



Stanford **ENERGY** RESEARCH

YEAR IN REVIEW 2021

A photograph of a Stanford University campus scene. In the foreground, a large, dark, spherical stone sculpture sits on a paved walkway. To its right, two students wearing face masks are sitting on the grass, engaged in conversation. The background features a modern building with large glass windows and lush green trees. The lighting suggests a bright, sunny day.

“ Stanford is taking the historic step of creating the university’s first new school in 70 years in response to the scale and urgency of threats facing our planet. We will marshal our resources to serve humanity’s top priority, which is to create a future in which all humans and natural systems can thrive together in concert and in perpetuity.”

—MARC TESSIER-LAVIGNE

President, Stanford University

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Photo: Linda A. Cicero



LETTER FROM KATHRYN MOLER

IMPACT IN THE WORLD STARTS WITH NEW DISCOVERIES

To me, no challenge in the world today seems more important than energy and the environment. One of the reasons I chose to work in the quantum materials field of physics as a graduate student was because I was highly optimistic that we could discover new materials that would transform the energy landscape.

In 2018, I became an administrator at Stanford as vice provost and dean of research because I felt like the energy and climate problem had become so severe for the world, while quantum materials had not yet produced those awesome high-temperature superconducting cables to send electricity across a continent with no loss of power. I decided that a good chunk of my time could be best spent creating an environment where our faculty and student researchers could do their best work.

Now, as transition dean for the Stanford Doerr School of Sustainability, I look forward to even greater contributions to sustainability, including energy and the environment, from our university. I'm really excited about the potential we have as a community to do scholarship that will help create solutions for problems both locally and around the globe. This school will be an important part of creating a better world for all people.

The energy transition is critical for that better world, and no small task. Completely reimagining

how we harness and use energy requires many talented, imaginative and passionate people around the world researching, inventing and scaling up sustainable energy technologies, as well as people creating the business models, financial structures and policies that will enable the best solutions to succeed. Stanford faculty, students and alumni are making powerful contributions across that entire spectrum.

Stanford is also confronting the climate challenge through the university's own operations. In March 2022, we celebrated a milestone when Stanford's second solar generating plant went online, completing the university's years-long transition to 100 percent renewable electricity. The momentous achievement is part of our larger journey to reach net-zero carbon emissions on campus.

Celebrating such achievements gives us hope and inspires us anew on our journeys. Learning about significant advances toward realizing the vision of sustainable, affordable and secure energy for all people certainly re-energizes me, as I hope the wonderful examples in this review will do for you.

We live at a critical time for the planet. We all have the potential to make important contributions to building a better future, and all are needed.

KATHRYN MOLER

*Transition Dean, Stanford Doerr School of Sustainability
Vice Provost and Dean of Research
Marvin Chodorow Professor and Professor of Applied
Physics and of Physics*



A W O R D F R O M T H E D I R E C T O R

WELCOME TO THE THIRD EDITION OF STANFORD ENERGY RESEARCH YEAR IN REVIEW. While this review is produced by Stanford University's Precourt Institute for Energy, it highlights research achievements across campus, much of which was performed independent of the institute.

During 2021, Stanford researchers advanced our ability to make energy systems more sustainable, affordable and secure for all people. These advances range from powerful new battery chemistries and carbon-neutral fuels to financial analyses and documenting energy's impacts on human health. This research review is by no means exhaustive. Instead, it presents notable examples of the comprehensive breadth and depth of energy research at Stanford.

Hundreds of Stanford faculty members and scientific staff work to realize the energy transition. Sustainable energy is a global challenge to create rapidly scalable real-world solutions. This purpose drives Stanford energy research, often executed by brilliant students. And it drives subsequent development of that research, often led by Stanford alumni.

In September 2022, the Stanford Doerr School of Sustainability will open its doors. The Precourt Institute for Energy with its many programs is a principal component of the new

school. Faculty members in energy research, whether they are members of a department in the Stanford Doerr School of Sustainability or not, will be vital to the new school's success.

Many hundreds of students and postdoctoral scholars perform much of the work of Stanford's energy research. They, too, are celebrated in these pages. They learn diverse new skills, from atomic-level imaging to policy making, which they then use to create new energy solutions. In turn, Stanford students can choose from hundreds of energy-related courses to expand their knowledge. These courses also educate students who are not involved in energy research on how to be sustainable users of energy and stewards of our environment.

All this research and education is supported by our donors, corporate affiliates and sponsors in the public and private sectors, to whom we owe great thanks. I hope this review provides a moment for collective pride for all our faculty, students, alumni, staff, collaborators and supporters. One can see progress right here and find hope.

YI CUI

*Director, Precourt Institute for Energy
Fortinet Founders Professor of Engineering and
Professor of Materials Science & Engineering*



STANFORD ENERGY RESEARCH HIGHLIGHTS

During 2021, Stanford scholars conducted research on a remarkably broad range of energy topics, from discoveries that could pave the way to next-generation batteries and solar photovoltaics, to practical insights addressing the environmental and health impacts of fossil fuels.

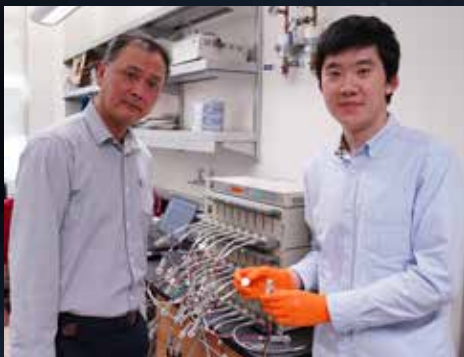
The following summaries feature more than two dozen high-impact energy studies published by Stanford authors. In each summary, the DOI number under the headline links to the published research, and the READ MORE button in the lower right links to the full news article.

Rechargeable metal-chlorine batteries that store six times more charge

Rechargeable Na/Cl₂ and Li/Cl₂ batteries. *Nature*, DOI: 10.1038/s41586-021-03757-z

Guanzhou Zhu, Xin Tian, Hung-Chun Tai, Yuan-Yao Li, Jiachen Li, Hao Sun, Peng Liang, Michael Angell, Cheng-Liang Huang, Ching-Shun Ku, Wei-Hsuan Hung, Shi-Kai Jiang, Yongtao Meng, Hui Chen, Meng-Chang Lin, Bing-Joe Hwang & Hongjie Dai

A Stanford-led research team has developed rechargeable batteries that can store up to six times more charge than commercially available batteries. The new alkali metal-chlorine batteries rely on the back-and-forth chemical conversion of sodium chloride or lithium chloride to chlorine, a highly reactive and unstable process. Equipped with electrodes made of porous carbon, the new batteries remained stable over 200 cycles of charging and discharging. The stability resulted from nanosized pores in the carbon material that act like a sponge, sopping up volatile chlorine



Hongjie Dai, the J.G. Jackson & C.J. Wood professor of chemistry (left) and Guanzhou Zhu, lead author of the new study, PhD student in Stanford's Department of Chemistry and a Bits & Watts PhD fellow

“A rechargeable battery is a bit like a rocking chair. It tips in one direction, but then rocks back when you add electricity. What we have here is a high-rocking rocking chair.”

—HONGJIE DAI, THE J.G. JACKSON AND C.J. WOOD PROFESSOR OF CHEMISTRY

molecules and storing them for later conversion to salt. The experimental battery can store up to 1,200 milliamp-hours per gram of positive electrode material, more than six times the energy density of a conventional lithium-ion battery. The new technology can be used to power small electronics, and could eventually enable electric vehicles that travel six times farther without a recharge and cell phones that only need charging once a week.

[READ MORE](#)



One of Earth's biggest carbon sinks has been overestimated

A trade-off between plant and soil carbon storage under elevated CO₂. *Nature*. DOI: [10.1038/s41586-021-03306-8](https://doi.org/10.1038/s41586-021-03306-8)

C. Terrer, R. P. Phillips, B. A. Hungate, J. Rosende, J. Pett-Ridge, M. E. Craig, K. J. van Groenigen, T. F. Keenan, B. N. Sulman, B. D. Stocker, P. B. Reich, A. F. A. Pellegrini, E. Pendall, H. Zhang, R. D. Evans, Y. Carrillo, J. B. Fisher, K. Van Sundert, Sara Vicca and R. B. Jackson

Carbon dioxide fuels plant growth. As atmospheric carbon levels rise, it's appealing to think of supercharged plant growth and massive tree-planting campaigns absorbing excess CO₂ produced by fossil fuel burning. But Professor Rob Jackson and colleagues have found that an increase in plant biomass is usually accompanied by a decrease in soil carbon storage. One likely explanation is that plants mine the soil for nutrients they need to keep up with carbon-fueled growth. Extracting the extra nutrients requires revving up microbial activity, which then releases CO₂ into the atmosphere that might otherwise remain locked in soil. This finding contradicts a widely accepted assumption in climate models that biomass and soil carbon will increase in tandem as greenhouse gas levels increase. The research also found that grasslands

“Soils store more carbon worldwide than is contained in all plant biomass. They need much more attention as we project the fate of forests and grasslands to the changing atmosphere.”

—ROB JACKSON, THE MICHELLE AND KEVIN DOUGLAS PROVOSTIAL PROFESSOR, AND PROFESSOR OF EARTH SYSTEM SCIENCE

may absorb unexpectedly large amounts of carbon in the future, while carbon uptake by forest soils remains flat, suggesting that trees should not be planted in natural grassland and savanna ecosystems.

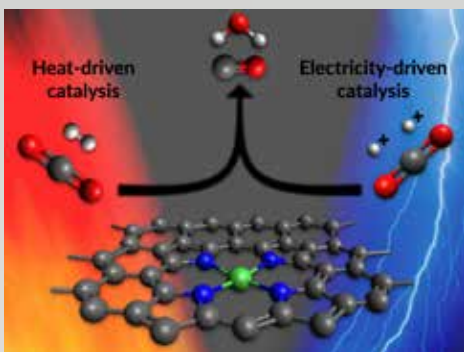
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Single catalyst can perform the first step of turning CO₂ into fuel in two very different ways

Bridging thermal catalysis and electrocatalysis: Catalyzing CO₂ conversion with carbon-based materials.
Angewandte Chemie, DOI: 10.1002/anie.202101326

David M. Koshy, Sindhu S. Nathan, Arun S. Asundi, Ahmed M. Abdellah, Samuel M. Dull, David A. Cullen, Drew Higgins, Zhenan Bao, Stacey F. Bent & Thomas F. Jaramillo

A new catalyst can use either heat or electricity to convert carbon dioxide into carbon monoxide – the first step in making renewable fuels and other useful products from CO₂. Recycling CO₂ at the industrial scale will require a new generation of cheap and efficient catalysts. Heat-driven catalytic reactions are commonly used in industry today, but some reactions require very high start-up temperatures.



This illustration shows one of the active sites of a new catalyst that accelerates the first step in making fuels and useful chemicals from carbon dioxide. The active sites consist of nickel atoms (green) bonded to nitrogen atoms (blue) and scattered throughout a carbon material (gray). SLAC and Stanford researchers discovered that this catalyst, called NiPACN, works in reactions driven by heat or electricity – an important step toward unifying the understanding of catalytic reactions in these two very different reaction environments. (Greg Stewart/SLAC National Accelerator Laboratory)

“We had theoretical reasons to think that the same catalyst would work in both sets of reaction conditions, but this idea had not been tested. These results open up a whole new avenue to look at catalysts in a much broader way.”

–THOMAS JARAMILLO,
ASSOCIATE PROFESSOR OF CHEMICAL
ENGINEERING AND OF PHOTON SCIENCE

Driving reactions with electricity instead of heat would be more efficient and take advantage of renewable solar and wind power. A Stanford-led research team has developed a nickel-based catalyst that speeds up CO₂ conversion using heat or electricity, two very different reaction environments. Researchers say it's an important step toward developing more efficient and sustainable ways to convert CO₂ into useful products.

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First glimpse of polarons forming in a promising solar cell material

Visualization of dynamic polaronic strain fields in hybrid lead halide perovskites.
Nature Materials, DOI: [10.1038/s41563-020-00865-5](https://doi.org/10.1038/s41563-020-00865-5)

Burak Guzelturk, Thomas Winkler, Tim W. J. Van de Goor, Matthew D. Smith, Sean A. Bourelle, Sascha Feldmann, Mariano Trigo, Samuel W. Teitelbaum, Hans-Georg Steinrück, Gilberto A. de la Pena, Roberto Alonso-Mori, Diling Zhu, Takahiro Sato, Hemamala I. Karunadasa, Michael F. Toney, Felix Deschler & Aaron M. Lindenberg

Polarons are fleeting, bubble-shaped distortions in a material's atomic lattice that form around moving electrons, then rapidly disappear. In some next-generation solar cells, such as hybrid metal-halide perovskites, electrons dislodged by sunlight are thought to quickly form polaronic distortions. Scientists suspect that polarons may be why hybrid perovskites, which are cheaper and easier to make than conventional silicon solar cells, are so efficient at converting sunlight to electricity. Now, for the first time, researchers at Stanford and SLAC National Accelerator Laboratory have observed the formation of polarons in perovskite crystals at the atomic level. They discovered that a polaronic bubble starts very small – on the scale of a few angstroms – and rapidly expands, nudging about

“Hybrid perovskites have taken the field of solar energy research by storm because of their high efficiencies and low cost, but people still argue about why they work.”

–AARON LINDENBERG, ASSOCIATE PROFESSOR
OF MATERIALS SCIENCE & ENGINEERING
AND OF PHOTON SCIENCE

10 layers of atoms slightly outward in just a few trillionths of a second. This protective bubble could help the electron travel efficiently through the solar cell to a metal contact where it flows out as electricity. However, more research is needed to explain the process in detail.

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Photo: Greg Stewart / SLAC National Accelerator Laboratory

Air pollution puts children at higher risk of disease in adulthood

Air pollution exposure is linked with methylation of immunoregulatory genes, altered immune cell profiles, and increased blood pressure in children. *Nature Scientific Reports*, DOI: 10.1038/s41598-021-83577-3

Mary Prunicki, Nicholas Cauwenberghs, Justin Lee, Xiaoying Zhou, Hesam Movassagh, Elizabeth Noth, Fred Lurmann, S. Katharine Hammond, John R. Balmes, Manisha Desai, Joseph C. Wu & Kari C. Nadeau

Children exposed to air pollution, such as wildfire smoke and car exhaust, for as little as one day may be doomed to higher rates of heart disease and other ailments in adulthood, according to research led by Professor Kari Nadeau. Their study is the first of its kind to investigate air pollution's effects at the single-cell level and to simultaneously focus on both the cardiovascular and immune systems in children. The researchers studied a predominantly Hispanic group of children ages 6 to 8 in California, who are often exposed to higher traffic-related pollution levels. Among the findings: Exposure to fine particulate matter, carbon monoxide and ozone over time can alter gene expression and cause an increase in white blood cells, which could predispose children to heart disease in adulthood. The results could change the way

“Nearly half of Americans and the vast majority of people around the world live in places with unhealthy air. Understanding and mitigating the impacts could save a lot of lives.”

–KARI NADEAU, NADDISY FOUNDATION
PROFESSOR OF PEDIATRIC FOOD ALLERGY,
IMMUNOLOGY AND ASTHMA,
PROFESSOR OF PEDIATRICS

people think about the air children breathe and inform clinical interventions. Nadeau is engaging multidisciplinary teams worldwide to continue research that has an impact on policy outcomes in air pollution and climate change.

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Mapping local earthquake risks from fracking in the Texas Eagle Ford formation

A risk-based approach for managing hydraulic fracturing-induced seismicity.
Science, DOI: [10.1126/science.abg5451](https://doi.org/10.1126/science.abg5451)

Ryan Schultz, Gregory C. Beroza & William L. Ellsworth

Stanford geophysicists have mapped the risk of noticeable shaking and building damage from earthquakes caused by hydraulic fracturing at all potential fracking sites across the Eagle Ford shale-oil formation in Texas, site of some of the largest fracking-triggered earthquakes in the country. The results show that the most

“If the goal is to treat everyone equally in terms of risk, our analysis shows more action should be taken at lower magnitudes for drill sites near the cities in the north of the Eagle Ford than for those in rural areas in the south.”

—WILLIAM ELLSWORTH,
PROFESSOR (RESEARCH) OF GEOPHYSICS

densely populated areas within the Eagle Ford – particularly a narrow section between San Antonio and Houston – face the greatest risk of experiencing shaking strong enough to be felt or to damage buildings. In sparsely populated areas in the southwestern section, damage is unlikely even if fracking causes magnitude 5.0 earthquakes. Thousands of wells drilled in the Eagle Ford over the past decade helped fuel the domestic shale boom and contributed to a dramatic increase in earthquakes in the central and eastern United States. The Stanford risk analysis should make it easier for local residents, operators and regulators to discuss the risks that are important to them without having technical expertise.

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Avoiding blackouts with clean, renewable energy

Zero air pollution and zero carbon from all energy at low cost and without blackouts in variable weather throughout the U.S. with 100% wind-water-solar and storage. *Renewable Energy*, DOI: 0.1016/j.renene.2021.11.067

Mark Z. Jacobson, Anna-Katharina von, Krauland, Stephen J.Coughlin, Frances C.Palmer, Miles M.Smith

For some, visions of a future powered by clean, renewable energy are clouded by fears of blackouts driven by intermittent electricity supplies. Those fears are misplaced, according to a Stanford study that analyzes grid stability under multiple scenarios in which wind, water and solar energy sources power 100 percent of U.S. energy needs. The study envisions a future without fossil fuels in 2051. Critics of such a shift have pointed to recent grid blackouts during extreme weather events in California and Texas as evidence that renewable electricity cannot be trusted for consistent power. But the researchers' simulations showed that in Texas, wind is stronger on average during cold spells, so increasing wind energy would help meet winter peak demand for heat. To avoid summertime

“ This study is the first to examine grid stability in all U.S. grid regions and many individual states after electrifying all energy and providing the electricity with only energy that is both clean and renewable. ”

—MARK JACOBSON, PROFESSOR OF CIVIL & ENVIRONMENTAL ENGINEERING

blackouts in California, the study suggests adding offshore wind turbines, since summer offshore winds are fastest in the evening when solar power output is reduced but demand for air conditioning is high.

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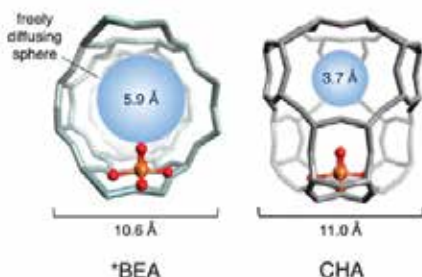
Photo: Pixabay/Kenueone

Turning methane into methanol at room temperature

Cage effects control the mechanism of methane hydroxylation in zeolites. *Science*, DOI: 10.1126/science.abd5803

Benjamin E. R. Snyder, Max L. Bols, Hannah M. Rhoda, Dieter Plessers, Robert A. Schoonheydt, Bert F. Sels & Edward I. Solomon

If natural gas, of which methane is the primary component, could be converted economically into methanol, the resulting liquid fuel would be cleaner and much easier to store and transport. A discovery by a Stanford-led research team could help pave the way to low-cost, environmentally friendly methanol production. The conventional industrial process for making methanol from



methane requires temperatures above 1800°F and extreme high pressure. A promising new technique uses common crystals called iron zeolites to convert natural gas to methanol at room temperature. Unfortunately, most iron zeolites deactivate quickly when exposed to

“Finding an efficient catalytic process for converting methane into methanol could have far-reaching environmental and economic implications.”

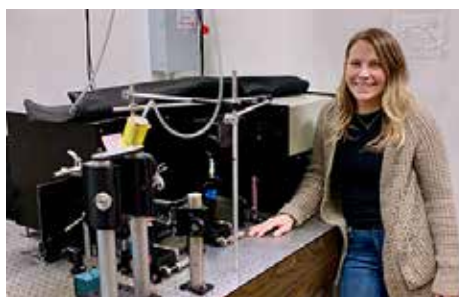
—EDWARD I. SOLOMON, THE MONROE E. SPAGHT
PROFESSOR OF CHEMISTRY, AND
PROFESSOR OF PHOTON SCIENCE

methane. To find out why, the scientists observed zeolite crystals at the atomic scale, focusing on the aluminum-silicon-oxygen lattice surrounding the iron active site where catalysis occurs. They discovered that if the pores in the lattice are too big, the active site deactivates after just one reaction with methane. But smaller pores continuously regenerate the active site while producing methanol, a significant conceptual advance toward industrial-scale catalysis.

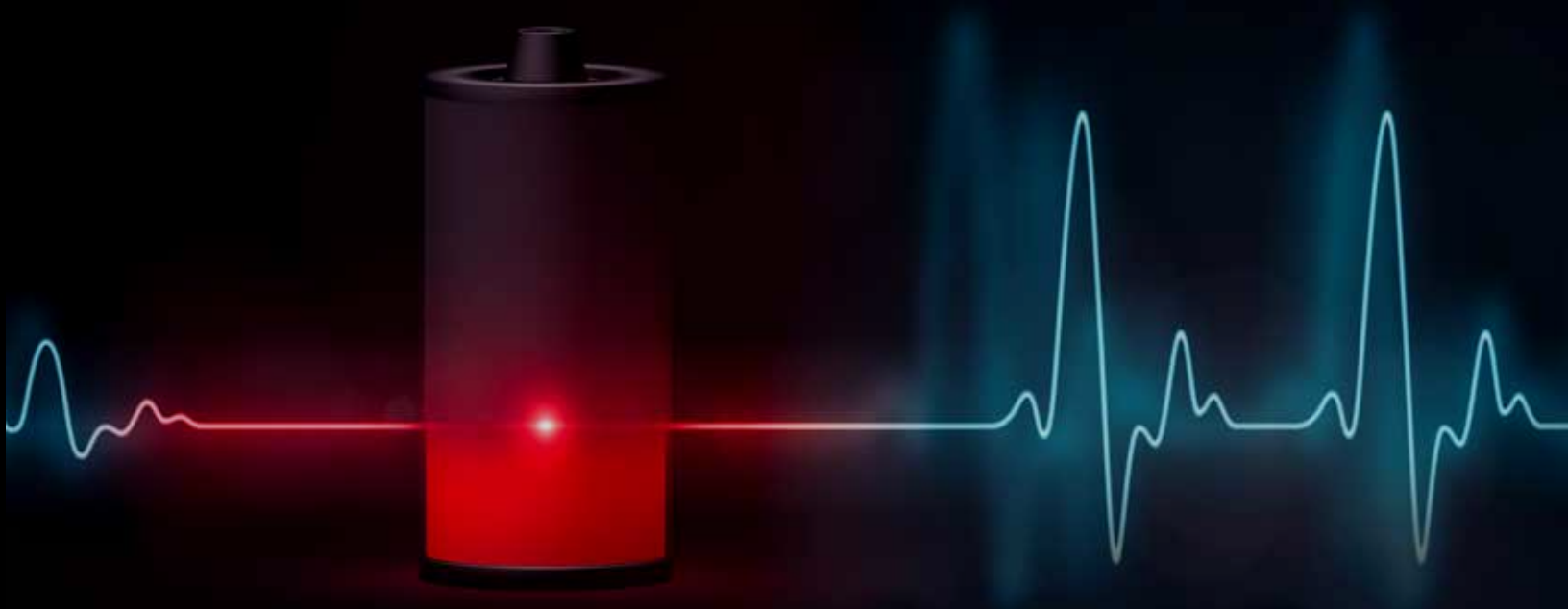
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Benjamin Snyder, PhD '18, (right) and his former PhD advisor, Edward Solomon, a professor of chemistry at Stanford and of photon science at SLAC. (Image credit: Linda A. Cicero)



PhD student Hannah Rhoda with the resonance Raman spectroscopy equipment, which shoots a laser into a sample to obtain vibrational information from the exact site being studied. Researchers in the current study used this technique to help assign the poisoned sites which illuminated the mechanism. (Image credit: Casey O'Sullivan)



Revitalizing batteries by bringing ‘dead’ lithium back to life

Dynamic spatial progression of isolated lithium during battery operations. *Nature*, DOI: 10.1038/s41586-021-04168-w

Fang Liu, Rong Xu, Yecun Wu, David Thomas Boyle, Ankun Yang, Jinwei Xu, Yangying Zhu, Yusheng Ye, Zhiao Yu, Zewen Zhang, Xin Xiao, Wenxiao Huang, Hansen Wang, Hao Chen & Yi Cui

Researchers at Stanford and SLAC National Accelerator Laboratory may have found a way to revitalize rechargeable lithium batteries, potentially boosting the range of electric vehicles and battery life in electronic devices. As lithium batteries cycle, they accumulate little islands of inactive lithium that are cut off from the electrodes, decreasing the battery’s capacity to store charge. The research team discovered that these isolated lithium islands are not “dead” at all but actually move slowly towards the anode during discharging and in the opposite direction while charging. Adding a brief, high-current discharging step right after the battery charges moved the isolated lithium far enough to reconnect with the anode, reactivating the lithium and increasing battery lifetime by

“Our findings have wide implications for the design and development of more robust lithium-metal batteries.”

—FANG LIU, POSTDOCTORAL SCHOLAR IN MATERIALS SCIENCE & ENGINEERING

Photo: Greg Stewart / SLAC National Accelerator Laboratory

nearly 30 percent. The researchers are now investigating whether the fast discharging step can help recover lost capacity in commercial lithium-ion batteries and promising lithium-metal batteries, which can store more energy per volume and weight.

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How extending Diablo Canyon nuclear plant would help California meet its climate goals

An assessment of the Diablo Canyon nuclear plant for zero-carbon electricity, desalination and hydrogen production, [Stanford & MIT Report \(pdf\)](#)

Justin Aborn, Ejeong [Baik](#), Sally Benson, Andrew T. Bouma, Jacopo Buongiorno, John H. Lienhard V, John Parsons & Quantum J. Wei

Extending the life of the Diablo Canyon Nuclear Power Plant could help California meet its climate change goals by providing clean, safe and reliable electricity, water and hydrogen fuel, according to a Stanford-MIT report. The Diablo Canyon plant provides eight percent of California's electricity production and 15 percent of its carbon-free electricity. The plant is slated to close in 2025, but researchers found that extending operations eight years would reduce annual carbon emissions from California's power sector by more than 10 percent, reduce reliance on natural gas and save utility customers \$2.6 billion. The report found that Diablo Canyon could also be enhanced to produce emission-free desalinated water and clean hydrogen. If operated beyond 2045, Diablo Canyon could save up to \$21 billion in power system costs.

“Diablo Canyon can continue to provide California reliable electricity output, while contributing to the state's goal to achieve climate neutrality by 2045.”

– EJEONG BAIK, DOCTORAL CANDIDATE,
ENERGY RESOURCES ENGINEERING

Photo: Joe Johnston / San Luis Obispo Tribune

In response to the report, scores of experts – including U.S. Energy Secretary Jennifer Granholm as well as two former U.S. energy secretaries – urged California to re-examine Diablo Canyon's closure.

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Living near oil and gas wells increases air pollution exposure

Upstream oil and gas production and ambient air pollution in California. *Science in the Total Environment*, DOI: 10.1016/j.scitotenv.2021.150298

David J.X. Gonzalez, Christina K. Francis, Gary M. Shaw, Mark R. Cullene, Michael Baiocchi & Marshall Burke

An analysis of California air quality from 2006 to 2019 revealed relatively high levels of air pollutants within 2.5 miles of oil and gas wells, likely worsening negative health outcomes for nearby residents. The analysis led by Stanford researchers found that wells emitted toxic particulate matter, carbon monoxide, nitrous oxide, ozone and volatile organic compounds. These findings will help determine how proximity to wells may increase the risk of adverse health outcomes, including preterm birth, asthma and heart disease. At least two million Californians, including many Black and Latino residents, live within one mile of an active well. Los Angeles County recently voted to phase out oil and gas drilling, citing issues of climate change and environmental equity, and other California

“While it’s not necessarily surprising that drilling and operating oil and gas wells emit air pollutants, knowing the magnitude of the effect improves our broader understanding of who is exposed to what and how to intervene to improve health outcomes.”

–MARSHALL BURKE, ASSOCIATE PROFESSOR OF EARTH SYSTEM SCIENCE

cities are in discussion about drilling regulations. The authors say the findings are likely applicable to other regions with oil and gas operations.

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New solar materials could usher in ultrathin, lightweight solar panels

High-specific-power flexible transition metal dichalcogenide solar cells.
Nature Communications, DOI: 10.1038/s41467-021-27195-7

Koosha Nassiri Nazif, Alwin Daus, Jiho Hong, Nayeun Lee, Sam Vaziri, Aravindh Kumar, Frederick Nitta, Michelle E. Chen, Siavash Kananian, Raisul Islam, Kwan-Ho Kim, Jin-Hong Park, Ada S. Y. Poon, Mark L. Brongersma, Eric Pop & Krishna C. Saraswat

Stanford engineers have significantly improved the power conversion efficiency of transition metal dichalcogenides, ultrathin materials that convert sunlight into electricity. While TMDs hold great promise, researchers have struggled to obtain a conversion efficiency rate above 2 percent. The Stanford team achieved 5.1 percent power conversion efficiency and is now working to surpass 20 percent, on par with conventional silicon solar panels available today, with the ultimate goal of 27 percent efficiency. Unlike silicon, which is bulky and rigid, TMDs are thin and flexible, ideal for powering wearable



Stanford electrical engineering Professor Krishna Saraswat (left) and PhD student Koosha Nassiri Nazif. (Image credit: Mark Golden)

“Silicon makes up 95 percent of the solar market today, but it’s far from perfect. We need new materials that are light, bendable and, frankly, more eco-friendly.”

– KRISHNA SARASWAT, THE RICKEY/NIELSEN
PROFESSOR OF ELECTRICAL ENGINEERING

Photo: Koosha Nassiri Nazif / Stanford University

devices and sensors. When fully assembled, the prototype cell is less than 6 microns thick, about as thin as a lightweight trash bag. The Stanford prototype also realized a 100-times greater power-to-weight ratio than other TMDs – a ratio important for charging drones and electric vehicles – and produced 4.4 watts of electricity per gram of weight, a figure competitive with thin-film solar cells made with other materials.

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Turning a climate problem into a profitable food security solution

Displacing fishmeal with protein derived from stranded methane.
Nature Sustainability, DOI: 10.1038/s41893-021-00796-2

Sahar H. El Abbadi, Evan D. Sherwin, Adam R. Brandt, Stephen P. Luby & Craig S. Criddle

Streams of methane, a potent greenhouse gas, can be captured at landfills, wastewater treatment plants, and oil and gas facilities, then converted into a microbial protein substitute for fishmeal, according to Stanford researchers. Their analysis suggests that this process will bring about climate change benefits and reduce ecosystem instability caused by overharvesting small fish for fishmeal production. The cost analysis focused on microbial bioreactors that can convert methane into a protein-rich fishmeal substitute. For methane captured at landfills and oil and gas facilities, the fishmeal alternative could cost about \$1,500 per ton – lower than the 10-year, \$1,600 average market price of processing conventional fishmeal. For wastewater treatment facilities, costs are slightly

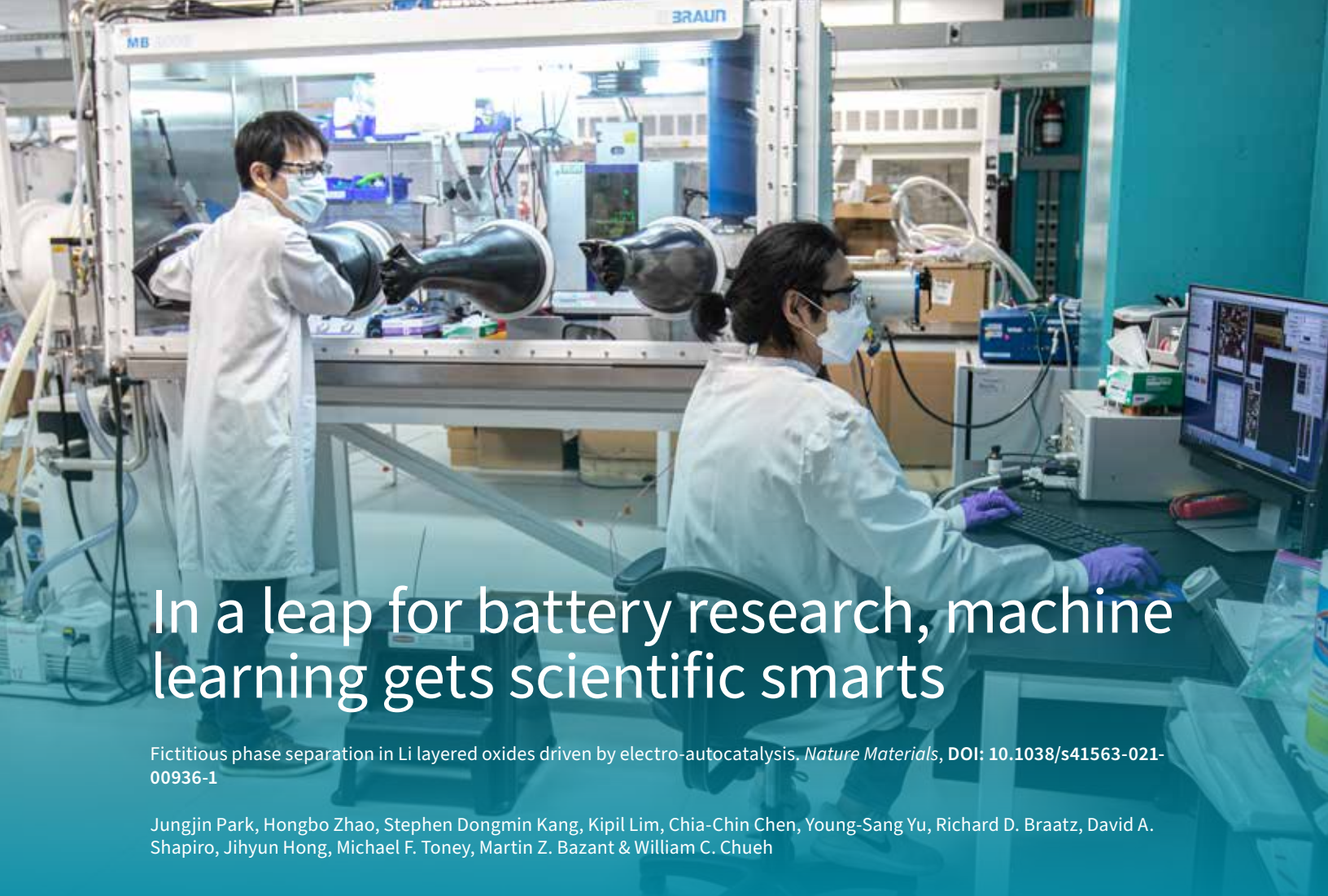
“This approach would result in multiple benefits, including lower levels of a potent greenhouse gas in the atmosphere, more stable ecosystems and positive financial outcomes.”

–CRAIG CRIDDLE, PROFESSOR OF CIVIL & ENVIRONMENTAL ENGINEERING

above current fishmeal prices, but several opportunities exist for cost reduction. The researchers found that methane from the natural gas grid would be somewhat more expensive depending upon the local price of electricity.

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In a leap for battery research, machine learning gets scientific smarts

Fictitious phase separation in Li layered oxides driven by electro-autocatalysis. *Nature Materials*, DOI: 10.1038/s41563-021-00936-1

Jungjin Park, Hongbo Zhao, Stephen Dongmin Kang, Kipil Lim, Chia-Chin Chen, Young-Sang Yu, Richard D. Braatz, David A. Shapiro, Jihyun Hong, Michael F. Toney, Martin Z. Bazant & William C. Chueh

For the first time, researchers used scientific machine learning to reveal the underlying physics and chemistry that make some lithium-ion batteries last longer. The Stanford-led research team combined conventional machine learning, which looks for patterns in data, with knowledge gained from experiments and equations to describe the process that shortens the lifetime of fast-charging batteries. The team focused on the battery electrodes, which consist of tiny particles that swell and crack during use. Repeated charging and discharging gradually decreases a battery's ability to store charge, and fast charging accelerates the problem. Scientists had assumed that lithium ions flow out of all the particles at once at roughly the same speed. The researchers here, however, discovered

“Fast charging is incredibly stressful and damaging to batteries, and solving this problem is key to expanding the nation's fleet of electric vehicles as part of the overall strategy for fighting climate change.”

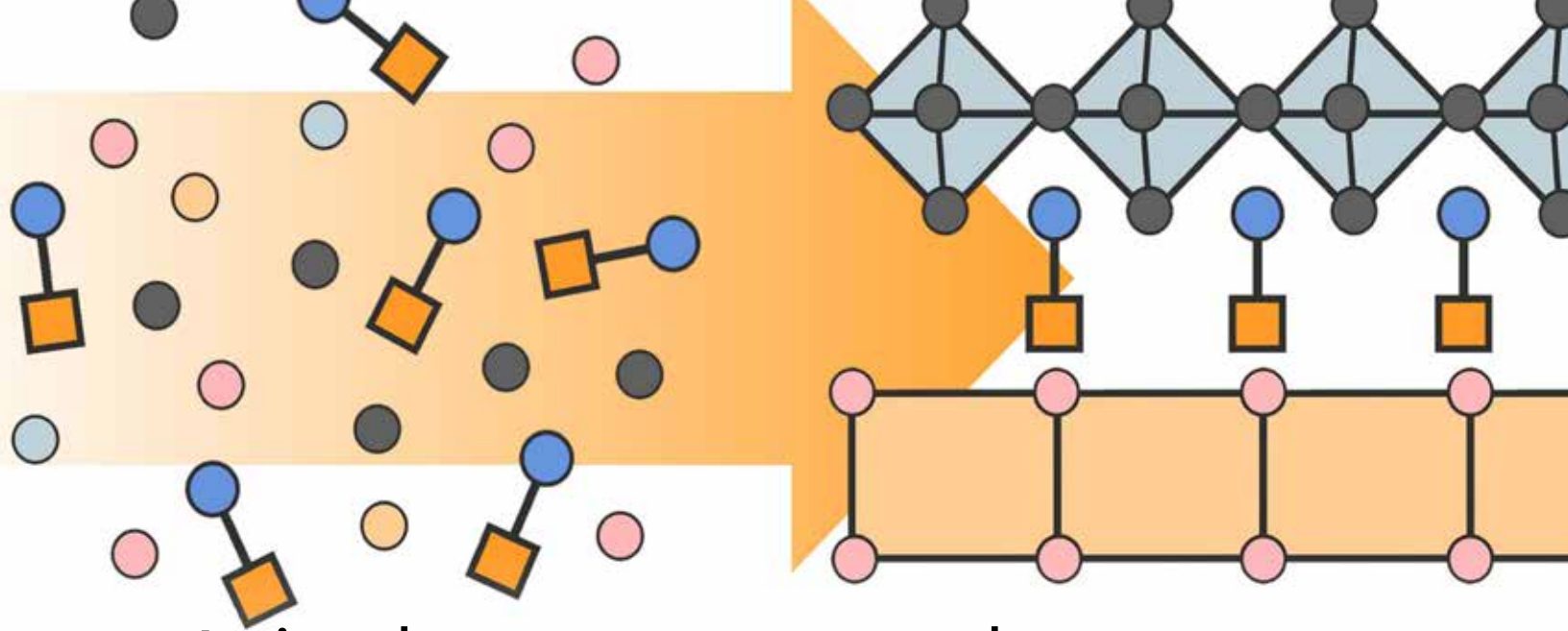
– WILLIAM CHUEH, ASSOCIATE PROFESSOR OF MATERIALS SCIENCE & ENGINEERING

that some particles release numerous ions quickly, while others slowly or not at all. This uneven pattern stresses the battery, reducing its lifetime. Understanding this process offers a new approach for improving fast-charging batteries for electric vehicles and the grid.

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Stanford Energy Research Year in Review 2021

Photo: Jacqueline Orrell / SLAC National Accelerator Laboratory



A simple way to get complex semiconductors to assemble themselves

Directed assembly of layered perovskite heterostructures as single crystals. *Nature*. DOI: 10.1038/s41586-021-03810-x

Michael L. Aubrey, Abraham Saldivar Valdes, Marina R. Filip, Bridget A. Connor, Kurt P. Lindquist, Jeffrey B. Neaton & Hemamala I. Karunadasa

Halide perovskites' ability to convert sunlight into electricity or emit different colors of light make them promising yet notoriously unstable materials for solar cells and light-emitting diodes, which are used for lighting and other applications. Layering perovskites with other materials could improve performance. Exciting electronic and optical properties have been observed at the interface where two materials meet, but making the interface usually involves peeling individual films, just one or two atoms thick, from bigger chunks of material. Stanford scientists have developed a faster technique in which two different materials actually assemble themselves in alternating layers. Assembly takes place in water-filled vials, where metal and halide ions tumble around with barbell-shaped

“Rather than manipulating materials one layer at a time, we’re just throwing the ions into a pot of water and letting them assemble the way they want to assemble. We are pretty thrilled about this general strategy that can be expanded to so many kinds of materials.”

—HEMAMALA KARUNADASA,
ASSOCIATE PROFESSOR OF CHEMISTRY

Photo: Jiyi Li / Stanford University

organic molecules. The molecular barbells carry templates that direct the assembly and link the finished layers in the correct order. This new self-assembly technique produces crystals made of alternating layers of perovskite and other materials with unusual electronic properties.

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Anticipated spill from deteriorating Red Sea oil tanker threatens public health

Public health impacts of an imminent Red Sea oil spill. *Nature Sustainability*, DOI: [10.1038/s41893-021-00774-8](https://doi.org/10.1038/s41893-021-00774-8)

Benjamin Q. Huynh, Laura H. Kwong, Mathew V. Kiang, Elizabeth T. Chin, Amir M. Mohareb, Aisha O. Jumaan, Sanjay Basu, Pascal Geldsetzer, Fatima M. Karaki & David H. Rehkopf

A massive spill from a deserted oil tanker in the Red Sea could lead to catastrophic public health effects in war-torn Yemen and neighboring countries unless urgent action is taken, according to a study from the Stanford School of Medicine. The FSO Safer, located about five nautical miles off Yemen, contains 1.1 million barrels of oil. Abandoned since 2015, the Safer is increasingly likely to leak oil due to deterioration of its hull or to catch fire. The dilapidated vessel is under the control of the Houthis, an insurgent Islamist group from Yemen. But negotiations between the United Nations and the Houthis to inspect and repair the ship have stalled. The study revealed that a full spill and subsequent port

closures could disrupt the delivery of food aid and threaten clean water supplies for millions of people. Air pollution from a full spill would also increase the risk of cardiovascular and respiratory hospitalizations by up to 42 percent.

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“We hope that our study puts more pressure on the international community to offload the oil and prevent this disaster.”

—DAVID REHKOPF,
ASSOCIATE PROFESSOR OF EPIDEMIOLOGY AND
POPULATION HEALTH, AND OF MEDICINE



A better way to track methane in the skies

Closing the methane gap in US oil and natural gas production emissions inventories. *Nature Communications*, DOI: [10.1038/s41467-021-25017-4](https://doi.org/10.1038/s41467-021-25017-4)

Jeffrey S. Rutherford, Evan D. Sherwin, Arvind P. Ravikumar, Garvin A. Heath, Jacob Englander, Daniel Cooley, David Lyon, Mark Omara, Quinn Langfitt & Adam R. Brandt

The U.S. Environmental Protection Agency tracks how much methane enters the atmosphere from oil and natural gas extraction. EPA estimates of this potent greenhouse gas rely on a bottom-up approach – counting major methane sources, such as well heads and pipelines, and calculating an annual average release per source. But other estimates based on data from top-down methods, such as airplane and satellite imagery, have revealed methane emissions twice as high as EPA totals. To bridge this gap, Stanford scientists developed a new bottom-up model using emissions data directly sampled at storage tanks, valves and other industry components where methane is most likely escaping. Results from the new model confirm what top-down modelers have been saying: Current EPA estimates are low. A major source of the


“Our model offers up some clear actionable steps to improve our inventories and ways operators can adjust their practices that could really make a difference in reducing the amount of methane entering the skies.”

– JEFFREY RUTHERFORD, DOCTORAL CANDIDATE,
ENERGY RESOURCES ENGINEERING

missing emissions is liquid storage tanks, where operator errors or equipment malfunctions can cause unintentional methane leakage. The new model offers actionable steps operators can take to reduce emissions and improve overall monitoring.

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Photo: Pixabay/StockSnap



For a low-carbon cement recipe, scientists look to Earth's cauldrons

Multi-scale imaging, strength and permeability measurements: Understanding the durability of Roman marine concrete. *Construction and Building Materials*, DOI: [10.1016/j.conbuildmat.2020.121812](https://doi.org/10.1016/j.conbuildmat.2020.121812)
Jackson MacFarlane, Tiziana Vanorio & Paulo J.M. Monteiro

Rock physics and experimentation in decarbonizing the future. *The Leading Edge*, DOI: [10.1190/tle40040245.1](https://doi.org/10.1190/tle40040245.1)
Margariete Malenda, Tiziana Vanorio, Saied Mighani, Jihui Ding & Jaehong Chung

As the most-used building material on Earth and one of the world's largest industrial contributors to global warming, concrete has long been a target for reinvention. Production of cement – the glue that holds concrete together – is responsible for about eight percent of global CO₂ emissions annually. Portland cement, widely used in construction, is made from carbon-rich limestone processed with other materials at high heat generated from fossil fuels. During the production process, decomposition of the limestone rock actually releases twice as much CO₂ as the amount emitted from burning fossil fuels. Stanford scientists are developing a cement-processing technique that replaces limestone with carbon-free volcanic rocks. The new process could significantly slash CO₂

“If we're going to draw down carbon emissions to promote environmental sustainability, we need to change the way we make cement and keenly look at what Earth has to offer.”

–TIZIANA VANORIO,
ASSOCIATE PROFESSOR OF
GEOLOGICAL SCIENCES

emissions during manufacturing and increase durability. Corrosion of reinforcing steel bars is the leading cause of deterioration in concrete. The scientists are studying alternative ways to reinforce concrete at nanoscale by mimicking how fibrous microstructures effectively reinforce rocks.

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Discovery could pave the way to fast, low-power computing

Ultralow-switching current density multilevel phase-change memory on a flexible substrate.
Science, DOI: 10.1126/science.abj1261

Asir Intisar Khan, Alwin Daus, Raisul Islam, Kathryn M. Neilson, Hye Ryoung Lee, H.-S. Philip Wong & Eric Pop

Researchers have spent decades searching for fast, energy-efficient memory technologies for laptops, cell phones and other devices. Among the most promising is phase-change memory, which is thousands of times faster than conventional hard drives but requires more power than competing storage technologies. Now Stanford engineers have made phase-change memory more energy efficient. In conventional memory like flash drives, data are stored by switching the flow of electrons on and off, a process symbolized by 1's and 0's. In phase-change memory, the 1's and 0's represent measurements of electrical resistance in a germanium-antimony-tellurium composite sandwiched between two electrodes. Switching from 1 to 0 and back again occurs in nanoseconds using heat from the electrodes, but this process

“The big appeal of phase-change memory is speed, but energy-efficiency in electronics also matters. Anything we can do to make lower-power electronics and extend battery life will have a tremendous impact.”

– ERIC POP,
PROFESSOR OF ELECTRICAL ENGINEERING

is inefficient energetically. The Stanford team designed a novel, low-power memory cell embedded in thermally insulating flexible plastic, which could enable widespread adoption of phase-change memory in a variety of electronics, from data centers to the Internet of Things.

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Photo: Crystal Alicia Nattao / Stanford University

Revealing the cost of a key climate solution

Energy and CO₂ emissions penalty ranges for geologic carbon storage brine management
Environmental Science & Technology, DOI: 10.1021/acs.est.0c06017

Timothy V. Bartholomew and Maegan S. Mauter

Capturing and storing carbon dioxide emissions underground has remained elusive due in part to uncertainty about its economic feasibility. Underground saline reservoirs are the most likely storage places for captured CO₂. But managing and disposing of concentrated brine water from these reservoirs will impose significant energy and emissions penalties, according to a Stanford-Carnegie Mellon study. On average, the salt concentration in underground brine water is nearly three times higher than seawater and must be disposed of via deep-well injection or desalinated for reuse. The study focused on the energy and emissions costs of brine treatment associated with storing CO₂ from coal-fired power plants. The researchers found that managing brine imposes the largest post-capture energy

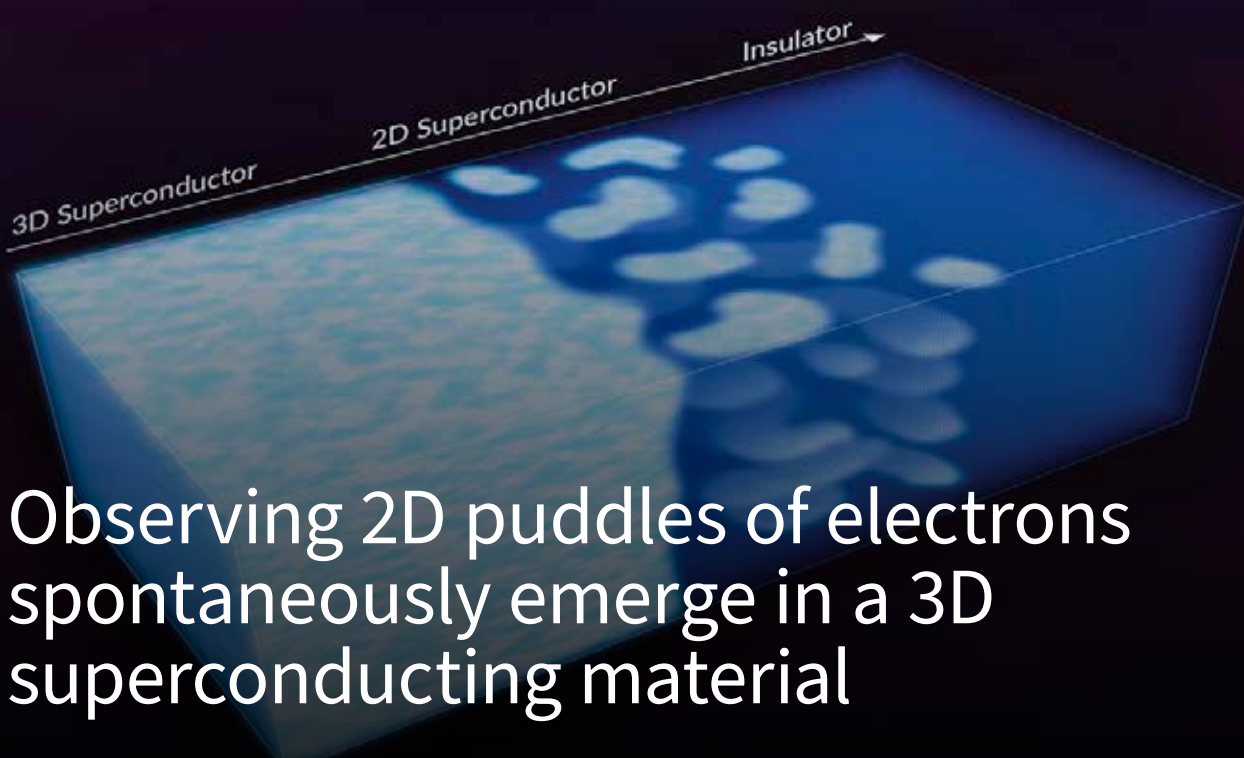
“There are water-related implications for most deep decarbonization pathways. The key is understanding the constraints in sufficient detail to design around them or develop engineering solutions that mitigate their impact.”

—MEAGAN MAUTER, ASSOCIATE PROFESSOR OF
CIVIL & ENVIRONMENTAL ENGINEERING

penalty per-ton of carbon dioxide, up to an order of magnitude greater than transporting CO₂. They offered potential solutions to reduce the energy penalty, including prioritizing CO₂ storage in low-salinity reservoirs.

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Photo: Pixelbay/netteta10



Observing 2D puddles of electrons spontaneously emerge in a 3D superconducting material

Signatures of two-dimensional superconductivity emerging within a three-dimensional host superconductor.
PNAS, DOI: [10.1073/pnas.2017810118](https://doi.org/10.1073/pnas.2017810118)

Carolina Parra, Francis C. Niestemski, Alex W. Contryman, Paula Giraldo-Gallo, Theodore H. Geballe, Ian R. Fisher & Hari C. Manoharan

Superconducting materials allow electrons to travel freely with zero resistance – ideal properties for high-efficiency power lines. Most materials become superconducting only in very cold conditions, so researchers have been looking for new materials that work closer to room temperature. Stanford scientists discovered that in one high-temperature superconducting material, electrons behave as if they are confined to two-dimensional, puddle-like areas instead of moving freely in any direction they like.



“It’s as if when given the power to superconduct, the 3D electrons choose for themselves to live in a 2D world.”

–HARI MANOHARAN,
 ASSOCIATE PROFESSOR OF PHYSICS

Photo: Greg Stewart / SLAC National Accelerator Laboratory

Atomic-scale microscopy revealed that the distance between puddles is short enough that the electrons can interact in a way that lets them move without resistance – the hallmark of superconductivity. The 2D puddles emerged as the scientists carefully adjusted the temperature and other conditions toward the transition point where the superconductor becomes an insulator. The discovery of this emergent property could lead to the development of new materials with 2D superconducting states.

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Want to kick-start climate action? Make companies report their carbon footprints

The Impact of carbon disclosure mandates on emissions and financial operating performance.
Review of Accounting Studies, DOI: 10.1007/s11142-021-09611-x

Benedikt Downar, Jürgen Ernstberger, Stefan Reichelstein, Sebastian Schwenen & Aleksandar Zaklan

Corporations should be required to disclose their carbon dioxide emissions in their annual reports, according to a study from the Stanford Graduate School of Business. Mandatory CO₂ reporting would not ask firms to cut their emissions, but simply oblige them to measure their carbon footprint from year to year. The study focused on the United Kingdom, which enacted a mandatory annual-disclosure policy in 2013. Researchers found that the affected British companies reduced their CO₂ emissions by at least eight percent over the next several years, compared with similar European firms. The British firms saw no significant decline in financial performance, despite incurring costs

“Mandatory carbon reporting is a modest proposal, but it is immediately feasible and an essential first step to reduce emissions.”

– STEFAN REICHELSTEIN, THE WILLIAM R. TIMKEN
PROFESSOR OF ACCOUNTING, EMERITUS

to modify their operations. This indicates that they could pass along those costs in higher prices, possibly because their carbon-cutting efforts increased customer loyalty.

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Tweaking one layer of atoms on catalysts could boost clean hydrogen production

Tuning electrochemically driven surface transformation in atomically flat LaNiO_3 thin films for enhanced water electrolysis. *Nature Materials*, DOI: 10.1038/s41563-020-00877-1

Christoph Baeumer, Jiang Li, Qiyang Lu, Allen Yu-Lun Liang, Lei Jin, Henrique Perin Martins, Tomáš Duchoň, Maria Glöß, Sabrina M. Gericke, Marcus A. Wohlgemuth, Margret Giesen, Emily E. Penn, Regina Dittmann, Felix Gunkel, Rainer Waser, Michal Bajdich, Slavomír Nemšák, J. Tyler Mefford & William C. Chueh

A slight rearrangement of atoms on the surface of a water-splitting catalyst significantly boosts the production of clean hydrogen, according to a Stanford-led study. The catalyst, lanthanum nickel oxide or LNO, splits water into hydrogen and oxygen in a reaction powered by electricity. If produced at scale, the hydrogen could provide emissions-free fuel for power plants and vehicles. Researchers discovered that tweaking the surface layer of LNO can improve its catalytic performance. The surface consists of alternating layers of material made of nickel and lanthanum. When grown at relatively cool temperatures, the material forms a nickel-rich layer on top. During the water-splitting reaction, atoms in that top

“If we can unlock the secrets of this transformation so we can accurately tune it, then we can leverage this phenomenon to make much better catalysts in the future.”

—MICHAL BAJDICH, STAFF SCIENTIST AT SLAC NATIONAL ACCELERATOR LABORATORY

layer rearrange in a way that makes the reaction run twice as quickly. The discovery that a slight surface transformation boosts LNO activity could apply to other, more efficient catalytic materials as well.

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Photo: CUBES3D Graphic

Uncovering how financing for emerging-market infrastructure is heating the planet

Hot money: Illuminating the financing of high-carbon infrastructure in the developing world.
iScience, DOI: 10.1016/j.isci.2021.103358

Jeffrey Ball, Angela Ortega Pastor, David Liou & Emily Dickey

New infrastructure in emerging markets and developing economies will shape the climate. Though myriad governments and corporations have pledged net-zero emissions by mid-century, assessing their – and the world’s – progress requires vastly better insight into financial flows to emerging-market infrastructure. Stanford research created a data tool, using new World Bank data for 2018 through 2020, that begins to provide that clarity – about who is investing how much in high-carbon and low-carbon projects, about the financing structures they’re using, and about the resulting emission trajectories. Among the key findings: More than half of new electricity generation financed in emerging economies is too carbon intensive to align with global climate goals. One reason is the quantity of new natural gas-burning power capacity; Nearly half the power capacity financed in emerging economies came not from foreign investors but from domestic ones.

“Vast sums bankrolling carbon-intensive infrastructure in emerging markets are warming the planet. The fix will require not just new technology but new power structures: realistically reoriented political economies.”

– JEFFREY BALL,
LECTURER IN STANFORD LAW SCHOOL

This underscores the importance of enabling realistic shifts in these countries’ political economies that spur meaningful decarbonization.

NEW YORK TIMES

BROOKINGS INSTITUTION

STANFORD DAILY

Scientists take first snapshots of ultrafast switching in a quantum electronic device

Universal phase dynamics in VO₂ switches revealed by ultrafast operando diffraction.
Science, DOI: 10.1126/science.abc0652

Aditya Sood, Xiaozhe Shen, Yin Shi, Suhas Kumar, Su Ji Park, Marc Zajac, Yifei Sun, Long-Qing Chen, Shriram Ramanathan, Xijie Wang, William Chueh & Aaron Lindenberg

Electronic circuits that compute and store information contain millions of tiny switches that control the flow of electric current. Now, a Stanford-led research team has made the first snapshots of atoms moving inside one of those switches as it turns on and off. The team designed miniature switches made of vanadium dioxide, a quantum material that can alternate between insulating and electrically conducting states near room temperature. The researchers used electrical pulses to toggle the switch back and forth between the two states. An ultrafast electron diffraction camera revealed subtle changes in the atomic arrangement of the switch when it changed from insulator to conductor. The researchers also discovered that when shocked electrically, the switch enters a

“Our approach will enable the creation of next-generation electronic devices that can meet the world’s growing needs for data-intensive, intelligent computing.”

—ADITYA SOOD,
RESEARCH SCIENTIST, STANFORD INSTITUTE
FOR MATERIALS & ENERGY SCIENCES

transient conducting state without any changes to the atomic arrangement. This short-lived transient state, which lasts billionths of a second, could lead to faster and more energy-efficient computing devices.

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Photo: Jacqueline Orrell/SLAC National Accelerator Laboratory

Stanford Energy Research in Review 20:2021

Methane removal: Research reveals potential of an overlooked climate change solution

Atmospheric methane removal: a research agenda. *Philosophical Transactions of the Royal Society A*, DOI: [10.1098/rsta.2020.0454](https://doi.org/10.1098/rsta.2020.0454)

Robert B. Jackson, Sam Abernethy, Josep G. Canadell, Matteo Cargnello, Steven J. Davis, Sarah Féron, Sabine Fuss, Alexander J. Heyer, Chaopeng Hong, Chris D. Jones, H. Damon Matthews, Fiona M. O'Connor, Maxwell Pisciotta, Hannah M. Rhoda, Renaud de Richter, Edward I. Solomon, Jennifer L. Wilcox and Kirsten Zickfeld

Methane removal and the proportional reductions in surface temperature and ozone. *Philosophical Transactions of the Royal Society A*, DOI: [10.1098/rsta.2021.0104](https://doi.org/10.1098/rsta.2021.0104)

S. Abernethy, F. M. O'Connor, C. D. Jones and R. B. Jackson

Two Stanford-led studies focused on new technologies for removing methane from the atmosphere, and modeling how the approach could help reduce future peak temperatures. Most methane is produced from agricultural sources, waste disposal, fossil fuel extraction and other human activities. Natural sources,

including soil microbes in wetlands, account for about 40 percent of global methane emissions. Removing methane could reduce global temperatures even faster than carbon dioxide removal alone, because methane, the main component of natural gas, is 81 times more potent than CO₂ in terms of warming the climate over the first 20 years after its release. One study found that removing about three years-worth of human-caused methane emissions would reduce global surface temperatures by about 0.21 degrees Celsius and reduce ozone levels enough to prevent about 50,000 premature deaths annually. The studies call for increased research on promising technologies for methane removal, and outline a framework for coordinating and accelerating its scale-up.

“This new model allows us to better understand how methane removal alters warming on the global scale and air quality on the human scale.”

– SAM ABERNETHY,
DOCTORAL CANDIDATE, APPLIED PHYSICS

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First closeups of how a lithium-metal electrode ages

Corrosion of lithium metal anodes during calendar ageing and its microscopic origins.
Nature Energy, DOI: 10.1038/s41560-021-00787-9

David T. Boyle, William Huang, Hansen Wang, Yuzhang Li, Hao Chen, Zhiao Yu, Wenbo Zhang, Zhenan Bao & Yi Cui

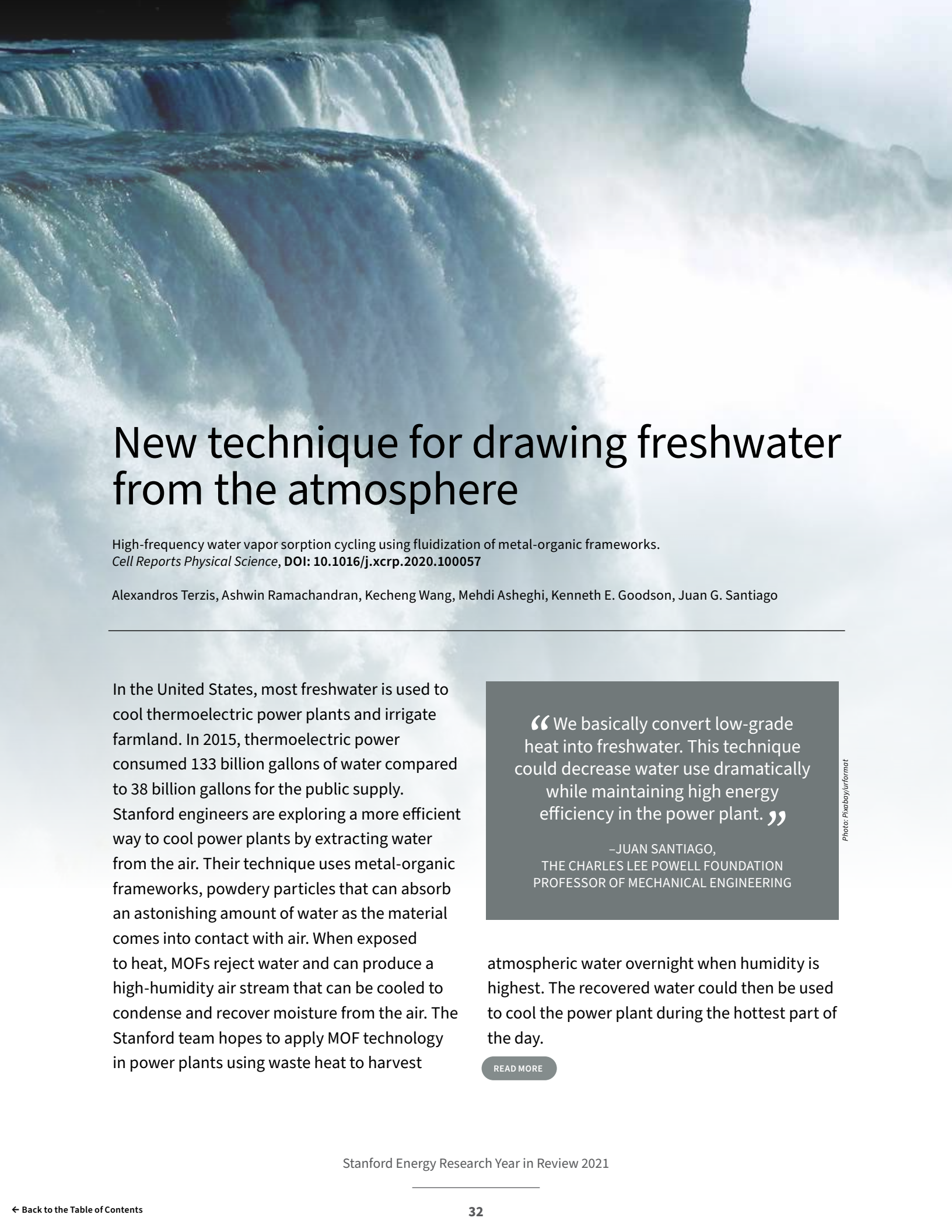
Lightweight lithium-metal batteries could significantly boost the driving range of electric vehicles, but the short life expectancy of these promising batteries is a major drawback. Now, Stanford scientists have taken the first atomic-scale look at the process that makes lithium-metal batteries lose charge over time. During charging a fresh layer of lithium metal is deposited on the battery's anode. The Stanford team discovered that the battery electrolyte, which carries charge between the anode and the cathode, causes the fresh metal layer to become irregular and clumpy. This corrosion process continues even after the battery is turned off, draining up to three percent of the battery's charge in just 24 hours and eventually reducing battery lifetime by 25 percent. The researchers

“Our work suggests that the electrolyte can make a big difference in the stability of stored batteries. This is something people haven't really spent time looking at or using as a way to understand what's going on.”

—YI CUI, THE FORTINET FOUNDERS PROFESSOR OF ENGINEERING, PROFESSOR OF MATERIALS SCIENCE & ENGINEERING

tested a variety of electrolytes and found that all were prone to drops in efficiency due to aging. The next challenge is to identify electrolytes that minimize corrosion and reduce charge seepage.

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New technique for drawing freshwater from the atmosphere

High-frequency water vapor sorption cycling using fluidization of metal-organic frameworks.
Cell Reports Physical Science, DOI: 10.1016/j.xcrp.2020.100057

Alexandros Terzis, Ashwin Ramachandran, Kecheng Wang, Mehdi Asheghi, Kenneth E. Goodson, Juan G. Santiago

In the United States, most freshwater is used to cool thermoelectric power plants and irrigate farmland. In 2015, thermoelectric power consumed 133 billion gallons of water compared to 38 billion gallons for the public supply. Stanford engineers are exploring a more efficient way to cool power plants by extracting water from the air. Their technique uses metal-organic frameworks, powdery particles that can absorb an astonishing amount of water as the material comes into contact with air. When exposed to heat, MOFs reject water and can produce a high-humidity air stream that can be cooled to condense and recover moisture from the air. The Stanford team hopes to apply MOF technology in power plants using waste heat to harvest

“ We basically convert low-grade heat into freshwater. This technique could decrease water use dramatically while maintaining high energy efficiency in the power plant. ”

—JUAN SANTIAGO,
THE CHARLES LEE POWELL FOUNDATION
PROFESSOR OF MECHANICAL ENGINEERING

Photo: Pixabay/urformat

atmospheric water overnight when humidity is highest. The recovered water could then be used to cool the power plant during the hottest part of the day.

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Dips in oil demand benefit climate more than previous estimates

Carbon implications of marginal oils from market-derived demand shocks.
Nature, DOI: 10.1038/s41586-021-03932-2

Mohammad S. Masnadi, Giacomo Benini, Hassan M. El-Houjeiri, Alice Milivinti, James E. Anderson, Timothy J. Wallington, Robert De Kleine, Valerio Dotti, Patrick Jochem & Adam R. Brandt

A decreasing reliance on oil for fuel will inevitably reduce the amount of carbon dioxide released into the atmosphere throughout the fuel's lifecycle, from extraction and refining to vehicle combustion. But the size of that impact varies depending on complex market factors. A Stanford-led study took a close look at the impact of oil markets and decreasing demand on global CO₂ emissions. The researchers found that in both competitive and noncompetitive oil markets, small drops in demand result in greater emissions reductions than large demand drops. That's because in small drops carbon-intensive heavy crudes are removed from production first. In big demand shocks, powerful oil cartels and oligopolies boost prices by reducing production

“To reduce carbon emissions by reducing demand for oil, policymakers must also take into account the global oil market's structure.”

—ADAM BRANDT, ASSOCIATE PROFESSOR OF
ENERGY RESOURCES ENGINEERING

of light and medium crudes, which emit less CO₂ per barrel of oil produced than heavy crudes. Overall, the study found that large and small dips in demand have more climate benefits than previous models had estimated.

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The background of the entire page is a photograph of the California State Capitol building in Sacramento. The building is a large, white, neoclassical structure with a prominent dome topped by a statue. The dome has a series of arched windows. The building's facade features many columns and arched windows. In the foreground, there are green trees and a grassy area. The sky is a clear, bright blue.

STANFORD ENERGY SPECIAL REPORTS

Stanford scholars co-authored four special reports in 2021. They covered net-zero financing, future U.S-China energy collaborations, decarbonizing trucks and other heavy-duty transport, and recommendations on how the State of California can incorporate climate risk in its investments.

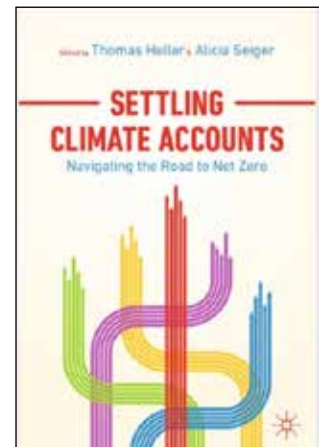
SPECIAL REPORT:

Settling Climate Accounts: Navigating the Road to Net Zero

Palgrave Macmillan, ISBN-13: 978-3030836498 or ISBN-10: 3030836495

Settling Climate Accounts: Navigating the Road to Net Zero, an edited book of essays by Stanford researchers, probes the emerging practice of net-zero financing, which seeks to eliminate greenhouse gas emissions by 2050. Hundreds of corporations and investors worldwide with more than \$100 trillion in total assets have pledged net-zero portfolios by mid-century. The book examines various challenges facing net-zero financing, including the need for universal measuring standards and accountability. It asks: Who ultimately is in charge of making net zero add up?

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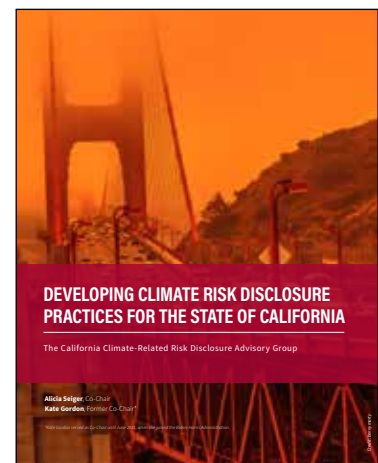
SPECIAL REPORT:

Developing Climate Risk Disclosure Practices for the State of California

Stanford Law School Publications

“Developing Climate Risk Disclosure Practices for the State of California” is a Stanford-led report commissioned by Governor Gavin Newsom. The report offers more than 45 recommendations to help the state translate specific risks associated with climate change into financial terms. It also recommends how California can use that information to decide how to spend its \$260 billion annual budget and manage more than \$1 trillion in state pension fund investments. Among the recommendations: California should require entities doing business with the state to disclose their decarbonization plans, and state employee pension funds should pressure companies they invest in to make climate risk part of their regular financial reporting.

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SPECIAL REPORT:

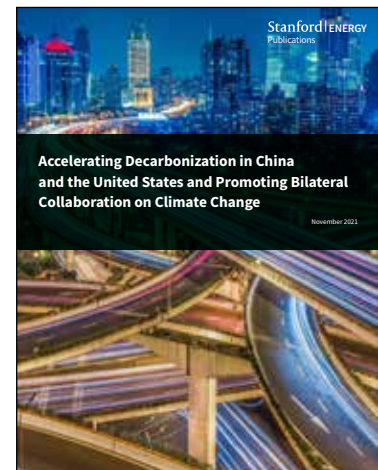
Accelerating Decarbonization in China and the United States and Promoting Bilateral Collaboration on Climate Change

Stanford ENERGY Publications

The Precourt Institute, Stanford Center at Peking University, Shorenstein Asia-Pacific Research Center's China Program and Peking University's Institute of Energy met to discuss how China and the United States can cooperate to meet their carbon neutrality goals by mid-century. In this report, the roundtable – which included participants from both countries – called for a just transition to carbon neutrality where the financial burdens and benefits of decarbonization are equitably distributed. Noting that tensions in U.S.-China relations have hindered the acceleration of decarbonization, the report identified several areas of research and development, such as green finance and carbon storage, where the countries could collaborate. The report said that rigorous R&D programs are needed to manage the energy transition with minimal economic disruption, and that open science in fundamental research must be encouraged.

Support from central and local governments will be critical to overcome political and institutional obstacles to meeting carbon-reduction pledges, the report concluded, adding that shared regulatory frameworks and standards would make trade, validation, accounting and climate-pledge fulfillment easier to implement.

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SPECIAL REPORT:

Decarbonizing Heavy-duty Transportation

Stanford Hydrogen Focus Group

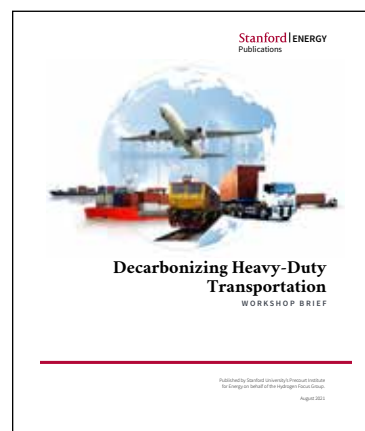
The Stanford Hydrogen Focus Group produced a report on challenges facing the transition to zero emissions in the heavy-duty transport sector – trucks, buses, trains, ships and airplanes. Battery and hydrogen fuel cell technologies have yet to significantly penetrate the heavy-duty transport market.

As the report explains, most experts see batteries gaining market share for lighter vehicles with low daily use, while fuel cells are the likely solution for heavier vehicles with high daily use. Battery electric technology for heavy-duty transport becomes challenged as power and energy density needs increase, and four-fold longer charging times become expensive for larger transport vehicles and vessels.

An ensemble of applications around industrial areas, such as commercial ports, may be restricted by land-use requirements for longer-duration electrical charging vs. refueling with hydrogen. Still, the report concludes, the heavy-duty transport sector has broadly diverse needs that warrant strong consideration of both batteries and hydrogen for decarbonization.

The Stanford Hydrogen Focus Group is a collaboration among SUNCAT Center for Interface Science & Catalysis, the Stanford Natural Gas Initiative and Stanford Energy Corporate Affiliates.

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RESOURCES FOR STANFORD FACULTY INTERESTED IN ENERGY RESEARCH

OPPORTUNITIES ON CAMPUS for Stanford faculty to get support for energy research are significant and growing.

Several cross-campus research initiatives fund work on a number of energy topics. The **StorageX Initiative** brings together Stanford faculty from materials science to computer science to economics to tackle the dominant challenges in energy storage, from transportation to grid-scale systems. The Sustainable Finance Initiative is developing the finance and policy tools needed for a decarbonized and climate-resilient global economy. These interdisciplinary initiatives join **Bits & Watts**, which focuses on innovations for the 21st Century electric grid, and the **Natural Gas Initiative**. A new **Hydrogen Initiative** is set to launch in May 2022.

Stanford also has energy-related industrial affiliate programs, which support education as well as research. Most commonly, corporate members subsidize the education of one or more graduate students working in the labs of Stanford faculty members of their choosing. Industrial affiliate members have also sponsored multi-year fellowships for PhD candidates and postdoctoral researchers. Some programs accept affiliate members' visiting scientists, who contribute to research in many ways, including informing faculty research agendas and moving lab successes to human benefits.

The **Stanford Energy Corporate Affiliates** program is a gateway to Stanford researchers working across the spectrum of energy topics. Other industrial affiliate programs focus on specific energy topics. These include the **Energy Modeling Forum**, and several programs at the **School of Earth, Energy & Environmental Sciences**.

Sponsored-research programs match firms and faculty members who share common research interests. Stanford's main program for energy research sponsored by the private sector is the Strategic Energy Alliance, which launched last March. This broad research program aims to accelerate the transformation of the world's energy infrastructure to make it more sustainable, affordable and secure—and to extend modern energy services to developing economies.

Also, several Stanford research centers provide seed grants for early-stage, proof-of-concept work in annual, competitive processes. These grants support novel proposals with a strong potential for high impact on energy supply and use. The funding bridges theory to early experiment and analysis. Proposals from research teams with faculty from different academic departments are strongly encouraged. The programs providing such seed grants include **Bits & Watts**, the **Natural Gas Initiative**, **Precourt Pioneering Projects**, and the **Sustainable Finance Initiative**.

Photo: Tamer Shabani

STANFORD ENERGY RESEARCH PROGRAMS

Bits & Watts Initiative:

bitsandwatts.stanford.edu

Center for Mechanistic Control in Unconventional & Tight Oil Formations:

efrc-shale.stanford.edu

Energy Modeling Forum:

emf.stanford.edu

Photonics at Thermodynamic Limits:

ptl.stanford.edu

Precourt Institute for Energy:

energy.stanford.edu

Program on Energy & Sustainable Development:

pesd.stanford.edu

School of Earth, Energy & Environmental Sciences industrial affiliate programs:

earth.stanford.edu/industrial-affiliate-programs

Shultz-Stephenson Task Force on Energy Policy:

hoover.org/taskforces/energy-policy

Stanford Center for Carbon Storage:

sccs.stanford.edu

Stanford Energy Corporate Affiliates:

seca.stanford.edu

Stanford Environmental & Energy Policy Analysis Center:

seepac.stanford.edu

Stanford Hydrogen Initiative:

hydrogen.stanford.edu

Stanford Institute for Materials & Energy Sciences:

simes.stanford.edu

Stanford Natural Gas Initiative:

ngi.stanford.edu

Stanford StorageX Initiative:

storagex.stanford.edu

Steyer-Taylor Center for Energy Policy & Finance:

steyertaylor.stanford.edu

Strategic Energy Alliance:

energy.stanford.edu/strategic-energyalliance

SUNCAT Center for Interface Science & Catalysis:

suncat.stanford.edu

Sustainable Finance Initiative:

sfi.stanford.edu

TomKat Center for Sustainable Energy:

tomkat.stanford.edu

STANFORD ENERGY RESEARCHERS

More than 300 faculty members and academic staff perform significant research related to energy at Stanford and SLAC National Accelerator Laboratory. For a searchable listing of them, with filters for topic areas and academic departments, visit: energy.stanford.edu/people/faculty.



George Shultz speaking in 2013 at the Energy@Stanford & SLAC boot camp for new graduate students interested in energy, a conference at which he spoke every year. Photo: Mark Shwartz

IN MEMORIAM: GEORGE P. SHULTZ

FORMER U.S. SECRETARY OF STATE GEORGE P. SHULTZ, distinguished fellow at the Hoover Institution and chairman of the Precourt Institute for Energy Advisory Council, who served three American presidents and played a pivotal role in shaping economic and foreign policy in the late 20th century, died Feb. 6, 2021, at his home on the Stanford campus. He was 100 years old.

One of the most consequential policy makers of all time and remembered as one of the most influential secretaries of state in U.S. history, Shultz was a key player, alongside President Ronald Reagan, in changing the direction of history by using the tools of diplomacy to bring the Cold War to an end. He knew the value of one's word, that "trust was the coin of the realm," and stuck unwaveringly to a set of principles. This, combined with a keen intelligence, enabled him not only to imagine things thought impossible but also to bring them to fruition and forever change the course of human events.

Shultz's extraordinary career spanned government, academia and business. He is one of only two Americans to have held four different federal cabinet posts – State, Treasury, Labor, and Office of Management & Budget. He taught at three renowned universities, and for eight years was president of a major engineering and construction company.

Shultz first joined Stanford in 1968 and had periodic affiliations with the university throughout his public service career, finally returning to campus in 1989. Always dedicated to his students and higher education, Shultz tackled some of humanity's most difficult issues – including nuclear disarmament, climate change and democratic governance – in the classroom, in book and article form, and at events he hosted. Those issues drove him to keep working at Stanford nearly every day until his passing.

In 1982, Reagan names Shultz secretary of state at a time of heightened global tensions with the Soviet Union.

The full measure of his talent at negotiation came when Shultz implemented a foreign policy approach that eased those tensions and led to several landmark arms control treaties. Shultz also was secretary of labor, the first director of the Office of Management & Budget and secretary of the treasury, all under President Richard Nixon.

Shultz was deeply committed to addressing climate change.

"Over the past four decades, the United States has been on an energy roller coaster that has landed us, unnecessarily, in a place that is dangerous to our economy, our national security and our climate," Shultz said in a 2008 announcement for an initiative he launched at the Hoover Institution, the Shultz-Stephenson Task Force on Energy Policy.

Shultz co-authored *The State Clean Energy Cookbook* – a collaboration between the Hoover Institution and the Steyer-Taylor Center for Energy Policy & Finance – that provided states with guidance on energy efficiency and renewable energy initiatives. The Precourt Institute changed the name of its student summer internship program working with state agencies in honor of Shultz in 2020.

Shultz's numerous honors include the Medal of Freedom (1989), the nation's highest civilian honor, as well as many honorary degrees. He was a member of the American Academy of Arts & Sciences and the American Philosophical Society.

Shultz's wife, Charlotte Mailliard Shultz, passed away on Dec. 3, 2021 at age 88. Secretary Shultz is survived by his five children: Margaret Tilsworth, Kathleen Jorgensen, Peter Shultz, Barbara White and Alexander Shultz, as well as 11 grandchildren and nine great-grandchildren.

(Adapted from the Stanford News obituary.)



ABOUT THE PRECOURT INSTITUTE FOR ENERGY

Through collaborations across campus, Stanford's Precourt Institute fosters and supports the Stanford ENERGY community. Through its multiple programs, the institute funds research that has the potential to solve today's toughest energy challenges and help transform the world's energy systems.

Stanford students can discover energy through the institute's Explore Energy program, which includes courses, internships, entrepreneurial activities and a one-week orientation for incoming graduate students interested in energy.

The Precourt Institute works with industry leaders, entrepreneurs and policymakers for the broad deployment of solutions. It also engages a wide range of stakeholders at events like the Global Energy Forum.

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Editors

Mark Golden
Mark Shwartz

Creative Director

Miki Yu

Graphic Design

Dolfin Leung

Cover Illustration by

Greg Stewart
SLAC National
Accelerator Laboratory

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Precourt Institute for Energy
Stanford University
Jerry Yang & Akiko Yamazaki
Environment & Energy Building
473 Via Ortega, Stanford, CA 94305