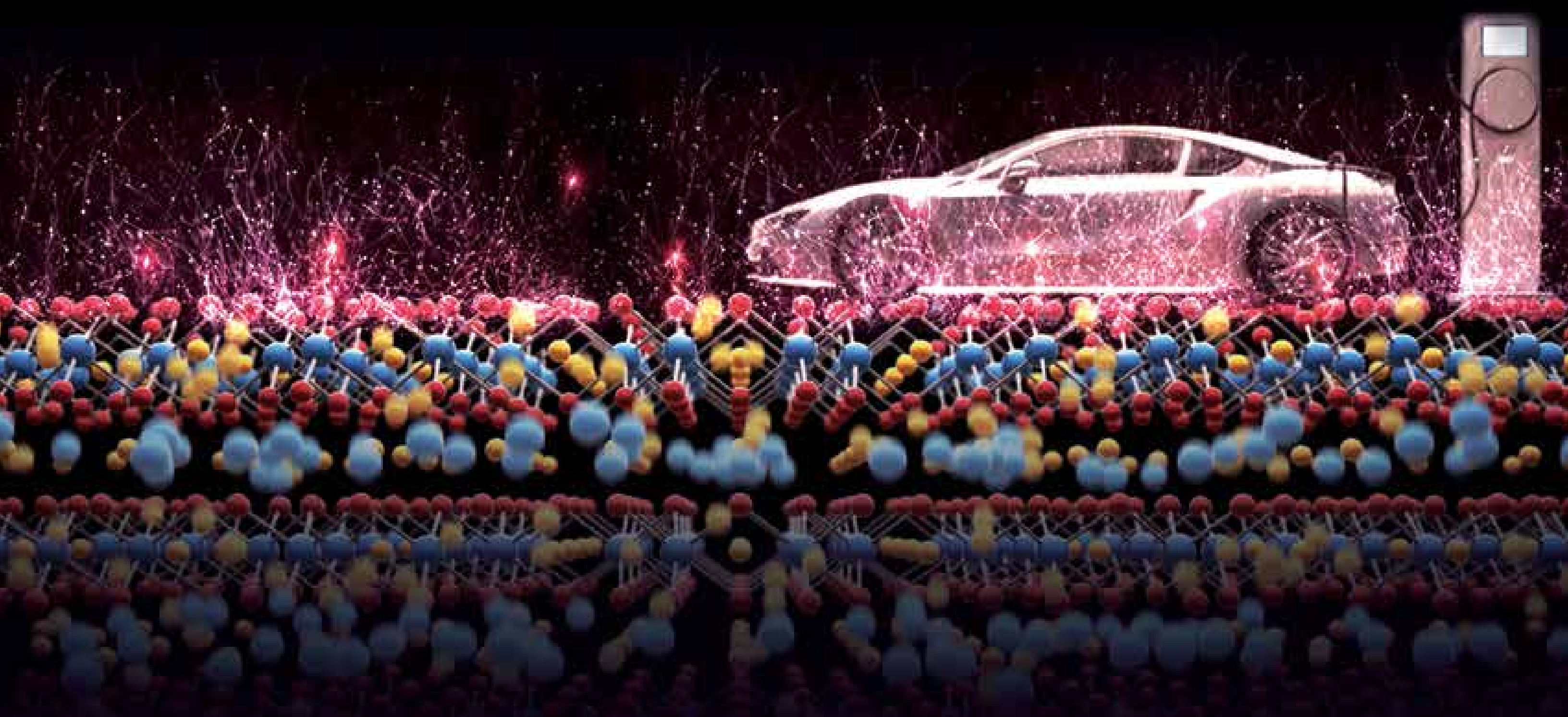
STANFORD
ENERGY RESEARCH

YEAR IN REVIEW 2018 – 2019



Stanford
ENERGY


Photo: GSB 2017

Promoting Sustainable Solutions

Experts navigate a critical moment in energy and climate science.

By Marc Tessier-Lavigne

Photo: L.A. Cicero

"We all stand at the threshold of a major energy transformation at a colossal scale. . . . This transformation will shape the economy, the environment, and the international security and geopolitics of the 21st century. Every nation, region, business and industry ought to pay close attention to this, because it will affect everyone." Arun Majumdar, co-director with Sally Benson of the Stanford Precourt Institute for Energy, delivered this call to action in his opening address at the inaugural Stanford Global Energy Forum, a gathering of policymakers, technology entrepreneurs, scientists and other energy thought leaders.

The forum highlighted the critical juncture we have reached in energy and climate science—a moment that presents both complex problems and new opportunities. The interlinked challenges of tackling climate change and providing clean, reliable energy on a global scale are, without question, defining issues of the 21st century.

Stanford is leading the charge to develop new energy strategies and to confront climate change through our research and education missions and through the university's own operations. Under Stanford's long-range vision, our sustainability design team has been tasked with prioritizing initiatives that Stanford can undertake to develop sustainability solutions for our region, nation and world.

We will achieve one of the goals set out in our long-range vision when Stanford's second solar power generating plant goes online in 2021. The new solar plant will enable Stanford to produce enough renewable electricity each year to equal the university's annual electricity consumption. This change, combined with our existing solar generating systems, will allow Stanford to achieve an 80 percent reduction in greenhouse gas emissions by 2025. The university is also on track to be zero waste by 2030.

On the research front, Stanford scientists are exploring more effective strategies for carbon management, from growing more forests to locking carbon dioxide in deep geological formations. They are re-envisioning the electricity grid to accommodate growth in renewable energy, storage needs and electric vehicle use. Experts are also using our university's interdisciplinary strength to address the secondary implications of climate change—everything from how to mitigate the impact on health and biodiversity to financial and policy solutions that accelerate decarbonization of both developed and developing economies.

While our experts are making progress, there will be work to do in energy and climate science for decades to come. That's why Stanford is educating leaders who will be equipped to address both current and future energy and sustainability challenges. Stanford students and postdocs receive support for transitioning their entrepreneurial ideas from the laboratory to the marketplace, including through the TomKat Center for Sustainable Energy's Innovation Transfer Program and the Stanford Woods Institute for the Environment's Realizing Environmental Innovation Program. Both programs award grants to develop prototypes, refine business plans and conduct market research.

In fact, the Forbes 2019 "30 Under 30 in Energy" list includes two Stanford students and two recent alumni. One featured alumnus founded a company that helps utilities manage electric vehicle charging. A Stanford undergraduate has developed a low-cost, high-performance membrane for batteries that holds promise for storing renewable energy. He is working to commercialize the technology while pursuing his studies in computer science and math.

The ongoing work by experts here at Stanford and around the world gives me great hope in our ability to engage across sectors and find practical solutions to the challenges posed by global energy demand and climate change. The challenges are complex, but if we approach our energy future with intention, I believe we can get to solutions and create a future that is bright with opportunity.

Marc Tessier-Lavigne is the president of Stanford University.

Courtesy: *Stanford Magazine* (March 2019)

"ENERGY IS A MAJOR RESOURCE for any society. Energy powers the economy and is an essential ingredient in national security. Energy also has a clear relationship to a variety of environmental issues, so work on this subject has enduring and vital significance.

Over the decades, energy use has changed, as has the relative prominence of related problems. History has been like a roller coaster ride. The Arab Oil Embargo in 1973 dramatically demonstrated to the U.S. population the importance of the subject, and the country began to think about new forms of energy and its efficient use. That episode made a deep impression on the body politic. When the price of fossil fuels is high and there is a scarcity, as in 1973, interest increases. When the price goes down, this interest falls away. We saw this happen again during the time of the Iranian revolution in 1979, when energy prices soared and the sense of urgency returned.

One fruitful response to that has been development of the capacity for horizontal drilling and hydraulic fracturing, and as a result the United States has become a large producer of oil and natural gas. That helps our economy and our national security, but it does not solve the problem of a warming climate. We must have ways to draw people's attention to that problem, too. My suggestion is a revenue-neutral carbon tax, an idea that is gradually catching on. And if people want to do more in the meantime, what to do? That's where research and development comes in.

Today scientists and engineers are doing more energy R&D than ever before. And the U.S. institution with the greatest capacity to affect long-term thinking is the university. It is up to us at Stanford and others at other leading universities to carry the torch and see that strong R&D work is maintained and encouraged. We have a good foundation to build on and impressive results to show that energy R&D has clearly contributed to a better energy future and can continue to do so."

– GEORGE P. SHULTZ

Thomas W. and Susan B. Ford Distinguished Fellow
Hoover Institution, Stanford University

Former U.S. Secretary of State George Shultz in conversation with former U.S. Defense Secretary William Perry (left) at the Stanford Global Energy Forum in 2018.

Photo: Rod Searcey

Photo: Carolyn Marie Raider

A WORD FROM THE CO-DIRECTORS

WELCOME TO the first edition of *Stanford Energy Research Year in Review.*

Over the past academic year, Stanford University researchers made remarkable contributions to understanding how we can make our energy systems around the world more sustainable, affordable and secure. These advances range from discoveries about energy processes at the molecular level to greater clarity about energy's impacts on our environment, from inventions of radically new devices to information that enables wise energy policies and business practices. The handful of examples in this review offer a glimpse into all that we have to celebrate.

This is an all-campus affair. Remarkably, researchers working on energy topics are in all seven of Stanford's schools. Faculty and staff energy researchers total almost 300 people. Two new, major research efforts in energy join the Natural Gas Initiative and Bits & Watts as cross-campus initiatives. They are the Sustainable Finance Initiative launched in the fall of 2018 and the Stanford StorageX Initiative, which will open its doors this fall.

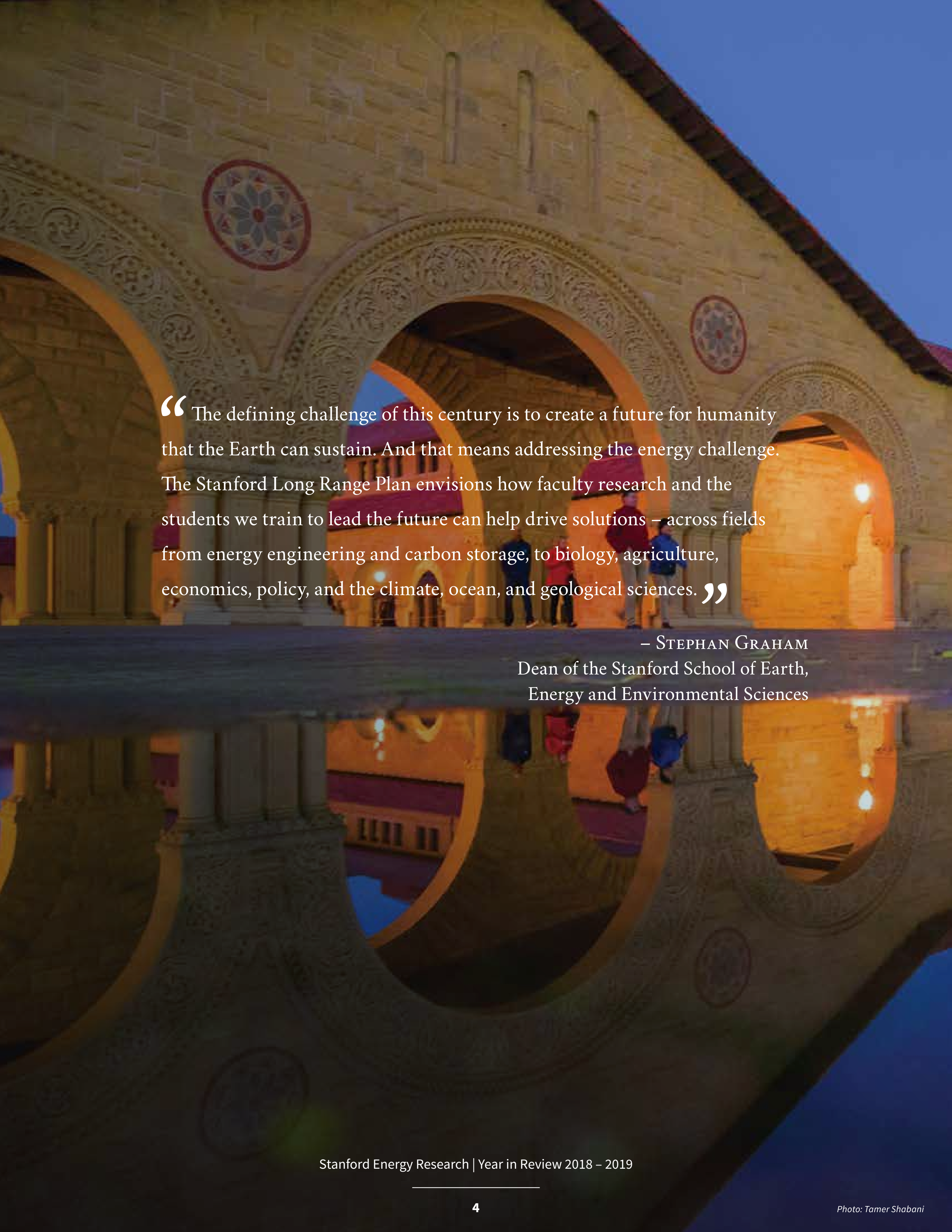
Beyond the faculty and staff researchers, hundreds of students and postdoctoral scholars perform much of Stanford's work in energy. They, too, are celebrated in these pages. Every year, students learn diverse new skills, like advanced imaging and machine learning, which they then apply to provide new energy solutions. In turn, they can choose from hundreds of energy-related courses to expand their knowledge. Many experiential learning opportunities exist, too, like the Summer Undergraduate Program on Energy Research internship program and the Stanford Energy Ventures class.

We also want to thank Stacey Bent for her leadership of the very productive TomKat Center for Sustainable Energy since its inception 10 years ago. Stacey, a professor in Chemical Engineering, is becoming Stanford's vice provost for graduate education and postdoctoral affairs. We wish her great success in her new endeavor.

For all our faculty, students, alumni, staff, collaborators and supporters, we hope this review provides a moment for collective pride in our accomplishments and excitement about the future.

SALLY BENSON
Co-director, Precourt Institute for Energy
Professor, Energy Resources Engineering

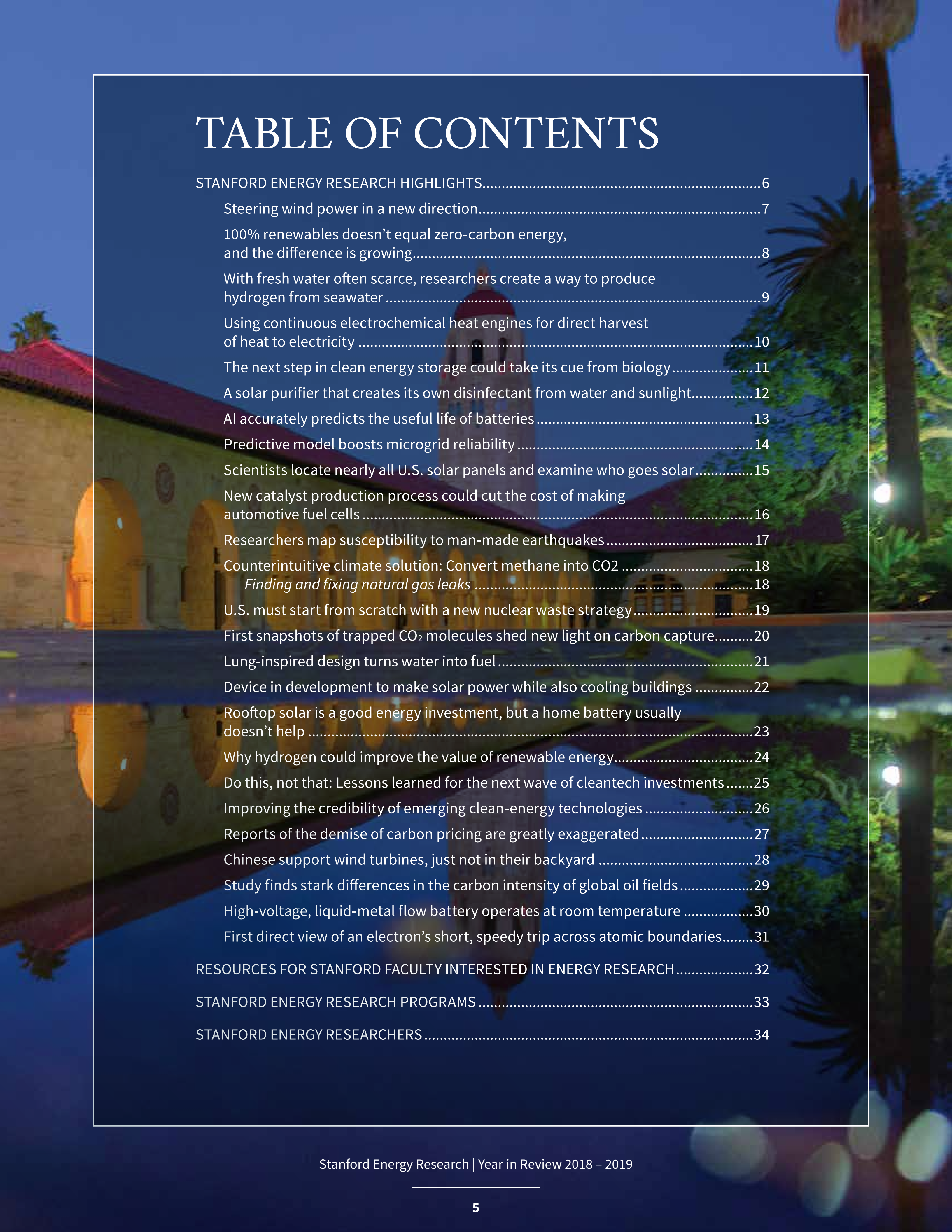
ARUN MAJUMDAR
Co-director, Precourt Institute for Energy
Jay Precourt Professor, Mechanical Engineering



“The defining challenge of this century is to create a future for humanity that the Earth can sustain. And that means addressing the energy challenge. The Stanford Long Range Plan envisions how faculty research and the students we train to lead the future can help drive solutions – across fields from energy engineering and carbon storage, to biology, agriculture, economics, policy, and the climate, ocean, and geological sciences.”

– Stephan Graham
Dean of the Stanford School of Earth, Energy and Environmental Sciences

Photo: Tamer Shabani



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STANFORD ENERGY RESEARCH HIGHLIGHTS

“The Among the most urgent issues facing society is how to provide humanity with the affordable energy it needs and stabilize the climate. Stanford Engineering is proud to play a role in seeking solutions.”

– Jennifer Widom
Dean of the Stanford School of Engineering

Steering wind power in a new direction

Howland, M.F.; Lele, S.K.; and Dabiri, J.O. (2019). Wind farm power optimization through wake steering. *Proceedings of the National Academy of Sciences*, **DOI:10.1073/pnas.1903680116**

From left, professors Sanjiva Lele and John Dabiri, and PhD student Michael Howland. (Photo: L.A. Cicero)

> “The traditional focus has been on the performance of individual turbines in a wind farm, but we need to start thinking about the farm as a whole and not just as the sum of its parts.”
>
> –JOHN DABIRI, PROFESSOR, CIVIL & ENVIRONMENTAL ENGINEERING and MECHANICAL ENGINEERING

Solitary wind turbines produce the most power when pointing directly into the wind. But when tightly packed turbines face the wind, wakes from upstream generators can interfere with those downstream. Like a speedboat slowed by choppy water from a boat in front, the wake from turbines in a wind farm reduces the output of those behind it.

Now, engineering professors John Dabiri and Sanjiva Lele have discovered that wake steering, or pointing turbines slightly away from oncoming wind, can reduce downstream interference and boost the quantity of power generated at wind farms. Working with PhD student Michael Howland, the researchers developed a quick way to calculate how best to position upstream turbines against prevailing winds to raise production downstream. They tested their wake-steering calculations at a Canadian wind farm and found that they could increase the overall power output of the entire farm by up to 47 percent in low wind speeds, depending on the angle of the turbines.

Image: Rebecca Konte

100% renewables doesn't equal zero-carbon energy, and the difference is growing

de Chalendar, J.A.; and Benson, S.M. (2019). Why 100% renewable energy is not enough.
Joule, **DOI:10.1016/j.joule.2019.05.002**

While many companies have committed to use "100 percent renewable energy," that does not mean "100 percent carbon-free energy," according to postdoctoral scholar Jacques de Chalendar and Professor Sally Benson. Current methods of estimating greenhouse gas emissions use yearly averages, even though the carbon content of electricity on the grid varies widely over the course of a day.

> "To guarantee 100 percent emissions reductions from renewable energy, power consumption needs to be matched with renewable generation on an hourly basis."
>
> –SALLY BENSON, PROFESSOR,
> ENERGY RESOURCES ENGINEERING

Calculating carbon emissions on an hourly basis provides a far more accurate picture, the researchers say. For example, a company equipped with solar panels generates more electricity in the afternoon than it uses. At night, the company has to buy power from the grid, but grid electricity often comes from burning fossil fuels. The researchers found that using annual accounting, a 100 percent solar strategy in 2025 could, on paper, reduce a company's carbon emissions by 119 percent. But using hourly emissions, that number shrinks to 66 percent.

With fresh water often scarce, researchers create a way to produce hydrogen from seawater

Kuang, Y.; Kenney, M.J.; Meng, Y.; Hung, W-H.; Liu, Y.; Huang, J.E.; Prasanna, R.; Li, P.; Li, Y.; Wang, L.; Lin, M-C.; McGehee, M.D.; Sun, X.; and Dai, H. (2019). Solar-driven, highly sustained splitting of seawater into hydrogen and oxygen fuels. *Proceedings of the National Academy of Sciences,* **DOI:10.1073/pnas.1900556116**

Splitting water into clean hydrogen and oxygen with electricity is a simple idea. But existing water-splitting methods rely on highly purified water, a precious resource. Abundant seawater is a promising alternative, but the negatively charged chloride in salt can corrode one of the two metal electrodes used to split the water.

Professor Hongjie Dai and colleagues devised a way to generate clean fuels using solar power, electrodes and seawater. They discovered that coating metal electrodes with layers rich in negative charges repels chloride and slows down the decay of the underlying metal. Without the negatively charged coating, electrodes immersed in seawater can only produce hydrogen for about 12 hours. But with the coating, the electrode runs for more than 1,000 hours. Because the new technology also produces breathable oxygen, researchers predict that divers and submarines could someday use seawater to generate oxygen without having to surface for air.

> “This technology provides an opportunity to use the Earth’s vast seawater resource as an energy carrier.”
>
> –HONGJIE DAI, THE J.G. JACKSON AND C.J. WOOD PROFESSOR IN CHEMISTRY

Photo: H. Dai, Yun Kuang, Michael Kenney

Hongjie Dai and his research lab at Stanford University have developed a prototype that can generate hydrogen from seawater.

Photo: Pexls from Pixabay

Using continuous electrochemical heat engines for direct harvest of heat to electricity

Poletayev, D.; McKay, I.; Chueh, W.C.; and Majumdar, A. (2018). Continuous electrochemical heat engines. *Energy & Environmental Science*, **DOI:10.1039/C8EE01137K**

Developing a heat engine that efficiently converts waste heat to electrical power could significantly reduce greenhouse gas emissions. Professor Arun Majumdar and colleagues have designed an electrochemical heat engine that does just that. The novel engine consists of two stacks of electrochemical cells connected in series. One stack runs a chemical reaction at a high temperature, while the other stack runs the reverse reaction at a cold temperature. Excess heat from the high-temperature cells is used to power the low-temperature chemical reaction. The voltage required by the hot cells is lower than the voltage generated by the cold cells.

This voltage difference produces a continuous electric current that can be used to power a variety of devices. With optimal design, continuous heat engines could achieve high efficiencies and high power densities, the researchers say. Operating the engine in reverse could in principle enable electrochemical refrigeration, they add.

> “Continuous electrochemical heat engines could fill a vital missing space in the existing landscape of energy harvesting technologies.”
>
> –ARUN MAJUMDAR, THE JAY PRECOURT PROVOSTIAL CHAIR PROFESSOR, MECHANICAL ENGINEERING

Image by David Reed from Pixabay

The next step in clean energy storage could take its cue from biology

Frauke, K.; Wong, A.B.; Maegaard, K.; Deutzmann, J.S.; Hubert, M.A.; Hahn, C.; Jaramillo, T.F.; and Spormann, A.M. (2019). Robust and biocompatible catalysts for efficient hydrogen-driven microbial electrosynthesis. *Communications Chemistry*, **DOI:10.1038/s42004-019-0145-0**

Professors Tom Jaramillo and Alfred Spormann are developing a practical way to use microbes to convert clean electrical energy into renewable methane fuel, an emissions-free alternative to natural gas. The ultimate goal is to create sustainable microbial factories that store surplus solar and wind power in the form of methane.

> “The goal is to create large bioreactors where microbes convert atmospheric CO_2 and clean electricity into renewable fuels and chemicals.”
>
> –ALFRED SPORMANN, PROFESSOR, CHEMICAL ENGINEERING and CIVIL & ENVIRONMENTAL ENGINEERING

The research focuses on microorganisms that ingest carbon dioxide and electrons from hydrogen, and then excrete methane gas as a byproduct. When the microbial methane is burned for fuel, CO_2 is released into the atmosphere. That CO_2 is then consumed by the microbes, making the entire process carbon neutral. To increase microbial methane production, the researchers used electricity from solar and wind sources to split water into oxygen and hydrogen. The hydrogen atoms then carried electrons to the microbes, which used the electrons to convert CO_2 from the air into methane. The water-splitting technique significantly boosted methane production by increasing the availability of hydrogen to feed the hungry microbes.

Photo: Mark Shwartz

A solar purifier that creates its own disinfectant from water and sunlight

Shi, X.; Zhang, Y.; Siahrostami, S.; and Zheng, X. (2018). Light-driven $BiVO_4$–C fuel cell with simultaneous production of H_2O_2. *Advanced Energy Materials*, **DOI:10.1002/aenm.201801158**

Xiaolin Zheng and colleagues have developed a device that uses sunlight and water to produce hydrogen peroxide, a powerful antiseptic that can purify water. The goal is to create inexpensive, portable water purifiers for billions of people who lack access to potable water. The device uses electrodes made of bismuth vanadate and carbon to convert water into hydrogen peroxide. Two tablespoons of hydrogen peroxide are enough to purify about 25 gallons of water. The technology could be used for solar-powered water purification in developing regions where freshwater is a precious commodity, or as an alternative to chlorine to cleanse swimming pools. However, much work remains to be done, including replacing bismuth vanadate, a toxic compound, with a harmless photoelectric material.

> “Between two and three billion people have no access to clean water. My vision is this will be a portable, distributed water-disinfection system for personal or single-family use.”
>
> –XIAOLIN ZHENG, ASSOCIATE PROFESSOR, MECHANICAL ENGINEERING

AI accurately predicts the useful life of batteries

Severson , K.A.; Attia, P.M.; Jin, N.; Perkins, N.; Jiang, B.; Yang; Chen, M.H.; Aykol, M.; Herring, P.K..; Fraggedakis, D.; Bazant, M.Z.; Harris, S.J.; Chueh, W.C.; and Braatz, R.D. (2019). Data-driven prediction of battery cycle life before capacity degradation. *Nature Energy*, **DOI:10.1038/s41560-019-0356-8**

In an advance that could accelerate battery development and improve manufacturing, scientists have found a way to predict the useful lifespan of lithium-ion batteries used in everything from mobile phones to electric cars. Combining comprehensive experimental data and artificial intelligence, the scientists from Stanford, MIT and the Toyota Research Center developed an algorithm that predicts how many cycles a battery will last based on voltage declines and other factors.

Separately, the algorithm categorizes batteries as either long or short life expectancy based on just the first five charge/discharge cycles. With this machine-learning method, electric vehicle batteries determined to have short lifespans—too short for cars—could be used instead to power street lights or back-up data centers. The technique could also help new battery designs reach the market more quickly by reducing one of the most time-consuming steps – battery testing.

> “Knowing when a battery is going to fail has tremendous value to the manufacturer and to the consumer.”
>
> –WILLIAM CHUEH, ASSOCIATE PROFESSOR, MATERIALS SCIENCE & ENGINEERING

Image: Younghee Lee, Cube3D

Predictive model boosts microgrid reliability

Du, Y.; Wu, J.; Li, S.; Long, C.; and Onori, S. (2019). Coordinated energy dispatch of autonomous microgrids with distributed MPC optimization. *IEEE Transactions on Industrial Informatics,* **DOI:10.1109/TII.2019.2899885**

The growing demand for clean energy has spurred interest in autonomous microgrids – small, independent power stations that generate electricity from solar, wind and other renewable sources. In southern China, isolated rural cities are being connected by autonomous microgrid networks that coordinate the production and delivery of clean electricity based on local supply and demand. Now, scientists at Stanford and Shanghai Jiao Tong University have created an algorithm to manage these networks in real time.

> “With this algorithm, we not only maintain a supply-demand balance in an economic way, but also improve the renewable-energy utilization of distributed microgrid systems.”
>
> –SIMONA ONORI, ASSISTANT PROFESSOR, ENERGY RESOURCES ENGINEERING

The algorithm rapidly predicts changes that could affect the energy needs of individual microgrids, then supplies that information to a network operator for a quick response. Consider, for example, a network of three autonomous microgrids powered by solar panels. When clouds pass over one of the microgrids, its electricity output drops. Using weather-forecasting data, the predictive algorithm calculates how much additional electricity the cloud-covered microgrid will need and for how long. Based on that forecast, the network operator can quickly borrow surplus energy from the other two microgrids until the clouds pass. The result: a more robust and reliable network.

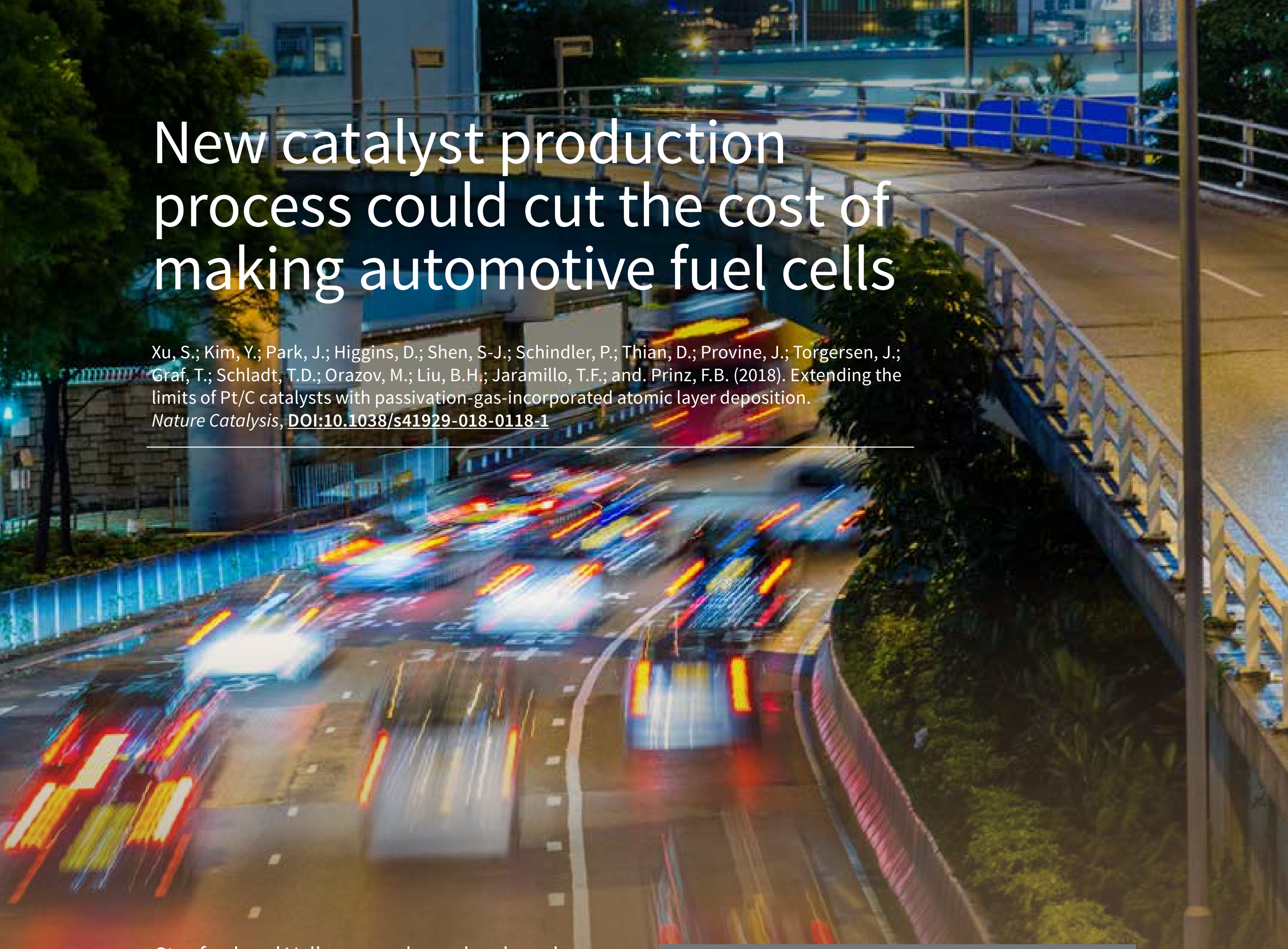
Scientists locate nearly all U.S. solar panels and examine who goes solar

Yu, J.; Wang, Z.; Majumdar, A.; and Rajagopal, R. (2018). DeepSolar: A machine learning framework to efficiently construct a solar deployment database in the United States. *Joule*, **DOI:10.1016/j.joule.2018.11.021**

Knowing which Americans have installed solar panels on their roofs and why they did so would be enormously useful for managing the U.S. electricity system. To get accurate numbers, Stanford scientists analyzed more than a billion high-resolution satellite images with a machine-learning algorithm, named DeepSolar, and identified nearly every solar power installation in the contiguous 48 states, a total of 1.4 million.

The team trained DeepSolar to recognize features associated with solar panels – such as color, texture and size – and then used those features to scan the satellite images and find solar installations. Using additional data from the U.S. Census, the study revealed that once solar penetration reaches a certain level in a neighborhood it takes off. But if the neighborhood has significant income inequality, that activator often does not switch on. The team also discovered a threshold of how much sunlight a given area needs to trigger adoption.

> "We can use recent advances in machine learning to know where all these solar assets are, which has been a huge question, and generate insights about where the grid is going and how we can help get it to a more beneficial place."
>
> –RAM RAJAGOPAL, ASSOCIATE PROFESSOR, CIVIL & ENVIRONMENTAL ENGINEERING



New catalyst production process could cut the cost of making automotive fuel cells

Xu, S.; Kim, Y.; Park, J.; Higgins, D.; Shen, S-J.; Schindler, P.; Thian, D.; Provine, J.; Torgersen, J.; Graf, T.; Schladt, T.D.; Orazov, M.; Liu, B.H.; Jaramillo, T.F.; and. Prinz, F.B. (2018). Extending the limits of Pt/C catalysts with passivation-gas-incorporated atomic layer deposition. *Nature Catalysis*, **DOI:10.1038/s41929-018-0118-1**

Stanford and Volkswagen have developed in partnership a new catalyst production process to reduce the comparatively high cost of automotive fuel cell technology. One of the biggest cost drivers for fuel cells is the use of the precious metal platinum as a catalyst to operate the cell. Platinum is conventionally distributed as particles on carbon powder. As a result, the desired catalytic process only takes place on the surface of the platinum, wasting large quantities of this expensive material.

> “This technology opens up enormous possibilities for cost reduction, as the amount of precious metal used is minimized, while service life and catalyst performance are increased.”
>
> –FRITZ PRINZ, THE LEONARDO PROFESSOR, MATERIALS SCIENCE & ENGINEERING and MECHANICAL ENGINEERING

In the new process, platinum atoms are placed on a carbon surface using a modified atomic layer deposition technique that produces extremely thin particles. This technique reduces the amount of platinum required to a fraction of the usual amount. Researchers say the process may have other automotive applications requiring high-performance materials, including next-generation lithium-ion batteries for electric vehicles.

Researchers map susceptibility to man-made earthquakes

Langenbruch, C.; Weingarten, M.; and Zoback, M.D. (2018). Physics-based forecasting of man-made earthquake hazards in Oklahoma and Kansas. *Nature Communications*, **DOI:10.1038/s41467-018-06167-4**

A computer model developed by Stanford geoscientists forecasts a decrease in man-made earthquakes in Oklahoma and Kansas through 2020. Induced earthquakes in those states had been on the rise because of the widespread practice of injecting produced water, a byproduct of oil and gas operations, deep underground. Produced water injection can increase pressure on pre-existing faults already under stress from tectonic processes, triggering potentially damaging earthquakes. Oklahoma's induced earthquakes peaked in 2015, with nearly 1,000 widely felt temblors across the state.

However, when the state mandated a 40 percent water-injection reduction in early 2016, the number of earthquakes declined. The Stanford model forecasts a 19 percent probability of potentially damaging earthquakes of magnitude 5.0 or above in 2020, compared to 70 percent in 2016 – an indication that Oklahoma's regulatory policies are working. Researchers also point out that the model helps identify specific areas in north-central Oklahoma and southern Kansas where oil and gas operations are underway and produced-water injection would be most likely to trigger seismicity.

> “Predictive maps can allow residents to see the probability that potentially damaging earthquakes will strike close to their homes and can be used by regulators to evaluate future water-injection sites.”
>
> –MARK ZOBACK, THE BENJAMIN M. PAGE PROFESSOR OF GEOPHYSICS

Counterintuitive climate solution: Convert methane into CO_2

Jackson, R.B.; Solomon, E.I.; Canadell, J.G.; Cargnello, M.; and Field, C.B. (2019). Methane removal and atmospheric restoration. *Nature Sustainability,* **DOI:10.1038/s41893-019-0299-x**

A seemingly counterintuitive approach—converting methane into carbon dioxide—could help turn the tide of climate change, while also turning a healthy profit. Methane, the main ingredient in natural gas, is 84 times more potent than CO_2 in terms of warming the climate system over the first 20 years after its release. A study led by professors Rob Jackson and Chris Field found that converting methane emissions to CO_2 would eliminate about one-sixth of all causes of global warming to date.

> “This technology could slow global warming and restore the atmosphere to pre-industrial concentrations of methane.”
>
> –ROB JACKSON, THE MICHELLE AND KEVIN DOUGLAS PROVOSTIAL PROFESSOR IN EARTH SYSTEM SCIENCE

Methane concentrations could be restored to pre-industrial levels by removing about 3.2 billion tons of the gas from the atmosphere and converting it into a relatively small amount of CO_2, the researchers say. One idea involves capturing atmospheric methane with sponge-like catalysts, and then heating the trapped methane to form CO_2. The process is potentially profitable, but only if a market or mandate for methane removal exists.

FINDING AND FIXING NATURAL GAS LEAKS

As it flows through pipelines from wells to stovetops, natural gas is prone to leaking, costing industry billions of dollars in lost revenue and jeopardizing human safety and the environment. Researchers with the Stanford Natural Gas Initiative are working on better ways to find and fix gas leaks quickly and inexpensively, from specially equipped cars that detect methane leaks in big cities, to analyses of industrial-scale leaks and their impact on climate change.

Read more: energy.stanford.edu/news/finding-fixing-natural-gas-leaks

"Radioactive Gordian Knot" by François Diaz-Maurin

U.S. must start from scratch with a new nuclear waste strategy

Ewing, R.; et al. (2018). ***Reset of America's Nuclear Management: Strategy and Policy.*** Stanford Center for International Security and Cooperation

The federal government has worked for decades and spent tens of billions of dollars in search of a permanent resting place for the nation's nuclear waste. Now, a panel led by Professor Rod Ewing recommends that the United States reset its nuclear waste program by moving responsibility for commercially generated, used nuclear fuel away from the federal government and into the hands of an independent, nonprofit nuclear waste management organization owned and funded by utilities.

The new organization would control spent fuel from the time it is removed from reactors until its final disposal in a geologic repository. Finland, Sweden, Switzerland and Canada have adopted a similar approach, and their nuclear waste management programs are moving forward, the panel said. They recommended that Congress gradually transfer the Nuclear Waste Fund, which totals more than $40 billion, to the new independent organization. If the organization identifies a permanent geologic repository, that site should also be used to store highly radioactive defense waste, the panel said.

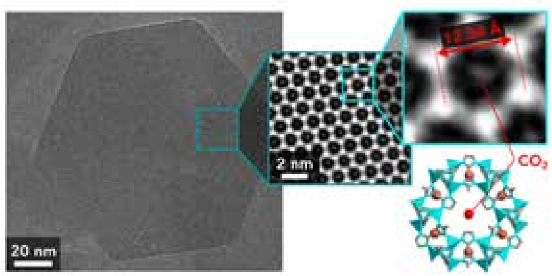
> "The U.S. nuclear waste program is in gridlock. No single group, institution or governmental organization is incentivized to find a solution."
>
> –ROD EWING, THE FRANK STANTON PROFESSOR IN NUCLEAR SECURITY, FREEMAN SPOGLI INSTITUTE FOR INTERNATIONAL STUDIES, and PROFESSOR, GEOLOGICAL SCIENCES

First snapshots of trapped CO_2 molecules shed new light on carbon capture

Li, Y.; Wang, K.; Zhou, W.; Sinclair, R.; Chiu, W.; Cui, Y. (2019). Cryo-EM structures of atomic surfaces and host-guest chemistry in metal-organic frameworks. *Matter*, **DOI:10.1016/j.matt.2019.06.001**

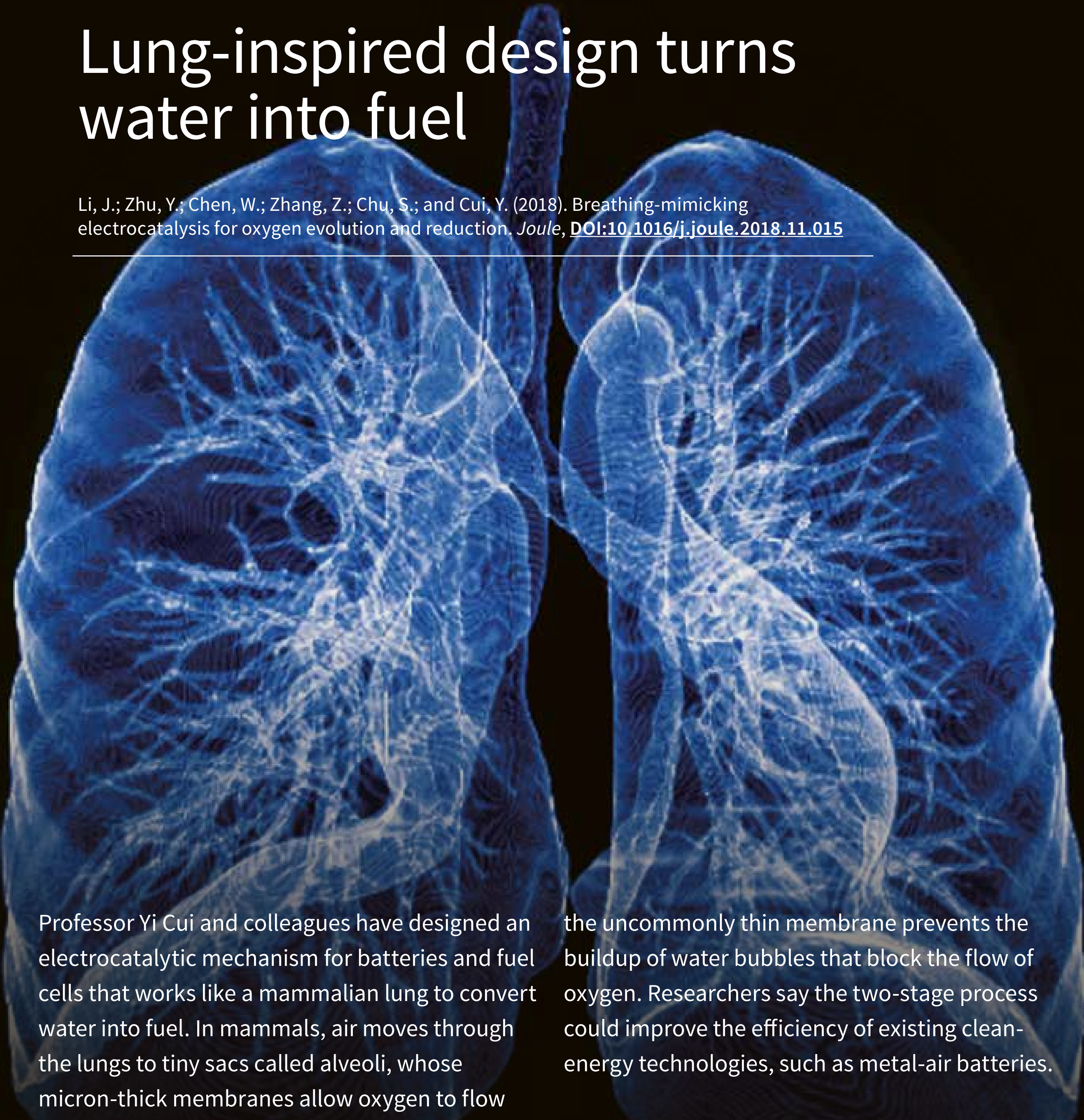
Researchers have taken the first atomic-scale images of carbon dioxide molecules trapped in highly porous nano-materials called metal-organic frameworks (MOFs). Designed like honeycombs, MOFs are filled with nano-size cages that can store CO_2 molecules captured from the atmosphere. To obtain the images, researchers trapped CO_2 molecules in MOF nano-cages, flash-froze the material in liquid nitrogen and examined it with an electron microscope.

The images revealed that the cages expand slightly as the CO_2 enters, and that new cages may form on the outer edges of the MOF as it grows. The findings provide insights on engineering new MOFs for specific tasks, such as permanently capturing CO_2 from smokestacks to combat climate change. MOFs have the largest surface area of any known material. One gram can equal the area of two football fields, offering plenty of space for guest molecules to enter millions of host cages, the researchers say.



The new electron microscope images at very low temperatures reveal step-like features at the edges of MOF particles (upper right) where scientists think new cages may form as the particle grows (bottom right). Image: Li et al., Matter, 26 June 2019

> “Metal-organic frameworks have the potential to reduce greenhouse gas emissions by capturing large quantities of CO_2 from the atmosphere. Revealing their atomic structure could help understand and design the efficient structures for CO_2 capture.”
>
> –YI CUI, PROFESSOR, MATERIALS SCIENCE & ENGINEERING



Lung-inspired design turns water into fuel

Li, J.; Zhu, Y.; Chen, W.; Zhang, Z.; Chu, S.; and Cui, Y. (2018). Breathing-mimicking electrocatalysis for oxygen evolution and reduction. *Joule*, **DOI:10.1016/j.joule.2018.11.015**

Professor Yi Cui and colleagues have designed an electrocatalytic mechanism for batteries and fuel cells that works like a mammalian lung to convert water into fuel. In mammals, air moves through the lungs to tiny sacs called alveoli, whose micron-thick membranes allow oxygen to flow freely to the bloodstream.

Drawing inspiration from alveoli, Cui's team created a new battery anode with a thin nano-polyethylene membrane that splits water into oxygen and hydrogen gas – a process similar to exhaling. The oxygen is then delivered to the cathode to drive electrochemical reactions, similar to inhalation. Like alveoli, the uncommonly thin membrane prevents the buildup of water bubbles that block the flow of oxygen. Researchers say the two-stage process could improve the efficiency of existing clean-energy technologies, such as metal-air batteries.

> “The novel breathing-mimicking structure offers exciting new opportunities for the field of catalysis.”
>
> JUN LI, PHD STUDENT, MATERIALS SCIENCE & ENGINEERING

Device in development to make solar power while also cooling buildings

Chen, Z.; Zhu, L.; Li, W,; and Fan, S. (2018). Simultaneously and synergistically harvest energy from the Sun and outer space. *Joule*, **DOI:10.1016/j.joule.2018.10.009**

Rooftop solar panels do one thing – they turn sunlight into electricity. But Professor Shanhui Fan's lab has built a device that could have a dual purpose – generating electricity and cooling buildings. Fan's team has developed materials that can cool buildings by radiating infrared heat away from rooftops and into outer space. In a recent experiment, the team attached these radiative-cooling materials to the bottom of a solar panel and placed the device on a sun-drenched rooftop on the Stanford campus. As expected, exposure to sunlight made the top solar cell hotter than the ambient air of the rooftop. But the bottom layer with the radiative-cooling material became significantly cooler. The goal of the research is to develop hybrid solar cells that generate electricity while simultaneously cooling buildings.

> "We've built the first device that could simultaneously make energy and save energy in the same place and at the same time by controlling two very different properties of light."
>
> –SHANHUI FAN, PROFESSOR, ELECTRICAL ENGINEERING

Photo: L.A. Cicero

Professor Shanhui Fan (left) and postdoctoral scholar Wei Li test the efficacy of a double-layered solar panel atop Stanford's Packard Electrical Engineering building. The top layer uses the standard semiconductor materials that go into energy-harvesting solar cells; the novel materials on the bottom layer perform the cooling task.

Rooftop solar is a good energy investment, but a home battery usually doesn't help

Davidsson Kurland, S.; and Benson, S.M. (2019). The energetic implications of introducing lithium-ion batteries into distributed photovoltaic systems. *Sustainable Energy & Fuels,* **DOI:10.1039/C9SE00127A**

Thinking about investing in rooftop solar? Probably a good idea environmentally almost anywhere. Eyeing a home battery, too? Think again, say postdoctoral scholar Simon Davidsson Kurland and Professor Sally M. Benson. Their study of five American states found that the energy produced over the lifetime of typical rooftop solar panels more than makes up for the energy it takes to build, mount and eventually recycle them – but only when homeowners send surplus power to the grid.

Adding a home battery, however, usually lowers those energy dividends, in part because of the additional fossil fuel required to build the battery. What's more, when homeowners charge a battery before supplying the grid, the energy return on investment for the entire system drops 21 percent on average. That's because the amount of electricity a battery discharges is 8 percent less than the amount of electricity required to charge it – a loss when compared to sending electricity directly to the grid where customers can use it immediately.

> "If a state encourages homeowners to invest in rooftop systems to reach clean energy goals, then letting excess power flow directly to the grid makes the most of those investments."
>
> –SALLY BENSON, PROFESSOR, ENERGY RESOURCES ENGINEERING

Photo: Linda A. Cicero

Why hydrogen could improve the value of renewable energy

Glenk, G.; and Reichelstein, S.J. (2019). Economics of converting renewable power to hydrogen. *Nature Energy*, DOI:10.1038/s41560-019-0326-1

> "With hybrid energy systems, you can give renewables a revenue boost by not having to sell power when market prices are unfavorable."
>
> –STEFAN REICHELSTEIN, THE WILLIAM R. TIMKEN PROFESSOR OF ACCOUNTING, EMERITUS, GRADUATE SCHOOL OF BUSINESS

Wind turbines and solar panels often generate electricity when it isn't needed, and this surplus energy doesn't fetch a good price. A partial solution may lie with hybrid energy systems that combine renewable power generation with electrolysis. That process uses electric power to split water into pure oxygen and hydrogen, with hydrogen being a valuable industrial commodity. But would the extra revenue from hydrogen sales be enough to justify investment in a hybrid energy facility? To find out, the researchers analyzed equipment costs, hourly wholesale electricity prices and the real-time power output generated by wind farms in Germany and Texas.

Their findings: Hybrid energy systems break even if the hydrogen sells for at least $3.50 per kilogram. Small- and medium-scale buyers of hydrogen typically pay about $4 per kilo. The economics of such hybrid systems is poised to improve in the coming years, the researchers say.

Do this, not that: Lessons learned for the next wave of cleantech investments

Weyant, J.; Fu, E.; and Bowersock, J. (2018). *Renewed Energy: Insights for Clean Energy's Future*. Kauffman Fellows Press, **ISBN-10: 1939533023**

An investment boom in clean-energy technology will likely go better the second time around, according to a Stanford analysis. Venture capital investments in cleantech startups peaked in 2008 and have been mired in a slump for several years. When funds dried up, a generation of companies merged, shut down or sold cheaply. The lessons learned from that boom-and-bust cycle will help guide investors, policymakers and entrepreneurs when cleantech investing rebounds, according to the book, *Renewed Energy: Insights for Clean Energy's Future*. Researchers interviewed 11 thought leaders in the energy sector, including former Energy Secretary Steven Chu, now at Stanford, and former EPA chief Carol Browner.

Among the findings: Fund managers should not invest in startups that are not ready for commercialization, and governments should not invest in companies that are fairly advanced. Instead, governments should fund the research and development of technologies considered too speculative for the private sector to sponsor.

> "The good news for cleantech is that an increasing number of managers from traditional energy companies now work at startups, providing much needed knowledge."
>
> –ERNESTINE FU, PHD STUDENT, CIVIL & ENVIRONMENTAL ENGINEERING

Improving the credibility of emerging clean-energy technologies

Carl, J., and Fedor, D. (2019). "**Cutting the Fat Tail of Climate Risk: Carbon Backstop Technologies as a Climate Insurance Policy**." Hoover Institution

A variety of promising technologies to reduce greenhouse gases are too expensive to justify broad deployment today, but public attitudes could change, say Jeremy Carl and David Fedor of the Hoover Institution's Energy Policy Task Force. The researchers examined several emerging clean-energy technologies, including small modular nuclear reactors, direct air capture of carbon dioxide, enhanced oil recovery and solar geoengineering. They concluded that despite high costs, continued government investment in these technologies could eventually improve their credibility with the public as a viable insurance policy to reduce the impact of severe climate change in the future.

> "Today's natural disasters that may be partially attributed to climate change have yet to produce the sort of change in public attitude that would be needed to support the significant ongoing costs and livelihood disruptions associated with deep decarbonization – but that could change."
>
> –DAVID FEDOR, RESEARCH ANALYST, SHULTZ-STEPHENSON TASK FORCE ON ENERGY POLICY, HOOVER INSTITUTION

Image: Idaho National Laboratory

Reports of the demise of carbon pricing are greatly exaggerated

Wolak, F.A. (2018). "**Reports of the Demise of Carbon Pricing are Greatly Exaggerated**." Stanford Institute for Economic Policy Research

Carbon pricing cannot reduce global greenhouse emissions if only a small fraction of jurisdictions around the world put a price on carbon, says Professor Frank Wolak. And setting more stringent caps or higher carbon taxes in the few jurisdictions that price carbon would be counterproductive, he adds.

Instead, governments with carbon pricing should focus on increasing the geographic scope and number of industries covered. After that, the focus can change to increasing the price of carbon to cut global emissions. Ultimately, a certain high price of carbon set through a carbon tax is likely to yield more long-lived investments in carbon-emissions abatement and lower carbon technologies than an uncertain price set through a low emissions cap from a cap-and-trade market, he adds.

> "It would be difficult to argue that any of the regions that currently price carbon have experienced a significant loss in aggregate economic activity. Unfortunately, the lack of evidence for adverse consequences from carbon pricing has not resulted in a significant increase in the adoption of carbon-pricing mechanisms."
>
> –FRANK WOLAK, THE HOLBROOK WORKING PROFESSOR OF COMMODITY PRICE STUDIES IN ECONOMICS

Photo: Denis Hiza from Pixabay

Chinese support wind turbines, just not in their backyard

Shen, S.V.; Cain, B.E.; and Hui, I. (2019). Public receptivity in China towards wind energy generators: A survey experimental approach. *Energy Policy*, **DOI:10.1016/j.enpol.2019.02.055**

Chinese city-dwellers may be somewhat resistant to building wind turbines in urban areas, with a surprisingly high proportion of people citing an unfounded fear of radiation as driving their concerns, according to the largest ever poll of Chinese public opinion toward wind generators.

Researchers at Stanford and the University of Virginia found that many urban residents in China were concerned about noise, cost and the impact turbines could have on birds and other wildlife.

Thirty percent of respondents also worried about radiation emanating from wind turbines, despite studies to the contrary. The survey found that less wealthy neighborhoods might be "more receptive to placing wind turbines in or near their communities, especially if doing so comes with monetary incentives provided by the government." China leads the world in wind-energy power generation and has set ambitious goals for the technology.

> "Some urban residents in China are supportive of wind energy development, but others resent the idea of wind turbines being close to them."
>
> –SHIRAN VICTORIA SHEN, STANFORD BILL LANE CENTER FOR THE AMERICAN WEST

Study finds stark differences in the carbon intensity of global oil fields

Masnadi, M.S.; Brandt, A.R.; et al. (2018). Global carbon intensity of crude oil production. *Science*, **DOI:10.1126/science.aar6859**

A Stanford assessment of greenhouse gas emissions from crude oil production suggests that avoiding the most carbon-intensive reservoirs and better management of natural gas could dramatically slash emissions. Nothing drives up carbon intensity like the practice of routinely burning, or flaring, natural gas, which consists primarily of methane, a significant contributor to global warming. Researchers found that in 2015, nearly 9,000 oilfields in 90 countries produced greenhouse gases equivalent to 1.7 gigatons of carbon dioxide – roughly 5 percent of all emissions from fuel combustion that year. Eliminating routine flaring, gas leaks and venting could cut as much as 43 percent of emissions from the oil sector's annual carbon footprint, according to the study.

> "Hopefully, we'll transition as quickly as possible to renewables, but while we use oil and gas in the meantime, let's do it responsibly."
>
> –ADAM BRANDT, ASSOCIATE PROFESSOR, ENERGY RESOURCES ENGINEERING

High-voltage, liquid-metal flow battery operates at room temperature

Baclig, A.C.; McConohy, G.; Poletayev, A.; Lee, J-H.; Chueh, W.C.; Rugolo, J. (2018). High-voltage, room-temperature liquid metal flow battery enabled by Na-K|K-β″-alumina stability. *Joule*, **DOI:10.1016/j.joule.2018.04.008**

A new combination of low-cost materials may realize the potential for a rechargeable flow battery that stores large amounts of renewable power for delivery to the electric grid when needed. Flow batteries store electron-donating and electron-absorbing fluids in two separate tanks, then flow the fluids together for a chemical reaction that produces an electrical current on demand.

The novel battery developed by Associate Professor William Chueh uses sodium and potassium for the electron-donor tank. When mixed at room temperature, these elements form a liquid metal with at least 10 times more available energy per liter of fluid than other chemicals. And while conventional water-based flow batteries are limited to open-circuit voltages of about 1.5 volts, the new device achieved voltages of 3.1–3.4 V. For stationary batteries, higher voltage results in lower manufacturing costs. The researchers are now investigating a variety of fluids for the electron-absorbing tank to improve the overall stability of the battery.

> “This is a new type of flow battery that could affordably enable much higher use of solar and wind power using Earth-abundant materials.”
>
> – ANTONIO BACLIG, POSTDOCTORAL RESEARCH FELLOW, MATERIALS SCIENCE & ENGINEERING

Image: Younghee Lee, Cube3D

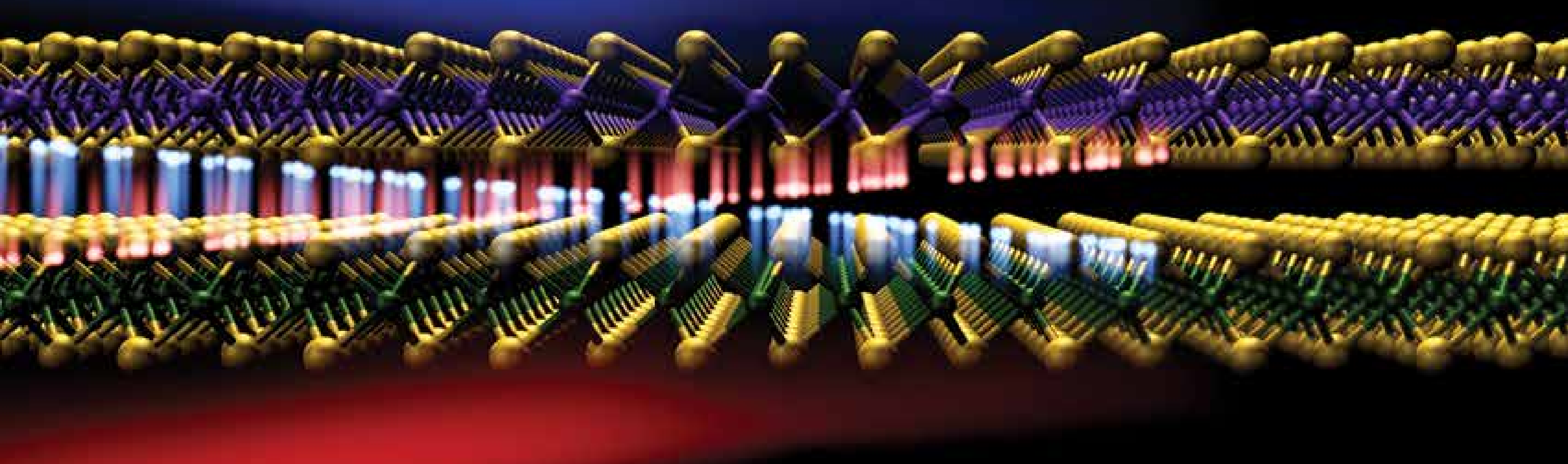
First direct view of an electron's short, speedy trip across atomic boundaries

Ma, E.Y.; Guzelturk, B.; Li, G.; Cao, L.; Shen, Z-X.; Lindenberg, A.M.; and Heinz, T.F. (2019). Recording interfacial currents on the sub-nanometer length and femtosecond time scale by terahertz emission. *Science Advances*, **DOI:10.1126/sciadv.aau0073**

Electrons flowing across the boundary between two materials are the foundation of many technologies, including batteries and solar cells. Now, for the first time, researchers led by Tony Heinz, professor in Stanford's Applied Physics Department, have directly observed and clocked these tiny cross-border movements. Until now, scientists had to track the electron flow indirectly, because the distances involved are so short – seven-tenths of a nanometer, about the width of seven hydrogen atoms – and the speeds so fast, 100 millionths of a billionth of a second.

The research team made the observations by measuring tiny bursts of electromagnetic waves given off by the traveling electrons. Those measurements revealed how far and fast the electric current traveled, and the direction it traveled in. The ability to watch electrons sprint between atomically thin layers of material could shed light on the fundamental workings of semiconductors, photovoltaics and other key technologies, the researchers say.

> "With the demonstration of this new technique, many exciting problems involving semiconductors and photovoltaics can now be addressed."
>
> –TONY HEINZ, PROFESSOR, APPLIED PHYSICS



Electrons traveling between two layers of atomically thin material give off tiny bursts of electromagnetic waves in the terahertz spectral range. This glow, shown in red and blue, allowed researchers to observe and track the electrons' ultrafast movements.

RESOURCES FOR STANFORD FACULTY INTERESTED IN ENERGY RESEARCH

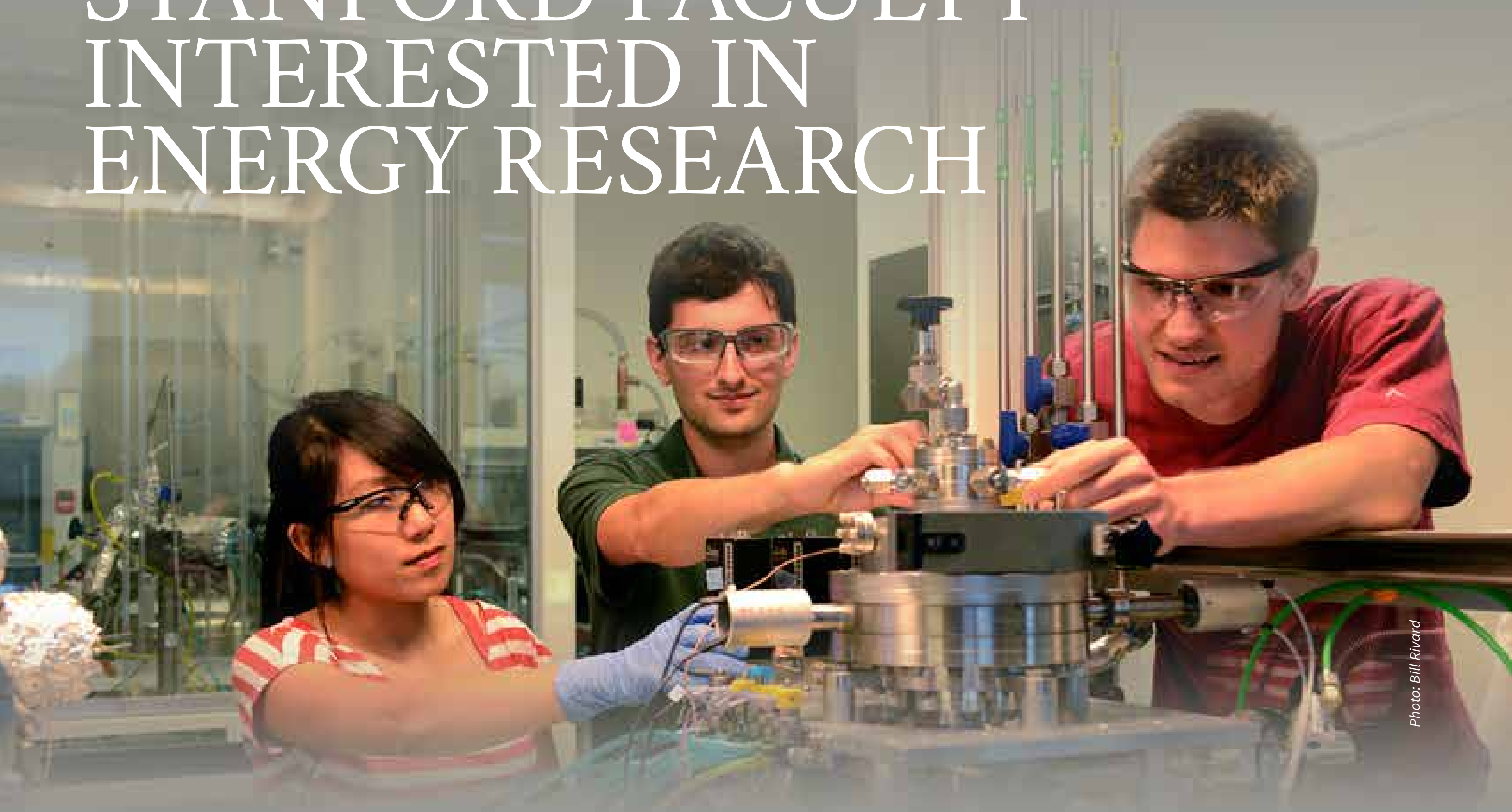


Photo: Bill Rivard

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 newest—**Stanford StorageX**—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**, which launched in the fall of 2018, 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**.

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.

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 **Center for Automotive Research at Stanford**, 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.

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**, the **Precourt Institute for Energy**, the **Sustainable Finance Initiative** and the **TomKat Center for Sustainable Energy**.

STANFORD ENERGY RESEARCH PROGRAMS

Bits & Watts Initiative:
bitsandwatts.stanford.edu

Center for Automotive Research at Stanford:
cars.stanford.edu

Center for Mechanistic Control of Water-Hydrocarbon-Rock Interactions 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 Institute for Materials & Energy Sciences:
simes.stanford.edu

Stanford Natural Gas Initiative:
ngi.stanford.edu

Steyer-Taylor Center for Energy Policy & Finance:
steyertaylor.stanford.edu

Stanford StorageX Initiative:
storagex.stanford.edu

Strategic Energy Alliance:
energy.stanford.edu/strategic-energy-alliance

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

The following list includes faculty and staff members conducting energy-related research, organized by school, followed by researchers who do not have a school-specific appointment. Postdoctoral scholars and students are not included here. Links go to researchers' Google Scholar pages for those researchers who have created user profiles on Google Scholar.

SCHOOL OF EARTH, ENERGY & ENVIRONMENTAL SCIENCES

FACULTY

Atilla Aydin, Professor, Emeritus, Geological Sciences

Khalid Aziz, Otto N. Miller Professor, Emeritus, Energy Resources Engineering

Ilenia Battiato, Assistant Professor, Energy Resources Engineering

Sally Benson, Professor, Energy Resources Engineering; Co-Director, Precourt Institute for Energy

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Biondi Biondo, Barney & Estelle Morris Professor, Geophysics

Dennis Bird, Professor, Emeritus, Geological Sciences

Adam Brandt, Associate Professor, Energy Resources Engineering

Gordon Brown, Dorrell William Kirby Professor of Geology, Emeritus, Geological Sciences

Jef Caers, Professor, Geological Sciences

Anne Dekas, Assistant Professor, Earth System Science

Noah Diffenbaugh, Kara J. Foundation Professor, Earth System Science

Eric Dunham, Associate Professor, Geophysics

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William Ellsworth, Professor, Geophysics

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Chris Field, Melvin & Joan Lane Professor for Interdisciplinary Environmental Studies, Biology and Earth System Science; Perry L. McCarty Director, Stanford Woods Institute for the Environment

Christopher Francis, Professor, Earth System Science

Margot Gerritsen, Professor, Energy Resources Engineering

Steven Gorelick, Cyrus Fisher Tolman Professor in the School of Earth Sciences, Earth System Science

Stephan Graham, Welton Joseph & Maud L'Anphere Crook Professor, Geological Sciences; Chester Naramore Dean of the School of Earth, Energy & Environmental Sciences

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Hamdi Tchelepi, Professor, Energy Resources Engineering

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Fu-Kuo Chang, Professor, Aeronautics & Astronautics

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Craig Criddle, Professor, Civil & Environmental Engineering

Yi Cui, Professor, Materials Science & Engineering; Co-Director, StorageX Initiative

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Christopher Edwards, Professor, Mechanical Engineering

Abbas El Gamal, Hitachi America Professor in the School of Engineering, Electrical Engineering

Stefano Ermon, Assistant Professor, Computer Science

Jonathan Fan, Assistant Professor, Electrical Engineering

Shanhui Fan, Professor, Electrical Engineering

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Curtis Frank, W.M. Keck Sr. Professor in Engineering, Chemical Engineering

Gerald Fuller, Fletcher Jones II Professor in the School of Engineering, Chemical Engineering

J. Christian Gerdes, Professor, Mechanical Engineering; Director, Center for Automotive Research at Stanford

Andrea Goldsmith, Stephen Harris Professor in the School of Engineering, Electrical Engineering

Kenneth Goodson, Davies Family Provostial Professor, Mechanical Engineering

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Piero Pianetta, Professor, Electrical Engineering

Eric Pop, Associate Professor, Electrical Engineering

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Ram Rajagopal, Associate Professor, Civil & Environmental Engineering

Evan Reed, Associate Professor, Materials Science & Engineering

Juan Rivas-Davila, Assistant Professor, Electrical Engineering

Alberto Salleo, Professor, Materials Science & Engineering

Juan Santiago, Professor, Mechanical Engineering

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Silvio Savarese, Associate Professor, Computer Science

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James Sweeney, Professor, Management Science & Engineering

William Tarpeh, Assistant Professor, Chemical Engineering

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Hai Wang, Professor, Mechanical Engineering

Shan Wang, Leland T. Edwards Professor, Materials Science & Engineering and Electrical Engineering

John Weyant, Professor, Management Science & Engineering; Director, Energy Modeling Forum

H.-S. Philip Wong, Willard R. & Inez Kerr Bell Professor, Electrical Engineering

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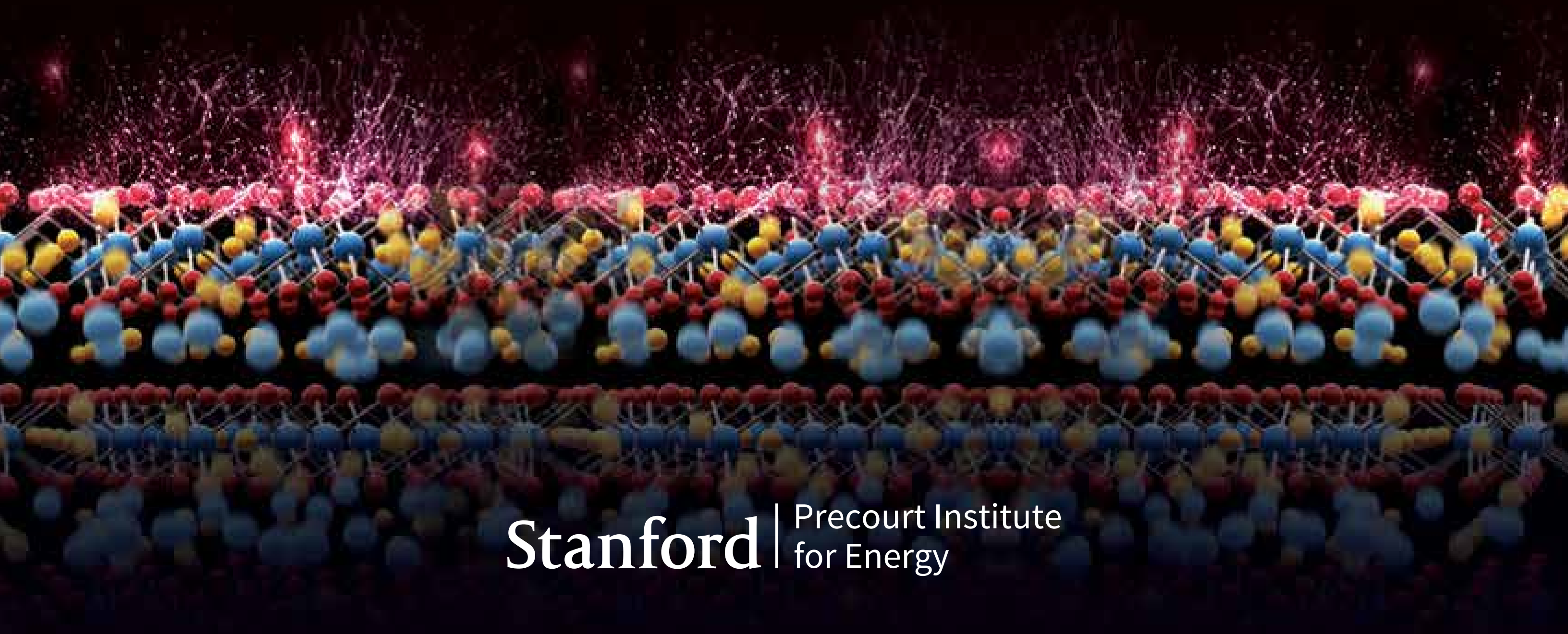

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