Latest Research Developments by the National Renewable Energy Laboratory - Part 2

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This course was adapted from the National Renewable Energy Laboratory (NREL), "Recent Developments in Renewable Energy Research at NREL Part 2", which is in the public domain.

Recent Developments in Renewable Energy Research at NREL Part 2

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 2 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. The Future of Distributed Wind in the United States: Considerations for Unlocking Terawatt-Level Potential

NREL's Distributed Wind Energy Futures Study Finds the Most Promising Locations, Sectors for Distributed Wind To Play a Meaningful Role in the U.S. Energy Future

May 12, 2022 By Madeline Geocaris

Distributed wind could play a meaningful role in the U.S. energy future. *Photo from David Nevala Photography for CROPP Cooperative*

The U.S. federal government has set a goal of 100% clean electricity in 2035 and a net-zero carbon economy in 2050. To achieve these ambitious targets, all forms of renewable power will be important—including distributed wind.

Distributed wind energy refers to wind technologies deployed as distributed energy resources. These technologies are place-based solutions that support individuals, communities, and businesses transitioning to carbon-free electricity.

Distributed wind can be placed in behind-the-meter applications, where the system directly offsets a specific end user's consumption of retail electricity supply, or in front-of-the-meter applications where the system is interconnected to the distribution network and provides community-scale energy supply while bolstering the robustness, reliability, and resiliency of the local distribution network. Distributed wind installations can range from a less-than-1-kilowatt off-grid wind turbine that powers telecommunications equipment to a 10-megawatt community-scale energy facility.

From 2003 through 2020, over 87,000 wind turbines were deployed in distributed applications across all 50 states, Puerto Rico, the U.S. Virgin Islands, and Guam, totaling 1,055 megawatts in cumulative capacity. Iowa, Minnesota, Massachusetts, California, and Texas lead the country with the most distributed wind capacity currently installed. As more communities come to understand the role that distributed energy resources could play in their own energy transitions and seek their environmental, economic, and social benefits, distributed wind could play a unique role in the future U.S. grid.

To explore opportunities for widespread deployment of distributed wind in 2035, the National Renewable Energy Laboratory (NREL) completed the Distributed Wind Energy Futures Study funded by the U.S. Department of Energy's Wind Energy Technologies Office. The highly detailed, comprehensive analysis reveals distributed wind has the potential to profitably provide nearly 1,400 gigawatts of capacity—today. That is enough energy to supply more than half of current U.S. annual electricity consumption.

But the right conditions must exist to realize the opportunities for distributed wind.

Modeling Innovations Provide Granular Insights

The Distributed Wind Energy Futures Study builds on NREL's 2016 first-ever exploratory analysis of future opportunities for behind-the-meter distributed wind systems.

For both the 2016 and 2022 studies, NREL used its Distributed Wind (dWind) model—a module within the Distributed Generation Market Demand (dGen™) model suite. This year, NREL added new, higher-resolution data and modeling capabilities to dWind to expand on the 2016 study. Notably, dWind now includes real-world dimensions from a data set of 150 million parcels of property in the United States to size turbines for those locations. NREL also improved dWind to consider front-of-the-meter wind systems. The model will be open sourced as part of dGen later this year.

"The potential of distributed wind projects can vary widely with local conditions, so it's important to study it at the most detailed level," said Kevin McCabe, NREL analyst and dGen developer. "Our study is one of the first demonstrations of parcel-level distributed energy resources analysis and advances wind economic and technical potential assessments with unprecedented resolution. With this new level of detail, we can identify trends by land-use type, end-use sector, and geography."

With these new modeling capabilities, dWind can now explore more community-scale distributed wind applications that could participate in the wholesale electricity market and a broader array of payment schemes. NREL modeled future scenarios with a variety of distributed wind system sizes in behind-the-meter and front-of-the-meter applications for specific land-use types, focusing on agricultural, commercial, and industrial areas.

A megawatt-class turbine in a behind-the-meter distributed wind application. *Photo by Hank Doster, One Energy Enterprises LLC*

Results: Economic Potential of Distributed Wind

Consistent with the 2016 study, NREL finds U.S. distributed wind has abundant economic potential, or the potential that would have a positive return on investment. Entire regions of the country could profitably provide hundreds of gigawatts today if deployed. In 2035, terawatts of capacity could be possible.

NREL examined three primary factors that could help unlock distributed wind's potential:

1. Improved financing and performance to reduce the cost of wind energy
2. Relaxed siting restrictions to open up more available land for wind development—a previous NREL study revealed a 7X difference in total U.S. wind technical potential in 2050 between the least and most restrictive siting restrictions
3. An investment tax credit renewal and net metering. Currently, customers can receive a 26% tax credit for qualifying wind turbines below 100 kilowatts and solar panels installed between 2020 and 2022. The tax credit will expire in 2024 unless Congress renews it. Net metering is a metering and billing arrangement where distributed energy generation

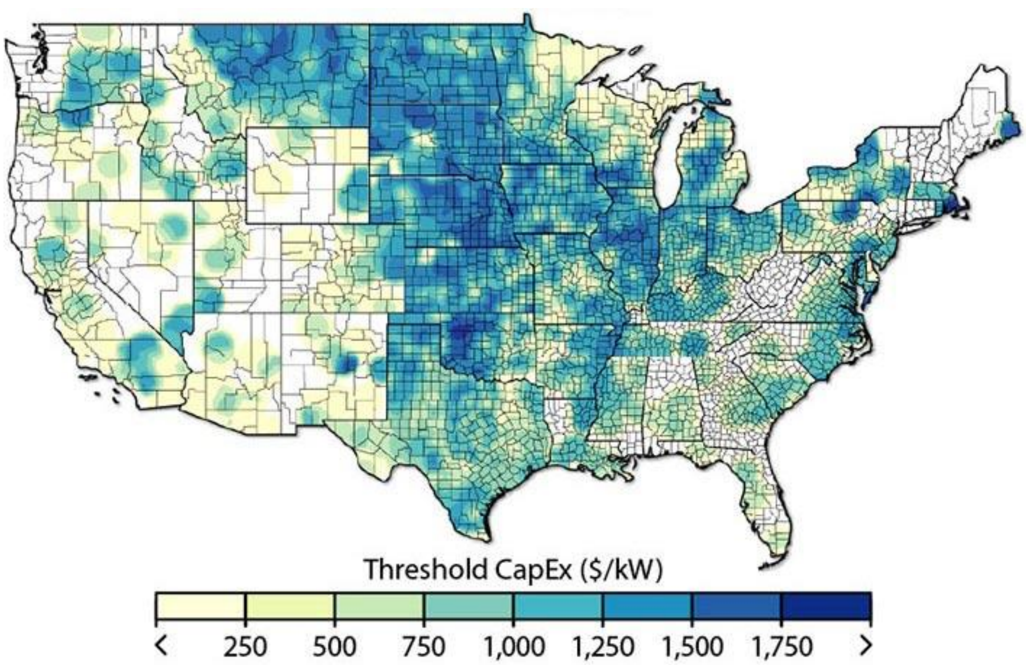
system owners are compensated for any generation that is not used and exported to the utility grid.

Under the most optimistic conditions—including aggressive cost declines, more relaxed siting constraints than today, and strategic extension and expansion of current tax credits and policies—NREL finds front-of-the-meter wind could provide over 4,000 gigawatts of capacity and behind-the-meter wind could provide over 1,700 gigawatts of capacity in 2035. In the least optimistic conditions, front-of-the-meter wind capacity decreases to 42 gigawatts and behind-the-meter wind capacity to 440 gigawatts in 2035.

"Our analysis suggests that technology cost reduction, performance improvements, and more relaxed siting restrictions are critical steps needed to realize the deployment potential of distributed wind," said Eric Lantz, principal investigator of the study. "At the same time, incentives like the investment tax credit, financing, and compensation mechanisms like net metering are also important to enhance system economics—and drive industry-wide growth that would fundamentally alter the outlook for distributed wind technologies."

Front-of-the-meter wind

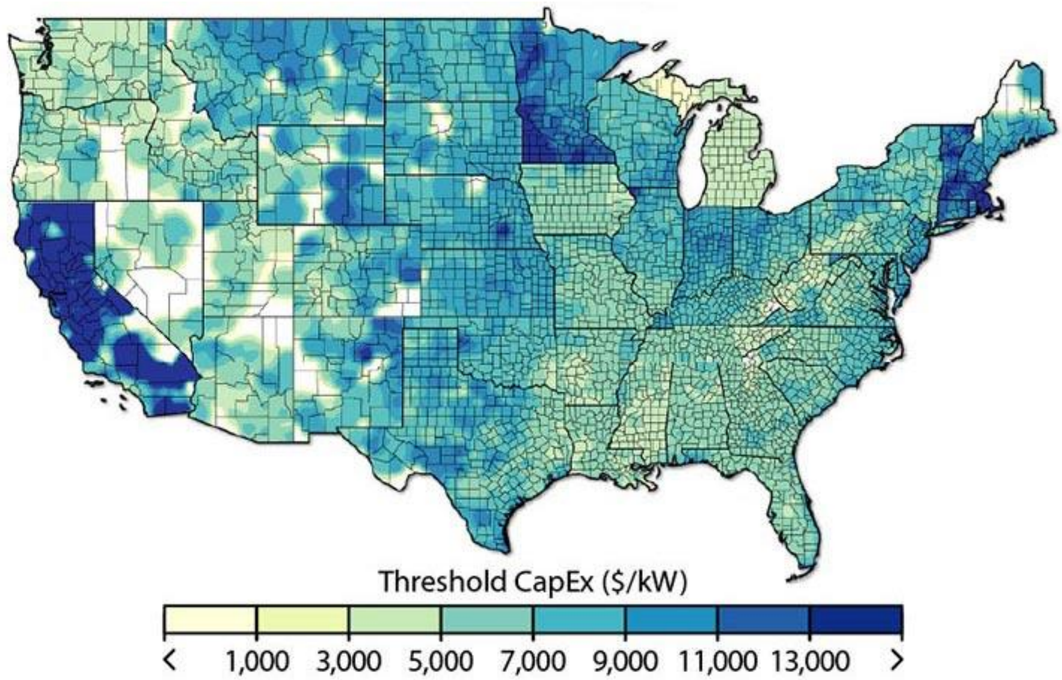
Baseline 2022 Scenario



The economic potential of front-of-the-meter wind applications in 2022. Oklahoma, Nebraska, Illinois, Kansas, Iowa, South Dakota, Pennsylvania, New York, Montana, and New Mexico have the highest potential.

Behind-the-meter wind

Baseline 2022 Scenario



The economic potential of behind-the-meter wind applications in 2022. Texas, Minnesota, Montana, Colorado, Oklahoma, Indiana, South Dakota, North Dakota, New Mexico, and Kentucky have the greatest economic potential.

Results: Regions, Sectors With the Lowest-Hanging Fruit

NREL finds the regions with the highest potential for distributed wind tend to have a combination of high-quality wind, relatively high electricity rates for behind-the-meter applications, higher wholesale power rates for front-of-the-meter applications, and siting availability.

The Midwest and Heartland regions overall have the highest potential for distributed wind, and the Pacific and Northeast regions have significant potential for expansion of behind-the-meter distributed wind deployments.

As modeled, agricultural land has the highest distributed wind potential, but residential, commercial, and industrial land also have gigawatt-scale potential, particularly for behind-the-meter applications.

NREL finds states with the most near-term potential for behind-the-meter applications include Texas, Minnesota, Montana, Colorado, Oklahoma, and Indiana. States with the most near-term potential for front-of-the-meter applications include Oklahoma, Nebraska, Illinois, Kansas, Iowa, and South Dakota.

States across much of the Northeast as well as California have lower quantities of profitable distributed wind potential, but there are select locations with significant wind resources, which when combined with generally higher retail electricity rates in these regions means there are compelling opportunities in there too.

Results: Distributed Wind Potential in Disadvantaged Communities

Some communities have long endured the negative aspects of energy and climate change and face more barriers to accessing clean energy. On-site energy generation, like distributed wind, could help reduce this inequity by extending the benefits of clean energy to more communities.

NREL modeled the technical and economic potential of distributed wind in parcels of property in communities with high risk to environmental hazards and/or high proportions of low-income households.

As modeled, disadvantaged communities represent 43% of all suitable U.S. parcels for front-of-the-meter wind, and 47% for behind-the-meter wind. There are significant opportunities to expand distributed wind in disadvantaged communities in the next decade, particularly for behind-the-meter deployments in Texas, Montana, Michigan, and California.

"With continued efforts to reduce cost, improve performance, and think more broadly about solutions to deployment, distributed wind could empower communities across the United States to transition to clean energy," Lantz said. "Taking steps to help realize the potential of distributed wind will be especially important in future scenarios with a lot of wind energy, as envisioned under economy-wide decarbonization. In those scenarios, distributed wind's ability to fit specific niches and provide local electricity supply could advance the nation's ability to use wind energy."

Chapter 2. From Full Fare to Fast Charging

Preparing for New York's Shift to Cleaner, Quieter Electric Cars for Hire

May 12, 2022 By Anya Breitenbach

Yellow cabs have been iconic symbols of New York City for more than a century. *Photo from iStock*

Stepping off the curb to hail a cab. Hopping in a taxi to get home from the train station. For more than a century, these yellow sedans have been iconic symbols of New York City and a daily presence in the lives of its residents.

In recent years, ride-hailing companies such as Uber and Lyft have taken on a significant share of rides traditionally provided by taxis. While conventional cab service endures, other changes are underway, as cars for hire in America's largest city make the shift to cleaner, quieter electric vehicles (EVs).

Researchers from the U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) are working to make sure that the city's EV charging network and local utility can meet the eventual demands of more than 100,000 electric cars for hire. Results of an initial study focusing on ride-hailing services were recently published in the journal *iScience*.

"While automotive technology has advanced, there's still some ground to cover before we have the infrastructure in place to support all of those EVs," said lead author and NREL Research Engineer Matthew Moniot. "Industry and government decision makers have to figure out the ideal number, types, and locations of charging stations—and a multitude of factors need to be weighed before making those determinations."

Moniot and his team of researchers performed simulations leveraging a multitude of data streams including real-world trip data, driver shift schedules, overnight charging access rates, and even weather to explore the need for public fast-charging stations. The findings reveal economic and operational insights that could prove valuable to ride-hailing, utilities, and charging operations.

The project facilitated discussions and gathering detailed data from industry stakeholders, including the New York City Taxi and Limousine Commission and utility operator Con Edison. Researchers then fed this information into NREL's Highly Integrated Vehicle Ecosystem Simulation Framework (HIVE) modeling tool. Based on these inputs, the HIVE simulation platform was used to model ride-for-hire demand for charging in space and time, siting networks that met performance metrics at the fleet and vehicle level.

Uber and Lyft have both pledged aggressive targets to fully electrify their fleets by 2030 across the United States. Historically, drivers for these ride-hailing services have used their own vehicles and refueled at the long-established network of city gas stations. This means that a shift to an electric ride-hailing fleet would not only require more ride-service drivers driving EVs but also convenient access to public fast-charging stations or at-home charging.

Public fast-charging stations are seen as a particularly crucial component in making the switch to electric rides-for-hire viable. Fast charging only takes about 30 minutes, while overnight charging can take up to seven hours. The quicker drivers can top off their batteries, the speedier their return to the streets and picking up fares.

The high volume of taxi and hailed rides in New York, along with traffic congestion, make more frequent recharging necessary for EVs in the city. Cold weather in the winter can further limit battery range. Even if EVs made up only 30% of the ride-for-hire vehicles, the study findings indicate that the city would need to increase today's count of 68 fast-charging ports to over 1,000 to meet the demand.

Information supplied by the study on the locations where and times when demand might spike can help charging network operators come up with strategies to accommodate ride-hailing services as well as the average driver.

"Unsurprisingly, the highest demand for EV charging appeared to be where most pickups occur in midtown Manhattan," said article co-author and NREL Integrated Transportation and Energy Systems Analyst Brennan Borlaug. "However, we also saw considerable demand for charging near driver residences."

The research team also found that giving drivers more convenient overnight charging options in their neighborhoods across the five boroughs of New York could reduce the number of public fast charging stations needed by as much as 65%. However, even this optimistic scenario would still require substantial expansion of the current network of fast chargers in New York City.

Electric vehicles and their need for grid-supplied power also represent a major opportunity for utilities who are interested in the prospects of load growth. However, utilities are scrambling to predict how much electricity will be needed, at what times, and at which locations.

The study, supported by the New York State Energy Research and Development Authority (NYSERDA), highlights how fast charging and overnight charging compare in terms of their impacts on the grid. Although overnight charging of an individual EV uses less power than fast charging, simultaneous charging of a large number of EVs can increase demands on the grid during the evening hours. That said, overnight charging was found to be dispersed more widely across the city, and neighborhood charging stations were used more consistently around the clock than fast-charging stations in busy midtown locations.

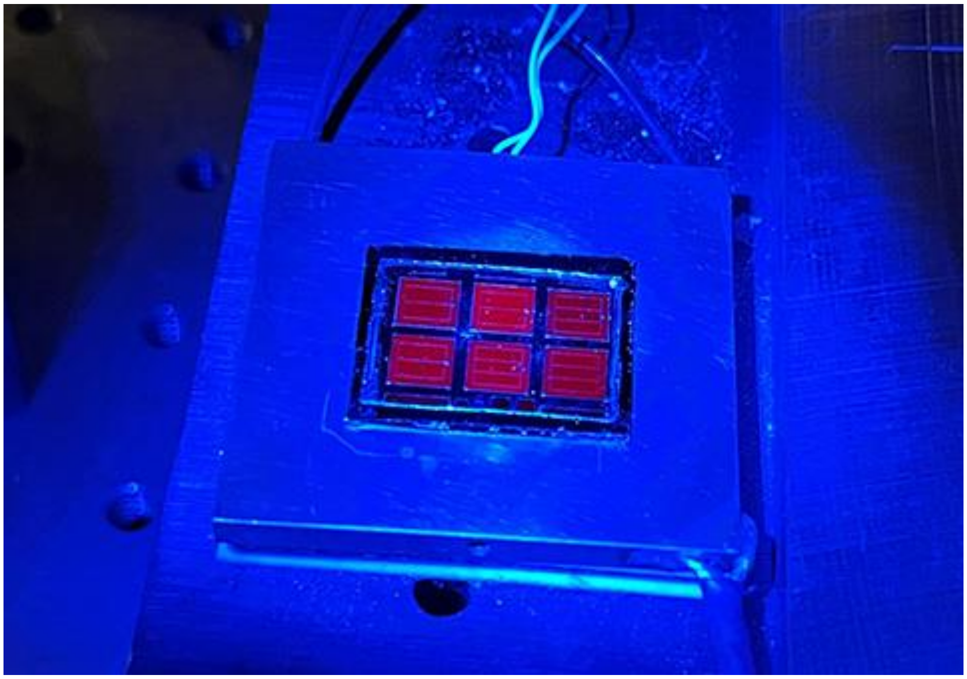
Just as ride-hailing vehicles comprise only a small portion of all light-duty vehicles, it is part of a larger New York state effort to identify infrastructure needed to support the goal of 850,000 EVs by 2025. A broader study will be published later this year.

"Switching these ride-hailing services to EVs will not only help cut air and noise pollution within New York City," Moniot said. "It will also represent the cutting edge of what business model innovations are needed to meet ride-hailing electrification targets, possibly serving as the model for other cities."

This research meshes with DOE's broader system-level research efforts, such as the Systems and Modeling for Accelerated Research in Transportation (SMART) Mobility Laboratory Consortium.

Chapter 3. NREL Creates Highest Efficiency 1-Sun Solar Cell

May 18, 2022



The record-setting solar cell shines red under blue luminescence. *Photo by Wayne Hicks, NREL*

Researchers at the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) created a solar cell with a record 39.5% efficiency under 1-sun global illumination. This is the highest efficiency solar cell of any type, measured using standard 1-sun conditions.

"The new cell is more efficient and has a simpler design that may be useful for a variety of new applications, such as highly area-constrained applications or low-radiation space applications," said Myles Steiner, a senior scientist in NREL's High-Efficiency Crystalline Photovoltaics (PV) Group and principal investigator on the project. He worked alongside NREL colleagues Ryan France, John Geisz, Tao Song, Waldo Olavarria, Michelle Young, and Alan Kibbler.

Details of the development are outlined in the paper "Triple-junction solar cells with 39.5% terrestrial and 34.2% space efficiency enabled by thick quantum well superlattices," which appears in the May issue of the journal *Joule*.

NREL scientists previously set a record in 2020 with a 39.2% efficient six-junction solar cell using III-V materials.

Several of the best recent solar cells have been based on the inverted metamorphic multijunction (IMM) architecture that was invented at NREL. This newly enhanced triple-junction IMM solar cell has now been added to the Best Research-Cell Efficiency Chart. The chart, which shows the success of experimental solar cells, includes the previous three-junction IMM record of 37.9% established in 2013 by Sharp Corporation of Japan.

The improvement in efficiency followed research into “quantum well” solar cells, which utilize many very thin layers to modify solar cell properties. The scientists developed a quantum well solar cell with unprecedented performance and implemented it into a device with three junctions with different bandgaps, where each junction is tuned to capture and utilize a different slice of the solar spectrum.

The III-V materials, so named because of where they fall on the periodic table, span a wide range of energy bandgaps that allow them to target different parts of the solar spectrum. The top junction is made of gallium indium phosphide (GaInP), the middle of gallium arsenide (GaAs) with quantum wells, and the bottom of lattice-mismatched gallium indium arsenide (GaInAs). Each material has been highly optimized over decades of research.

“A key element is that while GaAs is an excellent material and generally used in III-V multijunction cells, it does not have quite the correct bandgap for a three-junction cell, meaning that the balance of photocurrents between the three cells is not optimal,” said France, senior scientist and cell designer. “Here, we have modified the bandgap while maintaining excellent material quality by using quantum wells, which enables this device and potentially other applications.”

The scientists used quantum wells in the middle layer to extend the bandgap of the GaAs cell and increase the amount of light that the cell can absorb. Importantly, they developed optically thick quantum well devices without major voltage loss. They also learned how to anneal the GaInP top cell during the growth process in order to improve its performance and how to minimize the threading dislocation density in lattice-mismatched GaInAs, discussed in separate publications. Altogether, these three materials inform the novel cell design.

III-V cells are known for their high efficiency, but the manufacturing process has traditionally been expensive. So far, III-V cells have been used to power applications such as space satellites, unmanned aerial vehicles, and other niche applications. Researchers at NREL have been working toward drastically reducing the manufacturing cost of III-V cells and providing alternate cell designs, which will make these cells economic for a variety of new applications.

The new III-V cell was also tested for how efficient it would be in space applications, especially for communications satellites, which are powered by solar cells and for which high cell efficiency is crucial, and came in at 34.2% for a beginning-of-life measurement. The present design of the cell is suitable for low-radiation environments, and higher-radiation applications may be enabled by further development of the cell structure.

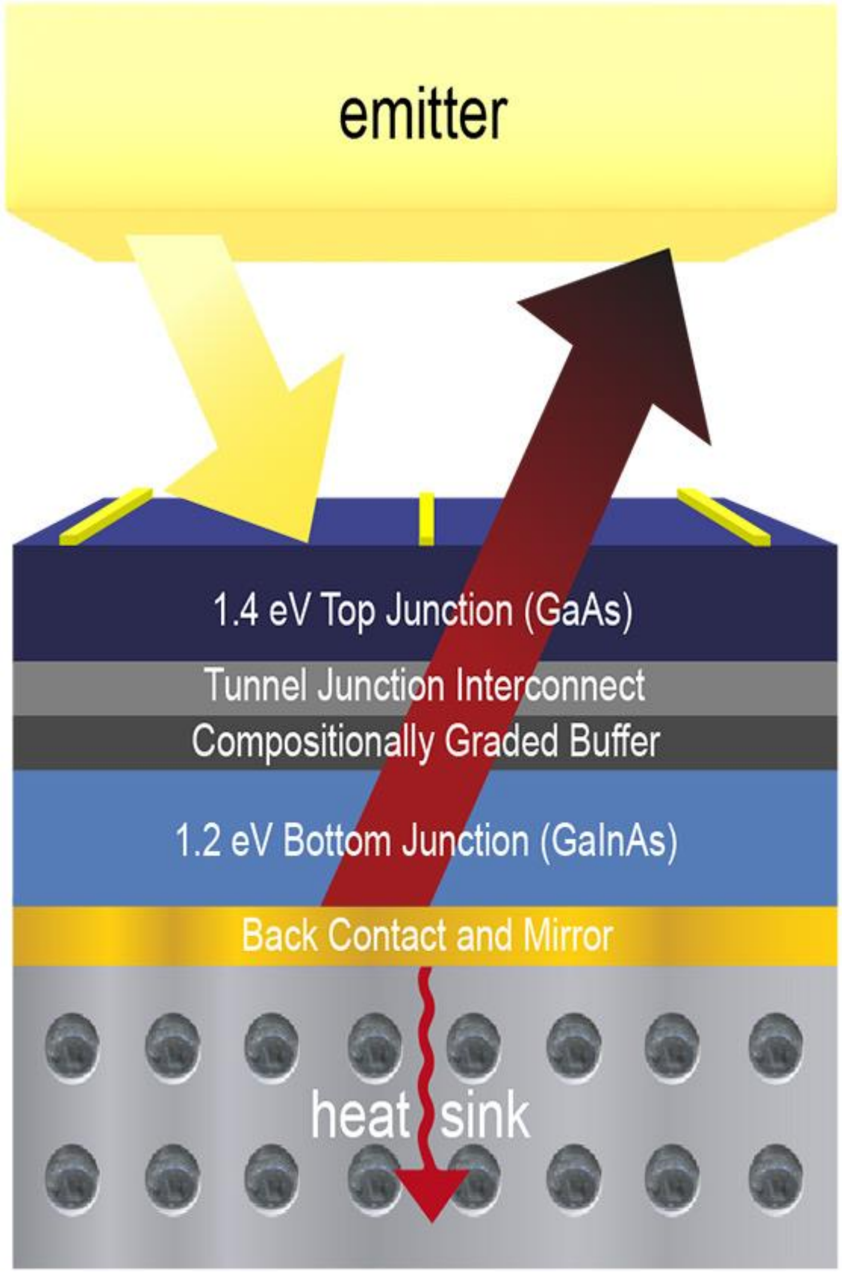
Chapter 4. Capturing Light From Heat at 40% Efficiency, NREL Makes Big Strides in Thermophotovoltaics

NREL's New Cell Exceeds Previous Efficiency Record by More Than 8 Percentage Points, Unlocking More Efficient Thermal Energy Storage Applications

May 18, 2022 By Harrison Dreves

The National Renewable Energy Laboratory (NREL) has a long history of building solar cells that capture light from the sun at record-setting efficiencies. But the sun is not the only light source from which photovoltaics can capture energy. Hot objects emit light, too—generally at longer, lower-energy wavelengths—and thermophotovoltaics (TPVs) are photovoltaic cells that are optimized to capture that light.

A new photovoltaic cell developed by NREL far surpasses the previous, 32% world-record efficiency for TPVs. The new device, developed for a joint demonstration with the Massachusetts Institute of Technology (MIT) of an electric-energy storage concept, is described in an article in *Nature*.



The device developed by the NREL/MIT team consists of two light-absorbing layers, backed by a highly reflective gold mirror layer and then a heat sink. The heat sink keeps the cell from becoming too hot, which leads to a loss of efficiency. *Figure adapted with permission from Alina LaPotin, MIT*

The record-efficiency device, which was designed to harvest energy from an object heated to 2,400°C, reached a maximum efficiency of 41.1% (± 1%), with an average efficiency of 36.2% over a range of relevant temperatures.

"High efficiency is crucial to the engineering and economic viability of TPV systems, and this new 41% record efficiency is a giant step toward making this thermal energy grid storage concept a reality," said Dan Friedman, an NREL author on the paper.

Improved Heat-to-Electricity Conversion Promises New Energy Storage Possibilities

Significantly, a TPV device with 40% efficiency can convert heat to electricity at greater efficiency than conventional steam turbines, such as those used in coal or nuclear power plants. TPVs offer the potential for lower costs, faster response times, compatibility with an extremely wide range of system sizes (from watts to gigawatts), and lower maintenance costs due to fewer moving parts.

The TPV cell is also optimized to operate with heat sources above 2,000°C, which are too hot for traditional steam turbines. Natural gas and hydrogen can be combusted at these temperatures, but, perhaps most importantly, low-cost, large-scale thermal energy storage systems have been envisioned to operate at these temperatures.

Thermal energy grid storage systems operate as a battery that takes in electricity and converts it to high-temperature heat for storage (think of a giant toaster). TPVs then convert that heat back to electricity when needed, providing low-cost, on-demand clean energy. The TPV device created by the team—once demonstrated in the larger joint project with MIT—could represent a crucial milestone in making clean energy storage low cost and scalable.

"So far, thermal energy grid storage has not yet gained significant attention because we've traditionally focused only on converting thermal energy to electric power, not the opposite," said Zhiwen Ma, an NREL researcher leading a separate thermal energy grid storage system project unrelated to this TPV research. "Using electrical-to-thermal conversion to store energy offers great benefits in scaling energy storage and siting it where it's needed. The development of a new world-record TPV cell improves the thermal-to-power conversion of thermal energy storage, making the technology more appealing than ever to support increasing needs for renewable integration."

Careful Design Yields World-Record TPV Cell

The 41%-efficient TPV device is a tandem cell—a photovoltaic device built out of two light-absorbing layers stacked on top of each other and each optimized to absorb slightly different wavelengths of light. The team achieved this record efficiency through the usage of high-performance cells optimized to absorb higher-energy infrared light when compared to past TPV designs. This design builds on previous work from the NREL team.

Another crucial design feature leading to the high efficiency is a highly reflective gold mirror at the back of the cell. Much of the emitted infrared light has a longer (less energetic) wavelength than what the cell's active layers can absorb. This back surface reflector bounces 93% of that unabsorbed light back to the emitter, where it is reabsorbed and reemitted, improving the overall efficiency of the system. Further improvements to the reflectance of the back reflector could drive future TPV efficiencies close to or above 50%..

Chapter 5. Scientists Look to the Sky in Effort To Mitigate Carbon Problem

Global Effort Backed by NREL Examines Potential for Using Direct Air Capture Technologies

June 29, 2022

A global research effort spearheaded by the National Renewable Energy Laboratory (NREL) has assessed two promising technologies to remove carbon dioxide from the atmosphere. While still in the early stages of development, direct air carbon capture and sequestration (DAC)—together with other carbon dioxide removal strategies—are considered critical to achieving a net-zero greenhouse gas emissions economy by 2050 and limiting global warming to less than 1.5 degrees Celsius by 2100.

Despite this important role, DAC technologies have yet to be assessed in a forward-looking, dynamic system context. That is why scientists from NREL, the Netherlands, Germany, and Switzerland as well as in Pennsylvania and California provided a dynamic life-cycle assessment of two promising DAC technologies to separate carbon dioxide from the air and sequester it in geological storage sites. The article, which appears in the journal *Nature Communications*, provides a first evaluation of the technologies' environmental trade-offs over a long-term planning horizon.

"We will not hit our carbon-neutral targets by midcentury or our climate targets by the end of the century if we don't push heavily for additional removal of carbon dioxide out of the atmosphere," said Patrick Lamers, a senior researcher in NREL's Strategic Energy Analysis Center and corresponding author of the new paper, "Environmental trade-offs of direct air capture technologies in climate change mitigation toward 2100." He had initiated this work and supervised another key contributor, Yang Qiu, a Ph.D. student at the University of California, Santa Barbara, during his internship at NREL last year.

The DAC technologies were assessed via a new computer model that puts them in the context of climate change mitigation scenarios developed by Integrated Assessment

Models. These are prominently used in projections reported by the United Nations' Intergovernmental Panel on Climate Change. In this case, the scenarios were created by researchers at Utrecht University in the Netherlands, which is where Lamers earned his doctorate, and are consistent with the climate targets of the Paris Agreement.

The researchers assessed the environmental performance of DAC in the context of three scenarios. The strictest called for climate change mitigation efforts that are in line with the current goals of the Biden administration for decarbonizing the domestic electricity sector by 2035, reaching a decarbonized economy by 2050, and thus staying in line with the Paris Agreement toward 2100. According to these scenarios, DAC would start to be deployed in the United States around 2050.

The two DAC technologies studied are:

- Solvent-based, in which a chemical solution reacts with the carbon dioxide and forms potassium carbonate, which then reacts with calcium hydroxide to generate calcium carbonate. The calcium carbonate is collected, dried, and exposed to temperatures of about 900 degrees Celsius to release the carbon dioxide, which is then collected for further storage.
- Sorbent-based, in which carbon dioxide binds to a silica part of an air contactor, which is then heated with steam at about 100 degrees Celsius to release the carbon dioxide, which is then cooled and has additional moisture removed.

In both systems, the carbon dioxide will be further compressed and transported through a pipeline to a storage site, where it will be compressed and injected into a geological reservoir through wells about 1.8 miles deep. Pilot plants are already testing both processes, with facilities operating in Canada (with the solvent method) and Iceland (using the sorbent method).

The analysis does not recommend a particular technology and is meant to guide policy discussions and help set priorities for emerging technology R&D that supports decarbonization and long-term climate change mitigation targets. Rather than picking winners or losers, the framework can help identify which technology and system factors tend to drive the results.

Given the energy intensity of DAC, its environmental trade-offs are directly influenced by the energy inputs of the DAC plants. Yet, the large-scale deployment of DAC changes the energy system load and creates a feedback effect in which the economy-wide decarbonization now balances an offsetting technology (DAC) and sectoral mitigation efforts. To evaluate this system trade-off, the researchers investigated the environmental impacts of the technologies coupled with the effects from a changing electricity sector.

The scientists noted the deployment of DAC can help achieve long-term climate goals but cautioned that decarbonization targets should not be relaxed. They determined that a rapid decarbonization is required to increase the efficiency of DAC in removing carbon dioxide and to mitigate the effects of climate change. In fact, the scientists underscored the simultaneous decarbonization of the electricity sector and improvements in DAC technology "are indispensable to avoid environmental problem-shifting." A clean energy system supports the reduction of the technologies' human toxicity or eutrophication impacts. Yet, further technology and material efficiency improvements for zero-emissions electricity technologies, such as solar and wind, are needed to limit the levels of ecotoxicity and metal depletion per ton of carbon dioxide sequestered via DAC over time.

Lamers said this life-cycle assessment framework provides a greater understanding of the implications of certain choices.

"It allows you to evaluate, prospectively, the consequences of specific actions and inactions in a complex and interrelated system," Lamers said. "The large-scale deployment of new technologies is likely going to create feedback effects within the system, and we need to preemptively assess these to avoid potential future, unintended consequences. Our analysis shows the net carbon dioxide removal benefits of different direct air capture technologies and highlights environmental performance improvements for metrics such as human toxicity in a changing energy system."

Lamers said he observed some metrics such as metal depletion and ecotoxicity increase over time.

"Yet, this is not the fault of the technology," he said. "This is the fault of postulating our energy system decarbonization as a one-fits-all solution. Thus, if you look closely, our work really stresses the importance of the circular economy of energy materials and how it is a precursor to a truly sustainable future energy system heavily dependent on clean, renewable energy sources."

The work by the NREL scientists was funded by the internal Laboratory Directed Research and Development program.

Chapter 6. NREL Researchers Plot Energy Storage Under Our Feet

Oil and Gas Wells No Longer in Use Could Be the Answer

April 8, 2022 By Wayne Hicks

NREL researchers Chad Augustine (left) and David Young, along with former colleague Henry Johnston, have been examining the idea of using depleted oil and gas wells as a reservoir for the storage of natural gas. The gas can then be released, as needed, to spin a turbine and generate electricity. *Photo by Werner Slocum, NREL*

Chad Augustine and his colleagues at the National Renewable Energy Laboratory (NREL) see opportunity where others might simply see a hole in the ground.

"It can't just be any hole in the ground," explained Augustine, a researcher with NREL's geothermal research group.

The idea is to use depleted oil and gas wells as a reservoir for the storage of compressed natural gas. As needed, the gas can be released to spin a turbine and generate electricity. The reservoir is recharged using excess electricity from the grid and the cycle repeats, providing a potential solution for the growing demand for energy storage.

Computer modeling done by scientists at NREL and Colorado School of Mines confirmed the feasibility of the idea.

Geology Limits Other Underground Storage

A similar idea, to use man-made salt caverns as a place to hold compressed air, has been proposed and implemented—but only in two places in the world. The technology is limited by geography because it requires geological salt dome formations.

The proposal to use depleted oil and natural gas wells takes advantage of a proliferation in the number of horizontal, hydraulically fractured, or “fracked,” wells. The technique, which the Energy Information Administration calculates accounts for about 75% of all newly drilled wells in the United States, drills down and then straight across through the rock. Water is then pumped into the well at high pressure to fracture the shale in order to free trapped oil and natural gas.

David Young, a senior scientist at NREL whose expertise lies with solar technology, had a “eureka” moment in coming up with the notion to use old oil and gas well sites for storage.

“I was taking a shower and I dreamed up the idea,” Young said. “That's how I got involved. I just was thinking about these million-dollar holes in the ground. There were so many of them out on the Front Range here and I thought there's got to be something we can do with those things.”

NREL researchers propose using fracking sites like this one, once no longer in use, as a place to store compressed natural gas. *Photo from iStock*

Young took his idea to Augustine. Together, along with Henry Johnston, a veteran of the oil and gas industry who worked at NREL for six years before retiring at the end of January, they examined the idea in detail. They published two papers detailing their work late last year and were awarded a patent protecting the process.

Horizontal wells have become the industry standard, with multiple wells drilled from a single pad. The volume produced outpaces vertical wells, but the amount of oil and natural gas yielded by horizontal wells declines over a short time span. Active wells can quickly become inactive.

“These horizontal wells deplete rapidly,” said Johnston, who worked at Shell Oil Co. for 31 years before joining NREL. “They can go from 10 million cubic square feet a day the first year to 3 million cubic square feet a day the second year, so they can lose a lot of their production early.”

Eventually, the wells become so depleted it does not pay to keep them going. These wells can then sit idle or plugged with cement. Researchers at NREL and Mines determined unplugged wells could serve as reservoirs for compressed natural gas.

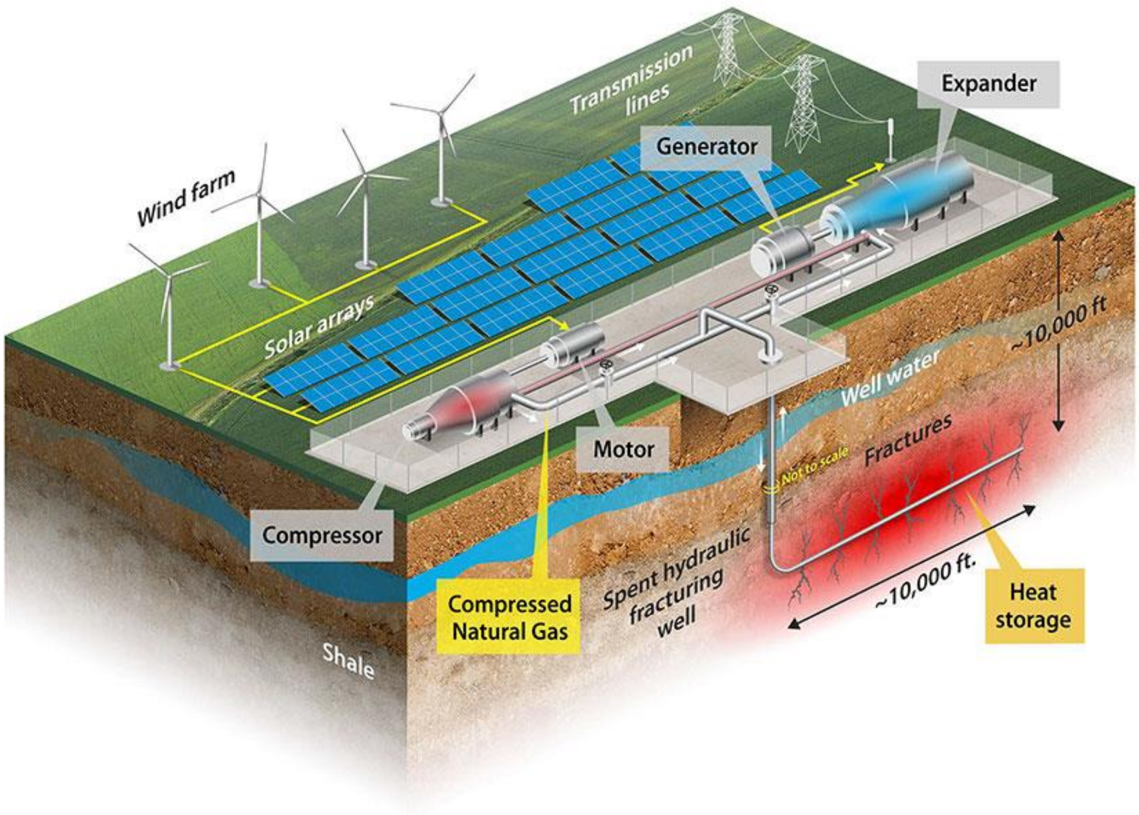
Unplugged wells can be injected with compressed natural gas, researchers at NREL and Mines determined after conducting multiple rounds of computer simulations. Writing in the *Journal of Energy Resources Technology*, the scientists predicted the technology would work for both short-term and long-term energy storage. NREL researchers followed that November paper with an article in *iScience* a month later that analyzed the potential costs.

Augustine said the next step involves setting up a pilot project to bring computer modeling into the real world. Beyond that remains the issue of transmission lines.

“The other thing we need is a good study of how many new wells that are out there that would be a good fit for this technology,” he said.

The number of active horizontal wells has jumped from about 9,000 in 2000 to more than a quarter-million in 2017.

The Department of Energy’s Geothermal Technologies Office, which funded the research conducted by Augustine and his colleagues, is separately investing in the possible use of inactive wells for geothermal energy.



A conceptual schematic of the energy storage system using old wells for energy storage. *Illustration by Al Hicks, NREL*

Idea First Touched on Air

The NREL researchers initially considered injecting compressed air into the old wells. Augustine took that idea through the Department of Energy's Energy I-Corps program in 2016. The program helps researchers determine the potential market for their technology. What Augustine discovered was adding air into a natural gas well carries a risk of sparking an explosion. In addition, "when it comes back out, it's going to have natural gas mixed with it. What do you do with that?"

They chose natural gas because of its availability and compatibility with the reservoir.

"We want to start the program with natural gas because it's easy and I think the people who own the wells, they'd get on board a lot easier," Young said. "Eventually, as you prove out the idea, you gradually shift over to a different gas to run the system. CO_2 would work. Nitrogen would work. Hydrogen. If you use CO_2 that could also be part of a carbon capture cycle."

Using compressed air as energy storage requires additional steps, including cooling the air after the compression stage and preheating it before releasing it. Projects using compressed air also can take years to build and cost hundreds of millions of dollars. By taking advantage of existing wells, a pilot site that uses natural gas can be installed for a few million dollars within months, the scientists estimated.

Their calculations show that depending upon the temperature and pressure in the well, the use of compressed natural gas to produce electricity can generate from hundreds of kilowatts to nearly a megawatt of power.

The technology, dubbed REFRAES (for REpurposed FRAcked wells for Energy Storage), relies on a four-phase process. In the first step, the gas is injected into the reservoir at a constant flowing bottomhole pressure to store energy. The well is then shut in so that the gas cannot escape. Next, the gas is produced from the reservoir at a constant pressure to generate electricity. Finally, there is a recovery period during which the well is again shut in.

After the recovery period, the storage cycle is repeated.

In the short term, the process can provide six hours of electricity. For longer, or seasonal, needs, the researchers calculate it can offer 90 days of electricity.

“Seasonal energy storage is very, very limited,” Young said. “There are only a few technologies that can do that. Pumped hydro would be one of those. This technology represents a possibility of being able to have very long-term storage, so we’re excited about that part of it.”

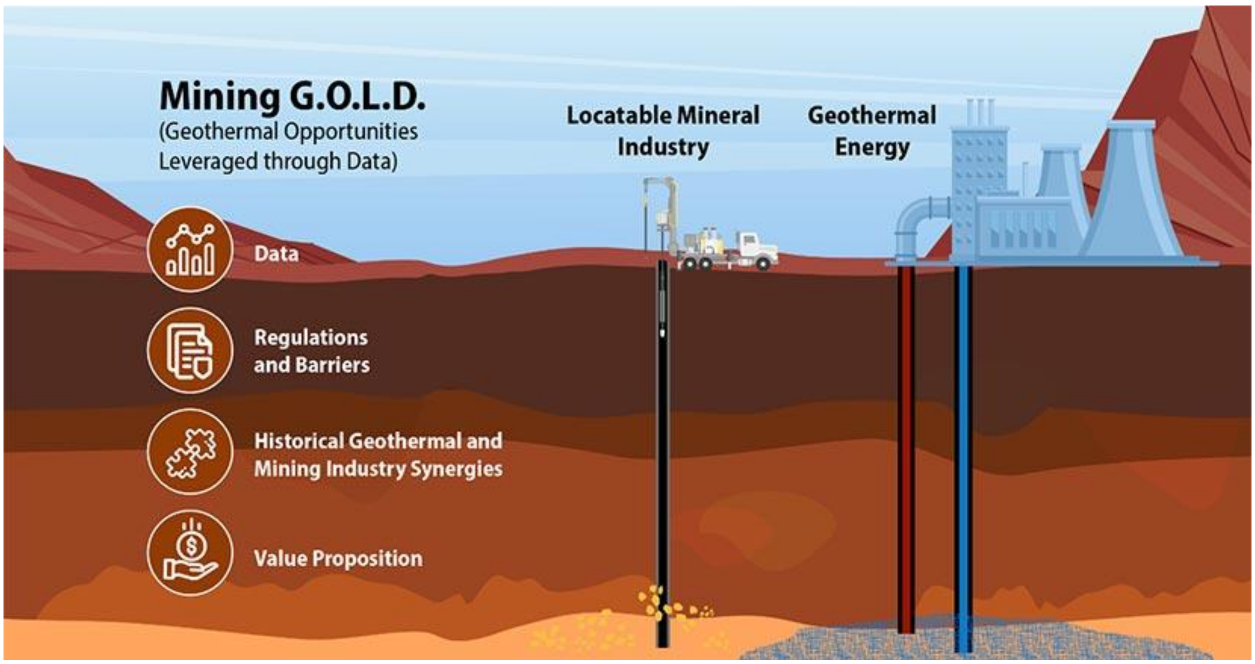
Pumped hydro, in which water flowing downhill generates electricity, is able to return 70%–85% of the stored energy. NREL researchers calculated the efficiency of REFRAES at about 40%–70%. The levelized cost of storage using natural gas could be as low as to $80 to $270 per megawatt-hour, while for pumped hydro it is $225.

Another advantage the REFRAES technology has over pumped hydro and the two reservoirs that it requires is its ability to be expanded. With multiple wells drilled on a single site, the method of storing natural gas can grow as needed by tying in additional holes, Augustine said. If a single well can store 500 kilowatts of energy, for example, adding each subsequent well increases the available storage capacity.

“That’s something I think that’s important to know,” Augustine said. “It can scale as needed.”

Chapter 7. Mining and Geothermal Industries Could Strike G.O.L.D. Through Partnership

June 15, 2022 By Ryan Horns



A partnership between the mining and geothermal industries could lead both toward a more lucrative and greener future.

Across the United States there are more than 3 million abandoned mining wells. Each hole drilled into the ground offers more than just the ghost of minerals never found. There are layers of valuable data waiting for the right audience.

National Renewable Energy Laboratory (NREL) Senior Legal and Regulatory Analyst Aaron Levine said he hopes the mining industry becomes that audience.

In his new research, "Mining G.O.L.D. (Geothermal Opportunities Leveraged Through Data): Exploring Synergies Between the Geothermal and Mining Industries," Levine offers a two-pronged strategy of investigating mining data and taking advantage of hidden geothermal renewable energy resources.

"Our goal is really to target the mining industry for this opportunity and really make them understand the potential synergies between the two industries," Levine said.

Geothermal energy is a hidden asset, he said, often located one or two miles underground. It is challenging for the geothermal industry to spend millions in exploration and find nothing.


P

Pictured is a geothermal production well in Steamboat Hills, Nevada. By partnering, NREL and the locatable mineral industry could identify vast amounts of unknown geothermal sources. *Photo by Dennis Schroeder, NREL*

One key geothermal exploration method is temperature gradient drilling. Throughout 2017, 31 wells were drilled in Nevada at already identified geothermal fields. In comparison, the mining industry drills more than 2,000 in Nevada per year and to similar depths.

Levine said the common ground between geothermal and mining industries doesn't end there. Additional shared exploration includes surface mapping, geophysical and geochemical analysis, remote sensing, and geologic and conceptual modeling.

NREL researchers are looking at data where mines were seeking gold or other minerals and found nothing, except perhaps evidence of geothermal energy resources. For minimal costs, the study recommends the mining industry catalog such explorative data and potentially monetize it for geothermal uses.

While some mining companies are shifting more toward renewable energy resources, Levine said many are still reliant on diesel fuel to power operations, especially at remote mines. The study discusses the potential of utilizing geothermal energy resources on-site to help achieve improved environmental performance and decarbonization.

Existing mines on federally managed public lands with approved plans of operation may even claim a noncompetitive leasing right to the geothermal resources, which may further simplify the exploration and development of geothermal resources discovered through mining data. Case studies described in the paper reveal how roughly 200 MW of net power was discovered via previous mining exploration activities.

Ultimately, leveraging mining industry data, knowledge, and expertise will expand the geothermal exploration workforce, increase the rate of geothermal resource discovery, and potentially reduce geothermal electricity's levelized cost of energy by up to 30%. The mining industries win by leveraging geothermal energy to provide a potential electricity source to improve environmental performance and decarbonization.

Chapter 8. NREL Releases Comprehensive Databases of Local Ordinances for Siting Wind, Solar Energy Projects

New Machine-Readable Data Sets Compile State, Local Zoning Laws and Ordinances for Siting Wind Energy and Solar Power Projects To Inform Planning for Decarbonization Goals

Aug. 9, 2022 | By Madeline Geocaris

Local ordinances and zoning laws can determine the parameters of wind and solar energy projects, like the mandatory required distance from other infrastructure such as roads. *Photos from iStock*

State and local zoning laws and ordinances influence how and where wind and solar energy projects can be sited and deployed—which can have a measurable impact on U.S. renewable energy resource potential. For example, previous National Renewable Energy Laboratory (NREL) research found that total U.S. wind energy technical potential is seven times greater under the least restrictive siting regimes as compared to the most restrictive siting regimes.

As the United States targets 100% clean electricity by 2035 and a net-zero carbon economy by 2050, local siting constraints have become a critical topic. However, publicly available data on state and local wind energy and solar power ordinances have not been available in one place—until now.

NREL released two new databases of state and local wind and solar energy zoning laws and ordinances in the United States. The data sets are machine-readable so geospatial analysts and researchers can readily analyze siting impacts. This work is part of ongoing research at NREL to explore the dynamics of land use and clean energy deployment.

"Our new, high-resolution data sets are tools that can help us better understand the complex interactions between siting considerations and large-scale clean energy development," said Anthony Lopez, NREL senior geospatial data scientist and project lead for the new data sets. "The data can inform discussions about balancing local clean energy deployment decisions with mitigating global climate change."

Ordinances Included in the Data Sets

NREL released two data sets: one including nearly 2,000 U.S. wind energy zoning ordinances and another including nearly 1,000 solar energy ordinances at the state, county, township, and city levels. Both data sets are formatted as downloadable spreadsheets and accompanied by interactive maps, illustrating the wind and solar energy zoning ordinance data by location and ordinance type.

The wind energy database includes setbacks—or the required boundaries around infrastructure where wind turbines cannot be installed—for property lines, buildings, roads, railroads, electric transmission lines, and bodies of water. Because setbacks are influenced by wind turbine tip heights—the taller the turbine, the larger the setback—the data set also includes height and rotor size restrictions. Other ordinances, like noise limitations, shadow flicker limits, and utility-scale wind bans or moratoriums, are also included.

Similarly, the solar energy database includes setbacks for property lines, buildings, roads, and water, as well as height restrictions, minimum and maximum lot sizes, solar power development bans or moratoriums, and more.

The two data sets join a suite of NREL-developed renewable energy supply curves, which characterize the quantity and quality of renewable resources. NREL develops and disseminates the foundational data to the research community to serve as the basis for a variety of analysis and modeling applications. The supply curves can be used to assess land availability for renewable energy projects, considering their intersection with the built and natural environment.

"Energy modelers, wind and solar energy technology engineers, land-use experts, ecologists, social scientists, and more, can use the new data to understand how other land uses may impact large-scale clean energy deployment," said Aaron Levine, NREL senior legal and regulatory analyst. "It can be used in modeling and analysis to assess trade-offs between emissions, costs, plant design, land use, wildlife habitat, and more."

The Rise of Siting Constraints in the Clean Energy Narrative

The NREL team first started thinking about the impact of land use restrictions on clean energy deployment, specifically for wind energy, about a decade ago. It wasn't a major topic of research at the time, but they believed it was a critical question that would need to be addressed.

Fast-forward to today, and Lopez and team have fine-tuned the spatial resolution of wind and solar energy technical potential assessments to account for 124 million buildings and every road, railway, transmission line, and radar tower in the United States. Their research has captured the attention of *The Wall Street Journal* and *The New York Times* in recent years as the United States pursues accelerated emissions-reduction goals.

Lopez and team have conducted several studies on land use dynamics of clean energy deployment, including a recent analysis of land area requirements and land use intensity of U.S. wind energy deployments from 2000 to 2020—finding that the total U.S. wind energy footprint is equivalent to the size of New Hampshire and Vermont combined. However, only a small fraction of that area (<1%–4%) is estimated to be directly impacted or permanently occupied by physical wind energy infrastructure.

Land use for solar development is also an active area of research, including recent projections of solar land use from the *Solar Futures Study*. Results show there is more than enough land available to support solar development in every studied future scenario. At the highest deployment level in 2050, ground-based solar technologies require a land area equal to 0.5% of the United States, which could be met with less than 10% of potentially suitable disturbed lands. However, solar installations will affect local communities, ecosystems, and agricultural areas.

"There are still a lot of questions that need to be studied," Lopez said. "National clean energy goals will happen at the local level. We will continue to drill down our resolution and analyze different aspects of the interactions between land use and clean energy deployment."

The work is funded by the U.S. Department of Energy's Solar Energy Technologies Office and Wind Energy Technologies Office.

Chapter 9. En Route to Market: Alder Fuels and NREL Partner To Scale Sustainable Aviation Fuel Technology for Commercial Use

Aug. 8, 2022 | By Erik F. Ringle

NREL researcher Jacob Miller adjusts a lab-scale catalytic upgrading flow reactor in NREL's Field Test Laboratory Building. *Photo by Werner Slocum, NREL*

A critical pathway for producing large quantities of low- to negative-carbon sustainable aviation fuel (SAF) is en route to market following a collaborative research and development agreement between the National Renewable Energy Laboratory (NREL) and Alder Fuels.

The technology—an advanced pyrolysis process that converts biomass into refinery-ready biocrude oil—is backed by millions of dollars in funding from United Airlines, Honeywell UOP, AvFuel, the U.S. Department of Defense, and the U.S. Department of Energy's (DOE's) Bioenergy Technologies Office.

"Climate alarm bells are being triggered every day around the globe," said Zia Abdullah, NREL biomass laboratory program manager. "In recognition of that reality, this agreement is a firm step for swiftly slashing the carbon impact of aviation in less than a decade. Even more than that, it shows how NREL can supply bold solutions for accelerating total aviation decarbonization."

According to Bryan Sherbacow, president and CEO of Alder Fuels, the partnership represents a giant step toward realizing the promise of climate-friendly SAF at scale.

"The United States has the potential to demonstrate to the world that we can think boldly and meet this challenge head on," he said. "The industry appetite to embrace the change is there, and we're at a tipping point. The next public-private push is going to make all the difference."

How To Scale SAF Production? Uncompromising Analysis With Critical Decision-Making

These technological breakthroughs underwrite United Airlines' commitment to buy 1.5 billion gallons of additional SAF over the next 20 years—one of the largest commercial investments in renewable energy in aviation history. Since then, the company has also announced additional partnerships with aviation leaders Avfuel and Boeing.

The success is a testament to the rigor of NREL and Alder Fuels' "stage gate" development process. The meticulous approach enables partners to pause and think critically about the engineering and commercial readiness of the technology. That way, partners can determine if it should proceed to the next phase of development.

"NREL are the leaders when it comes to developing cutting-edge research and rigorous technical audits that can advance our collective journey towards a sustainable future," Sherbacow said. "We're so excited to team up with them and to get their expertise as we successfully test and evaluate every step of our conversion process."

Indeed, although SAF technologies may be reaching the tipping point to commercialization, uncompromising analysis is key for readying them for adoption at airports across the country.

For example, NREL and Alder Fuels continue to develop and mature a novel recipe for making carbon-negative SAF from wet waste, a low-cost resource that includes food waste, animal manure, sewage, and inedible fats, oils, and greases. First described in a leading scientific journal in early 2021, that technology continues to edge closer to market adoption.

According to Alder Fuels Chief Technology Officer Derek Vardon, the close public-private partnership between NREL and Alder Fuels promotes technical readiness and commercial viability.

"NREL has brought the brightest scientific minds in the world together to focus on the challenge of turning bio-based and waste feedstocks into low-carbon fuels for aviation," he said. "Bringing industry leaders to the table, particularly our partners at Honeywell UOP, we at Alder Fuels are committed to convening a powerhouse public–private team to make our technology a scalable commercial reality."

A Breakthrough Technology To Support U.S. Climate Commitments

SAF production is cited as a core strategy in the Biden–Harris administration's goals to reduce aviation emissions 20% by 2030 and reach zero emissions by 2050. Because SAF is made from a wide range of renewable biomass and waste resources, the fuel can net deep reductions in GHG (greenhouse gas) emissions compared to conventional jet fuel.

Analysis by NREL shows that Alder Fuels' greencrude technology—which includes NREL's SAF from wet waste and Alder's advanced pyrolysis technology—can make energy-dense liquid fuels with a negative carbon footprint. When blended with conventional jet fuel in high volumes—up to 100%—the resulting fuel could support net-zero-carbon flight.

Alder Fuels' pyrolysis technology uses only residual materials—such as sugarcane bagasse or sustainably harvested forestry waste—or purpose-grown grasses that can be planted on marginal land not suitable for growing food. Such perennial grasses, like miscanthus, can reverse desertification by restoring nutrients to the earth and building soil. Furthermore, by converting wet waste into greencrude—the precursor for converted SAF—Alder Fuel's technology avoids landfill methane emissions, a climate pollutant 20 times more potent than carbon dioxide.

Getting More SAF to Airports Across the Country

NREL's partnership with Alder Fuels is one example of its numerous research and development projects that support a sustainable aviation future. With access to world-class lab spaces, NREL scientists are sought after for their expertise and analysis on biofuels.

- NREL is a key player in a DOE commitment to invest $65 million in innovative research to advance biofuel production.
- NREL is actively working with multiple U.S. commercial airlines in support of industry goals of carbon neutrality by 2050.
- NREL researchers lead or co-lead six of nine DOE Bioenergy Technologies Office consortia, which draw expertise from across DOE's national laboratory system to develop technologies for converting biomass and waste resources into sustainable fuels and chemicals.
- Not least, the laboratory is a core player in DOE's Sustainable Aviation Fuel Grand Challenge, a project of federal agencies to grow the SAF market to meet 100% of aviation fuel demand by 2050.

"Partnerships like the one between NREL and Alder are essential to meeting the goals of the U.S. Sustainable Aviation Fuel Grand Challenge," said Valerie Reed, director of the DOE Bioenergy Technologies Office. "DOE is committed to pursuing technology demonstrations that will decarbonize the economy, including aviation."

"We see these efforts directly translating to more SAF at airports across the country," Abdullah said. "That is transformational. To decarbonize aviation by mid-century, our success will be measured by the gallon."

Chapter 10. Cadmium Telluride Accelerator Consortium Aims To Reduce Costs, Speed Deployment of Low-Carbon Thin-Film Solar Technologies

$20 Million Going To Support CdTe Research and Development

Aug. 4, 2022

A 0.6-kW First Solar cadmium telluride photovoltaic test array was installed in June 1995 at NREL's Outdoor Test Facility. *Photo by Dennis Schroeder, NREL*

This week, U.S. Department of Energy (DOE) announced a new three-year consortium intended to accelerate the development of cadmium telluride (CdTe) technologies by lowering the cost and increasing the efficiency of the thin-film solar cells.

CdTe is the second most common photovoltaic (PV) technology in the world, after silicon. The thin-film technology has achieved a record 22.1% cell efficiency in converting sunlight into electricity and can be manufactured at costs that are competitive with silicon solar panels. Commercially produced CdTe panels also have the lowest carbon and water footprints and the fastest energy payback times of panels available today.

The CdTe Accelerator Consortium (CTAC) will work to enable cell efficiencies above 24% by 2025 and above 26% by 2030, while steadily reducing the per-watt cost of manufacturing.

The 22.1% record efficiency was achieved by First Solar in 2016. First Solar reported an average commercial module efficiency of approximately 18% at the end of 2020.

“CTAC will work to enhance U.S. technology leadership and competitiveness in CdTe PV and bring together leading organizations to impact the entire domestic CdTe supply chain,” said Nancy Haegel, director of the National Renewable Energy Laboratory's (NREL’s) Materials Science Center. “Research, manufacturing, and deployment of CdTe PV technology is a U.S. success story. CTAC investment and innovation will encourage future growth.”

CTAC will be led by the University of Toledo, First Solar, Colorado State University, Toledo Solar Inc., and Sivananthan Laboratories.

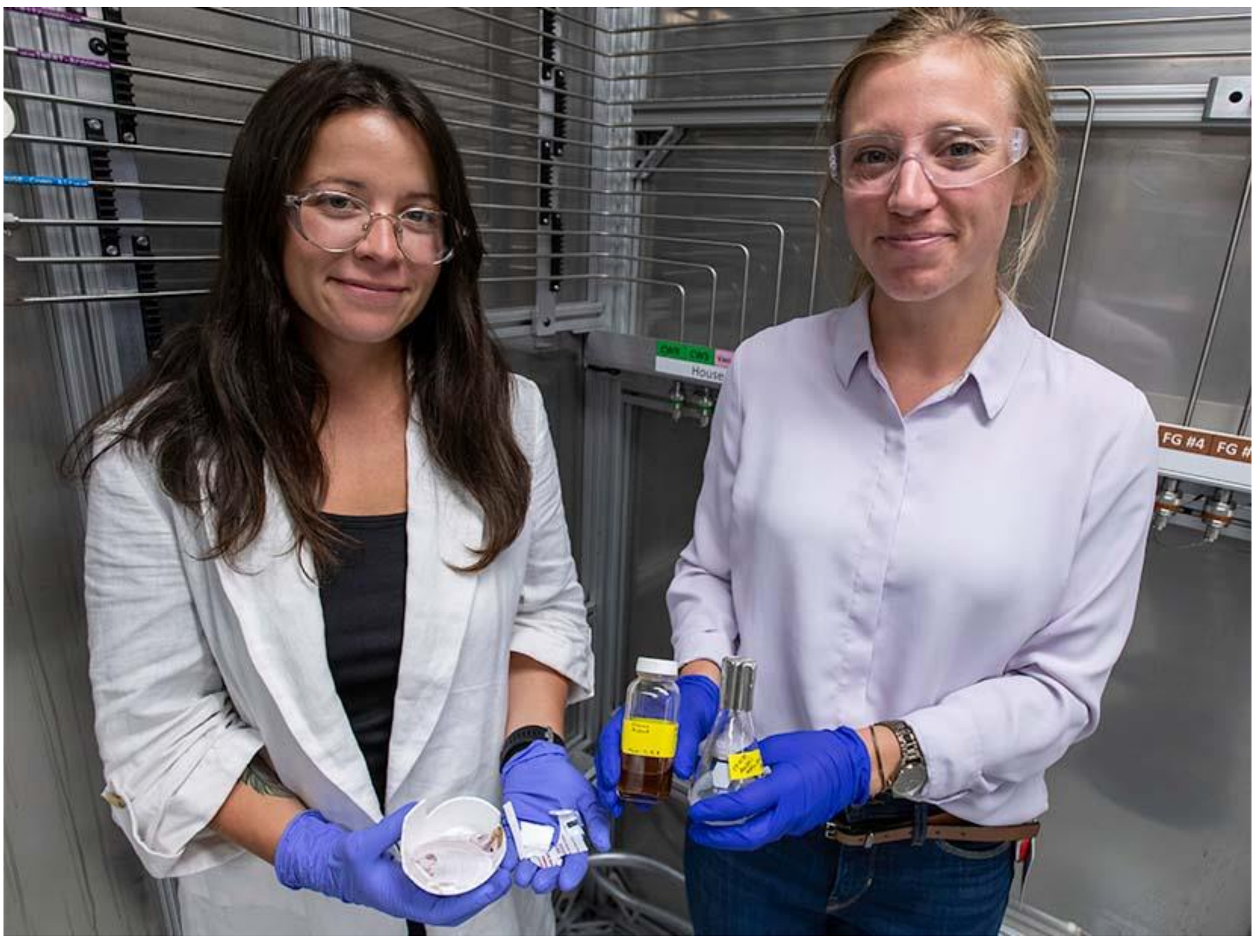
The consortium leadership was selected through a competitive solicitation released by NREL last year. The solicitation was for a CdTe technology development consortium that would expand domestic CdTe PV material and module production, support the domestic CdTe supply chain, and enhance U.S. competitiveness.

NREL will oversee the consortium, acting as a resource, support, and technical analysis center. The laboratory also will support CTAC in launching additional research efforts to meet targets set by the consortium’s technology road map.

A combined $20 million is going to support CdTe research, with $17 million going toward the consortium. The funding is provided by DOE’s Solar Energy Technologies Office, which works to lower costs, improve performance, and speed the deployment of solar energy technologies. Investing in solar technology is key to achieving DOE’s goals of cutting the cost of solar energy by 60% within the next 10 years, improving performance, and paving the way for a clean energy future.

Chapter 11. NREL Selected for Space-Bound Research To Solve the Plastic Waste Dilemma

July 28, 2002 | By Wayne Hicks



NREL researchers Katrina Knauer and Allison Werner will study how spaceflight can affect the composition and function of microbial activities. *Photo by Bryan Bechtold, NREL*

Circular Economy for Energy Materials

This research aligns with one of NREL's critical objectives.
Researchers at the National Renewable Energy Laboratory (NREL) will send an engineered bacteria into space as early as next year as part of ongoing research into solving the problem of plastic waste mitigation on Earth.

Deconstructed plastics, using the NREL oxidation platform, will be flown to the International Space Station (ISS), where astronauts will conduct an experiment involving bacteria engineered to upcycle oxidized plastic. The Center for the Advancement of Science in Space (CASIS) selected the NREL project as part of the ISS National Laboratory Sustainability Challenge: Beyond Plastics. The beauty brand Estée Lauder is providing financial backing for the challenge, with costs going to ISS National Laboratory partner Rhodium Scientific to provide engineering and flight support.

After hearing pitches from various organizations earlier this year, CASIS asked NREL and five other research teams to submit a full proposal. CASIS selected two to take part.

The NREL effort will see astronauts expose a mixture of oxidized plastic waste (a Styrofoam cup, which is made of polystyrene; a Dr Pepper bottle made of polyethylene terephthalate; and a milk jug made of high-density polyethylene) to an engineered strain of *Pseudomonas putida*. While these types of plastics can be recycled, the process of separating each can be time-consuming and costly. Scientists have been exploring technologies that are robust to plastic mixtures. Researchers at NREL have been developing a chemo-biological platform that uses oxidation to break down mixtures of plastic waste into bioavailable intermediates that can be funneled by engineered bacteria to yield a single bioproduct, thus overcoming the economic barriers of plastic sortation.

“We’re combining chemistry and biology into an integrated process, and space comes into play on the biology part,” said Katrina Knauer, a polymer scientist at NREL and chief technology officer of the U.S. Department of Energy’s BOTTLE Consortium, which is based at NREL. BOTTLE, which stands for “Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment,” and is funded by the Bioenergy Technologies Office and Advanced Manufacturing Office, is dedicated to finding ways to address the plastics problem. BOTTLE estimates 5.7 billion metric tons of discarded plastic has never been recycled.

Before going into space, the plastic will be subjected to an accelerated oxidation process that breaks down the chemical bonds of the materials, creating a carbon source for the bacterium. The bacteria then convert the plastic-derived chemicals into new bioproducts that can be sold back into the chemical supply chain.

The scientists hypothesize that the conditions of spaceflight—such as microgravity and increased radiation—could boost the performance of the engineered bacterial strain.

“Researchers have found that exposure to microgravity conditions onboard the ISS can affect the composition and function of microbial activities, and in some cases, increase the metabolic activity,” Knauer said. “Essentially, we can use conditions onboard the ISS to push the limits of this bacteria and generate new strains on Earth. In other words, no carbon left behind.”

Knauer is joined in this project by Allison Werner, a cell and molecular biologist at NREL. Knauer and Werner will work directly with the astronauts to prepare them to conduct these experiments. After the astronauts complete the incubation experiment for NREL on the ISS, the samples will be frozen and returned to Earth for characterization and further microbial engineering. The scientists will then determine if the proteins and enzymes produced by the bacterium in space can digest plastic even more efficiently.

“We have this incredible opportunity to go to space. How can we leverage the unique stressors of spaceflight to learn something new about our bacterium?” Werner said. “Something that we’ve barely scratched the surface of is microbial evolution in spaceflight. We have an opportunity to understand how evolutionary trajectories can change, and potentially improve, our strain during spaceflight. If these improvements can be linked to DNA edits, we can put the changes back—through genetic engineering—into strains that are active on Earth.”

Werner said the genome of the spacefaring bacterium will be mapped and compared to its Earth-bound counterpart to see what evolutionary differences occurred. If the scientists determine a change occurred and prove that it caused an improvement in the bacterium’s ability to convert oxidized plastics into new materials, further genetic engineering can take place to improve the bioprocess on Earth.

In addition to Knauer and Werner, the NREL team includes Kelsey Ramirez, who analyzes the chemical composition of deconstructed plastics and bacterial cultivations. Olivia Gamez Holzhaus, founder and CEO of the Houston-based biotechnology company, Rhodium Scientific, has signed on as an industry partner for the project.

Chapter 12. Federal Aviation Administration Partners With NREL for a Holistic Look at Energy Needs of Electrified Aircraft

NREL's Analysis of Electric Charging Infrastructure Will Prepare Airports To Welcome Sustainable Aircraft While Boosting Grid Resilience and Connecting Communities

July 20, 2022 | By Moriah Petty

NREL researchers are working with the FAA to analyze the integration of increased electrification at airports across the country, including adding more renewables to support energy needs of airports and surrounding communities.

The first federal office on aviation was established in 1926, a pivotal age for opening air commerce, travel, and technology. Within a year, Charles Lindbergh completed his history-making transatlantic flight from the United States to France. Crowds of onlookers jammed Le Bourget Field, near Paris, to glimpse the airplane and pilot that had flown 3,610 miles to their shores. Only 24 years had passed since the Wright brothers flew a mere 120 feet at Kitty Hawk.

Read NREL's technical report on Electrification of Aircraft: Challenges, Barriers, and Potential Impacts (Schwab, Amy, et al., Oct 2021).

Aviation has undergone several periods of rapid innovation in the last hundred years, and an emerging trend in electrified aircraft is pushing the industry to its next frontier.

As new models of aircraft come online, the federal government continues to play a critical role in certifying airworthiness and promoting safety in the skies and on the ground. This is now the responsibility of the U.S. Department of Transportation's Federal Aviation Administration (FAA).

With integrated analysis from the National Renewable Energy Laboratory (NREL), the FAA can create safety standards and recommend efficient and resilient airport infrastructure able to support these advanced aircraft designs.

NREL's Holistic Planning Integrates Aircraft and Airports

NREL will assess a selection of U.S. airports to determine solutions for implementing electrical infrastructure at scale, with a focus on energy efficiency, cost savings, and resilience.

"We asked, who is evaluating the infrastructure for electrified flight?" said Scott Cary, NREL's lead for various sustainable aviation initiatives. "We are now digging into that component so the FAA can provide the guidance airports need if they choose to be an early adopter."

Multiple electric aircraft are currently in certification, with targeted markets of cargo, passenger, and special purpose needs over short distances. Many take off and land without a runway, like helicopters, and some are preparing for pilotless operation.

The FAA will provide safety guidance for the planning and design of landing areas and on-the-ground infrastructure to support these aircraft at public facilities. Historically, most airport electrical systems were not built to support megawatt-level charging, and energy for facilities is managed independently of energy for the aircraft.

"The Federal Aviation Administration is researching the infrastructure needs of these unique aircraft," said FAA airport research specialist Wesley Major. "NREL's analysis of airport infrastructure is a critical component in this strategy."

Aside from charging services and safety, the study will measure associated factors such as the growth potential for jobs supporting the advanced air mobility, particularly in underserved areas, and the reduction in greenhouse gas emissions. This comprehensive understanding will enable ambitious energy-saving goals and illuminate pathways to transition legacy systems to support next-generation aviation.

Stabilizing the Grid With Local Generation

Airport location is determined by transportation needs, not energy supply. Many aviation hubs, particularly in rural areas, are located at the end of the distribution lines where power supply is already limited.

"The question is, if you bring a new energy load into a community, can you bring in a source of generation with it?" Cary said. "Smaller airports may receive two scheduled flights per day. That aircraft could recharge using on-site generation or generation on adjacent land leased to an energy provider, and for the remainder of the day those resources are making the local grid more stable. It establishes energy closer to where people are using it and connects communities."

NREL's analysis uses data from real airports and generic specifications of aircraft currently in certification. Site assessments will identify recommended locations for charging and scenarios for providing energy, including integrating various mixes of energy storage and generation. The FAA recently updated guidance on siting solar photovoltaics and battery energy storage and streamlined the review process for airports. According to a 2020 study from the University of Colorado, 20% of public airports in the United States had adopted solar PV technology.

Airport infrastructure on the ground currently accounts for 9%–20% of total emissions from aviation. This could be greatly reduced using ecosystem-wide adaptations. Diversifying energy sources, along with innovative fuels (including those derived from renewable sources), could lead to more consistent power supply for the airport and the communities it serves.

NREL's research team is also performing a hazard analysis to help the FAA set standards for energy security and resilience. The robust analysis anticipates the likelihood and effects of disruptions such as lightning, a power surge, water or debris, cord damage, and many other possible events, and the mitigation measures that limit the risk and impact. A high-level cybersecurity assessment will inventory possible cyber-related risks and draw on NREL's past research in the cybersecurity of extreme fast-charging stations for electric cars and trucks.

"Leveraging the U.S. Department of Energy's laboratory system supplements the FAA's programs and capabilities," Major said. "Working with NREL allows the FAA to leverage existing transportation research to aerospace needs."

Balancing loads and generation, considering stakeholder perspectives, and performing techno-economic analysis with site-specific complexities is characteristic of NREL's energy systems integration capabilities. The laboratory has spent more than 20 years supporting the electric, hydrogen, and biofuels industries on the ground—now it is time to take it into the sky.

Chapter 13. NREL Set To Receive $5.4 Million in Funding To Research Turning Buildings Into Carbon Storage Structures

July 15, 2022 | By Susannah Shoemaker

Photo by Molly Rettig, NREL

The National Renewable Energy Laboratory (NREL) has been selected to receive over $5.4 million from the U.S. Department of Energy Advanced Research Projects Agency-Energy (ARPA-E) for the development of technologies that can transform buildings into carbon storage structures. The funding is part of ARPA-E's Harnessing Emissions into Structures Taking Inputs from the Atmosphere (HESTIA) program, which aims to address barriers to designing and constructing carbon-storing buildings.

The building construction sector is responsible for a significant fraction of total annual greenhouse gas emissions in the United States, making it an important target for decarbonization—as well as one of the most difficult sectors to decarbonize.

Within the HESTIA program, NREL researchers will develop ways to increase the total amount of carbon stored in buildings to create carbon sinks, which absorb more carbon from the atmosphere than the amount released due to manufacturing of building materials and the construction process.

Of the 18 projects funded, NREL received two prime awards and is a sub-awardee on a third.

Insulation You Can Grow

A team led by Robbin Garber-Slaght at NREL and co-principal investigator Philippe Amstislavski at the University of Alaska Anchorage received nearly $2.5 million in HESTIA funding to develop cost-effective, bio-based insulation materials. The project, "Celium: Cellulose-Mycelium Composites for Carbon Negative Buildings/Construction," will create carbon-negative insulation by combining foamed cellulose with mycelium—the root network of fungi.

"The idea behind the project is that we're taking cellulose and binding it together with mycelium," said Garber-Slaght, a sustainable buildings engineer at NREL's Cold Climate Housing Research Center. "What's more carbon-negative than insulation you can grow?"

The NREL team has been working with the University of Alaska Anchorage for nearly six years to refine the technology. The group is focusing on cellulose specific to Alaska—a market in which insulation can represent 30%–50% of the cost of home building supplies.

"For this technology, I'm the end user," said Garber-Slaght, who lives and works in Fairbanks, Alaska. "Buildings in Alaska are incredibly inefficient, and trying to bring them up to any level of efficiency is very difficult. Our goal is to develop modular, portable fabrication units, so that we can harvest local trees or cellulose and develop insulation on site. Coming up with something that doesn't have to be shipped represents a huge savings, both costwise and energywise."

In addition to the cost and energy savings, the new method for creating insulation also has a thermal performance that makes it comparable to plastic foam—bringing the team closer to a direct (and cleaner) replacement for plastic insulation.

"We're finally to a point where the technology is close to something we can commercialize," Garber-Slaght said. "Three years from now, we intend to have a marketable insulation product. Five years from now, I'd like to see modular fabrication out in rural communities. And 10 years from now, I hope that we're able to retrofit every building in Alaska."

In addition to the University of Alaska Anchorage, the NREL team has been working with the VTT Technical Research Center of Finland and the U.S. Department of Agriculture's Forest Products Laboratory as collaborators. Although Garber-Slaght is based in Alaska, the team has a robust collaboration with NREL's Golden, Colorado, office. Key NREL contributors include Peter Ciesielski, Mike Himmel, Gokulram Paranjothi, and Ryan Tinsley.

Carbon-Negative Concrete

NREL Researcher Wale Odukomaiya and his team received approximately $1.8 million in funding for their project, "High-Performing Carbon-Negative Concrete Using Low Value Byproducts from Biofuels Production," which focuses on decarbonizing the concrete used for building construction.

The project aims to create new, bio-based supplementary cementitious materials (SCMs) that can replace a significant amount of cement that is used in concrete. The new, bio-based SCMs will enable the carbon dioxide (CO_2) sequestered from the atmosphere by the native biomass to be locked away in concrete. The team chose to focus on cement—the "glue" that holds the other constituents of concrete together—because of its significant carbon impact.

"The use of cement in concrete is responsible for about 8% of global greenhouse gas emissions caused by humans. That's equivalent to 40% of the United States' emissions, and twice Japan's emissions," said Odukomaiya, a researcher in NREL's Building Energy Science group. "Concrete is the second-most consumed material globally after water. And most of its emissions—between 80% and 85%—come from the cement that is used in concrete."

The team is leveraging the low-value byproducts from another NREL project—Sustainable Aviation Fuel From [i] Renewable Ethanol (SAFFiRE)—to create LignoCrete, their new, lower-carbon concrete.

"If the SAFFiRE process scales the way we think it will, then we'll have enough byproducts for LignoCrete to replace between 20% and 60% of the concrete used in the United States annually," Odukomaiya said. "There are a few existing SCM options for cement substitution, but most of them don't have the potential to scale to such quantities, and their supply is tied to other polluting industries, such as coal and steel."

In addition to developing concrete with a lower carbon footprint, the team also hopes to demonstrate improved strength and increased thermal insulation.

"We're excited for the potential to use a more insulative concrete in buildings to improve their thermal performance," Odukomaiya said. Most residential buildings have foundations and basement walls made from concrete, so there's a lot of opportunity there."

As with NREL's other ARPA-E projects, collaboration and industry partnerships are key. The team is partnering with Carbon Upcycling Technologies (CUT) and the University of Colorado Boulder to develop and characterize their new concrete. CUT's technology will allow the team to enhance the properties of their bio-SCMs while enabling additional CO_2 sequestration.

"In addition to our industry and university partners, we have a really interdisciplinary team across several centers at NREL," Odukomaiya said. "This is really a team effort."

From Microalgae to Cement

NREL is also contributing to a University of Colorado Boulder-led project on biogenic-limestone-based cement, titled "A Photosynthetic Route to Carbon-Negative Portland Limestone Cement Production." Of the $3.2 million awarded for this project, the NREL team—led by Michael Guarnieri—is set to receive $1.2 million.

The project, led by the University of Colorado Boulder's Wil Srubar, aims to manufacture and commercialize a carbon-storing portland limestone cement using biogenic limestone—a type of limestone that uses biogenic cement clinker derived from coccolithophores, microalgae that sequester carbon dioxide via photosynthesis and calcification, to store carbon.

"At present, most cement-related CO_2 emissions are caused by calcining quarried limestone to CaO, which releases CO_2. So it's a pretty heavy greenhouse-gas-emitting process," Guarnieri said. "The potential to generate a green alternative is really exciting."

The project will leverage NREL's existing capabilities in algae engineering and cultivation. For the past decade, NREL's algae research has been working toward commercialization of algal biofuels. But now this work is finding new applications.

"The foundation we have built on NREL's algae platform will enable a lot of this work in this new space. We've spent years developing broad host-range genetic tools that will improve strains used to make this cement," Guarnieri said. "It really shows the broad potential impact of work we do at national labs."

The team already has a pathway to commercialization in place via their industry partner, Minus Materials. The University of North Carolina Wilmington is also collaborating on the project, providing expertise in coccolithophore cultivation. The team's goal over the funding period is to demonstrate that the integration of components is economically viable.

"Much of this proposed work lies in the integration of established, disparate technologies, but the overarching process is novel," Guarnieri said. "And the sustainability and potential life-cycle impact of this work is massive."

Chapter 14. NREL Scientists Explore How To Make PV Even Greener

July 1, 2022 | By Susannah Shoemaker

The 1-MW photovoltaic array at NREL's Flatirons Campus. *Photo by Werner Slocum, NREL*

How do we reduce the carbon impact of an already green technology?

This is the question that NREL researchers Hope Wikoff, Samantha Reese, and Matthew Reese tackle in their new paper in *Joule*, "Embodied Energy and Carbon from the Manufacture of Cadmium Telluride and Silicon Photovoltaics."

In the paper, the team focuses on the two dominant deployed photovoltaic (PV) technologies: silicon (Si) and cadmium telluride (CdTe) PV. These green technologies help reduce carbon emissions and meet global decarbonization goals—but their manufacturing processes can themselves result in greenhouse gas emissions.

"Green technologies are awesome, but as we are working to scale them up to an incredible magnitude, it makes sense to take a close look to see what can be done to minimize the impact," said Samantha Reese, a senior engineer and analyst in NREL's Strategic Energy Analysis Center.

To understand the overall impact of these green technologies on global decarbonization goals, the team looked beyond traditional metrics like cost, performance, and reliability. They evaluated "embodied" energy and carbon—the sunk energy and carbon emissions involved in manufacturing a PV module—as well as the energy payback time (the time it takes a PV system to generate the same amount of energy as was required to produce it).

"Most advances have been driven by cost and efficiency because those metrics are easy to evaluate," said Matthew Reese, a physics researcher at NREL. "But if part of our goal is to decarbonize, then it makes sense to look at the bigger picture. There is certainly a benefit to trying to push efficiencies, but other factors are also influential when it comes to decarbonization efforts."

"One of the unique things that was done in this paper is that the manufacturing and science perspectives were brought together," Samantha Reese said. "We combined life-cycle analysis with materials science to explain the emission results for each technology and to examine effects of future advances. We want to use these results to identify areas where additional research is needed."

The manufacturing location and the technology type both have a major impact on embodied carbon and represent two key knobs that can be turned to influence decarbonization. By looking at present-day grid mixes in countries that manufacture solar, the authors found that manufacturing with a cleaner energy mix—compared to using a coal-rich mix—can reduce emissions by a factor of two. Furthermore, although Si PV presently dominates the market, thin-film PV technologies like CdTe and perovskites provide another path to reducing carbon intensity by an additional factor of two.

This insight matters because of the limited carbon budget available to support the expected scale of PV manufacturing in the coming decades.

"If we want to hit the decarbonization goals set by the Intergovernmental Panel on Climate Change, as much as a sixth of the remaining carbon budget could be used to manufacture PV modules," Matthew Reese said. "That's the scale of the problem—it's a massive amount of manufacturing that has to be done in order to replace the energy sources being used today."

The authors' hope is that by illustrating the magnitude of the problem, their paper will cause people to take another look at the potential use of thin-film PV technologies, such as CdTe, and manufacturing with clean grid mixes.

Ultimately, accelerating the incorporation of low-carbon energy sources into the electrical grid mix is paramount.

"One of the big strengths of PV is that it has this positive feedback loop," said Nancy Haegel, center director of NREL's Materials Science Center. "As we clean up the grid—in part by adding more PV to the grid—PV manufacturing will become cleaner, in turn making PV an even better product."