How Federal Funding for Basic Research Spurs Clean Energy Discoveries the World Needs: Eight Case Studies

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We need new breakthroughs in clean energy technology to address climate change. Recent discoveries in areas such as nuclear fusion and biofuels illustrate how government investment in early-stage research is a critical part of the process.

KEY TAKEAWAYS

- Addressing climate change on a global scale will require a wide array of clean energy technologies that are as cheap and effective as dirty energy. But the world is still a long way away from developing all the clean technologies we need.
- Funding for early-stage climate-tech research at universities is largely overlooked by policymakers, as advocates call for policies to force markets to adopt the clean energy solutions that are available now. This needs to change.
- Despite breakthroughs in university-based clean energy research, costs and other barriers continue to obstruct pathways to market-ready innovations.
- Policies that prioritize funding for basic research projects are bolstering the nation's power to innovate and therefore are fostering long-term economic growth.

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INTRODUCTION

Addressing climate change is urgent, which is why so many activists, pundits, and elected officials argue for taking action now by banning fossil fuels, subsidizing or mandating the production or consumption of more expensive clean energy alternatives, and changing individual behaviors. They also argue that we would have all the technology we need to solve climate change if we would just muster the political will to use it.

However, global warming is global, so the solutions must be able to scale globally—not just in rich nations that can afford to pay more for clean energy but also in developing nations that cannot and will not. Economic reality therefore dictates that clean energy technologies must reach price and performance parity (P3) with dirty energy. At that point, market forces can serve as the lever to drive rapid decarbonization on a global scale. But we are still a long way away from achieving P3 on the wide array of technologies that will be necessary to decarbonize every sector of the global economy.[1] And in the meantime, mandating a transition to more expensive or less effective clean energy technologies simply will not work.

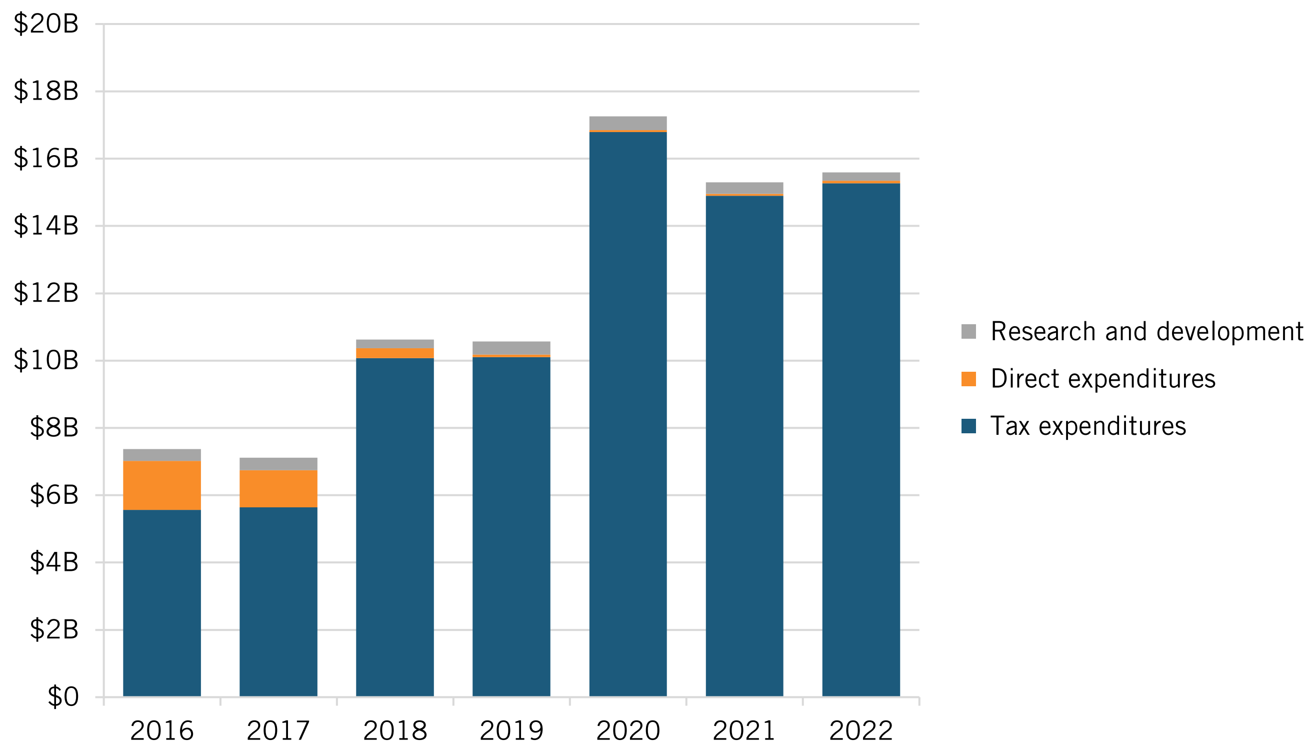
Instead, getting to P3 will require the hard work of scientific and engineering research, much of which is still very basic or in early stages. Yet, funding for early-stage climate-tech research at universities is largely overlooked by policymakers, as advocates call for policies to force markets to adopt the clean energy solutions that are available now. This needs to change. The reality is we have no choice but to develop new clean energy breakthroughs if we want to effectively address climate change. We can't wish into existence fusion energy, cheap grid-scale storage, or affordable green hydrogen.

But the good news is new clean energy breakthroughs are achievable when governments provide funding to support basic research. This report provides a sample of recent government support for high-risk, high-reward clean energy technology projects led by universities.

THE CHALLENGE

Unfortunately, because of the pressure to "act now," very little of the U.S. federal government energy budget has gone to research, much less to early-stage university research. Rather, most of it has gone to tax expenditures—and, with the tax expenditure-heavy Inflation Reduction Act (IRA) program, that share will decline even more. See figure 1.

Figure 1: Federal renewable energy spending by type, fiscal years 2016–2022[2]



While organizations such as ARPA-E (Advanced Research Projects Agency–Energy) play a key role in funding research, much of what they fund is at technology readiness levels (TRLs) 3 to 6. This is important, but we can't overlook TRLs 1 and 2 (basic principles observed; technology concept, application formulated, or both; and analytical and experimental function). Universities play a key role in these stages.

METHODOLOGY

This series of case studies includes eight clean energy innovations; six were conducted at U.S. universities, two were completed abroad, and all were funded by their national governments. These case studies were selected after surveying a series of potential clean energy breakthroughs and prioritizing those that received government investment and were conducted by university-based research projects. Once these criteria were met, we ensured a sampling of a diverse array of energy solutions to cover broad categories such as power storage and energy sources. Within these categories, case studies were selected to cover biofuel, solar, nuclear, hydrogen, hydroelectric power generation, and power storage devices.

Individual case studies were investigated through observational research. We surveyed technical reports on innovative research findings and conducted supplementary background research on each innovation's challenges in order to achieve scalability. In addition to analyzing the technological development of these projects, supplemental interviews were conducted with lead researchers on these innovation projects to identify if and where gaps remain in achieving scalable, commercialized innovations beyond the research stage. We assessed federal clean energy policy and investment to identify grant rules and milestone requirements.

CASE STUDIES

Case 1: Is Silicon the Key to Scaling Up Lithium Battery Power?

Lithium batteries are today's leading power source for many electric vehicles and electrical devices. Graphite is often the electrode or conductor used within these batteries due to its cost efficiency, accessibility, and high energy density. But if electric vehicles (EVs) are going to replace internal combustion engines globally, we will need batteries with enhanced battery life and greater energy efficiency that can compete with the driving range of internal combustion engines. According to recent estimates by the Department of Energy (DOE), 2021 model-year EVs had a median driving range of about 60 percent that of gasoline-powered vehicles.[3] Performance expectations of mileage and energy capacity outpace the current capabilities of graphite-lithium batteries. In recent electrochemical research, silicon has emerged as a potential solution. Recent studies by Rice University demonstrate that silicon can pack more lithium ions than graphite can and improves the anode energy density, resulting in greater energy efficiency.[4]

Researchers at Rice University experimented with coating silicon anodes with a stabilized lithium metal particle (SLMP) to scale up battery power and pioneered a potentially transformative discovery. The researchers identified a positive correlation between coating silicon anodes and increased battery efficiency. Further, they determined that with more SLMP coating, the battery had increasingly greater efficiency. According to DOE estimates, EVs last from 110 miles to over 300 miles per full charging cycle.[5] This Rice University technique allows for an increase of 22 to 44 percent in battery power, which could improve the use and reliability of electrical devices and vehicles, enabling faster charging times and improving battery life, among other benefits.

One challenge the researchers identified when evaluating this process was that while applying the SLMP created the chemical environment for a more rapid charge, batteries tended to fade faster in later cycles when charged to 100 percent. Batteries are expected to lose their ability to hold a full charge over time, but coating the anodes this way causes a more rapid degradation in the quality of energy the battery has the capacity to deliver. Although silicon is the leading solution to fill the gaps that graphite cannot, it has its unique challenges. Silicon forms a solid-electrolyte interphase and consumes the lithium within the battery cell over time. Pairing silicon-lithium batteries and an improved process of SLMP coating that ensures lithium retention and battery efficiency over time could be a transformative step in the path toward energy efficiency and increased capacity of EVs.

Due to the wide use of lithium-ion batteries, successful advancements in energy efficiency would be relatively easy to commercialize. This innovation remains in the concept development stages. Researchers must address the additional challenges of battery degradation following subsequent charges to attain the P3 of legacy power storage units.

This was funded by Ford Research Company and the National Science Foundation (NSF), with NSF funding amounting to more than $9.8 million.

Case 2: Controlled Nuclear Fusion Energy

Nuclear fusion is a potential energy solution to achieve clean energy goals. It is a zero-carbon energy source that occurs naturally within the sun and stars through the heating of plasma and the natural interaction between nuclei fusing together, thereby producing energy. According to research by the International Atomic Energy Agency (IAEA), "If nuclear fusion can be replicated on earth at an industrial scale, it could provide virtually limitless clean, safe, and affordable energy to meet the world demand."[6] Further, according to DOE estimates, a pickup truck filled with fusion fuel has the equivalent energy of 2 million metric tons of coal or 10 million barrels of oil.[7]

Scientists replicate the celestial power source through tokamaks. A tokamak is a nuclear fusion reactor considered the leading candidate to make global fusion energy science aspirations and clean energy diversification a reality. The purpose of tokamak devices is to advance nuclear fusion science through tokamak device development and studying energy cultivation findings for future commercialization of fusion power plants. According to DOE, the tokamak is the leading plasma refinement concept for future fusion power plants. A coalition of nations have partnered to develop the first and largest international tokamak in southern France called the International Thermonuclear Experimental Reactor (ITER). Development partners include China, the European Union, India, Japan, Korea, Russia, Switzerland, the United States, and the United Kingdom. According to DOE estimates, "The ITER central [magnet] will be the largest superconducting magnet ever built. It will produce a field of 13 tesla, equivalent to 280,000 times the earth's magnetic field."[8] The ITER is set to break several fusion energy research records, as the larger the magnetic field, the greater the energy output.

Fusion energy science requires combined efforts from nuclear engineers, physicists, and computer scientists. In tokamak device development and fusion power testing, machine learning technology is deployed to train tokamak generators to identify potential disruptions and adjust to prevent the same. However, according to Huazhong University of Science and Technology nuclear fusion research, "[These reactors] cannot provide enough unmitigated disruption data at high performance to train the predictor before damaging themselves."[9] These disruptions cause dramatic dips in temperature during the fusion process, leading to a phenomenon called "runaway electrons." These runaway electrons disrupt plasma confinement, resulting in energy loss and damage to tokamak machines. Only limited nuclear fusion research has been conducted to address this challenge.

Researchers at Princeton University's Plasma Physics Laboratory (PPL) have identified a breakthrough method to mitigate energy loss and subsequent damage to tokamak machines. The researchers studied Alfvén waves, which are known to loosen the confinement of high-energy particles. By studying these waves, PPL nuclear physicists discovered that loosening electron bonds through Alfvén waves prevents massive electron loss. According to PPL reporting, "The scientists found that such loosening can diffuse or scatter high-energy electrons before they can grow into avalanches that damage tokamak components."[10] These circulatory interactions control runaway electrons, preventing the avalanche of energy loss. These findings and implications will transform tokamak development and research as research centers replicate the PPL mitigation process. This fusion energy science breakthrough could further ITER aims in France, where an international tokamak—the largest ever fusion power plant—is being built.

Nuclear energy has historically been among the most highly contested energy sources among the American public; however, public opinion appears to be turning a corner. According to a National Nuclear Energy Public Opinion Survey conducted by Bisconti Research, over 75 percent of Americans support nuclear energy.[11] The White House Office of Science and Technology Policy released a statement indicating that the National Academies of Sciences, Engineering, and Medicine along with the Fusion Energy Science Advisory Committee recommend that the government continue rigorously supporting nuclear fusion energy research, development, and demonstration (RD&D) programs.[12] The statement also indicated that private sector support has increased since the 2021 White House Fusion Summit. Addressing critical challenges in the workforce, supply chains, and regulatory and market development will be central to taking nuclear fusion energy to P3. Due to the vast systemic adjustments needed to enable the commercialization of this technology, the Biden administration favors a dual-processing framework wherein, while innovation progresses, stakeholders convene to craft the necessary workforce training, regulatory measures, and supply chains needed to ensure an energy integration that will advance the American economy.

Nuclear power plays a unique role in American energy strategy, with strong proponents urging that the energy source could serve as a de-risking agent alongside renewable energy integration. According to a report by IAEA, potential nuclear energy integration includes electricity production and energy storage. The report indicates that "instead of the U.S. $25 trillion required to maintain oil flows until 2050, the clean energy substitute fuels would cost the U.S. $17 trillion. These estimates contrast further with the U.S. $70 trillion for a renewables-only strategy." With the necessary regulatory, workforce, and market preparation, fission energy stands to serve as a successful research breakthrough, advancing U.S. energy goals upon commercialization. This project was funded by DOE's Office of Science and Technology in the Princeton PPL, a U.S. DOE national laboratory managed by Princeton University.

Case 3: Wheat Straw for Biofuel Extraction

Researchers are looking to biofuels as a replacement for fossil fuels. Biofuels are extracted from renewable biological sources such as plants or algae and are used in liquid form. Lignin is found in most plants and is a substance that consists of large clusters of molecules or polymers that hold carbon dioxide that plants capture from the environment. Lignin is one of the earth's most abundant renewable carbon sources as a biocarbon that regularly regenerates carbon dioxide through photosynthesis and is the earth's second most abundant renewable carbon source. It is a particularly attractive biofuel, as using lignin in batteries can reduce cost and improve efficiency.

Lignin has previously been explored as a potential source of biofuel; however, due to challenges separating the substance from plant matter while maintaining its structural integrity, it has not been an attractive fuel resource for industry use. Researchers at Washington State University's Linda Voiland School of Chemical Engineering and Bioengineering have developed a novel method of extraction that allows for the chemical separation of lignin from plant matter without damaging its key properties or natural structure. The Washington University report states, "Up to 93.7 percent of lignin was extracted from wheat straw biomass at varying conditions from 90 degrees C to 145 degrees C."[13] This research establishes a first-of-its-kind method of extracting lignin holistically and marks a breakthrough in biofuel research. The researchers will next work to decrease chemical separation processing time and the amount of purification chemicals needed to scale up their production for commercialization.

According to University reports, the university's Office of Commercialization has filed a provisional patent and will support this biofuel development's scale-up and commercialization. Further commercialization entails engaging workforce, regulatory processes, and market readiness. Biofuel is becoming more cost competitive. According to research by the Argonne National Laboratory, "Biofuel combined with advanced engine design can reduce greenhouse gas emissions by roughly 60 percent while improving fuel efficiency or reducing tailpipe emissions."[14] Their study also finds that biofuels are cost competitive with current petroleum fuels. This innovation is on course to achieving P3 with legacy energy systems. This research was sponsored by NSF, the U.S. Department of Agriculture National Institute of Food and Agriculture, and WSU's Commercialization Gap Fund.

Case 4: Hydrogen-Proof Combustion Engines

Energy diversification will require innovation and ingenuity in the systems and structures that transmit clean power. DOE estimates that the U.S. transportation sector accounts for approximately 30 percent of total U.S. energy demand and 70 percent of petroleum consumption.[15] Tapping into the transportation market with clean hydrogen power could advance U.S. energy security and clean energy goals—although, as the Information Technology and Innovation Foundation (ITIF) has documented, clean hydrogen is expensive to produce and difficult to distribute, so battery electric vehicles (BEVs) are more likely to replace internal combustion engine vehicles than hydrogen fuel cell vehicles (HFCVs) are.[16]

But despite the practical obstacles to widespread adoption, hydrogen is an attractive fuel alternative due to its zero-emissions nature and domestic production capabilities. According to the DOE estimates, "The energy in 2.2 pounds (1 kilogram) of hydrogen gas is about the same energy in 1 gallon (6.2 pounds, 2.8 kilograms) of gasoline."[17] Hydrogen may even unlock access to previously untapped parts of the transportation industry. According to Environmental Protection Agency estimates, hydrogen can benefit heavy-duty transportation sector applications (e.g., long-haul trucks, locomotives, ships, etc.) where current battery technology might not suit specific transportation modes (e.g., the necessary battery weight would be too substantial).[18] Hydrogen can also store energy for long periods and is extremely light, so it needs to be compressed or liquified, making it challenging and expensive to transport, store, and use.

Among the many EV options available for consumers, there are several HFCV models available, and according to the International Energy Agency 2022 report, hydrogen fuel-cell vehicle purchases grew by 40 percent in 2022 compared with 2021. The proliferation of hydrogen in clean transportation technology is driving researchers to investigate pathways to achieving a hydrogen-proof combustion engine. Hydrogen combustion vehicles differ from hydrogen fuel cell vehicles in that combustion uses heat to create mechanical energy, while hydrogen fuel cells generate energy through electrochemical processes.

Hydrogen combustion, however, has faced stark challenges, as the combustion process degrades the internal mechanics of engines. Hydrogen-proof engines are essential to commercializing hydrogen combustion engines, and researchers are seeking innovative ways to create engine infrastructures that can withstand hydrogen reactions. The University of Southern California (USC) is developing a process to create hydrogen-resistant engines. The process entails spraying a thermal barrier coating within the engine to prevent the erosion of the engine interior, as occurs with hydrogen combustion. The team's research includes mapping the distance of the fuel nozzle from the engine wall and accounting for the speed of hydrogen injection, engine temperature level, and ideal spray characteristics.[19] The researchers create modeling techniques to understand these complex variables and create a scalable design. This USC-led project engages statisticians, thermal physicists, systems engineers, and private sector partners to model hydrogen fuel cells.

Hydrogen-proof engine research is still ongoing and remains in the nascent stages of development with a TRL of 2. As such, commercialization of this technology remains to be seen as the development process progresses. Once modeling is complete, testing will begin, followed by large-scale demonstrations and adjustments to optimize vehicle reliability, efficiency, and cost effectiveness. Gas fuel currently costs about $4 per gallon in most states, while hydrogen costs about $16 per kilogram, making hydrogen more costly to the end user than are fossil fuels. As hydrogen manufacturing processes are refined, and clean energy is used to produce hydrogen, costs are expected to drop and become more competitive with traditional energy sources.

This development does not appear to be on track to reach P3. Hydrogen prices are expected to decrease; however, hydrogen-proof engine research is still developing. Due to the lower energy density of hydrogen cars, manufacturers will need to account for the larger fuel tank size and will have a smaller market of consumers due to the decreased vehicle space. Despite these drawbacks, hydrogen combustion is anticipated to fill an essential niche by harnessing established technologies and supply chains. Declining hydrogen prices make hydrogen-focused technologies particularly palatable to investment, especially for commercial vehicles. Further, hydrogen combustion and hydrogen fuel cells are described as complementary technologies, further cementing hydrogen's role in energy diversification. This research was sponsored by DOE.

Case 5: Plant Matter for Sustainable Aviation Fuel

The path to decarbonization will require innovation in critical sectors such as transportation and manufacturing. According to Nancy Stauffer from the Massachusetts Institute of Technology (MIT) Energy initiative, "While the growing use of electric vehicles is helping to clean up ground transportation, today's batteries cannot compete with fossil fuel-derived liquid hydrocarbons in terms of energy delivered per pound of weight [presenting] a major concern when it comes to flying."[20] According to International Energy Agency (IEA) data, in 2022, aviation accounted for 2 percent of global energy-related carbon dioxide. And travel demand is also projected to grow along with the consumption of jet fuel, which is projected to double between now and 2050.[21] While aviation pollution contributes only a fraction of total transportation-related carbon dioxide emissions, innovation in this sector will be in the form of refining and advancing the clean transportation of goods, people, and fuel.

Integrating clean energy technology into the aviation sector has been met with many challenges. Aviation fuels are stringently regulated, with standardization of jet-fuel requiring certification qualification. Electrochemists are faced with a unique set of challenges, including crafting the appropriate combination of chemical compounds that produce successful fuel that does not freeze due to a change of elevation, temperature, or pressure. Additionally, according to MIT researchers, the fuel plays a critical role in ensuring the seals between components of an aircraft's fuel system are tight.[22] To meet the challenge of clean aviation fuel, electrochemists must meet the task of crafting aromatic and aliphatic chemical compounds, both of which are core components of aviation fuel. Aromatic compounds are widely considered to contribute to pollution; however, they play a critical role in ensuring power generation and resilient engine efficiency.

Researchers at MIT's Office of Energy and DOE's Bioenergy Technologies office have created a new method of producing bio-aviation fuel from plant matter, with the former crafting a process using lignin to create a critical component of aviation fuel. Lignin is typically discarded plant matter, and the industrial processes that use biopolymers degrade lignin through subsequent chemical reactions after the substance is discarded. At this level, lignin is not useful for aviation fuel. To circumvent this degradation, MIT researchers utilize a catalyst that creates a new chemical reaction that allows them to remove lignin and produce lignin oil. As MIT researchers reported, "When we do our chemistry with the molybdenum carbide catalyst our total carbon yields are nearly 85 percent of the theoretical carbon yield. In most lignin-conversion processes, the carbon yields are very low, on the order of 10 percent."[23] This breakthrough innovation has generated unprecedented carbon yields with the catalyst.

Results from MIT initial testing and simulations have been promising and the team has sent samples to Washington State University for further testing and is working with the National Renewable Energy Lab to scale up their methods. Researchers are continuing to observe how the fuel performs inside jet engines amidst varied temperatures. Additional testing required for full certification due to the stringent control requirements on aviation fuel testing will be composed of several phases that will include laboratory engine simulations. According to the MIT report, current predictions indicate that the material should flow more easily and be less likely to freeze than conventional aromatics, also generating less soot in the atmosphere when it burns. However, challenges remain in making lignin economically viable in a scalable manner. Although this innovation is currently at a TRL of 3, with a promising proof of concept, when evaluating its P3 with legacy energy systems, the innovation has many shortcomings. Due to its recalcitrance and the challenges to make lignin chemically react in useful ways, the technology is currently not on track to reach P3.

This research was initially funded by the Center for Bioenergy Innovation, a DOE research center supported by the Office of Biological and Environmental Research in DOE's Office of Science. More recent funding has come from DOE's Bioenergy Technologies office and Eni S.p.A. through the MIT energy initiative.

Case 6: Solar-to-Hydrogen Conversion

Ensuring a sustainable energy future will require diversification and ramping up the use of diverse energy sources to meet global energy demand. Hydrogen has been touted as a potential replacement for traditional fossil fuels in a range of use cases, including providing energy for transportation, power generation, and more. According to a recent estimate by the Fuel Cell & Hydrogen Energy Association, "Hydrogen can reduce carbon emissions in the United States transportation sector by 30 percent, lower [nitrogen oxide] emissions by 36 percent, and directly reduce United States carbon emissions by 16 percent." However, as ITIF has documented, clean hydrogen is expensive to produce, difficult to transport, and a second- or third-best clean energy solution in most proposed markets, so a realist approach to hydrogen policy must address all these practical challenges.[24]

Hydrogen has historically been used as rocket fuel.[25] Green and blue hydrogen have been the prevailing forms of the gas. Green hydrogen is produced using electricity to split water (H_2O) into hydrogen (H_2) and has zero emissions. Similarly, blue hydrogen is produced using methane and H_2O, which also produces H_2; however, this process is dirtier and emits carbon. Green hydrogen is more desirable than its blue counterpart due to its zero-emissions nature.

Both clean and renewable, hydrogen is a generally attractive power source in the search for clean energy solutions, as it has the highest energy content of any fuel by weight. Hydrogen can be used to store energy, and if it is run through a fuel cell, it produces electricity with only water as the byproduct. The element has diverse uses in liquid and gaseous forms as transportation fuel and fuel to power generators.

Creating green hydrogen by water splitting can be done in a myriad of ways. Researchers at Rice University designed a historic system that uses photovoltaics (PVs), which absorb solar power and complete electrochemical water-splitting chemistry, producing green hydrogen. The researchers use a photoelectrochemical (PEC) cell, which converts solar energy into electricity. In this process, a semiconductor absorbs solar cells and generates electron pairs, which is followed by a reaction that produces an electrical current. This energy conversion technique is vital to driving a carbon-zero future and integrating renewable energy into the global energy mix.

Rice University researchers reported, "Until now, using photoelectrochemical technology to produce green hydrogen was hampered by low efficiencies and the high cost of semiconductors."[26] Creating an electrochemical cell that can convert solar energy to hydrogen requires a powerful semiconductor. Specifically, to separate water to produce hydrogen using solar heat entails stringent semiconductor and design requirements. Semiconductors are crucial to this power conversion as the semiconductor absorbs sunlight. The researchers leveraged halide perovskites, a low-cost semiconductor, and designed a conductive adhesive barrier (CAB). This barrier allows for PV conversion into a PEC cell. The team had conducted small scale demonstrations indicating that their CAB design worked for different chemical reactions and with different semiconductors, making it applicable across many systems. The device has record-breaking efficiency and can convert solar energy into hydrogen with 20.8 percent efficiency.[27] The electric potential generated from the photoelectric effect is directly converted to chemical energy, eliminating the need for battery storage.[28]

The research was sponsored by DOE and conducted by Rice University and the National Renewable Energy Lab. This innovation is currently at a TRL of 4. Using more affordable and easy-to-access semiconductors has improved opportunities for commercialization for the first time in solar conversion energy history. Solar technology can be seen as an energy production equalizer wherein energy can be absorbed and stored as long as there is sunlight. However, installation and start-up costs remain a challenge in solar energy technology. According to Rice University's researchers, their CAB in solar-hydrogen conversion will lead to efficient, durable, and low-cost solar-driven water-splitting technology. However, hydrogen is expensive, difficult to transport, and is not on track to P3. More targeted research and development is needed to accelerate hydrogen for long-duration storage.

Case 7: More Power per Drop, Developments in Rain Panel Technology

Hydroelectric power has emerged as a leading strategy in the global push for sustainable energy solutions. According to IEA analysis, hydropower remains the largest renewable source of electricity, generating more than all other renewable technologies combined.[29] U.S. Geological Survey data demonstrates that rainfall can range from 0.01 to over 900 inches globally, depending on geographic area.[30] Each drop of rain contains kinetic energy from the gravitational pull on accumulated precipitation. Due to the natural occurrence of rain and its abundance in many regions, raindrop electricity generation is an energy solution worth exploring. Rain energy is harvested through droplet-based triboelectric nanogenerators (D-TENG) that convert the motion of raindrops into energy. While the kinetic energy within an individual raindrop is minute, the compounding energy of several raindrops harvested through panels has the potential to be a cost-effective and sustainable power source; however, methods to increase the energy efficiency of this process have been met with challenges.

The process of combining rain cells has been modeled after similar solar cell processes in which solar cells are combined on a single circuit. When solar cells are combined on one circuit, it produces a larger panel of cells able to collect more energy; however, when raindrop power collection cells are combined, coupling capacitance occurs wherein power is lost instead of compounded as intended. A group of Tsinghua Shenzhen International Graduate School researchers in China claim that they have found a solution to the issue of coupling capacitance that would make energy-harvesting rain panels a more practical reality. They claim that the unintended coupling capacitance of raindrops can be reduced through bridge array generators (BAGs). These generators can reduce the amount of unintended power loss that occurs from coupling capacitance.

The Tsinghua Shenzhen researchers applied multiple D-TENGS to keep rain power cells operating separately and discovered that isolating the power cells, applying multiple D-TENGs with low array electrodes, and enhancing the rain panels' thickness allowed for more efficient and instantaneous rain power output. According to the Tsinghua report, "When the area of the raindrop energy harvesting device is 15 x 15 cm^2, the peak power output of BAGs is nearly five times higher than that of the conventional large-area raindrop energy with the same size, reaching 200 W/m^2."[31] This development has the ability to transform rain energy harvesting, thereby increasing energy efficiency and boosting power output.

Chinese investment in rain power is successfully rearing greater energy cultivation strategies. However, the large-scale commercialization of rain panels remains a slow adoption process due to the lack of performance parity with other leading clean energy resources such a solar and wind or other hydroelectric power processes. While this innovation surpasses and successfully addresses technical limitations of previous rain panel research, this technology use remains in its nascent stages and lacks large-scale buy-in. This research was sponsored by the National Natural Science Foundation of China.

Case 8: Harvest Untapped Energy: Transparent Solar Panels

The use of solar power in energy diversification is increasing globally in both utility and residential use. According to a report by the Energy Information Agency, in 2022, 21 percent of electrical energy generation was produced from renewable sources, 3.4 percent of which was solar power.[32] Solar panels, or solar PV panels, are a clean energy success story converting energy from the sun into electricity. Both clean and renewable, solar energy generation is attractive due to its climate-friendly nature and cost-effectiveness. According to DOE quarterly estimates, U.S. electric capacity will increase from 45 percent in 2022 to 62 percent in 2024 from solar power.[33] Solar Energy Industries Association reports indicate that 162.8 gigawatts (GW) of solar capacity is currently installed nationwide, nearly 275,000 Americans are working in solar industries, and over 4.6 million solar energy systems are installed nationwide.[34] According to DOE's Office of Energy Efficiency & Renewable Energy research, "In the first half of 2023, Photovoltaic (PV) installations increased significantly in China (153 percent) and Germany (102 percent), and to a lesser extent the United States (34 percent)."[35] The increase in installations is centralized in China, leading to an oversized manufacturing capacity compared to industry competitors. According to IEA, global solar PV manufacturing capacity in 2022 increased by over 70 percent from 2021 to reach 450 GW for polysilicon and 640 GW for modules, with China accounting for more than 95 percent of new facilities throughout the supply chain.[36] China remains a global leader in solar panel manufacturing and supply chain control.

A critique of solar energy has been its visual obstructiveness and lack of aesthetically pleasing qualities. Solar panels are most often used in solar farms, large plots of land covered with solar panels that provide electricity to the grid, or in residential areas on top of houses and other buildings. Due to their current design, solar panels have limited applications. These critiques and a desire for broader application of solar technology are driving researchers to design and test for transparent solar panel technology. Transparent solar cells address these concerns and open new doors for technical deployment and energy cultivation. A clear sheet of solar panel technology could be applied to windows of buildings and cars and to a myriad of electrical devices, or so is the concept for a group of Japanese researchers at Tohoku University's Graduate School of Engineering in Sendai, Japan.

Aesthetic and logistical barriers have impeded solar PVs from wider application; however, Japanese researchers at Tohoku University believe that their transparent solar panels solve these challenges. By creating transparent solar cells, the technology would no longer be limited to rooftops and solar farms, as the innovation could be mounted on surfaces currently not used for energy production. Integrating solar technology in infrastructure and vehicles alone would transform power demand and energy efficiency. Consider more mileage in between charges due to constant energy storage and power collection during light hours, or self-charging devices.

This innovation is not the first of its kind; in 2021, Michigan State University (MSU) and Ubiquitous Energy worked together to design solar panel windows. According to the subsequent MSU report, "Transparent solar glass expands solar power options tremendously and changes how we think about generating power. There is no longer a tradeoff between aesthetics and renewable energy."[37] The MSU installation marks the first deployment of this technology on any building outside of Ubiquitous Energy and its commercial partners. It is also a first for any university. Once installed, the panels are visibly indistinguishable from traditional windows. The Japanese design intends for a much broader use application.

Considering its TRL, price, and performance parity, this technology could make a meaningful difference in the global energy mix. After initial testing, the researchers have acknowledged that there are still challenges to be addressed before the transparent cells can be widely adopted and it remains at a TRL of 3 with proof-of-concept validation. The researchers have successfully identified the best materials for transparency, conductivity, and ability to convert light into electricity. However, additional design adjustments are needed to scale up the project.

Solar energy is already price competitive with legacy energy resources; however, there are sizable up-front installation costs—despite which, many estimate that these investments will pay for themselves in the long run. Tax incentives and long-term savings make solar energy a commercially viable alternative to traditional energy sources. A central challenge is ensuring that solar technology does not become subsidy dependent in order to be affordable, but the technology remains promising. Despite the high up-front costs, solar panels are considered more cost efficient to the average homeowner and can last 25 to 30 years before efficiency declines.[38] The cost prospects are promising; however, performance parity is met with challenges. Energy flows as long as the sun is shining, but energy access becomes disrupted by rain, clouds, or other weather incidents. Solar batteries help mitigate gaps in power loss, but also come with additional costs. Solar power faces challenges such as recycling materials, land use, and workforce development. This research was supported in part by a JST-PRESTO grant, the JSPS A3 Foresight Program, and a grant for a basic science research project from Sumitomo Foundation and the Cooperative Research Project Program of the Research Institute of Electrical Communication, Tohoku University. The lead author is funded by the China Scholarship Council from the Ministry of Education of the People's Republic of China.

ANALYSIS

Federal investment in early-stage research is a catalyst for scientific and engineering breakthroughs that continually yields social and economic benefits.[39] Research institutions, often universities operating with federal funding, help drive technological developments that are later commercialized and contribute to market growth. Major innovations from smartphones and the Internet to wind energy and RNA were supported by federal funding. Basic research is the first step in the innovation pipeline and impacts more sectors in more countries and for a more extended period than applied research does.[40] Efforts to mitigate the impacts of climate change while fortifying energy independence and security will be more difficult if nations do not invest more in early-stage clean energy research.

POLICY RECOMMENDATIONS

The government's main job is to help a wide array of technologies get to P3, and federal investment in research and development (R&D) is a key capacity-building force enabling colleges and universities to conduct basic research that can lead to P3 solutions. Certain solutions require technological breakthroughs or scale to become competitive, and governments must help them do so by the following:

- NSF must allocate funds to basic research and ensure consistent financing throughout the innovation cycle, from basic research to applied RD&D. Each phase of this assembly line is critical in ensuring American competitiveness and innovation.
- Congress must enact full appropriations by continuing resolution deadlines and ahead of April's Fiscal Responsibility Act deadlines when the next wave of discretionary spending caps will be instituted.
- Congress should increase discretionary spending for R&D to ensure robust funding is available to address the Biden administration's goals of reaching net zero.
- Partnerships with universities through the new NSF directorates should be bolstered.

CONCLUSION

We need technological breakthroughs to address climate change. Government investment in early-stage research is integral to clean technology innovation. The series of case studies herein demonstrate the advancements in clean energy research made possible through federal support to universities. Some of this research may proceed to demonstration and proof of concept. Still others might be commercialized. But 100 percent success is not the point. Taking a lot of "shots on goal" is the point because, without risks, there will be no ultimate reward: developing a wide array of technologies that reach P3.

Nonetheless, researchers from the U.S. universities we spoke with reported interest from venture capital firms and connections with university offices of technology transfer. Yet, persistent gaps in financing the innovation still exist. But even with government support, universities report needing additional funding to take these innovations to the next phase. Costs and other barriers continue to obstruct pathways to market-ready innovations. That is why programs such as ARPA-E are so important to help move such early discoveries to the next stage. As such, as Congress and the administration continue to focus on addressing climate change, it is important that they not lose sight of the importance of spurring fundamental breakthroughs by supporting early-stage university research in clean energy areas.

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ENDNOTES

1. Ahmet Ali Taskin and Firat Yaman, "The effect of branching deregulation on finance wage premium," FAU Discussion Papers in Economics, Friedrich-Alexander University Erlangen-Nuremberg, Institute for Economics, November 8, 2023, https://EconPapers.repec.org/RePEc:zbw:iwqwdp:280992.
2. "Federal Financial Interventions and Subsidies in Energy in Fiscal Years 2016–2022," U.S. Energy Information Administration, August 2023, 8, https://www.eia.gov/analysis/requests/subsidy/pdf/subsidy.pdf#page=13.
3. "At a Glance: Electric Vehicle," United States Department of Energy, Office of Renewable Energy, August 2023, https://afdc.energy.gov/files/u/publication/electric-drive_vehicles.pdf.
4. Quan Anh Nguyen et al., "Prelithiation Effects in Enhancing Silicon-Based Anodes for Full-Cell Lithium-Ion Batteries Using Stabilized Lithium Metal Particles," ACS Applied Energy Materials, 2023, https://pubs.acs.org/doi/10.1021/acsaem.3c00713.
5. "FOTW #1221, January 17, 2022: Model Year 2021 All-Electric Vehicles Had a Median Driving Range about 60% That of Gasoline Powered Vehicles," United States Department of Energy, Vehicle Technologies Office, January 17, 2022, https://www.energy.gov/eere/vehicles/articles/fotw-1221-january-17-2022-model-year-2021-all-electric-vehicles-had-median.
6. Matteo Barbarino, "What is Nuclear Fusion?" International Energy Agency, https://www.iaea.org/newscenter/news/what-is-nuclear-fusion.
7. "Department of Energy Explains…Fusion Energy Science," Department of Energy, https://www.energy.gov/science/doe-explainsfusion-energy-science.
8. "Department of Energy Explains…Tokamaks," Department of Energy, https://www.energy.gov/science/doe-explainstokamaks.

9. Wei Zheng et al., “Disruption Prediction for Future Tokamaks Using Parameter-Based Transfer Learning,” Communications Physics, July 17, 2023, https://www.nature.com/articles/s42005-023-01296-9#citeas.
10. John Greenwald, “A Breakthrough Discovery Could Accelerate the Arrival of Controlled Fusion Energy on Earth,” Princeton Plasma Physics Laboratory, September 15, 2023, https://www.pppl.gov/news/2023/breakthrough-discovery-could-accelerate-arrival-controlled-fusion-energy-earth.
11. Ann S. Visconti, “2023 National Nuclear Energy Public Opinion Survey: Public Support for Nuclear Energy Stays at Record Level for Third Year in a Row,” Bisconti Research, Inc., April 2023, https://www.bisconti.com/blog/public-opinion-2023.
12. The Whitehouse Office of Science and Technology Policy (2022) Parallel Processing the Path to Commercialization of Fusion Energy https://www.whitehouse.gov/ostp/news-updates/2022/06/03/parallel-processing-the-path-to-commercialization-of-fusion-energy/#_ftn9.
13. Tina Hiding, “Lignin Separation Method Could Make Renewable Material Profitable,” Washington State University Insider. https://news.wsu.edu/press-release/2023/07/31/lignin-separation-method-could-make-renewable-material-profitable/.
14. Beth Burmahl, “Biofuel on the Road to Energy, Cost Savings,” Argonne National Laboratory, November 10, 2022, https://www.anl.gov/article/biofuel-on-the-road-to-energy-cost-savings.
15. “Hydrogen Benefits and Considerations,” United States Department of Energy, https://afdc.energy.gov/fuels/hydrogen_benefits.html.
16. Robin Gaster, “A Realist Approach to Hydrogen,” Information Technology and Innovation Foundation, January 2024, https://itif.org/publications/2024/01/16/a-realist-approach-to-hydrogen/.
17. “Hydrogen Basics,” United States Department of Energy, https://afdc.energy.gov/fuels/hydrogen_basics.html.
18. “Green Vehicle Guide” United States Environmental Protection Agency, https://www.epa.gov/greenvehicles/hydrogen-transportation.
19. Matilda Bathurst, “Designing an Engine Ready for Hydrogen Combustion,” University of Southern California Viterbi, September 8, 2023, https://viterbischool.usc.edu/news/2023/09/designing-an-engine-ready-for-hydrogen-combustion/.
20. Stauffer, N.W., (2023) MIT Energy Initiative https://news.mit.edu/2023/making-aviation-fuel-biomass-0823.
21. “IEA 50: Why is Aviation important,” International Energy Agency, July 11, 2023, https://www.iea.org/energy-system/transport/aviation.
22. Michael L. Stone et al., Joule Cell Press. “Continuous Hydrodeoxygenaiton of Lignin to Jet-Range Aromatic Hydrocarbons,” Joule, September 22, 2022, https://www.cell.com/joule/fulltext/S2542-4351(22)00406-8.
23. Nancy W. Stauffer, “Making Aviation Fuel from Biomass,” MIT News, August 23,2023, https://news.mit.edu/2023/making-aviation-fuel-biomass-0823.
24. Gaster, “A Realist Approach to Hydrogen.”
25. “The U.S. Cannot Achieve its Climate Goals Without Clean Hydrogen,” Fuel Cell & Hydrogen Energy Association, https://www.cleanhydrogentoday.org/?gclid=EAIaIQobChMI-63g1K-MggMVcc7ICh1ubweaEAAYASAAEgK5WPD_BwE.
26. Silvia Cernea Cleark, “Device Makes Hydrogen from Sunlight with Record Efficiency,” Rice University Office of Public Affairs, July 20, 2023, https://news.rice.edu/news/2023/device-makes-hydrogen-sunlight-record-efficiency.

27. Austin M.K. Fehr et al, “ Integrated Halide Perovskite Photoelectrochemical Cells with Solar-Driven Water-Splitting Efficiency of 20.8 percent,” Nature Communications, June 26, 2023, https://www.nature.com/articles/s41467-023-39290-y.
28. Craig Hill, “Photoelectrochemical Cell, Recent Hilights II. Industrial Applications of Nanomaterials https://www.sciencedirect.com/topics/engineering/photoelectrochemical-cell.
29. “Tracking Clean Energy Progress 2023,” International Energy Agency, July 2023, https://www.iea.org/reports/tracking-clean-energy-progress-2023.
30. “Rain and Precipitation,” United States Geological Survey, July 6, 2019, https://www.usgs.gov/special-topics/water-science-school/science/rain-and-precipitation#overview.
31. Zong Li et al., “Rational TENG arrays as a panel for harvesting large-scale raindrop energy," Tsinghua University Press, June 2023, https://ieeexplore.ieee.org/document/10185664.
32. “What is U.S. Electricity Generation by Energy Source,” Energy Information Agency, February 29,2024, https://www.eia.gov/tools/faqs/faq.php?id=427&t=3.
33. “Quarterly Solar Industry Update,” Department of Energy, January 25, 2024, https://www.energy.gov/eere/solar/quarterly-solar-industry-update.
34. “Solar State By State,” Solar Energy Industries Association, 2024, https://www.seia.org/states-map.
35. “Quarterly Solar Industry Update,” Department of Energy, January 25, 2024, https://www.energy.gov/eere/solar/quarterly-solar-industry-update.
36. “Solar PV,” International Energy Agency, July 11, 2023, https://www.iea.org/energy-system/renewables/solar-pv.
37. “Power Generation You Can See Through,” Michigan State University Today, August 25,2017, https://msutoday.msu.edu/news/2021/solar-glass-panels-installed.
38. Benjamin Mow, “STAT FAQs Par 2: Lifetime of PV Panels,” National Renewable Energy Lab, April 23, 2018, https://www.nrel.gov/state-local-tribal/blog/posts/stat-faqs-part2-lifetime-of-pv-panels.html
39. “American-Made Innovation Sparking Economic Growth: Facts & Figures,” The Science Coalition, https://www.sciencecoalition.org/sparking-economic-growth/home.
40. Philip Barrett et al., “Why Basic Science Matters for Economic Growth,” International Monetary Fund Blog, October 6, 2021, https://www.imf.org/en/Blogs/Articles/2021/10/06/blog-ch3-weo-why-basic-science-matters-for-economic-growth.