get even better for farmers like Kerr who live in wind-rich states like Oklahoma. In the spring of 2022, researchers at the National Renewable Energy Laboratory (NREL) will launch an international, multi-institutional wind energy field campaign called the American WAKE experimeNt (AWAKEN). Funded by the U.S. Department of Energy (DOE) Wind Energy Technologies Office, the study will amass the world’s most comprehensive dataset on a wind energy atmospheric phenomenon including wakes that can cost the average wind farm about 10% of its potential energy. Once complete, those data could help wind farms—and farmers who lease their land, like Kerr—produce even more energy and earn even more profits, too.

Like motorboats, fast-moving wind turbine blades create wakes that can change how much energy reaches downwind turbines and plants. But current energy prediction models are too imprecise to tell exactly how much wakes cost in terms of lost energy or profits—or how to prevent that loss.

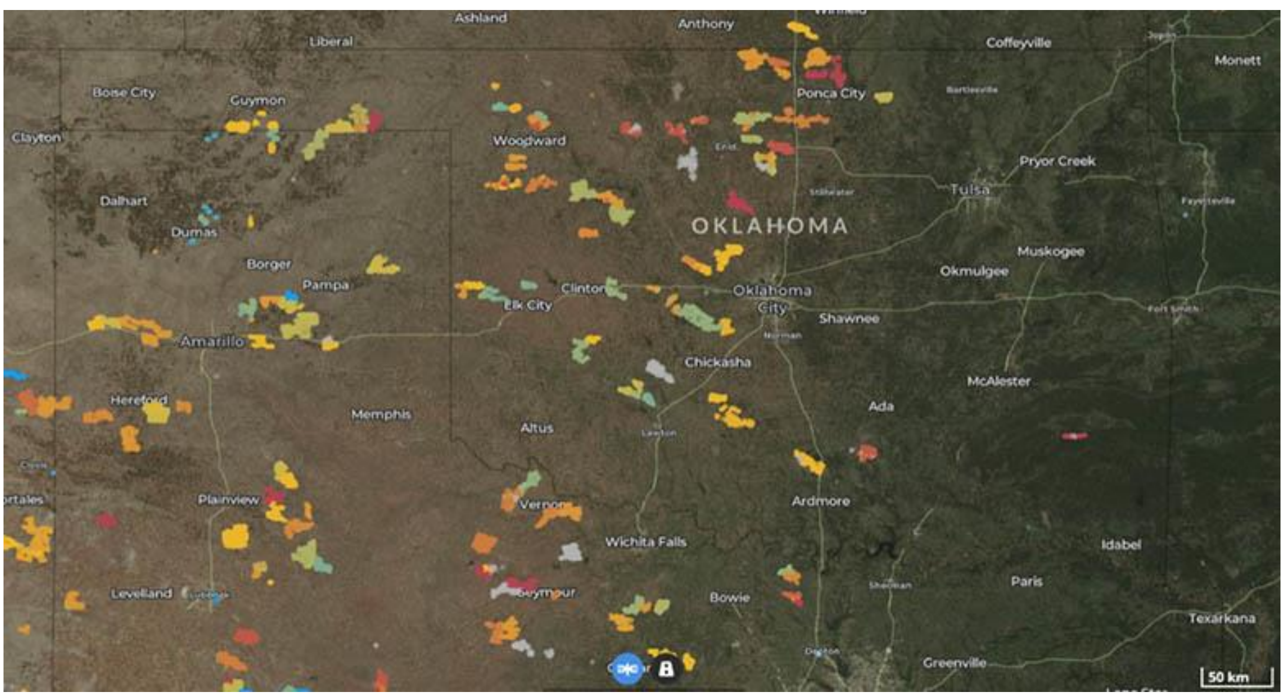
NREL researchers plan to change that.

"This field campaign," said Patrick Moriarty, a senior engineer at NREL who is leading the AWAKEN project, "will give us the highest resolution observations of wind farm atmosphere interactions available in the world today."

Previously, Moriarty and his NREL colleagues designed models and simulations to estimate how winds might move through wind plants. But without observational data to back them up, Moriarty said, "we don't know how accurate our models are." Now, from the spring of 2022 through October 2023, the team will gather this observational data using a vast array of sensors, including those mounted on aircraft, in and around operational wind farms.

But before any data collection could happen, Moriarty and his research team needed to find the right locations to place their instruments to get clear shots of the turbines. "If there are trees or buildings or hills in the way, that would block our efforts," Moriarty said. And there were: During a July field trip to Oklahoma, the team found plenty of obstacles to navigate.

Then, once they found optimal spots to nestle their sensors, the researchers had to convince landowners to house them—in exchange for rent, of course. Back in July, Moriarty met one "very friendly" rancher who peppered the researchers with questions about the wind farms in his backyard. Kerr is not the only one interested in a new kind of farming.




These smudges represent the many wind farms scattered across the wind-rich state of Oklahoma. The varying colors represent how powerful the wind turbines are, with blue indicating those that produce less energy and red representing larger wind turbines. *Screenshot of the by NREL*

For the next several years, those sensors will train their lasers on five wind farms in northern Oklahoma—a location chosen for its large number of current wind farms and great future potential. Posted on or near turbines, the sensors' laser and radar beams (like those used by traffic cops to monitor vehicle speeds) will reflect dust and bugs—because different wind speeds and paths change how those particles wobble, that data can help create a three-dimensional picture of how wind currents are moving around the turbines.

But large-scale wakes can persist 20 miles or more and reach entirely different wind plants. "No observation system has that kind of range," Moriarty said. "Sooner or later, you need an aircraft."

For the final step of the AWAKEN field campaign, specialized aircraft will fly sensors from plant to plant to collect that large-scale data and understand how wakes from one wind plant might affect its neighbors. At the same time, drones will use faster sensors to pick up more precise data than previous tools.

Then, when the data are compiled in 2023, the researchers will map out atmospheric effects and create an open-source, globally accessible dataset (to be hosted in the DOE Wind Data Archive and Portal). That data could give wind farm developers much-needed guidance on how to position their wind turbines to maximize their plants' energy production. Such well-informed wind plant designs could potentially generate up to 5% more energy (and, with it, more revenue).

After AWAKEN wraps up, Moriarty hopes to perform a similar massive field campaign to map out wake effects in offshore wind plants—especially floating plants, for which little data exist. But Moriarty also hopes to improve their data collection tools to eventually make an even higher-resolution map of how winds move through wind plants.

"We're getting closer," Moriarty said. First stop: Oklahoma.

# Chapter 2. Next-Gen Concentrating Solar Power Research Heats Up at NREL

## Molten Salts Can Melt Down the Price of Concentrating Solar Power-Plus-Storage

Feb. 9, 2022

An employee runs diagnoses on heliostats at a solar thermal facility in Nevada. *Photo by Dennis Schroeder, NREL*

Concentrating solar power (CSP) has long held promise as a renewable energy technology. CSP uses mirrors, or heliostats, to harness the power of the sun by heating and storing an inexpensive medium such as sand, rocks, or molten salt for on-demand energy dispatch.

To spur CSP industry advancement and achieve an energy cost goal of 5 cents per kWh, the U.S. Department of Energy's (DOE's) Gen3 CSP program funds research to explore the potential of several heat transfer mediums. National Renewable Energy Laboratory (NREL) researchers are contributing to this effort, tackling several challenges related to the use of one potential medium—liquid-hot molten salt—for energy transfer and storage.

## Off to the Races: Three Potential Pathways to Cost-Effective CSP

Three years ago, the Gen3 program established three pathways to potentially reach the CSP energy cost goal: a liquid pathway (exploring use of molten salt as a heat transfer material, led by NREL), a particle pathway (using sand-like particles as a heat transfer material, led by Sandia National Laboratories), and a third pathway exploring the use of gas as heat transfer material (led by Brayton Energy).

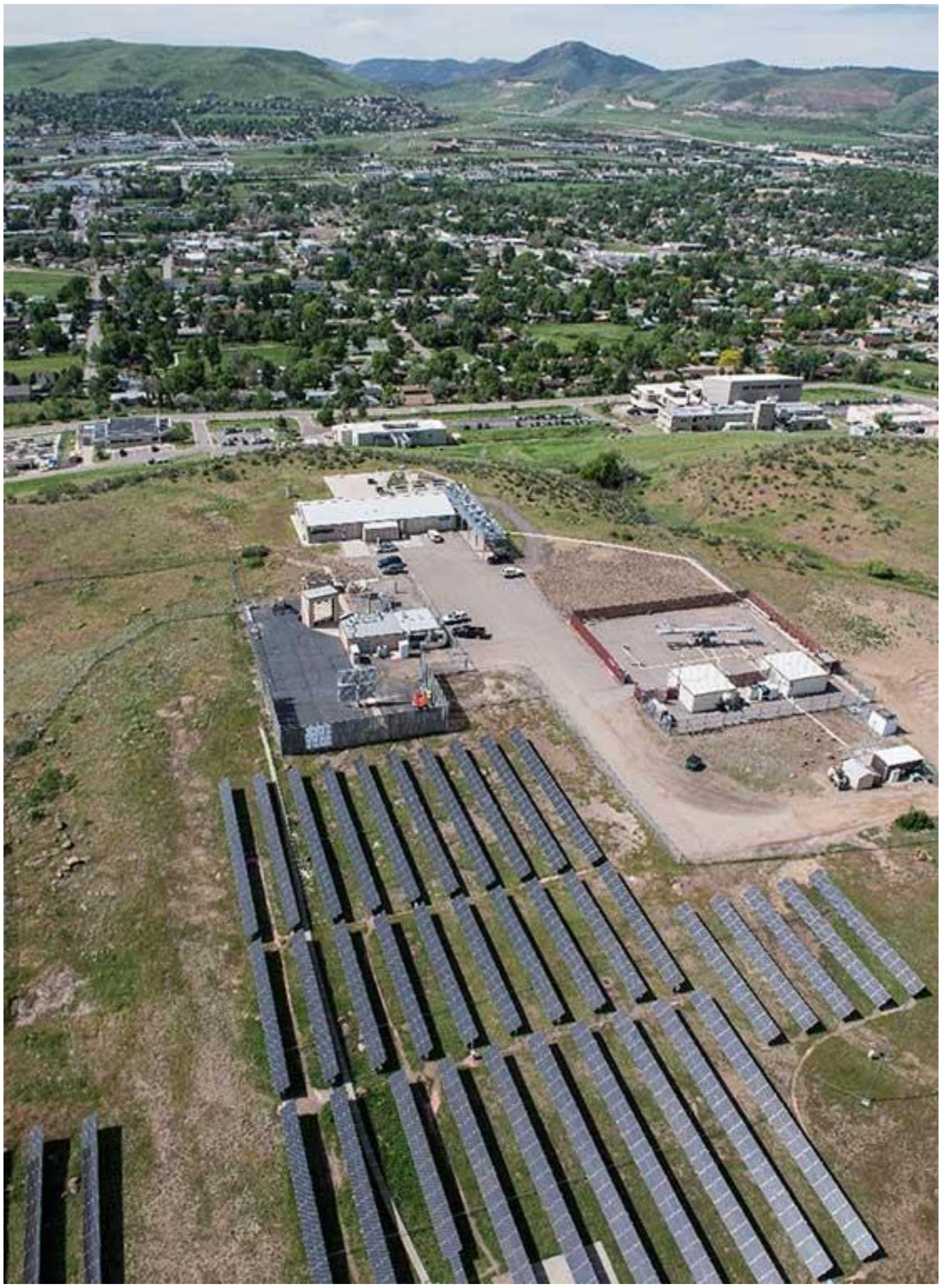
In March of 2021, DOE down-selected among the three pathways to fund further research into particle-based storage, but also created an opportunity for NREL to further develop the liquid pathway over the next two years.

Molten salt thermal energy storage technology is an efficient, reliable, and cost-effective way to store solar power at large scale. *Photo by Julianne Boden, DOE*

## Liquid Pathway Research at NREL: Singling Out Salts

Craig Turchi leads thermal energy science and technologies research at NREL. He said that molten salts are a desirable option for a heat transfer and storage material—liquids are easy to work with as they can be pumped through pipes and heat exchangers to move around a CSP system. Unfortunately, some practical challenges also remain, which are the focus of current NREL research.

# Challenge 1: Tackling Tank Design To Keep It Hot



The prototype molten chloride salt tank will be built on the mesa top above NREL's Golden, Colorado, campus. *Photo by Dennis Schroeder, NREL*

While easy to move around, salts are also corrosive to the tanks and pipes that hold them. In fact, according to Turchi, "Everyone initially thought that salt corrosivity would torpedo this effort. We actually solved that problem by and large. NREL and partners did a lot of great science on the salt chemistry—how to purify it, how to make it relatively noncorrosive if you control the chemistry, and we demonstrated that in the lab."

So, corrosivity is not the biggest problem with using molten salts. Instead, the challenge lies in achieving very high temperatures needed for a high-efficiency power plant. The salt's energy density requires relatively large—and therefore, expensive—storage tanks and one must keep the salts from freezing in the pipes (while thermally stable as a liquid to very high temperature, these salts freeze at a not-so-chilly 400°C).

Turchi said this is related to how you insulate the system. "We had performed testing to show which materials could work but hadn't actually built a tank to demonstrate that it did work. Our design is a steel tank, but whereas the current tanks are insulated on the outside, our proposed tank was insulated on the inside to protect the steel."

DOE awarded NREL $2 million to build a prototype tank to evaluate its integrity when filled with molten salt. The tank is currently being built and will be operated on the mesa above NREL's Golden, Colorado, campus.

## Challenge 2: Finding the Right Salts To Shake Things Up

There is more than one kind of salt, so NREL's work developing the Gen3 CSP liquid path also involved selecting and experimenting with new salts. Commercial molten salt systems use nitrate salts; however, these start to degrade once the system reaches a certain temperature. The NREL team wanted to reach higher temperatures to achieve more efficient energy conversion for higher-efficiency power plants, so they explored an alternative—chloride salts.

Youyang Zhao is an NREL researcher who has been studying salt chemistry for the Gen3 liquid pathway project for the last three years. Zhao said he started out by finding ways to reduce the impurity levels of industrial salt. Additionally, Zhao said, "We were optimizing the salt composition to lower the melting point of the salt. The lower the melting point, the more time we have to work with the material."

Zhao's work led to the decision to design the new prototype tank for chloride salt.

This new opportunity is an important continuation of their efforts. "At a high level," Zhao explained, "we are connecting fundamental science to future engineering. I'm not creating the component design, but trying to find out the basics, such as chemistry and material knowledge, to provide information so people can design systems better."

## Challenge 3: Electrochemical Approaches To Support Gen3 Liquid Pathway Research

Kerry Rippy is an NREL expert in inorganic chemistry and has supported the Gen3 CSP liquid pathway in several capacities. In the lab, her team explored and demonstrated electrochemical methods to remove corrosive impurities in molten chloride salt. Now, they are continuing this work with the University of Wisconsin to demonstrate the reliability of the purified molten chloride salt as it flows through a scaled-up prototype that mimics an industrial system.

Rippy is also supporting the mesa top tank testing project. The cost of the containment vessels is high, so the team is investigating new materials to store the salt, at varying temperatures and in large volumes for up to 10 hours at a time. Rippy is helping to develop an electrochemical sensor inside the tank to monitor the purity of the salt during experimentation.

## Variety Is the Spice of Life: Wide-Ranging Molten Salt Applications

Rippy said a molten salt chloride pathway merits further exploration for the benefit of CSP and beyond: "There are multiple potential avenues for this research to be valuable. It can be beneficial for solar fuel synthesis; it could enable high-temperature fuel cells, and the nuclear industry is also really interested in this research."

Turchi concurred. "The nuclear industry is developing a number of 'Gen4' reactors of its own, some of which use molten chloride salts." Results from the upcoming tank testing could drive down tank costs for a number of energy industries.

# Chapter 3. A Window Into the Future of Wave Energy

## Award Helps Move Cost-Effective, Productive, Robust Wave Energy Design a Step Closer to Commercialization and Widespread Use

### Feb. 16, 2022 | By Caitlin McDermott-Murphy

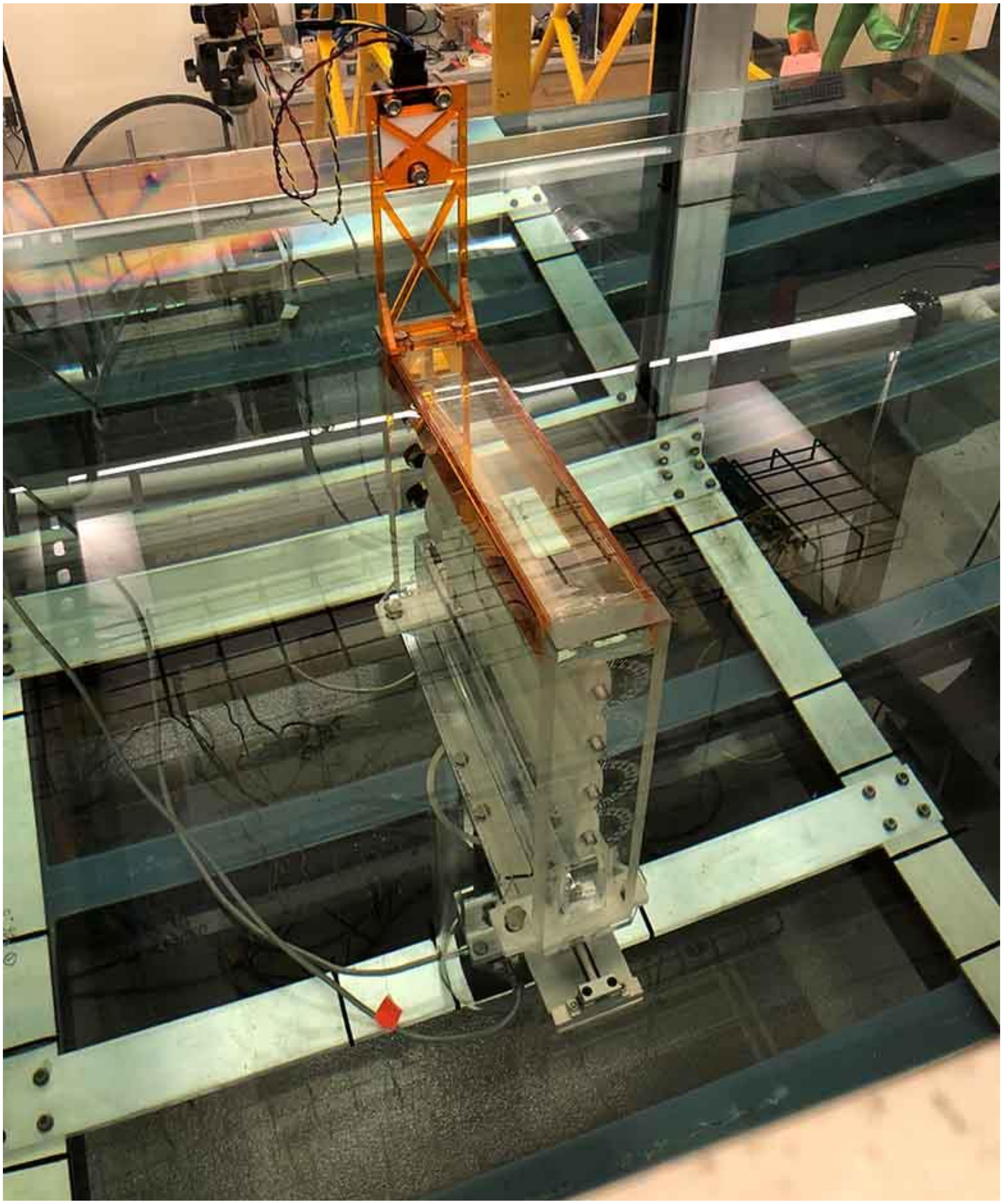
In 1974, Stephen Salter, a professor at the University of Edinburgh, sent his “ducks” into the Scottish seas, launching the world’s first major wave energy project. But the ocean’s rough heaves and surges proved too much for his house-sized, floating generators. Like the more recent Pelamis’ P-750 model and Aquamarine’s Oysters, they succumbed to the power they were meant to harness.

"We have to ask ourselves," said Krish Thiagarajan Sharman, the endowed chair in renewable energy at the University of Massachusetts Amherst, "why have we been working on this for so long? Why don't we have grid-ready, commercial-scale wave energy systems out in the world?"

The answer: Wave energy technology needs to be cheaper, produce more energy, and brave the ocean's brawn better and for longer.

Now, the marine energy team at the National Renewable Energy Laboratory (NREL), has designed a system that could achieve all three needs. The variable-geometry, oscillating, surge wave energy converter creates windows for waves to pass through so wave energy devices don't bear the full force of their power. The design could also be more cost-effective, productive, and resilient.

Two years ago, that concept earned a competitive award from the U.S. Department of Energy's Technology Commercialization Fund (TCF), a nearly $30-million funding opportunity designed to help promising, high-impact energy technologies move toward commercialization. With the TCF award's critical support, Nathan Tom, a mechanical engineer at NREL, partnered with Sharman. Together, they moved the wave energy converter system from theory to practice, nudging the potential solution closer to commercialization and wave energy closer to widespread deployment.



This small prototype (seen from above) can open slats to allow waves to flow through rather than crash on the device. This wave escape hatch protects the technology from forceful impacts, which can help it endure longer in the ocean. *Photo from Jacob Davis, University of Massachusetts Amherst*

“All wave energy devices need a way of surviving for several years in the ocean,” said Sharman. “This is one way.”

Wave energy might not match the global power production of wind and solar energy anytime soon, but it's still a critical source of clean, renewable energy. Waves are more predictable and reliable than solar or wind energy, and they could power hard-to-reach locations, like coastal communities and remote islands, which currently depend on expensive, carbon-intensive diesel imports. Wave energy devices could also power offshore fishing, marine research, or military operations that need to reach deeper waters. In the United States, waves carry the equivalent of about 80% of the country's energy needs. Not all that energy can be practically harnessed, but the industry could access enough to ease the country's transition to 100% clean energy.

Today, wave energy isn't powering much—yet. Today's designs falter for the same reason Salter's ducks struggled; the ocean packs power stronger than any winds, and while some recent wave energy inventions are outfitted with steel hulls, this armor is too heavy and expensive to make the technology viable. Today, about 35%–50% of wave energy costs are spent on structural enhancements.

"Our systems are just too heavy," Tom said. "To withstand really extreme loads, orders of magnitude higher than when the device is operating and producing power, they're built with too much steel. We need to start thinking outside the box."

NREL's design is certainly outside the steel box. To source electricity from waves, the more-cost-effective, lighter, more-robust wave energy converter uses a rectangular paddle that sways back and forth on a bottom hinge, like a cattail in the wind. The swaying paddle is a common design feature for wave energy devices. But this one is far more adaptable. As waves go from productive to destructive, the device's operator can open one or more horizontal flaps, creating gaps for that violent energy to escape.

This extra level of control not only protects the device, it could also help the converter produce more energy. When seas change, remote operators can toggle each flap to extract as much energy as possible.

Using the funding from the TCF award, Tom and Sharman built their first small-scale prototype to test in the university's wave tank. The project team included University of Massachusetts Amherst graduate student Jacob Davis and postdoctoral scholar Jessica Nguyen (Nguyen started out as a graduate student). Cole Burge and Salman Husain, National Renewable Energy Laboratory undergraduate and graduate research interns, also contributed.

"The variable geometry project has had a tremendous influence on my career trajectory," said Davis. "In fact, this experience spurred my passion so much, that the focus of my present Ph.D. work is entirely on the measurement and understanding of ocean surface waves. I look forward to a career spent applying this knowledge to a broad range of ocean-related challenges, including the role of waves in marine energy conversion, weather, and climate."

Together, the team checked their theoretical models against experimental data and found, to their relief, that the models accurately predicted the device's performance. That was a promising start. But the design needs to go through far more iterative steps before it can reach the ocean.


With this wave tank at the University of Massachusetts Amherst, researchers verified that their variable-geometry oscillating surge wave energy converter prototype performed as well as their theoretical models predicted. *Photo by Jacob Davis, University of Massachusetts Amherst*

"I could quickly design something to go in the water," said Tom, "but what if it only produces 1 watt? It's going to cost me a lot of money—boats, divers, pulling a cable from sea to land—which is not cheap."

That "big move," said Tom, which comes with large expenses and high risk, makes potential wave energy industry partners wary of investing in even highly promising designs, like their variable-geometry prototype. Many tend to wait for concepts to prove their success in low-risk environments, like numerical models and wave tanks.

But that progressive work requires funding, too, which is why TCF awards are a critical bridge from theory to market. "We want to develop a patented technology far enough where industry thinks, 'OK, this is a good idea. That's something I want to try to incorporate into my design,'" said Tom. "That's when we'll transfer it over to industry. And for that, the TCF award is super helpful."

The award also allowed the team to test another novel aspect of their design: a raised foundation. Often, oscillating surge wave energy conversion devices are fixed to the seabed where swirling debris and sand can interfere with operation. Lifted off the seafloor on a column, the device can avoid those obstacles and access a greater number of locations between sand and surface or in deeper waters. Because surface waters are often more energetic, devices that can reach those areas could produce more power.

Together, the raised foundation and variable-geometry could help wave energy devices adapt to their ocean environment better than previous designs, including Salter's ducks (though these early forays were critical to moving the industry forward).

"We look at waves not as a force to reckon with," said Sharman, "but to use to harness energy. It's a very holistic, symbiotic approach to manage our interaction with the ocean."

# **Chapter** 4. Beyond Fossil Carbon? Green Electricity Is Opening Doors to Low-Emission Alternatives for Making Fuels and Chemicals

## With Extensive Data, Broad Analyses, and Detailed Models, NREL Scientists and Collaborators Stake the Boundaries of Producing Chemicals and Fuels From Carbon Dioxide, Biomass, and Renewable Electricity

Feb. 23, 2022 | By Erik F. Ringle

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Uncovering Costs, Risks, and Opportunities—NREL researchers, including scientist Zhe Huang (pictured), are analyzing the technical and economic potential of electrifying—and decarbonizing—fuel and chemical production. *Photo by Werner Slocum, NREL*

Petroleum, coal, and natural gas are not the only starting points for making fuels and chemicals. In fact, growing supplies of renewable electricity open exciting new doors for making identical products at potentially a fraction of the climate cost.

It begins with the steady turn of a wind turbine or a solar panel baking in the mid-afternoon sun. A current flows through an electrochemical cell filled with carbon dioxide ($CO_2$)—siphoned from the air or captured from an ethanol refinery, cement plant, or other industrial source.

Energized by ions and radicals created by the charge, the carbon atom in the gas unglues itself from its oxygen neighbors and looks for new companions to bond with. It quickly latches itself to other newly freed carbon, as well as hydrogen atoms that are generated in the cell.

The exact molecule the carbon helps form depends on the electrocatalyst in the cell and the voltage applied at the outset:

- Formic acid used as a food additive
- Carbon monoxide for making numerous other chemicals
- Ethylene—a precursor in the global plastics market
- And more.

It is an electrochemical reaction, an emerging pathway for upgrading $CO_2$ and even biomass-derived compounds into the many plastics, detergents, fuels, and compounds that undergird the modern economy.

Alongside a broader set of technologies that wield renewable electricity to synthesize chemicals and fuels, the technology holds promise for helping decarbonize heavy industry. But are they really ready for market?

# On the Costs, Risks, and Opportunities of Electrifying Chemicals and Fuels Production

"Essentially, we are talking about an intersection of electrification and utilization of low-carbon feedstocks like carbon dioxide and biomass," said Joshua Schaidle, National Renewable Energy Laboratory (NREL) laboratory program manager for the U.S. Department of Energy's Office of Fossil Energy and Carbon Management. Schaidle also leads NREL's catalytic carbon transformation research and directs the U.S. Department of Energy's Chemical Catalysis for Bioenergy Consortium. "Powered by renewable energy instead of fossil-based electricity, these systems could allow industries to move beyond fossil carbon."

According to Schaidle and his NREL colleague Gary Grim, that alternative method of making fuels and chemicals could be a critical tool in decarbonizing an economic sector that often leaves deep carbon footprints in its wake.

Instead of dredging up "fossil" carbon stored underground, such methods recycle "modern" carbon found in $CO_2$ or biomass. And rather than relying on carbon-intensive energy sources, they are powered by renewable, zero-emission electricity. The result could be a fuel and chemical production process that is significantly less carbon intensive.

Still, many questions remain about the costs, risks, and technical challenges of making chemicals and fuels from green electricity and recycled carbon. "Where are the technologies at today? Where could they be in the future? And how does that play a role in next steps and future research needs?" Schaidle asked.

In a pair of papers published in *Energy and Environmental Science* and *ACS Energy Letters*, Schaidle, Grim, and colleagues explore those questions and others on the technical and economic potential of electrifying—and decarbonizing—fuel and chemical production.

With plenty of uncertainty remaining, they hope doing such work can help mark the path forward from the lab benchtop to the commercial world.

# Paper 1: The Economics of Carbon Dioxide Utilization

Studies suggest that technologies exist today for converting $CO_2$ into all the top globally consumed carbon-based chemicals and products—a market currently dominated by fossil sources of carbon.

For example, every year over 10 gigatonnes of carbon is emitted as $CO_2$ around the world. If captured and sent through an electrochemical cell instead, that $CO_2$ can become a feedstock supply—one large enough to produce over 40 times the entire global production of ethylene and propylene.


Through an online visualization tool, NREL offers insight into the economic feasibility and key cost drivers of producing chemical intermediates from $CO_2$ and electricity across five different conversion pathways. These include pathways that use renewable electricity directly to chemically upgrade $CO_2$ to chemicals, as well as pathways that use electricity indirectly via intermediate electron carriers, such as hydrogen. *Photo by Werner Slocum, NREL*

In an *Energy and Environmental Science* paper, "The Economic Outlook for Converting $CO_2$ and Electrons to Molecules," NREL researchers Zhe Huang, Schaidle, Grim, and Ling Tao analyze the economics of electrochemical $CO_2$ utilization today and in the future. The paper considers numerous technology factors and cost drivers that might impact the feasibility of producing chemicals, fuels, and materials from $CO_2$ and renewable electricity at scale.

It could soon be as cost effective to make some of the most widely used chemicals out of $CO_2$ and green electricity as it is to make them using current petroleum-based methods.

“We take a broad look across multiple technologies to multiple products,” Grim said. “The key point is that we are using consistent economic assumptions for our analysis.”

According to their study, it could soon be as cost effective to make some of the most widely used chemicals out of $CO_2$ and green electricity as it is to make them using current petroleum-based methods. At the current rate of falling electricity prices and expected improvements in technology, it could even become cheaper in some cases.

“The advancements we are seeing, the activity we are seeing—we will have commercial offerings in the next 5 to 10 years,” Schaidle said. “I think there are opportunities to get down to cost competitiveness, especially as you start to consider any low-carbon credits that come along.”

To arrive at such conclusions, the study incorporates a broad range of assumptions. It considers energy prices and the cost to build new facilities or install new equipment. It factors in technical and chemical influences that could impact the viability of a technology, such as the speed or efficiency of a certain electrochemical reaction.

Not least, the analysis takes a close look at the impact of $CO_2$ source and concentration on the price to make a given chemical, be it carbon monoxide, ethylene, or a hydrocarbon fuel. Where $CO_2$ siphoned directly from the atmosphere is relatively dilute, for example, capturing it from a power plant or biorefinery yields higher concentrations.

To make it easier to sift through the data behind their analysis, Schaidle, Grim, and their colleagues have published a powerful online visualization tool. It includes interactive charts on the economic feasibility and key cost drivers of producing chemical intermediates from $CO_2$ and electricity across five different conversion pathways.

In this way, the takeaways from the paper become easily accessible for a broad audience. For example, their analysis concludes that carbon monoxide made from $CO_2$ and electricity via high-temperature electrolysis—a specific kind of electrochemical technology—would be relatively expensive by today’s standards, at $0.38 per kilogram. Move into the near future, however, and the economics flip. The study projects the price to fall well below today’s market price to $0.15 per kilogram.

“Is this a reality? How close can we get on a cost-competitive basis?” reflected Schaidle. “What are the performers or non-performers?”

With the new paper and visualization tool, arriving at answers is easier than ever before.

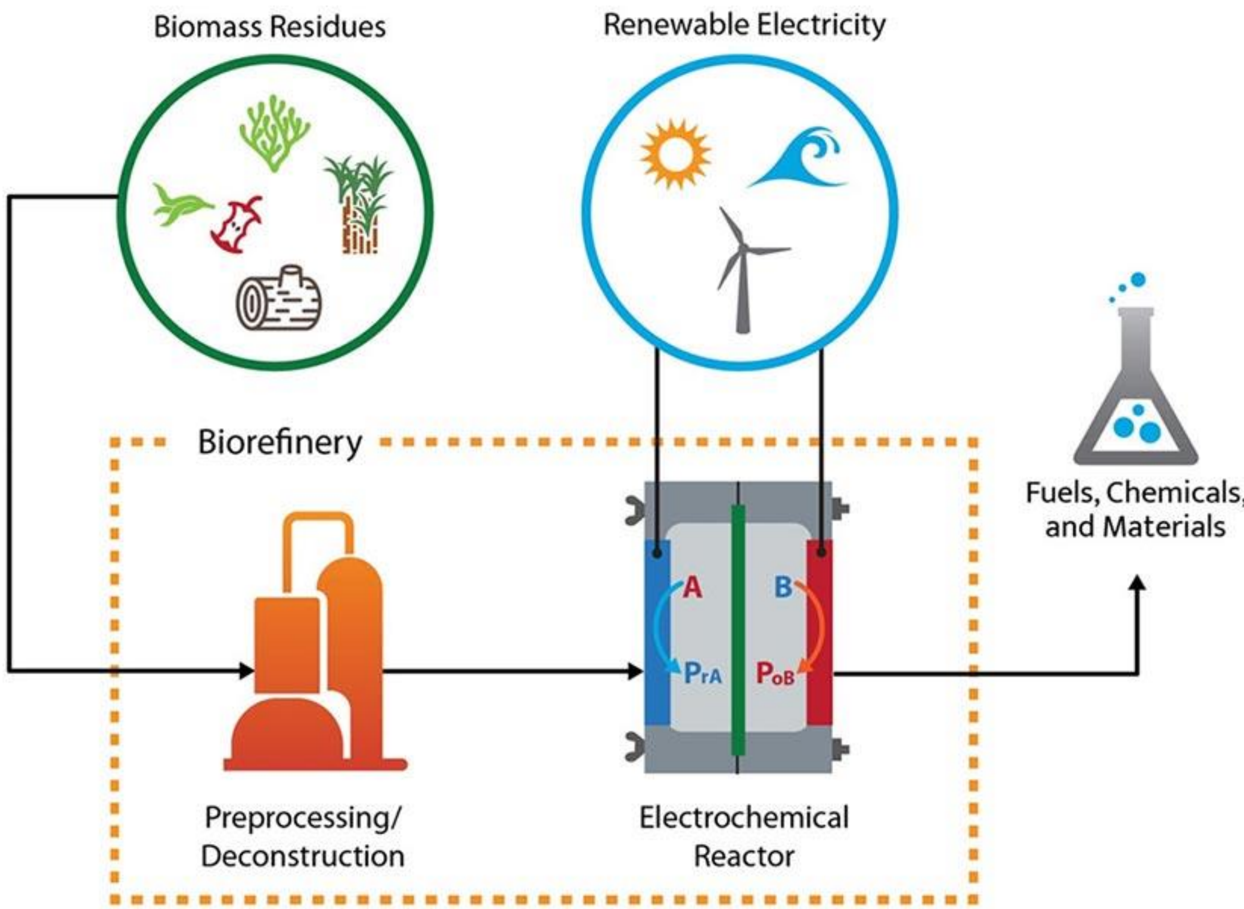
# Paper 2: The Status of Electrochemical Conversion of Plentiful Biomass

According to the U.S. Department of Energy, biomass resources in the United States could be harnessed to produce up to 50 billion gallons of biofuel each year, more than enough to cover the entire U.S. demand for jet fuel.

But where the carbon in $CO_2$ forms a simple chemical configuration—a gas with one part carbon, two parts oxygen—the renewable carbon in that plentiful biomass is integrated into fibrous networks of lignin and carbohydrates. That makes the starting point for making chemicals with biomass fundamentally different.

Biomass—which includes energy crops, forestry waste, and other organic matter—must first be broken apart into chemical intermediates: polyols, furans, carboxylic acids, amino acids, lignin, and others. Once stored in a more basic form, that renewable carbon can then be more easily accessed, amended, and rearranged.

“You can convert these intermediate molecules thermochemically and biologically, but you can also look at electrochemistry,” Schaidle explained. “Our review focuses on the latter piece, where you are looking at converting an intermediate into a product rather than starting with whole biomass.”




A large number of fuels, chemicals, and materials can be accessed from biomass using renewable electricity. In the electrochemical reactor, “A” and “B” represent biomass-derived compounds that are upgraded by forming either reduction products (blue arrow, PrA) or oxidation products (red arrow, PoB).

In a second paper published in *ACS Energy Letters*, Schaidle, Grim, and a larger team of scientists—including Francisco W.S. Lucas and Adam Holewinski from the University of Colorado, Boulder—analyze over 82 reactions driven by the electrochemical synthesis of biomass intermediates. Those reactions have potential advantages, according to the paper.

“Conventional methods only have heat and pressure as their hammers,” Grim explained. “With electrochemistry and biomass intermediates, we have the ability to target specific chemical bonds or groups that can be otherwise difficult to access.”

Grim said that could give industries more latitude to invent chemistries otherwise hard to achieve—a potential advantage over conventional, petroleum-based refining. Still, the electrochemical synthesis of biomass intermediates is immature compared to $CO_2$ utilization.

"If you want this technology to get closer to becoming market competitive, you have to have an electrochemical process that is overall more efficient," Schaidle added. "It makes the best utilization of the carbon coming in and the best utilization of the electrons coming in. That is where a lot of the technology advancements need to happen."

By pulling together over 500 publications on the field—articles often focused on specific reactions using electrochemistry—the paper serves as a roadmap for assessing the state of electrochemistry with biomass-derived intermediates and finding the best entry points for improving the technology. With this broad analysis, the team of scientists aims to foster more focus and intentionality in future research.

"This is cross-cutting analysis to help people move forward," Schaidle added. "We are synthesizing all the science to give a clear blueprint for strategic research."

## Slow But Steady: Steps To Decarbonizing Chemical Manufacturing

Schaidle and Grim are honest about the challenges ahead. After all, should we even try to electrify biomass conversion? Why convert $CO_2$ and not just capture it and put it underground?

"The short answer is that there are a lot of challenges," Grim said. "Petroleum- and fossil-based processes have had nearly a century head-start on some of these emerging technologies. Those systems are highly optimized, very well studied—and hydrocarbons have a lot of energy already built in."

With no energy content whatsoever, $CO_2$ must be pumped with massive amounts of cheap, clean energy to successfully transform it into something usable. Many electrochemical technologies for converting biomass intermediates have yet to be scaled beyond the lab—an essential step for demonstrating the stability, efficiency, and affordability of any bioenergy technology. Not least, robust supply chains of renewable electrons, $CO_2$, and biomass are only just emerging.

"The jury is still out: Is this the best use of that abundant future electricity?" Grim asked. "We are still working to understand if these technologies are the best solution for addressing a lot of our climate issues."

Electrons to molecules uses affordable, renewable electricity to convert low-energy molecules—such as water and carbon dioxide—to generate cleaner, higher-value, and higher-energy chemicals, fuels, and materials.

Despite the challenges, Schaidle and Grim remain optimistic that these technologies can play a critical role in decarbonizing fuel and chemical manufacturing.

Supported by the U.S. Department of Energy Bioenergy Technologies Office, ARPA-E, and other energy programs, a range of targeted research projects are already helping push down the cost and increase the efficacy of such technologies. One NREL-led team, for instance, is exploring how to use electrochemistry to enable biorefineries to recycle waste $CO_2$—increasing fuel yields by as much as 40% and decarbonizing the production of ethanol, as well as lipids.

With a nudge in the right direction, more breakthrough projects could be on the horizon.

“How do we guide this field to collectively accelerate everyone’s work?” Schaidle said. “That’s what we wanted to do—to take this blob of an amoeba and turn it into a foundational first step for people to build off of.”

By gathering all the available data—standardizing it, making it comprehensible, giving it form—they hope they can collapse the timeline for improving the technologies. And with deadlines looming for making meaningful progress to lower climate-warming emissions, accelerating R&D could be just what is needed to start eliminating the weighty carbon footprint of making fuels and chemicals.

# Chapter 5. Small City Sets Example for Floating Solar, Empowered by NREL Data Set

## A First-Ever Approach to Municipally Owned Floating Solar Emerges in Upstate New York

Feb. 28, 2022 | By Connor O'Neil

The Cohoes, New York, municipal reservoir (without floating solar), identified by NREL as suitable for floating solar PV, will become the first city-owned-and-operated floating solar installation in the nation. *Image from Google Earth*

Two city employees of Cohoes, New York, were brainstorming how to power the city's municipal buildings with renewable energy, but few options made sense. Cohoes does not have acres of unused land for solar panels, and the slate-topped buildings cannot hold rooftop solar. Moreover, with its high amount of low- and moderate-income (LMI) residents, 17,000-person Cohoes was not swimming in cash. The solution had to be something local—something to keep cost savings within the community.

"We looked at every aspect of how to add clean energy to our working-class community," said Theresa Bourgeois, director of operations for the city of Cohoes. "Then my colleague came upon the idea of floating solar. We considered our 10-acre water reservoir and asked, 'Can we really utilize this?' The more we researched, we realized yes, we can! In fact, it's the best possible answer."

No U.S. cities have done anything like what Cohoes was proposing: a municipally-owned and operated floating solar installation—but there was no reason it would not work. Bourgeois and City Planner Joe Seman-Graves did their research and learned that the technology of floating solar is sound and that their reservoir could hold enough panels to power all Cohoes city-owned buildings and streetlights—erasing around $500,000 in annual electricity costs—with 40% of the generated electricity remaining for civic use. Everything about the project lined up, but at a cost of $6 million, Cohoes needed buy-in from others.

Such clean energy investments are especially challenging for small and LMI cities because municipalities cannot access the same tax incentives as private companies when developing renewable energy. Instead, the city would need to make the case for state, federal, and foundation funding, and for that, they found their pitch in a 2018 National Renewable Energy Laboratory (NREL) report.

## Discovery of NREL Study and Data Set Buoys Support for Floating Solar

The NREL report that Bourgeois discovered was “Floating Photovoltaic Systems: Assessing the Technical Potential of Photovoltaic Systems on Man-Made Water Bodies in the Continental United States.” The report provides coarse yet comprehensive data about potential U.S. “floatovoltaic” sites, including each reservoir’s estimated size, proximity to electric transmission, ownership status, and current use. For Bourgeois and Seman-Graves, NREL’s data set was the missing link.

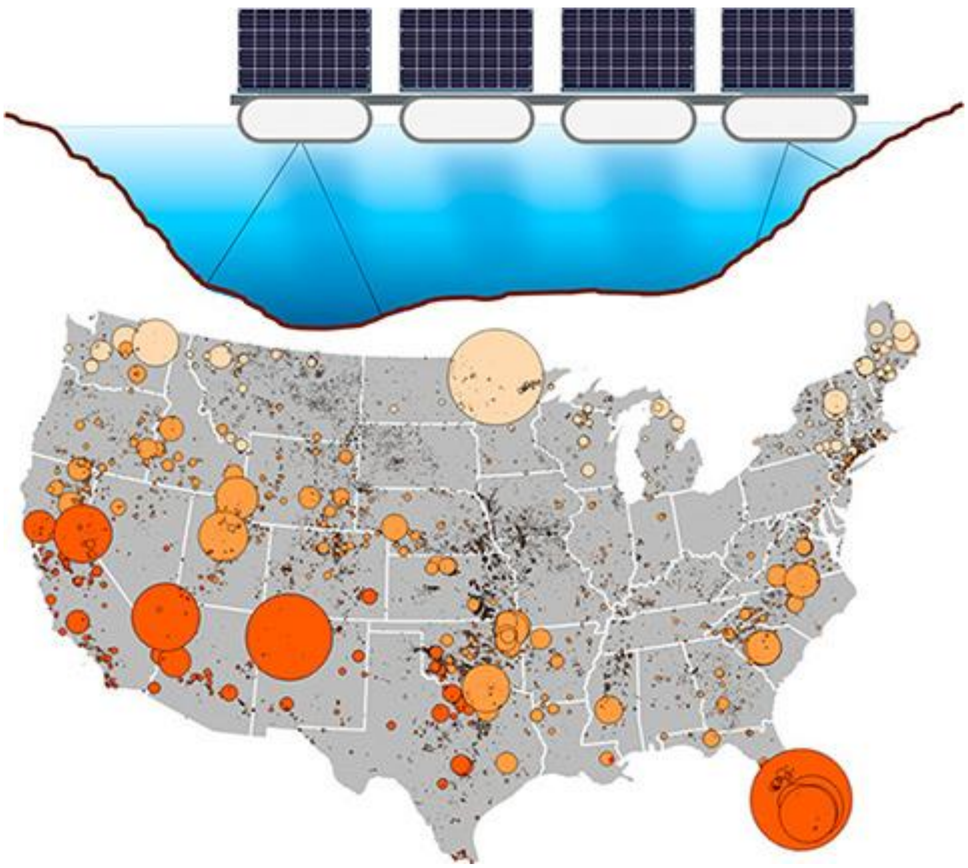
“NREL’s study gave us confidence and credibility in the power of this idea, that we could generate clean energy in Cohoes,” Bourgeois said. “We used the basic results in that study to provide information to Congress, to our representatives, to the public, showing that we have a viable option. It really drove our success in building support for the project.”

The report portrays floatovoltaics as a large, unexplored opportunity for renewable energy. NREL found that if even a portion of the most suitable reservoirs were covered, floating solar could generate almost 10% of national electricity. That includes almost 25,000 human-made water bodies unused for recreation, mine tailings, and fish and wildlife.

In one instance, the report was invaluable when Cohoes first ran the idea by New York state agency officials. Bourgeois and Seman-Graves referenced the number of possible reservoirs that could support floating solar—492 in New York—to substantiate that not only are floatovoltaics viable, but that Cohoes could be at the forefront of a replicable model worth pursuing and funding. It was a strong enough case to win Cohoes some preliminary support.

Cohoes had similar success when running the idea by elected officials. NREL’s data identifies a value proposition for renewable energy that appealed to state and federal representatives alike, with the latter advocating to fund about 50% or more of project costs.

NREL also found that many of the suitable reservoirs are in water-stressed areas with expensive land and electricity—these areas could find a shortcut to solar power with floatovoltaics. But for Cohoes, one statistic was missing in the data: What about floating solar's proximity to low-income communities? If the technology is such a practical option, how many other communities can use their own down-the-road reservoir for clean energy?



NREL has identified almost 25,000 human-made bodies of water that would be suitable for floating PV, yet there are currently less than 10 installments across the country.
*Image by NREL*

As the Cohoes Municipal Floating Solar Demonstration project becomes a model for municipal ownership and small-city sustainability, the city is using NREL's data to share resources, educate, and advocate for environmental justice in related clean energy projects around the state, region, and country.

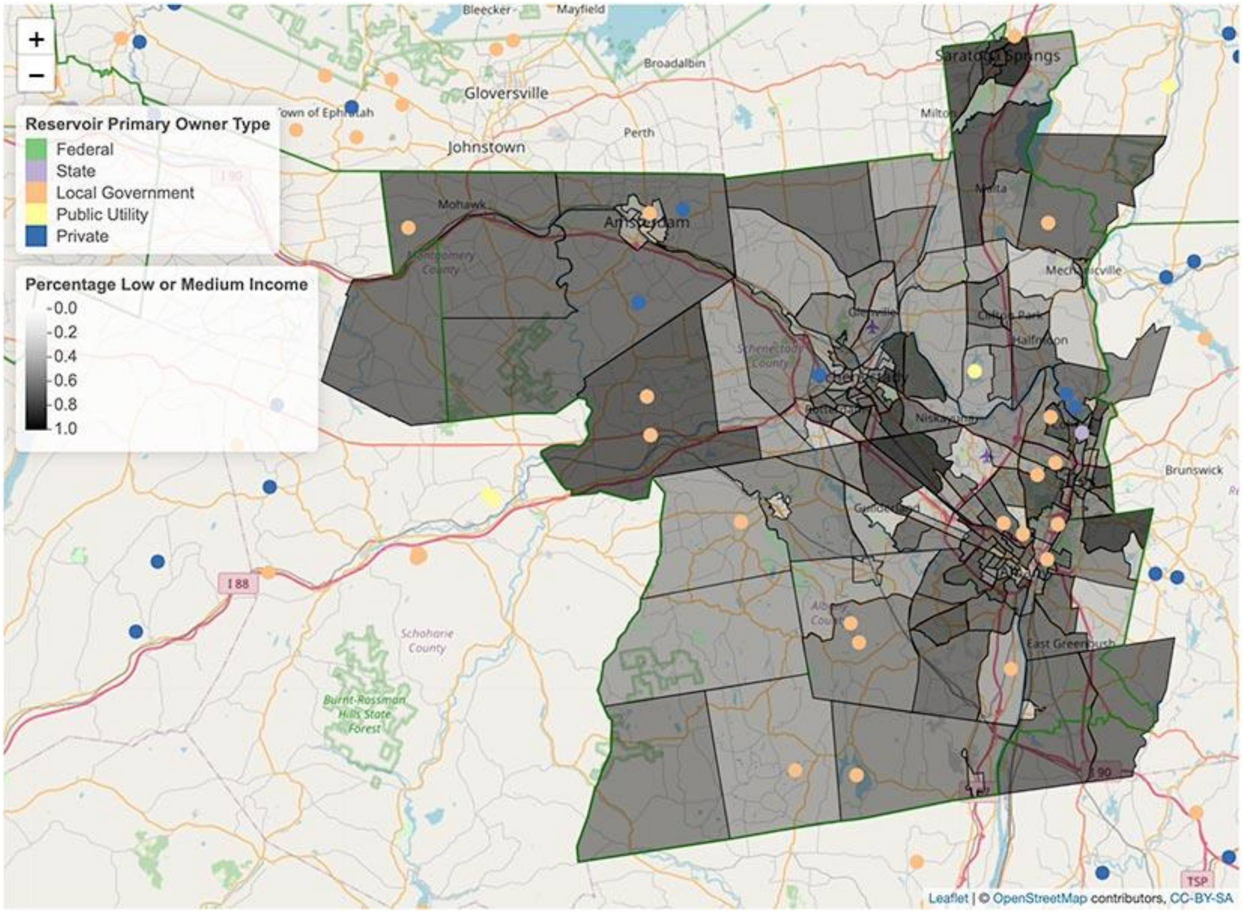
## A New Life for NREL's Data

While pitching the project, Bourgeois wondered whether NREL's data could be even more impactful; a visualization that breaks the data into congressional districts and economic factors might sum all 7,000 words up in a few seconds to show the economic imperative for Cohoes. Bourgeois connected with NREL and learned that no such visuals were planned, but the authors would happily provide input; so, Bourgeois teamed with nearby Rensselaer Polytechnic Institute, sending NREL's paper to Rensselaer's Institute for Data Exploration and Applications (IDEA) where students and faculty engage with data of imminent societal importance.

The request was shared with John Erickson, director of research operations at IDEA, who is drawn to visualizing economic and technical data. He enthusiastically jumped in. His first goal was to visualize NREL's data overlaid with LMI maps.

"Plotting the two data sets together was an eye-opener," Erickson said. "Right away the possibilities for low-cost clean energy become clear."

Erickson collaborated with Bourgeois and Seman-Graves to create the Floating Solar Explorer. The exploration tool is available online and includes a map of all the suitable reservoirs identified by NREL, as well as congressional district-scale LMI information layered over New York. Erickson originally bootstrapped the data explorer to share with Cohoes project stakeholders, but it is now shaping up to be a nice undergraduate elective.




A data exploration tool layers NREL data for potential floating PV sites with census data of income distributions to reveal potential opportunities for community ownership of low-cost renewable energy. *Image from John Erickson*

“We try to have our students be driven by questions from elsewhere. NREL’s floating solar data set is an excellent launching point for students to use data to explore topics of deep importance,” Erickson said.

The exploration tool is a perfect example of the cross-community collaboration that Bourgeois and Seman-Graves envision and which is already accounted for. They plan for NREL’s data and accompanying visualization to be part of a wider virtual platform where the city can share and access information about the floating solar installation and where Cohoes can be a resource for K–12 education, university-based research, workforce development, and economic collaboration, all of which provide a roadmap for others to adopt community ownership.

“Supporting Cohoes in their ongoing effort to install floating solar has been a great example of one of the many ways NREL can support cities in deploying innovative renewable energy systems,” said Sika Gadzanku, who leads some of NREL’s floating solar projects and has led engagement with Cohoes over the last year.

“Creative solutions such as the Cohoes floating PV project are helpful for extending the benefits of solar to LMI communities,” said Jenny Heeter, lead author of NREL's Affordable and Accessible Solar for All: Barriers, Solutions, and On-Site Adoption Potential report. LMI households can face barriers to installing rooftop PV such as difficulty financing a system, higher rental rates, and underinvestment in marketing and education to their communities. Likewise, communities are generally left out of tax incentives that are meant to spur renewable development. The newly updated DOE Solar Power in Your Community Guidebook offers resources for other communities wanting to install solar on government property and also includes discussion of both floating PV and engaging LMI communities.

NREL also began cost benchmarking floating PV systems in 2021 to track their cost competitiveness nationwide. Another recent publication analyzed the benefits of pairing hydropower and floating PV systems around the world—a hybrid energy opportunity that could also be surprisingly cost friendly.

With Cohoes taking the charge toward clean energy justice, the success of NREL’s research in supporting the small-city energy transition is a case study in going from R&D to deployment.

# Chapter 6. Trial by Water: NREL’s Wave-Powered Desalination Device Sets Sail

## March 7, 2022 | By Brittany Enos


NREL’s hydraulic and electric reverse osmosis wave energy converter device consists of a mechanical drivetrain and hydraulic pump that, once anchored, uses the vertical movement generated by passing waves to pump water to a reverse osmosis desalination unit on the pier. *Photo from Andrew Simms, NREL*

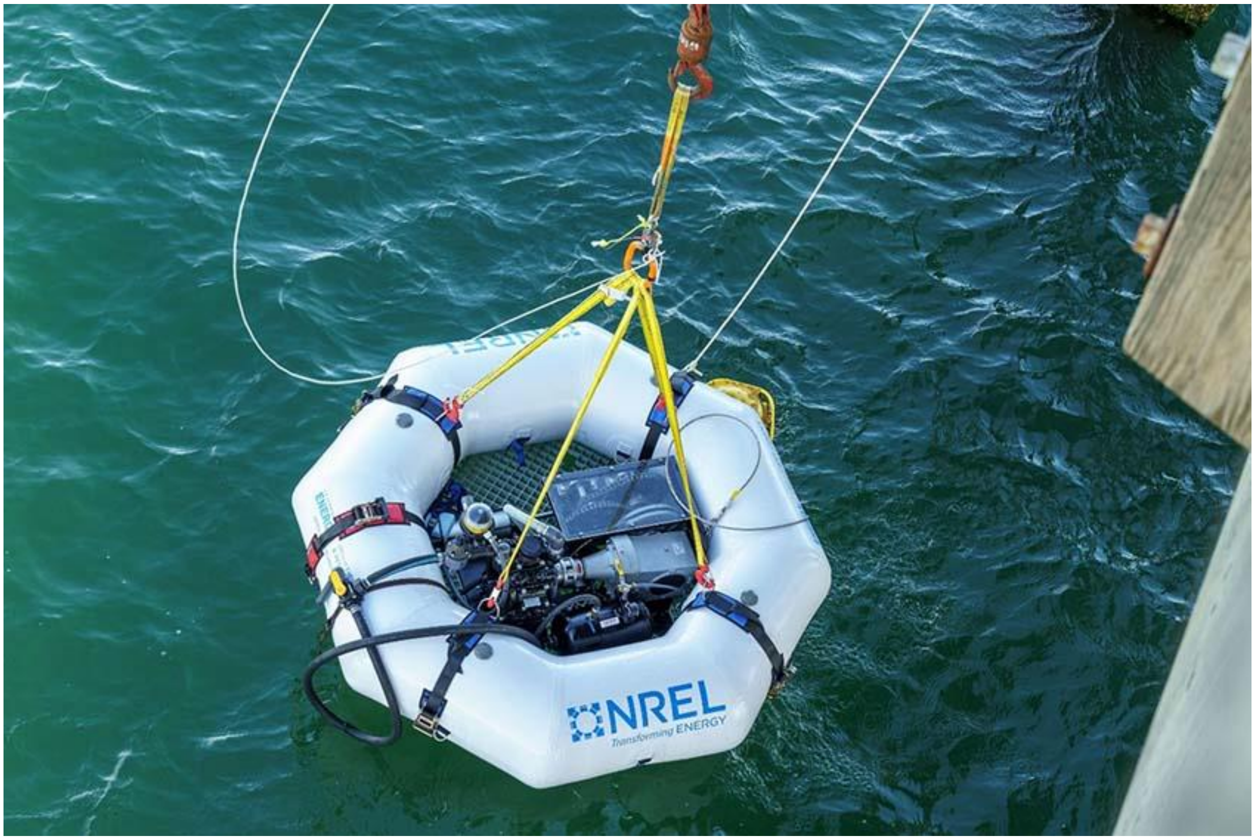
On a sun-filled winter day, National Renewable Energy Laboratory (NREL) researchers visited Jennette’s Pier, which sits on the shore of Nags Head beach in North Carolina. Amid salty air and crashing waves, the crew deployed a wave-powered desalination test device and anchored it to the nearby seabed—a long-awaited feat for the research team.

“Getting to this point has required a lot of patience and perseverance, but that's part of developing new renewable marine energy technologies,” said Scott Jenne, NREL’s marine energy systems engineering and techno-economic lead and principal investigator for the U.S. Department of Energy’s Waves to Water Prize. “Between building the device and finding a good-weather window in which to deploy, there were obstacles along the way, but we overcame those challenges and finally got the test device into the water.”


Scott Jenne prepares the HERO WEC device for its ocean outing. *Photo from Andrew Simms, NREL*

NREL researchers began designing the hydraulic and electric reverse osmosis (HERO) wave energy converter (WEC) device in summer 2020 and finished building it in January 2022. The team spent all of 2021 designing and constructing the HERO WEC, which is about 6 feet in diameter or roughly the size of a round dining table. After a year of facing unexpected supply-chain challenges, the team finally found a chance to test the device in the laboratory just before shipping it to North Carolina for ocean trials.

With help from the Coastal Studies Institute, NREL deployed the HERO WEC from Jennette's Pier—the same location where Waves to Water Prize finalists will launch their wave-powered desalination prototypes. With the help of a spider crane, the 714-pound HERO WEC was hoisted over the pier's railing, suspended about 2 feet above the water, and then swiftly dropped into the ocean. Experts at the Coastal Studies Institute then towed the device to its anchor site, where it was thoroughly secured overnight before being retrieved. The crew will run through the same motions with Waves to Water Prize competitors' devices this spring; however, competitors' prototypes will weather up to 5 days of in-water testing.




NREL’s HERO WEC hangs suspended over the water at Jennette’s Pier in Nags Head, North Carolina. *Photo from Andrew Simms, NREL*

As NREL’s first marine-powered desalination device to weather real ocean waters, the HERO WEC deployment signals advancements for marine renewable energy and desalination technologies but also ensures a fair contest in the nearing Waves to Water Prize DRINK Finale, set to take place in April 2022. Supported by the U.S. Department of Energy’s Water Power Technologies Office and administered by NREL, the five-stage, $3.3 million contest aims to accelerate innovation in small, modular, wave-powered desalination systems capable of producing clean water in disaster and recovery scenarios, as well as in water-scarce coastal and islanded locations.

Since 2019, NREL researchers have been working closely with the Coastal Studies Institute and Jennette’s Pier to ensure that the DRINK Finale is a safe and fair competition. With the Waves to Water Prize guidelines in mind, NREL designed and built the HERO WEC device to help the entire crew better understand the competitors’ designs and installation requirements.

The HERO WEC gave both NREL and the Coastal Studies Institute a chance to deploy and retrieve a WEC device, which is exactly what the crew will do with competitors’ prototypes during the DRINK Finale. The practice run also gave researchers an idea of what to expect during finale testing, like tuning devices for various wave conditions and preparing for possible prototype repairs.

“With the crew knowing we can safely and successfully install these wave-powered desalination systems, we’re now fully prepared to help prize finalists get their wave-powered desalination prototypes in the water,” Jenne said.

The public is invited to join prize finalists in North Carolina’s Outer Banks for the long-awaited finale of the DRINK Stage, where competitors will demonstrate their wave-energy-powered desalination systems for the chance to win part of the $1 million cash prize pool. Starting in late March 2022, events, including device viewings, in-water testing, and celebratory activities, will take place over a 3-week period.

After the finale concludes, the NREL team hopes to deploy the HERO WEC device again in North Carolina’s Outer Banks. With a second outing later this year, the HERO WEC can spend more time in the water collecting data to further complete NREL’s research on small-scale WECs.

# Chapter 7. Aging Gracefully: How NREL Is Extending the Lifetime of Solar Modules

## NREL-Led Consortium Studies Why Solar Modules Fail in the Field and How To Extend Their Life

### March 15, 2022 | By Kassidy Gamble

What makes for a good solar module? A few things are obvious: high energy yield, low cost, and reliable in the field.

Reliability plays a huge role in the lifetime costs and performance of solar modules and systems. These high-tech semiconductor devices must continue generating electricity for 30 to 40 years of sun, wind, hail, snow, and heat.

We expect modules to slowly degrade and produce slightly less electricity over time as they are exposed to outdoor conditions over the years. A major question in the solar energy industry is exactly how much we should expect solar modules to degrade each year (generally 0.5%–1%) and when they will eventually degrade so much that they no longer produce adequate power (often about 20% loss from their original output) or become unsafe.

For modules built today, it is probably 30 years. Each additional year makes the cost of electricity from that module cheaper and means we will need to mine or recycle fewer raw materials to reach our clean energy goals. Could research push that age of retirement to 50 years?

An electroluminescence image shows the cracking that can occur from standing on a solar module. How much these cracks can reduce a module's electricity output seems to vary by conditions and time. *Photo by Byron McDanold, NREL*

Launched in November 2016 with funding from the Department of Energy's (DOE's) Solar Energy Technologies Office (SETO), the Durable Module Materials (DuraMAT) Consortium is a multi-laboratory consortium led by the National Renewable Energy Laboratory (NREL), with Sandia National Laboratories and Lawrence Berkeley National Laboratory as core research labs. Additional researchers from multiple universities, solar companies, other national laboratories, and an industry advisory board provide perspectives from across the solar energy community.

After five years of researching solar module reliability and awarding $30 million in high-impact projects, DuraMAT was awarded an additional $36 million by SETO for six more years of funding starting in 2021, as the consortium continues its focus on five core objectives intended to accelerate a sustainable, just, and equitable transition to zero-carbon electricity generation by 2035.

# Solar Modules: Where We Have Been and Where We Are Going

Photovoltaic (PV)—meaning they convert light to electricity—modules have existed in their modern form since the middle of the 20th century, but the technology has seen explosive growth over the last two decades. And the next two decades promise even greater growth for solar technologies.

"If solar is going to expand and become this ubiquitous technology that we have across our power system, on our houses—and be responsible for 40% of our electricity generation—old technologies are not enough," said Teresa Barnes, a senior researcher at NREL and director of DuraMAT. "PV modules need to be made more efficient, less expensive, and more sustainably at much larger scale. But we also need to know that these new modules—whether they're new module designs or new cell technologies like bifacial or tandem cells—will perform predictably in the field."

DuraMAT is exploring ideas that could extend solar module lifetime up to 50 years. And it is looking at new variations of module and cell technologies, such as bifacial modules that also collect reflected light on their backsides, or new, high-efficiency cells that require advanced packaging to survive for longer than 30 years.

*Photo by Dennis Schroeder, NREL*

To better understand how modules fail, DuraMAT has developed accelerated stress tests based on the environmental conditions seen in different climates. These tests are paired with powerful materials science forensics (think CSI but for degraded PV modules) and detailed physics modeling of those failures to better understand what causes module degradation, with the ultimate goal of predicting when they will fail. To top it all off, DuraMAT collects the resulting data in a central, shared data repository and applies its insights to develop new, creative approaches to improve module durability.

The ultimate goal is to better predict how new materials and module designs will perform, building confidence that they will last for more than 30 years in the field, despite our lack of long-term field data for new technologies. Field data shows that older PV technologies are durable. DuraMAT is applying that knowledge to make more accurate predictions about newer technologies.

## Sweating the Degradation Details

One of DuraMAT's most celebrated successes is its application of combined, accelerated stress testing. Traditional stress testing subjects solar modules to a range of stressors—such as heat, humidity, or sunlight—but only one, or perhaps two, at a time. However, some of the failures seen in fielded modules are not easy to reproduce in these traditional stress tests, possibly because outdoor conditions stress modules in combination—heat, light, and voltage often occur together on sunny days, or wind and rain during a storm. DuraMAT researchers have found that stressors often need to be applied in combination to get field-relevant results more quickly.

A screenshot from a video filmed by NREL researcher Peter Hacke shows the interior of one of the combined, accelerated testing chambers in Golden, Colorado. The "donut" rings periodically press down and flex the modules to provide mechanical stress, while the chamber subjects them to water, heat, cold, electrical loading, and ultraviolet light.

While combined stress testing is not an entirely new idea, DuraMAT has taken it to a new level. In controlled chambers at NREL's Outdoor Test Facility, PV modules are subjected to multiple stressors, such as extreme temperatures (both hot and cold), being drenched in water, and ultraviolet light exposure to simulate in a few weeks or months what happens outside over years.

Other tests are meant to simulate other stresses, such as how years of wind exposure could expand cracks in PV cells (see video below). DuraMAT then pairs that information with computer modeling and microscopic materials analysis from solar modules that failed in the field to better understand the mechanisms that drive these failures.

## Early-Career Scientists Prove It Works

One such effort was led by a team of early-career scientists—DuraMAT places an emphasis on opportunities for early-career researchers. The team combined expertise and strengths from several national laboratories to develop a method to predict which backsheet materials would crack in the field based on accelerated testing. The industry experienced a fairly large batch of module failures (approximately 10 gigawatts) due to a new backsheet material that was widely used between about 2010 and 2015. This material started cracking after a few years in the field, despite passing all of the industry's standard qualification tests.

A backsheet is the bottom layer of a solar module that encloses the back of the module and is often made from polymer (plastic) materials. This layer provides critical electrical insulation and mechanical integrity to a module, and the material's failure forced PV developers to replace modules with the "bad" backsheet. (The PV industry also has several well-established "good" backsheet materials that have lasted for decades.)

Using the known good and bad backsheets enabled the DuraMAT team to develop a procedure to validate new test sequences. Combining that sequence with advanced materials analysis techniques, the team was able to understand why backsheets of the "bad" material were failing on both a chemical and mechanical level. By comparing the samples that failed under combined stress tests with failed modules from the field, the team of early-career researchers validated that the stress-test failures match this type of field failure. Now the team is examining other types of module materials and designs, including the screening procedures for new backsheet material development and studies of modules with glass backsheets.

"DuraMAT, in the way that it's structured, incubates early-career scientists in a unique way," said Laura Schelhas, who participated on the team as an early-career researcher at SLAC National Accelerator Laboratory and has since moved to NREL as executive director for the second phase of DuraMAT. "DuraMAT allows early-career researchers to try their hand as the principal investigator on projects, and it gives them a taste of reporting, project management, staffing, and budgeting that really speaks to career development for less-experienced researchers. The backsheet project was a great example of how that works—we got a lot of highly collaborative publications. The early-career researchers were invited to conferences to present their work, and some have transitioned to staff positions within NREL and other labs."

# What's Next for DuraMAT?

After starting from scratch five years ago, the next, six-year phase of DuraMAT is off to a strong start. Many projects having already been awarded from the $36 million in total funding available for the consortium's work in the second phase.

"A lot of our research continues to focus on reliability and durability in the commercial technology portfolio," said Barnes, when asked where DuraMAT is headed. "We are now shifting our emphasis towards predictive testing and modeling methods that will enable us to assess reliability more quickly and more accurately in new technologies. Solar needs to keep improving, and product development cycles can be a lot faster than reliability testing cycles. We need to find a way to assess reliability and durability at the speed of product development as the industry scales up rapidly."

It is a challenging goal, but the DuraMAT community is now aiming to begin predicting module lifetime and how that could shape the materials supply chain for solar modules. Driven by physics of failure and physics of degradation mechanisms, there will be more focus on predictive lifetime modeling, allowing for further research and possible commercialization of modules with 50-year lifetimes.

"We are trying to shift into a reliability research mode where we're directly targeting modules that last 50 years," Barnes said. "We're very focused on high-energy-yield modules and making those in a sustainable way. We know there are going to be big material and energy impacts from ramping up deployment as fast as we need for the energy transition. But our question is, 'How can we do that in a way that's environmentally sustainable and in a way that our supply chain can keep up?'"

"We're aiming for the same high quality of research but at a greater quantity in this phase," Schelhas said.

# Chapter 8. Battery Research Tackles New Challenges for Behind-the-Meter Stationary Storage Systems

March 24, 2022 | By Rebecca Martineau

Stationary batteries, like the one pictured, allow buildings to reduce reliance on grid power by storing energy that can be used during times of peak demand. *Photo by Dennis Schroeder, NREL*

The national transition to net-zero carbon emissions by 2050 will demand more from our electric grid than ever before. Stationary energy storage systems are critical to grid resiliency by ensuring that the power from renewable energy sources is available when and where it is needed.

Energy efficient buildings of the future are turning to holistic behind-the-meter storage (BTMS) system designs to minimize costs and grid impacts due to their ability to integrate electric vehicle charging, photovoltaic generation, and building demands using controllable loads to generate and store energy on-site.

As part of the U.S. Department of Energy's BTMS Consortium, researchers at the National Renewable Energy Laboratory (NREL) are leading the development of new lithium-ion (Li-ion) battery designs specific to the stationary storage requirements.

"We already know a lot about Lithium-ion batteries, but batteries for different applications have different requirements," said NREL Researcher and Project Leader Yeyoung Ha. "Our research looks at how to leverage the developments from electric vehicle battery research for new applications in stationary storage."

BTMS systems have different charging and discharging patterns than a typical electric vehicle and require Li-ion battery materials that meet these unique priorities. Li-ion battery designs using a $Li_4Ti_5O_{12}$ (LTO) anode and $LiMn_2O_4$ (LMO) cathode are promising critical-material-free candidates that offer the safety and long lifespan required of BTMS systems. While these cells in conventional design have a comparatively low energy density, new research at NREL, published in the *Journal of the Electrochemical Society*, delved further into promising opportunities, as well as limitations, of using LTO/LMO battery cells for stationary storage use.

This project evaluated the temperature-dependent performance of LTO/LMO cells with various electrode loadings. Researchers determined that using thicker electrodes in battery designs can increase the cell capacity and energy density, while decreasing overall cell costs. However, these thicker electrodes require ions to travel a longer path, limiting the utilization of electrodes. Temperature adjustments can alleviate these negative impacts but may introduce added complications. The trick is to design a battery that offers the best balance for stationary applications.

"Our goal with this research is to identify a 'sweet spot' to leverage the advantages of electrode loading and increased temperatures to maximize the performance of LTO/LMO battery cells," Ha said. "Our research refined material designs for BTMS specifically, converting this well-known power chemistry to energy cells."

The NREL team further verified their findings by applying electrochemical modeling to simulate reactions at different temperatures and electrode thickness. This modeling, in alignment with experimental results, emphasized the impact of transport limitations and informed strategies to improve the cell performance. By allowing batteries to have intermittent rest during discharge, instead of being fully discharged as for electric vehicles, the electrode utilization was significantly improved. Researchers found this type of pulsed discharge is well suited for BTMS stationary applications, where the batteries will be used only when there is intermittent demand and then transitioned back to a resting stage.

Although these optimized LTO/LMO battery cells offer many advantages, the research team is also exploring cathode options that may better meet BTMS system needs. NREL's expertise in materials development will be combined with the cutting-edge electrochemical modeling used in this project to streamline further research into new materials and experimental battery designs for stationary storage and beyond.

# **Chapter** 9. Amazon Joins NREL-Led BOTTLE Consortium To Help Change the Way We Recycle

## March 30, 2022 | By Erik Ringle

Breaking Down the Issue—Among BOTTLE's strategies is to develop scalable technologies for breaking down plastic, such as the polyester shown here before and after enzymatic degradation. *Photo by Dennis Schroeder, NREL*

An estimated 5.7 billion metric tons of discarded plastic has never been recycled—more weight than food produced every year globally. Though a fraction of that plastic waste has been landfilled, much has escaped waste management, becoming a pollutant that can persist for centuries in forests, lakes, and oceans.

That hard reality is prompting the global community to rethink how plastic is created, managed, and recycled. A circular plastics economy—facilitated in part by chemical technologies designed to break apart and upcycle all kinds of plastics—could help lower greenhouse gas (GHG) emissions and save energy relative to virgin plastics manufacturing. That way, the world might reap the substantial benefits that plastics offer, while reducing environmental costs.

Adding weight to that effort is a new collaboration between Amazon and the National Renewable Energy Laboratory (NREL)-led BOTTLE™ Consortium. Amazon will leverage BOTTLE's primary research strategy—contributing research on plastic deconstruction, upcycling, and redesign—and implement solutions in company efforts of eliminating or reducing packaging waste.

According to Gregg Beckham, an NREL senior research fellow and CEO of BOTTLE, adding Amazon to the consortium's growing list of industry partners is a major step toward developing solutions to the world's most critical plastic pollution problems.

"Amazon is poised to catalyze new upcycling paradigms with direct exposure to billions of consumers," he said. "Its size and scale allow it to influence the plastic supply chain in a holistic manner."

Short for "Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment," BOTTLE is a U.S. Department of Energy (DOE)-funded consortium that brings together an interdisciplinary team of experts from 10 partner institutions to meet the critical need for new technology on plastics recycling and upcycling. Two primary thrusts ground the collaborative effort:

1. Development of chemical upcycling strategies for today's plastics
2. Redesign of tomorrow's plastics to be recyclable by design.

In support of this strategy, much of the work with Amazon will focus on advancing chemical processes for deconstructing plastics commonly found in packaging, such as polyethylene and polyesters. By exploring a range of catalytic technologies, the team targets scalable strategies for breaking down plastic packaging into smaller chemical building blocks. These can then be used to synthesize new plastics or—better still—to create classes of higher-value replacements.

Threaded throughout that research will be comprehensive analysis to understand environmental, technical, social, and economic merits of new technologies and processes.

"In partnership with BOTTLE, we plan to make significant progress in developing new technologies and materials that will lead to less material in landfills and more back into the circular economy," said Alan Jacobsen, principal materials scientist at Amazon. "Science and innovation are at the heart of our sustainability work at Amazon, and we are committed to using our size and scale to reduce and eliminate our use of materials and find new ones that can be applied to our operations and other industries around the world."

# Chapter 10 Plant-Based Epoxy Enables Recyclable Carbon Fiber, Improves Economics for Mass Market Electric Vehicles

Jan. 27, 2022

A Bio-Based Solution—An NREL researcher synthesizes a plant-derived epoxy that can be fully depolymerized at room temperature with a special catalyst. *Photo by Dennis Schroeder, NREL*

Ten times stronger than steel, nearly half the weight of aluminum, far stiffer than fiberglass—carbon fiber carries a package of advantages, making it a preferred material for use in luxury sedans and Formula One racecars alike.

But it still needs perfecting to become economical for mass market vehicles, according to National Renewable Energy Laboratory (NREL) scientist Nicholas Rorrer. "Carbon fiber is expensive," he explained. "It is also energy intensive to make, so it is not exactly greenhouse gas (GHG) friendly. Making carbon fiber readily recyclable could help in both these regards."

Thanks to recent advances in bio-based material design, recycling carbon fiber at an industrial scale could already be close at hand.

Through a project supported by the U.S. Department of Energy's Vehicle Technologies Office, under the Composites Core Program, Rorrer and other NREL researchers have shown that making carbon fiber composites with bio-based epoxies and an anhydride hardener makes the material fully recyclable by introducing linkages that are more easily degraded. In fact, the recycling process—called methanolysis—can be selectively triggered at room temperature without degrading the quality or orientation of the fibers. That could represent a strong step toward a circular material, which can make carbon fiber cheaper and greener when used across multiple lives.

## A Close Look at Carbon Fiber

Strong, Featherweight, and Not Recyclable—Today's carbon fiber is made by setting woven carbon filaments in glue-like epoxy, yielding a material that can improve car performance but cannot be effectively recycled.

At once strong and featherweight, carbon fiber's advantages come from its layered design. It is a composite material of both long filaments of pure carbon and a glue-like epoxy coating known as a "thermoset." When curing, molecules in the liquid resin bind with each other and around the woven carbon filaments, hardening into a strong and rigid lattice.

When produced with a mold, the material can take a range of shapes for a variety of applications, from car bumpers to wind turbine blades and more.

However, the thermoset-nature of the cured epoxy makes those superior products difficult to break apart, especially without severely damaging the carbon filaments. Products made from carbon fiber—despite their premium price—often head to the landfill at the end of their lives, along with any efficiency benefits they may have earned.

Indeed, although carbon fiber could cut the weight of a typical passenger car in half—boosting its fuel efficiency by as much as 35%—any efficiency benefits are effectively offset by the GHG-intensive energy used to manufacture it. Synthesizing carbon fiber involves temperatures of more than 1,000°C.

That reality got Rorrer thinking: "Is there a way to reuse carbon fiber over multiple material lives to reclaim that fiber and get more value and environmental benefits?"

# Making Epoxy Recyclable by Design

Rorrer and teammates began experimenting with the chemistry of biomass to understand if it could enable a new epoxy designed for recyclability. Compared to the hydrocarbons in petroleum, biomass contains higher levels of oxygen and nitrogen, offering a different set of chemical possibilities.

"We essentially redesigned the epoxy amines resins—today's thermosets in carbon fiber—with epoxy and anhydrides synthesized from biomass, predominantly from the biological and chemical conversion of sugars," Rorrer explained. "We have shown that that reformulated resin can maintain and/or exceed all the same properties as in today's epoxy amine resins, but also make them recyclable by design—and at room temperature."

This research aligns with one of NREL's critical objectives.
Using a special catalyst, the NREL team was able to break down the bio-based resin at room temperature, a process known as "depolymerization." That allowed them to recover the carbon filaments while maintaining their quality and alignment.

"We can actually maintain the fiber quality over at least three material lives," Rorrer said. "So not only are we able to recycle it; we are able to recycle it without any detriment to properties. We are not downcycling the material at all."

Combined with NREL's research into low-cost, bio-based acrylonitrile as a carbon fiber precursor—which earned an R&D 100 award in 2018—the breakthrough in epoxy could go a long way in making carbon fiber composites more cost effective and environmentally friendly.

Being able to extract and recycle the carbon fiber could make the material more economical for mass market electric vehicles, freeing up weight and space for batteries. It would also lower the material's GHG footprint by 20%–40%. Better yet, it could achieve all that without increasing manufacturing costs, as Rorrer estimates NREL's epoxy could be produced for roughly the same price as today's petroleum-based epoxy-amine resins.

"By using bio-based feedstocks instead of petrochemical feedstocks, we don't have to use extra energy to dramatically retool their chemistries," Rorrer added. "That allows us to more precisely, cheaply, and effectively design advanced materials with performance and environmental advantages."

# Chapter 11. News Release: Scientists Show Large Impact of Controlling Humidity on Greenhouse Gas Emissions

## Research Effort by NREL and Xerox PARC Offers Predictions for 2050. It Suggests New Technologies are Needed

### March 14, 2022

Greenhouse gas emissions from air conditioners are expected to climb as economic growth drives efforts to control both temperature and humidity, according to an analysis by scientists from the National Renewable Energy Laboratory and Xerox PARC.

The research, which explores the environmental impact of controlling humidity, appears in the journal *Joule* as “Humidity’s impact on greenhouse gas emissions from air conditioning.” While the energy used to power air conditioners has clear implications on greenhouse gas emissions, the impact from removing moisture from the air has escaped in-depth study until now. The researchers showed that controlling humidity is responsible for roughly half of the energy-related emissions, with the other half due to controlling temperature.

"It's a challenging problem that people haven't solved since air conditioners became commonplaces more than a half-century ago," said Jason Woods, an NREL senior research engineer and co-author of the new study. His co-authors from NREL are Nelson James, Eric Kozubal, and Eric Bonnema. The collaborators from Xerox PARC, an R&D company working on ways to remove humidity more efficiently from the air, are Kristin Brief, Liz Voeller, and Jessy Rivest.

The researchers pointed out the increasing need to cool the air is both a cause and an effect of climate change.

Even a small amount of moisture in the air can cause people to feel uncomfortable and even damage buildings in the form of mold and mildew. Furthermore, controlling indoor humidity through commercially available air conditioning technologies impacts the environment in three ways: 1) They consume a considerable amount of electricity, 2) they use and leak CFC-based refrigerants with global warming potential that is 2,000 times as potent as carbon dioxide, and 3) the manufacturing and delivery of these systems also release greenhouse gases.

The researchers calculated air conditioning is responsible for the equivalent of 1,950 million tons of carbon dioxide released annually, or 3.94% of global greenhouse gas emissions. Of that figure, 531 million tons comes from energy expended to control the temperature and 599 million tons from removing humidity. The balance of the 1,950 million tons of the carbon dioxide come from leakage of global-warming-causing refrigerants and from emissions during the manufacturing and transport of the air conditioning equipment. Managing humidity with air conditioners contributes more to climate change than controlling temperature does. The problem is expected to worsen as consumers in more countries—particularly in India, China, and Indonesia—rapidly install many more air conditioners.

"It's a good and a bad thing," Woods said. "It's good that more people can benefit from improved comfort, but it also means a lot more energy is used, and carbon emissions are increased."

To calculate the emissions to manage both temperature and humidity, the researchers divided the globe into a fine grid measuring 1 degree of latitude by 1 degree of longitude. Within each grid cell, the following characteristics were considered: population, gross domestic product, estimated air conditioner ownership per capita, carbon intensity of the grid, and hourly weather. They ran nearly 27,000 simulations across the globe for representative commercial and residential buildings.

Climate change is affecting ambient temperatures and humidity around the globe, making it warmer and more humid. As part of the study, the researchers considered the impact of the changing climate on air conditioner energy use by 2050. For example, the study projects air conditioner energy use to increase by 14% in the hottest climate studied (Chennai, India) and by 41% in the mildest (Milan, Italy) by 2050. The increase in global humidity is projected to have a larger impact on emissions than the increase in global temperatures.

“We’ve already made the existing, century-old technology nearly as efficient as possible,” Woods said. “To get a transformational change in efficiency, we need to look at different approaches without the limitations of the existing one.”

Existing vapor compression technology is optimized to cool our buildings using a “vapor compression cycle.” This cycle uses harmful refrigerants to cool air down low enough to wring out its moisture, often over-cooling the air and wasting energy. Improving the vapor compression cycle is reaching practical and theoretical limits, thus pointing to a need to leap-frog to an entirely new way to cool and dehumidify buildings. New technologies that split this cooling and humidity control problem into two processes show potential to improve efficiency by 40% or more. One such technology space is the use of liquid desiccant-based cooling cycles such as the many liquid desiccant air conditioning technologies that NREL is currently developing with many partners, such as Emerson and Blue Frontier.

The researchers point out that the use of liquid desiccants fundamentally changes the way humidity is controlled and has theoretical efficiency limit that is 10 times higher than the vapor compression cycle alone. A hypothetical technology—at only half this new limit—would reduce cooling-energy emissions by 42% in 2050, with the equivalent of avoiding 2,460 million tons of carbon dioxide annually.

The Department of Energy’s Building Technologies Office funded the research published in *Joule*.

# Chapter 12. A Year in Review: Advancing Energy Storage and Conversion Research

Jan. 10, 2022


The energy system of the future must successfully utilize large amounts of variable and intermittent renewable energy sources to meet demand for power generation, decarbonization, grid resilience, and energy efficiency.

As communities across the country invest in renewable energy technologies, energy storage systems must be optimized to meet demand for power generation, decarbonization, grid resilience, and energy efficiency. The National Renewable Energy Laboratory (NREL) is focused on developing and accelerating the implementation of holistic future energy systems with purpose-driven, interconnected technologies that improve flexibility and balance to maximize renewable energy generation, storage, and conversion. Over the past year, NREL researchers have pioneered innovative, interdisciplinary, and integrated research and development for technology advancements in electrochemical, molecular, thermal, and mechanical energy storage systems.

As a result of NREL's groundbreaking energy storage research, R&D World magazine recognized the Wave Energy Converter Simulator (WEC-Sim) as one of the 100 most innovative technologies of the past year with an R&D 100 Award. WEC-Sim is the first open-source code allowing wave energy developers to simulate WEC dynamics and performance—dramatically reducing the uncertainty around how WECs will perform in real-world marine environments—which lowers costs and reduces R&D cycle time in this pivotal and growing field.

## Research Reveals Opportunities in Integrated Energy Storage

## New NREL Report Details Current State and Vast Future Potential of U.S. Geothermal Power and Heat

The 2021 U.S. Geothermal Power Production and District Heating Market Report developed at NREL showcases the current state of geothermal energy use in the United States and identifies geothermal opportunities for a renewable, decarbonized energy system. Innovative approaches to geothermal district heating involve integrating heat pump technology and thermal energy storage, as well as implementation and optimization of energy districts. This report will be valuable for policymakers, regulators, developers, researchers, engineers, financiers, and other decision makers.

## NREL Options a Modular, Cost-Effective, Build-Anywhere Particle Thermal Energy Storage Technology


Particle thermal energy storage systems can be constructed with existing infrastructure from retired coal and gas power plants. *Image by Jeffrey Gifford and Patrick Davenport, NREL*

NREL researchers developed a prototype to test a game-changing new thermal energy storage technology using inexpensive silica sand as a storage medium. Economic Long-Duration Electricity Storage by Using Low-Cost Thermal Energy Storage and High-Efficiency Power Cycle (ENDURING) is a reliable, cost-effective, and scalable solution that can be sited anywhere. The baseline system is designed for economical storage of up to a staggering 26,000 MWh of thermal energy, offering building and industrial process heating opportunities to replace coal or natural gas. NREL has partnered with Babcock & Wilcox, who has an exclusive intellectual property option agreement to license this ENDURING thermal energy storage technology.

## New Financial Analysis Tool for Long-Duration Energy Storage in Deeply Decarbonized Grids

Researchers at NREL developed a rigorous new Storage Financial Analysis Scenario Tool (StoreFAST) model to identify potential long-duration storage opportunities in the framework of a future electric grid with 85% renewables penetration. StoreFAST analyzes both energy storage systems and flexible power generation systems on a side-by-side basis to provide insights into the levelized cost of energy, financial performance parameters, and time series charts that will be vital to integrated energy storage research. A recent Joule article used StoreFAST to identify clean hydrogen systems with geologic storage and natural gas with carbon capture and sequestration as the lowest-cost options for long durations of energy storage.

## NREL Develops FLASH Hydropower Framework for a Greener Grid

The new Framework for Linked Analysis of Streamflow and Hydropower (FLASH) tool provides insight into how much hydropower is available and when, improving hydropower's representation within grid operations models. FLASH will help users better understand the link between river-basin operations and hydropower’s availability, opening new opportunities for renewable energy to support the grid. Unlike wind or solar power, hydropower not used today can be stored for later use and has the additional advantage that it does not have to be converted into another form of energy. That makes hydropower ideal for helping the grid accommodate variable renewable energy sources.

About 2,500 dams across the United States produce electricity. Pictured here is Gross Reservoir Dam in Colorado. *Photo courtesy of Brent Olson, U.S. Department of Energy*

## NREL Advances in Battery Research with Physics-Based Machine Learning Accelerate Characterization of Cell Performance, Lifetime, and Safety

Energy storage scientists at NREL are turning to cutting-edge machine-learning techniques to strengthen their understanding of advanced battery materials, chemistries, and cell designs. These complex computer algorithms help accelerate the characterization of battery performance, lifetime, and safety by offering insights into potential patterns within data sets. Researchers are using machine learning and artificial intelligence to evaluate manufacturing quality, lifetime and performance, materials research, and safety protocols for energy storage applications.

## Grid-Scale U.S. Storage Capacity Could Grow Fivefold by 2050

The Storage Futures Study considers when and where a range of storage technologies are cost-competitive, depending on how they're operated and what services they provide for the grid. Ongoing research from NREL's Storage Futures Study analyzes the potentially fundamental role of energy storage in maintaining a resilient, flexible electrical grid through the year 2050. NREL researchers are collaborating across technologies to consider the role of specific storage approaches. One report, *Economic Potential of Diurnal Storage in the U.S. Power Sector*, described the significant market potential for utility-scale diurnal storage (up to 12 hours) in the U.S. power system through 2050. The research team—Will Frazier, Wesley Cole, Paul Denholm, Scott Machen, Nathaniel Gates and Nate Blair—found storage adds the most value to the grid, and deployment increases when the power system allows storage to simultaneously provide multiple grid services and when there is greater solar photovoltaic penetration.