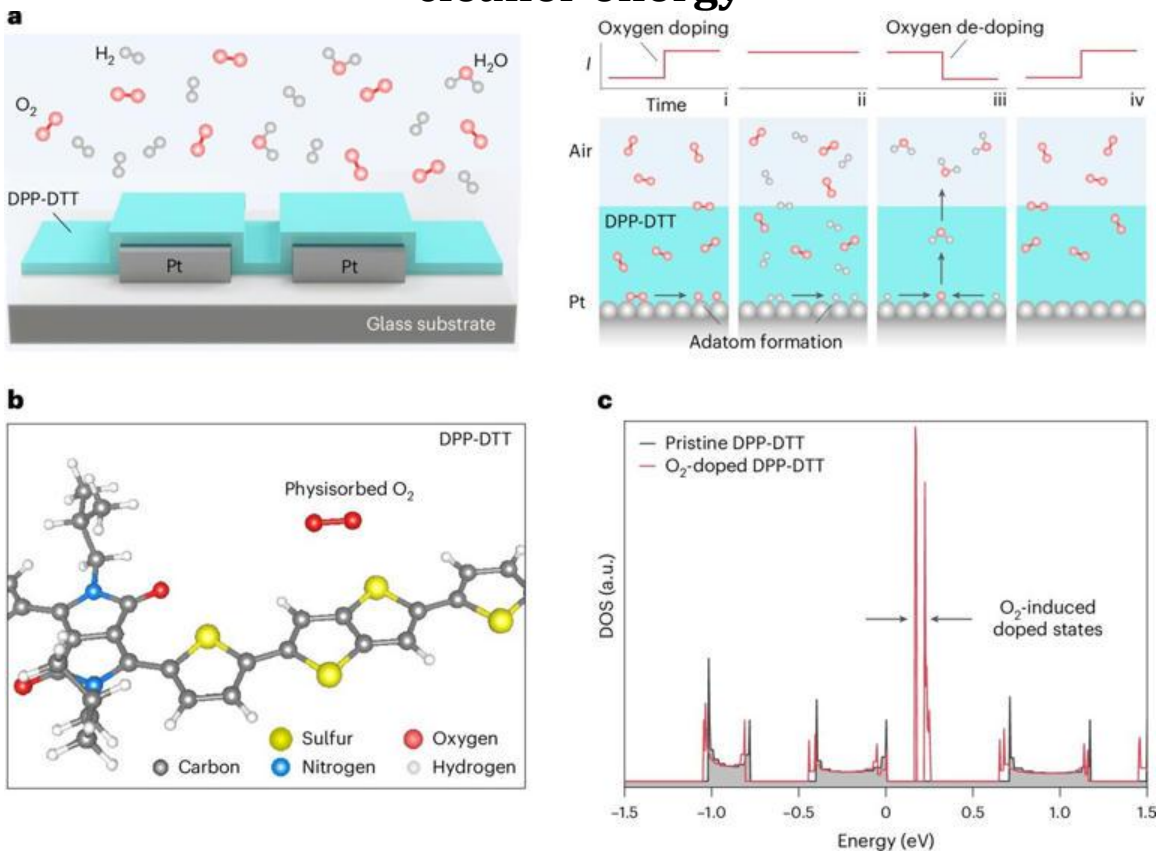
HYDROGEN TECH VOL 2

Hydrogen sensor that could pave the way for safer, cleaner energy



Working principle of the device and theoretical data. Credit: Nature Electronics (2025). DOI: 10.1038/s41928-025-01352-y. https://doi.org/10.1038/s41928-025-01352-y

Scientists have developed a hydrogen sensor that could accelerate the transition to clean hydrogen energy. As the world transitions away from fossil fuels, hydrogen is considered a key player to the transition to cleaner energy. However, the clear, odorless and highly flammable gas is hard to detect using human senses and poses a challenge for its safe deployment.

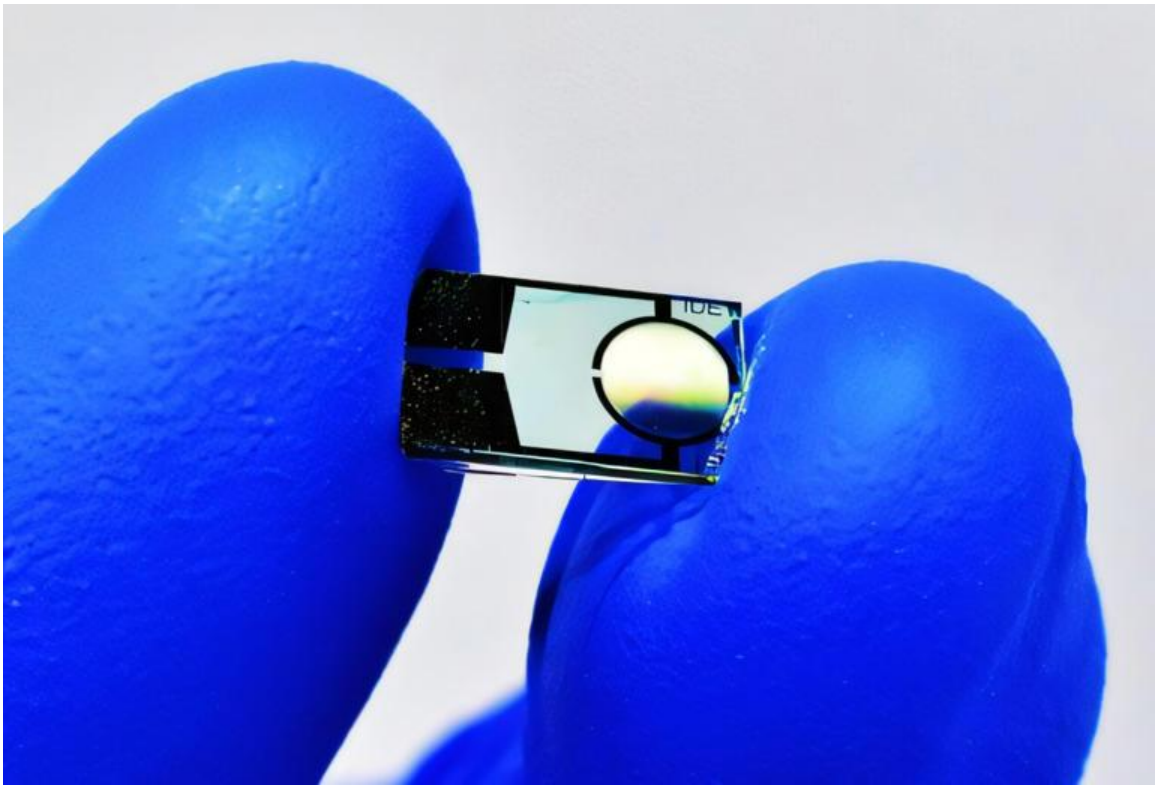
The sensor, developed by a scientist at The University of Manchester, can reliably detect even the tiniest amounts of hydrogen in seconds. It is small, affordable, and energy-efficient—and its results outperform portable commercial hydrogen detectors.

The research, in collaboration with the King Abdullah University of Science and Technology (KAUST) in Saudi Arabia, was published today in the journal *Nature Electronics*.

"This sensor could offer a breakthrough in hydrogen safety technology. By combining affordability, reliability, and high performance, it has the potential to transform how we handle hydrogen across industries, homes, and transportation. I hope our organic sensor will help build trust in emerging hydrogen technologies, making them more accessible and safer for everyone," says Thomas Anthopoulos.

The operation of the new organic semiconductor sensor relies on a process known as "p-doping," where oxygen molecules increase the concentration of positive electrical charges in the active material. When hydrogen is present, it reacts with the oxygen, reversing this effect and causing a rapid drop in electrical current. This change is fast and reversible at room temperature up to 120°C.

The sensor was tested in various real-world scenarios, including detecting leaks from pipes, monitoring hydrogen diffusion in closed rooms following an abrupt release, and even being mounted on a drone for airborne leak detection. In all cases, the sensor proved faster than portable commercial detectors, demonstrating its potential for widespread use in homes, industries, and transport networks.



Hydrogen sensor. Credit: Thomas Anthopoulos

Importantly, the sensor can be made ultra-thin and flexible and could also be integrated into smart devices, enabling continuous distributed monitoring of hydrogen systems in real-time.

The team is now focusing on advancing the sensor further while assessing its long-term stability in different sensing scenarios.

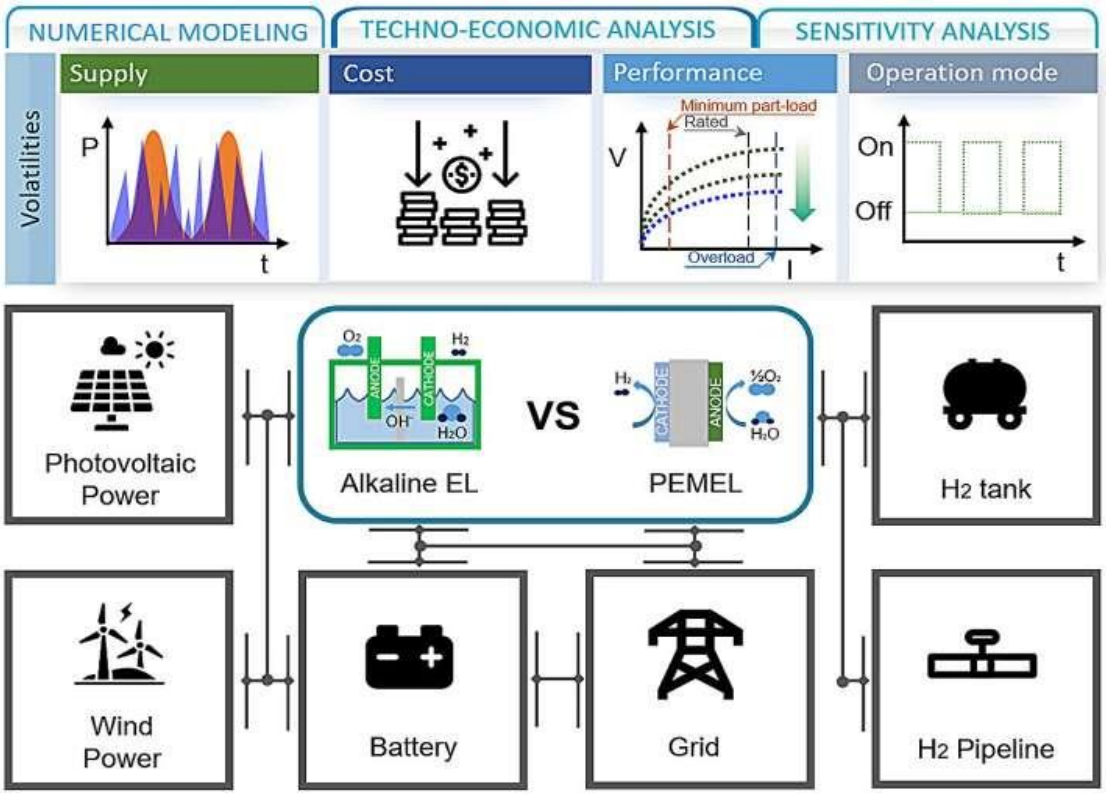
More information: Suman Mandal et al, A robust organic hydrogen sensor for distributed monitoring applications. *Nature Electronics* (2025). DOI: 10.1038/s41928-025-01352-y

Provided by University of Manchester

MARCH 12, 2025

A blueprint for the cost-effective production of eco-friendly green hydrogen

by National Research Council of Science and Technology



Conceptual Framework of a Techno-Economic Analysis Comparing Alkaline and PEM Water Electrolysis. Credit: Korea Institute Of Energy Research

A research team from the Korea Institute of Energy Research (KIER) has conducted an economic analysis of water electrolysis, a key technology for future eco-friendly hydrogen production, and presented optimal operation strategies to maximize efficiency and reduce costs. The study is published in the journal *Energy Conversion and Management*.

Green hydrogen, considered a key eco-friendly fuel of the future, is primarily produced using two technologies: alkaline water electrolysis and proton exchange membrane (PEM) water electrolysis. Among these, alkaline water electrolysis is the most widely commercialized technology, as it enables the low-cost, large-scale production of hydrogen. However, it requires a high and stable power supply to operate, making it difficult to effectively couple with renewable energy sources, which often generate electricity intermittently.

In the case of PEM water electrolysis, hydrogen can be produced even with a relatively small power supply, allowing it to operate solely on renewable energy. However, its drawbacks include high initial installation costs and a lower level of technological maturity compared to alkaline water electrolysis. These challenges make it difficult to build a green hydrogen production infrastructure relying on just one technology.

To address this, the research team conducted a comparative analysis of the technical characteristics and economic feasibility of alkaline water electrolysis and PEM water electrolysis, ultimately deriving optimal operation strategies. In particular, they proposed that the most cost-effective approach is to use the existing power grid as a supplemental power source to provide a stable electricity supply for operating alkaline water electrolysis systems.

If a stable power supply is not maintained for alkaline water electrolysis systems, repeated start-up and shutdown cycles can cause degradation, reducing both the system's lifespan and efficiency. To overcome this, it is essential to continuously supply power using auxiliary sources such as energy storage systems (ESS).

Dr. Joungho Park explains the economic comparison of water electrolysis technology. Credit: Korea Institute Of Energy Research

According to the research team's analysis, when using renewable energy combined with an energy storage system (ESS) as a backup power source, the hydrogen production cost was estimated at up to $8.60 per kilogram. In contrast, securing supplementary power from the existing fossil fuel-based power grid could reduce the cost to around $6.60 per kilogram.

While, for now, linking to the existing power grid is the more economical option, this approach does not resolve environmental concerns. In the long term, the study suggests that reducing ESS costs and increasing the share of carbon-free power sources—such as biomass and nuclear energy—will be essential to achieving both economic and environmental sustainability in hydrogen production.

For PEM water electrolysis, the research team suggested that applying an electrical overload could actually improve economic efficiency. This is because PEM systems are capable of overload operation, allowing excess power beyond the required amount to be supplied in order to increase hydrogen production. The analysis showed that by boosting renewable energy output and supplying 1.5 times the required power, the hydrogen production cost could be reduced to as low as $5.80 per kilogram.

Based on these findings, the research team concluded that PEM water electrolysis is the most suitable option in environments with a high share of renewable energy and a stable power supply. In other cases, the ideal approach is to combine alkaline water electrolysis with a carbon-free power grid.

Additionally, the research team proposed an optimal water electrolysis-based hydrogen production combination tailored to Korea's energy landscape. Based on an analysis using meteorological data from Jeju Island, the study found that, in the future, a stable hydrogen supply at approximately $4 per kilogram could be achieved by combining a 100-megawatt (MW) water electrolysis system with 100 MW of offshore wind power and 100 MW of solar power.

Dr. Joungho Park, who led the study at KIER, stated, "This research is significant in that it clearly analyzes the technical differences between alkaline and PEM water electrolysis and presents optimal design and operation strategies tailored to different energy environments.

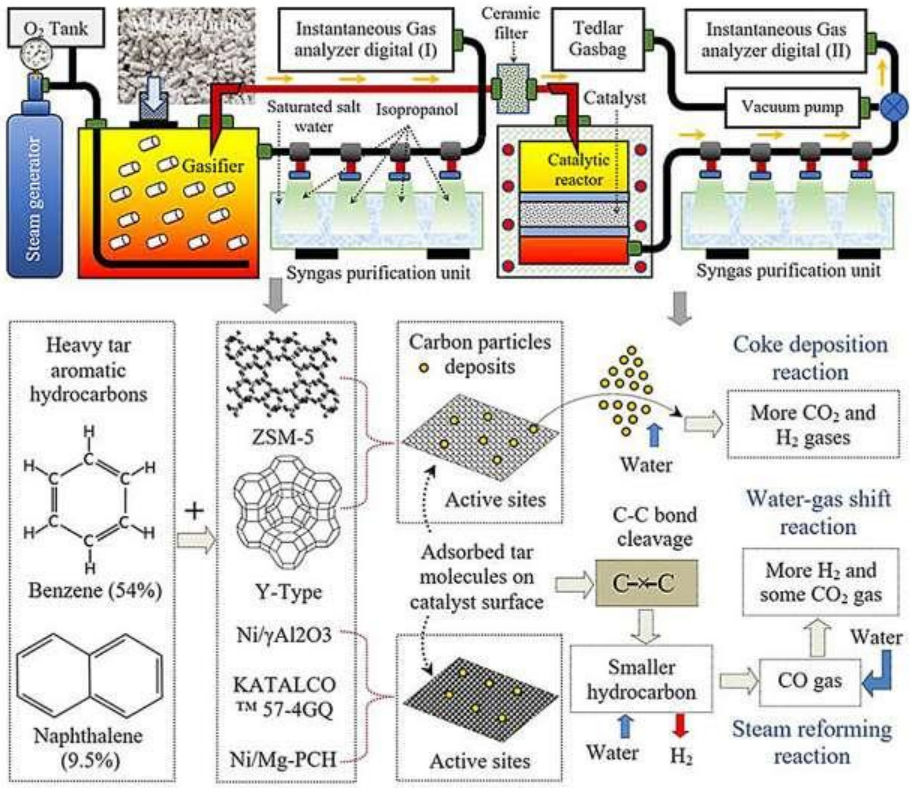
"We expect these findings to serve as a valuable reference for selecting technologies and guiding investment decisions when building hydrogen production systems using renewable energy in the future."

More information: Joungho Park et al, Comparative techno-economic evaluation of alkaline and proton exchange membrane electrolysis for hydrogen production amidst renewable energy source volatility, *Energy Conversion and Management* (2024). DOI: 10.1016/j.enconman.2024.119423
Provided by National Research Council of Science and Technology

MARCH 17, 2025

Innovative hydrogen production: Scientists eliminate tar in gasification

by Kaunas University of Technology



Credit: *Energy* (2024). DOI: 10.1016/j.energy.2024.134184

As the global demand for sustainable energy solutions continues to grow, Lithuanian researchers have taken a step forward by developing a technology that not only transforms waste into valuable hydrogen but also eliminates a long-standing issue in gasification—the presence of tar. This new method offers an efficient and eco-friendly way to produce high-purity hydrogen from various waste materials, representing a significant advancement in clean energy production.

Hydrogen is a key element in the transition to cleaner energy. However, conventional gasification methods are often unable to ensure its high purity—synthesis gases contain very low concentrations of hydrogen.

This inefficiency limits the industrial application of hydrogen as a clean gas fuel, highlighting the need for more advanced production methods.

To address this, Kaunas University of Technology (KTU) and Lithuanian Energy Institute (LEI) scientists have developed a two-step conversion system: an updraft gasifier followed by a catalytic reforming reactor.

The work is published in the journal *Energy*.

Increased hydrogen production

The process begins with gasification, where waste is heated in a controlled steam-oxygen environment to produce syngas, also known as synthetic gas.

"Gasification treatment is an emerging, promising, and eco-friendly technology that can convert waste into syngas as a major product besides soot as a by-product," says KTU Chief researcher Dr. Samy Yousef.

However, the produced syngas contains tar, which not only reduces efficiency and can damage equipment due to corrosion effects, but also interferes with hydrogen production by affecting key chemical reactions. To solve this, the syngas is passed through a catalytic reforming reactor to break down the tar into smaller molecules. These catalysts also enhance chemical reactions that increase the hydrogen content of the syngas, reaching up to 60 vol%, making it a cleaner and more efficient fuel source.

According to the KTU expert, a crucial factor in this technology is the choice of catalysts used in the reforming reactor. That is why researchers tested most commercially available catalysts and laboratory-developed options.

"Experimental results demonstrated the technology's efficiency under various conditions. Among the tested catalysts, KATALCO 57-4GQ proved to be the most effective, as its high surface area, stability, and durability played a key role in breaking down tar and enhancing hydrogen production," says Dr. Yousef.

Can be applied to all types of waste

Unlike conventional gasification techniques, which require high-energy plasma systems or complex pressure-based processes, this new method operates at atmospheric pressure. This reduces the need for high-cost infrastructure and enhances operational safety.

Compared to the dominant hydrogen production method, steam methane reforming (SMR), this new approach offers a more energy-efficient and environmentally sustainable alternative. SMR relies on natural gas, a non-renewable resource, and emits large amounts of carbon dioxide, making it less viable for long-term sustainability goals.

"Unlike SMR, which operates under extreme conditions and requires high-pressure reactors, our method works at atmospheric pressure and utilizes waste as a cost-effective and renewable raw material, making it a cleaner solution," says Dr. Yousef.

While the initial research focused on medical waste, the technology has the potential for broader applications. "This technology is versatile and can be applied to various types of organic and industrial waste, including plastics, textiles, and biomass. Before processing, the waste must be collected, sorted, and pre-treated to ensure a consistent composition and size, allowing for more efficient conversion," KTU expert explains.

When discussing industrial implementation, the researcher highlights that this innovation has reached Technology Readiness Level 5 (TRL5). This level is part of a globally recognized scale that measures a technology's maturity.

"Being at TRL5 means the technology has been tested in an environment that simulates real industrial conditions using reactors that closely resemble industrial-scale systems and is progressing toward full-scale deployment," says Dr. Yousef.

As research continues, further scaling and optimization could pave the way for commercial implementation, making sustainable hydrogen production a reality in the near future.

More information: Samy Yousef et al, Catalytic reforming of tar for enhancing hydrogen production from gasification of hazardous medical waste, *Energy* (2024). DOI: 10.1016/j.energy.2024.134184 Provided by Kaunas University of Technology

54,000-ton: World’s first hydrogen-powered cruise ship can make 6,000 kW electricity

Hydrogen will be stored directly on the vessel through a newly developed containerized system.

Updated: Apr 10, 2025

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Scheduled for late 2026 delivery, the ship measures 239 meters in length.

Shipbuilder Fincantieri and cruise line Viking have unveiled the “Viking Libra,” the world’s first cruise ship set to be powered by hydrogen stored onboard.

Currently under construction at Fincantieri’s Ancona shipyard in Italy, the ship will utilize advanced hydrogen fuel cell technology to generate up to 6 megawatts (MW) of power for propulsion and onboard electricity, which will be sufficient for its 499 rooms.

The 54,300 gross ton ship, which measures 784 feet (239 meters) in length, is designed to accommodate 998 passengers and is scheduled for delivery in late 2026.

Its pioneering hydrogen propulsion system will enable zero-emission navigation and operation.

"Designed with sustainability in mind, the ship will be capable of navigating and operating with zero emissions, allowing it to access even the most environmentally sensitive areas," said the company in a press release.

Onboard hydrogen storage

The new system involves storing hydrogen directly on board within a specialized containerized system.

"The vessel will feature first-of-a-kind solutions to load and store hydrogen directly onboard the ship thanks to a containerized system to overcome supply chain constraints," explained the shipbuilder.

This hydrogen will fuel state-of-the-art polymer electrolyte membrane (PEM) fuel cells, which are specifically optimized for cruise operations and supplied by Fincantieri subsidiary Isotta Fraschini Motori (IFM).

"With the Viking Libra, we are not only delivering the world's first cruise ship powered by hydrogen stored on board, but we are also reinforcing our commitment to shaping the future of sustainable maritime transportation," stated Pierroberto Folgiero, CEO and Managing Director of Fincantieri.

He highlighted the project's role as a catalyst for the industry's green transition and Fincantieri's capability to integrate disruptive technologies.

Agreement for additional vessels

Viking is doubling down on this technology with its subsequent ocean ship, the "Viking Astrea," which is also under construction in Ancona and set for a 2027 delivery.

Further, the two companies have also announced an additional agreement.

"Fincantieri and Viking also today announced that they have signed an agreement for the construction of two new cruise ships for delivery in 2031, plus an option for two additional vessels, based on the successful features of the previous units, which Fincantieri has already built for this shipowner in its Italian yards," highlighted the press release.

These vessels will adhere to the latest environmental regulations and incorporate modern safety systems.

“Viking made the principled decision to invest in hydrogen, which offers a true zero-emission solution,” remarked Torstein Hagen, Chairman and CEO of Viking.

“We look forward to welcoming the world’s first hydrogen-powered cruise ship to our fleet in 2026.”

Impact of hydrogen technology

The world has been witnessing several developments in the field of hydrogen-powered vehicles, ships, and even robots.

Recently, Japanese giant Kawasaki unveiled a concept model for a hydrogen-powered, four-legged robot designed to be ridden by humans.

Earlier, South Korea’s Hyundai unveiled a new hydrogen-powered fuel cell electric vehicle, NEXO, that has extended the driving range to over 435 miles (700 km) per refill.

Now, the latest development regarding the “Viking Libra” could be a game-changer in maritime decarbonization.

APRIL 10, 2025

New technology suppresses temperature rise during hydrogen charging, enabling safer, more efficient refueling

by National Research Council of Science and Technology

Dae-Hwan Kim (left), Principal Researcher at the Busan Machinery Research Center of the Korea Institute of Machinery and Materials (KIMM), explains the internal liquid level gauge of the hydrogen charging demonstration equipment. Credit: Korea Institute of Machinery and Materials (KIMM)

The world's first technology to fundamentally prevent temperature rise during high-pressure hydrogen charging has been developed. This innovation significantly shortens refueling time and reduces the cost of establishing and operating hydrogen refueling infrastructure.

By greatly enhancing the safety and efficiency of hydrogen refueling systems, the technology is expected to accelerate the adoption of hydrogen mobility and infrastructure, ultimately strengthening global competitiveness in the hydrogen economy.

A research team led by Principal Researcher Dae-Hwan Kim at the Nuclear Equipment Verification Laboratory of the Busan Machinery Technology Research Center under the Korea Institute of Machinery and Materials (KIMM) has successfully developed and demonstrated this new technology using an incompressible fluid.

Through 350-bar hydrogen charging demonstration tests, the team proved that the internal temperature rise of the tank can be suppressed to within 5°C, enabling hydrogen charging without any need for pre-cooling.

Traditionally, hydrogen refueling has relied on injecting hydrogen cooled to -40°C to prevent a rise in temperature during charging. However, this method results in longer charging times and requires additional cooling systems, which in turn increases infrastructure costs.

The newly developed method stands out by fundamentally eliminating temperature rise using an incompressible fluid, enabling safe and stable hydrogen charging without a cooling system.

The principle behind the technology involves pre-filling the hydrogen tank with an incompressible fluid (such as water) before charging. As hydrogen is introduced, the fluid is simultaneously extracted, preventing adiabatic compression within the tank. This process mitigates the rapid temperature increase of hydrogen and the corresponding rise in internal pressure, allowing faster and more efficient refueling.

The research team at the Department of Nuclear Equipment Qualification & Safety of the Busan Machinery Research Center at KIMM, which developed the "Technology to Prevent

Temperature Rise in Hydrogen Tanks During Refueling" (center: Principal Researcher Dae-Hwan Kim). Credit: Korea Institute of Machinery and Materials (KIMM)
This innovation not only improves charging speed compared to existing methods, but also keeps temperature under control—enhancing user convenience and economic benefits for infrastructure operators.

Since it does not require high-performance cooling systems, it also offers a substantial reduction in facility setup and maintenance costs. Additionally, by preventing thermal degradation of internal tank components, it improves long-term durability, further lowering maintenance costs for hydrogen vehicles and infrastructure.

Principal Researcher Dae-Hwan Kim stated, "This newly developed technology overcomes the limitations of existing hydrogen charging methods and dramatically improves infrastructure efficiency. We are currently exploring its potential application not only in vehicles, but also in large-capacity hydrogen containers used in ships, trains, and military vehicles. This will be a pivotal technological advancement for promoting the hydrogen economy and securing global market competitiveness."

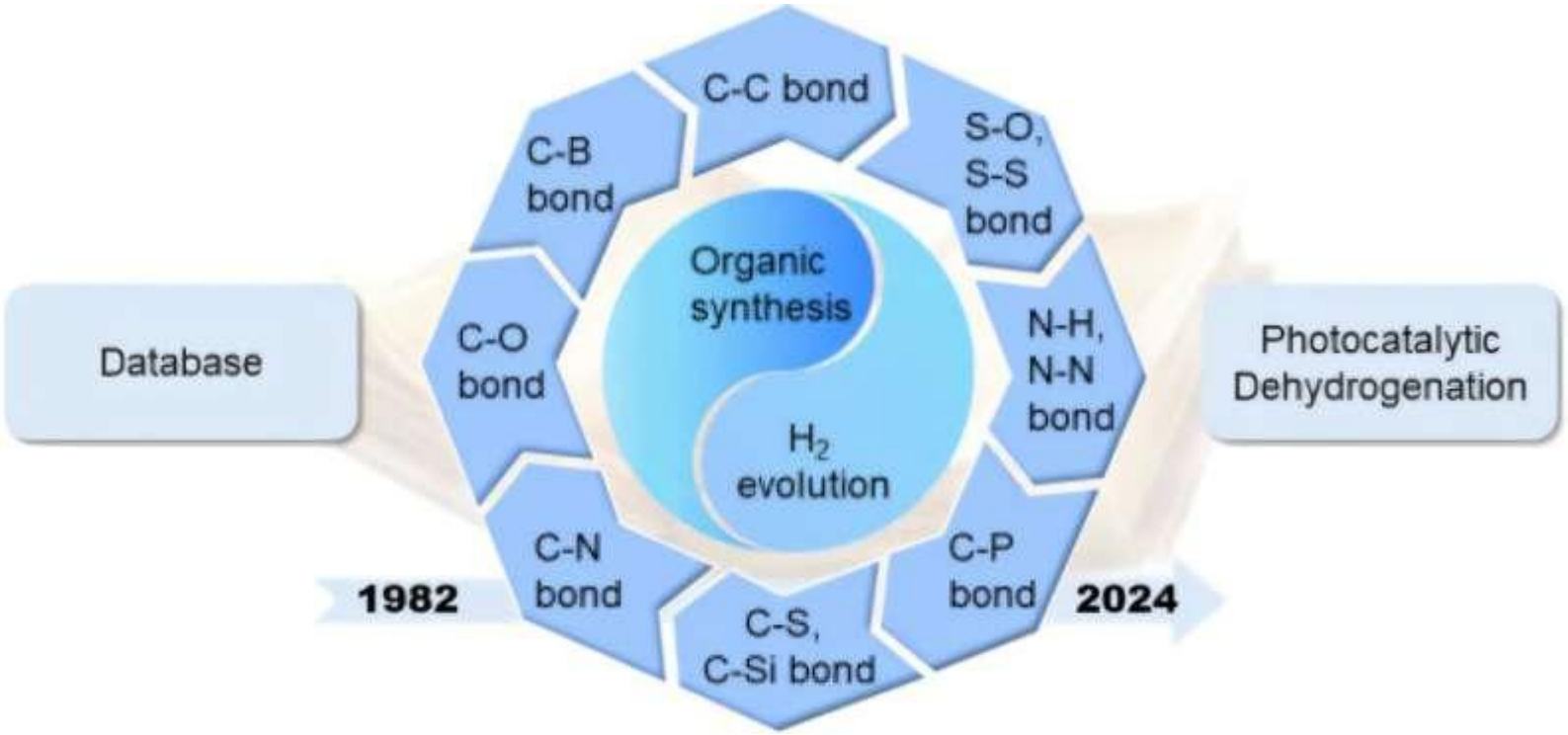
This research was conducted under the initiative, "Industrial Support and Planning for Promising Future Mechanical Technologies—Development of Temperature Rise Prevention Technology for Hydrogen Tanks During Refueling."

Provided by National Research Council of Science and Technology

APRIL 14, 2025

Harnessing photocatalysis: Hydrogen generation and organic synthesis explored through new database

by Chinese Academy of Sciences



Reactions of organic compounds conversion into unsaturated products and hydrogen (H_2) by means of photocatalysis that have been developed in the past 40 years are categorized, summarized and analyzed. Credit: *Chinese Journal of Catalysis* (2025). DOI: 10.1016/S1872-2067(24)60216-0

Generation of hydrogen (H_2) by means of photocatalysis has been at the forefront of research since the 1970s because it can potentially fulfill the demand for this green fuel by employing abundant solar light as the only energy source. It encompasses mainly two approaches: overall water splitting and selective dehydrogenation of organic compounds.

Research in overall water splitting focuses on the design and preparation of more effective photocatalysts capable of utilizing a wider range of the electromagnetic spectrum and operating at lower overpotentials for water oxidation and proton reduction half-reactions. In recent years, the field has made considerable progress in advancing experiments beyond the laboratory stage.

On the other hand, selective dehydrogenation of organic compounds is a more complex and multifaceted area of research. There are nearly an infinite number of organic compounds capable of serving as H_2 sources, while the products of their dehydrogenation are valuable chemicals.

However, the dehydrogenation of most organic molecules could proceed to different extents and yield a range of products. Therefore, selectivity towards a specific product is a central parameter in this area of research, which could be modulated by selecting the right photocatalysts and adjusting process parameters.

Despite its importance for fundamental and applied research, an overarching summary of the progress that has been achieved by the community in selective dehydrogenation of organic compounds in the past 40 years was missing. To fill this gap, recently, Prof. Oleksandr Savateev (the Chinese University of Hong Kong) created a "Database of Photocatalytic Dehydrogenation Reactions."

The database contains 236 entries, which were extracted from 216 articles published between 1982–2023 and more than 100 descriptors that are associated with each entry. For example, these descriptors are:

- Reaction classification according to the type of formed bond, such as C–B, C–C, C–H, C–N, C–O, C–P, C–S, C–Si, S–S, Si–O, N–N.
- Type of the photocatalyst (homogeneous, heterogeneous), its chemical structure and performance, such as yield rate of H_2 and the organic product.
- Quantum yield of the reaction, and others.

These data were analyzed by the team led by Prof. Oleksandr Savateev (the Chinese University of Hong Kong), in cooperation with Prof. Junwang Tang (Tsinghua University) and Prof. Shaowen Cao (Wuhan University of Technology), and the results of the analysis are published in the review article in the *Chinese Journal of Catalysis*.

Among the findings that outline future directions of the field development are:

- More efficient utilization of the solar spectrum. Dehydrogenation of organic compounds is thermodynamically less challenging—the Gibbs free energy change is less positive than that of water splitting. Therefore, in principle, photocatalysts with an energy gap narrower than 1 eV and photons in the near IR region of the electromagnetic spectrum are sufficient to drive these reactions. However, there are only a few examples of photocatalysts and reactions performed at longer wavelengths, around 500 nm. The vast majority of reactions are enabled by photocatalysts having the band gap in the range 2.8–3.5 eV, requiring photons at the edge of the visible spectrum and near UV.
- Development of new organic reactions. There are many examples of photocatalytic dehydrogenation of organic compounds that proceed together with the formation of C–C, C–O, and C–N bonds. However, there are only a few examples of constructing more complex organic molecules via C–S, C–Si, and N–N coupling of molecular fragments accompanied by H_2 evolution. This outlines opportunities for making organic synthesis more atom-efficient—H_2 is a light molecule and the only byproduct in acceptorless dehydrogenative cross-coupling.

There are numerous areas where the database and the results of its analysis may be applied immediately. They allow researchers to accurately rank the performance of their newly developed photocatalytic systems in a selected dehydrogenation reaction under given conditions with respect to other reported photocatalysts.

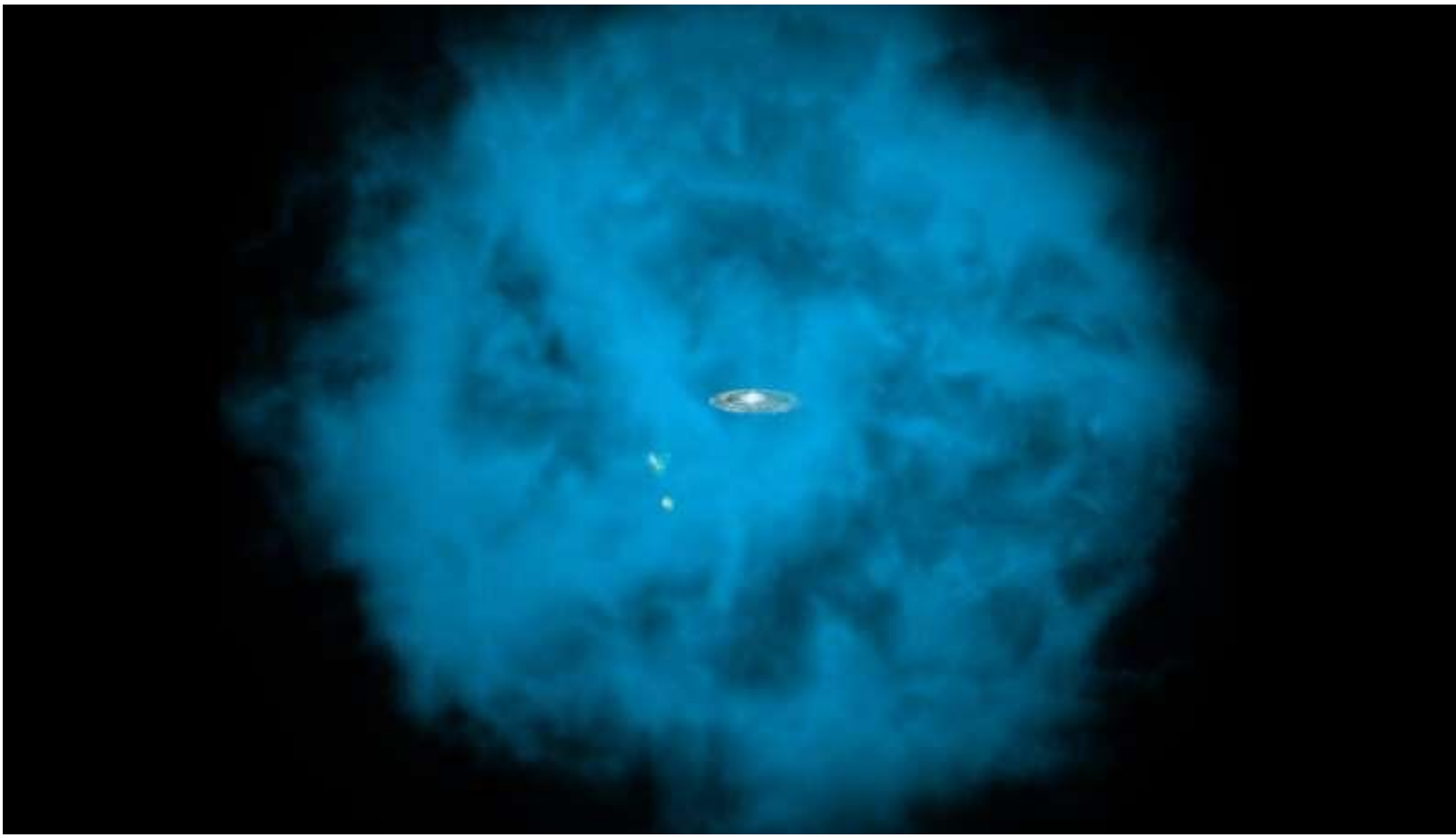
On the other hand, they allow the identification of the most promising photocatalysts and photocatalytic dehydrogenation reactions, those with higher quantum yields and yield rates of H_2 and organic products, to develop at a higher technology readiness level.

More information: Oleksandr Savateev et al, Photocatalytic water splitting versus H2 generation coupled with organic synthesis: A large critical review, *Chinese Journal of Catalysis* (2025). DOI: 10.1016/S1872-2067(24)60216-0
Provided by Chinese Academy of Sciences

APRIL 14, 2025

Half of the universe's hydrogen gas, long unaccounted for, has been found

by Robert Sanders, University of California - Berkeley



An artist's depiction of the halo of hot hydrogen gas surrounding the Milky Way galaxy (center) and two satellite galaxies, the Large and Small Magellanic Clouds. The halo is more extended that astronomers originally thought, and contains enough hydrogen gas to resolve the problem of the universe's missing baryonic mass. Credit: NASA/CXC/M.Weiss; NASA/CXC/Ohio State/A Gupta et al

Astronomers tallying up all the normal matter—stars, galaxies and gas—in the universe today have come up embarrassingly short of the total matter produced in the Big Bang 13.6 billion years ago. In fact, more than half of normal matter—half of the 15% of the universe's matter that is not dark matter—cannot be accounted for in the glowing stars and gas we see.

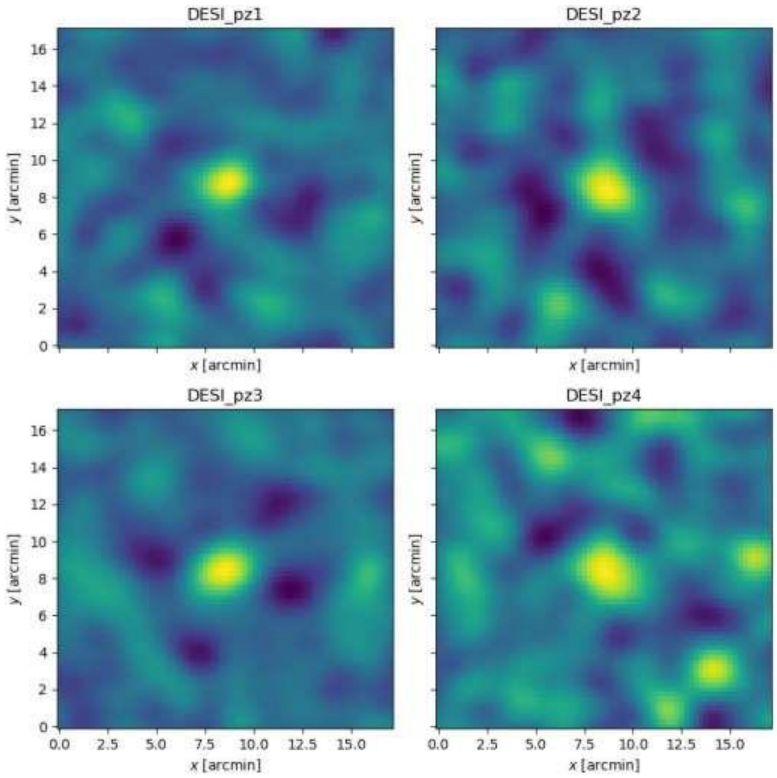
New measurements, however, seem to have found this missing matter in the form of very diffuse and invisible ionized hydrogen gas, which forms a halo around galaxies and is more puffed out and extensive than astronomers thought.

The findings not only relieve a conflict between astronomical observations and the best, proven model of the evolution of the universe since the Big Bang, they also suggest that the massive black holes at the centers of galaxies are more active than previously thought, fountaining gas much farther from the galactic center than expected—about five times farther, the team found.

"We think that, once we go farther away from the galaxy, we recover all of the missing gas," said Boryana Hadzhiyska, a Miller postdoctoral fellow at the University of California, Berkeley, and first author of a paper reporting the findings. "To be more accurate, we have to do a careful analysis with simulations, which we haven't done. We want to do a careful job."

"The measurements are certainly consistent with finding all of the gas," said her colleague, Simone Ferraro, a senior scientist at Lawrence Berkeley National Laboratory (Berkeley Lab) and at UC Berkeley who saw hints of this extensive ionized hydrogen halo in analyses published three years ago.

The results of the study, co-authored by 75 scientists from institutions around the world, have been presented at recent scientific meetings, posted as a preprint on *arXiv* and are undergoing peer review at the journal *Physical Review Letters*. Hadzhiyska and Ferraro are researchers at the Berkeley Center for Cosmological Physics in UC Berkeley's Department of Physics, as well as at Berkeley Lab.



To detect the faint signal of ionized hydrogen gas around very bright red galaxies, the researchers stacked images of more than a million galaxies on top of one another. These four frames are stacks of galaxies at different distances from Earth, showing only the electromagnetic frequency range affected by electron scattering (the kinematic Sunyaev-Zel'dovich effect). The blue and green colors represent minute temperature fluctuations in the cosmic microwave background (CMB) radiation. The yellow center indicates the CMB light scattered by the extensive hydrogen gas envelope that surrounds these galaxies. In visible light, the galaxies would appear as a few pixels at the center of the yellow patch. Credit: Boryana Hadzhiyska and Simone Ferraro, with data from DESI and ACT; Hadzhiyska et al

Stacking galaxies

While the still mysterious dark matter makes up the bulk—about 84%—of matter in the universe, the remainder is normal matter. Only about 7% of normal matter is in the form of stars, while the rest is in the form of invisible hydrogen gas—most of it ionized—in galaxies and the filaments that connect galaxies in a kind of cosmic network.

The ionized gas and associated electrons strung out in this filament network are referred to as the warm-hot intergalactic medium, which is too cold and too diffuse to be seen with the usual techniques at astronomers' disposal, and therefore has remained elusive until now.

In the new paper, the researchers estimated the distribution of ionized hydrogen around galaxies by stacking images of approximately 7 million galaxies—all within about 8 billion light-years of Earth—and measuring the slight dimming or brightening of the cosmic

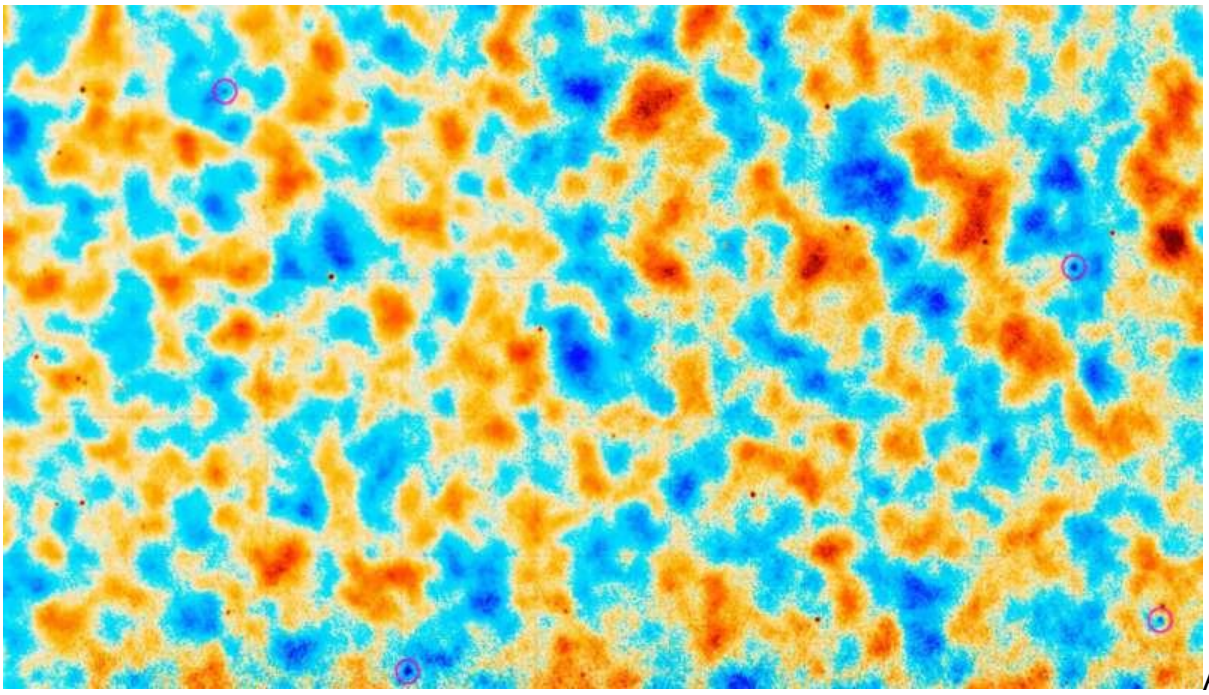
microwave background caused by a scattering of the radiation by electrons in the ionized gas, the so-called kinematic Sunyaev-Zel'dovich effect.

"The cosmic microwave background is in the back of everything we see in the universe. It's the edge of the observable universe," Ferraro said. "So you can use that as a backlight to see where the gas is."

The galaxy images used—all luminous red galaxies—were collected by the Dark Energy Spectroscopic Instrument (DESI) on the Mayall 4-meter Telescope at Kitt Peak National Observatory in Tucson, Arizona. The instrument, built by a collaboration headquartered at Berkeley Lab, is surveying tens of millions of galaxies and quasars to construct a 3D map spanning the universe out to 11 billion light years from Earth in order to measure the effect of dark energy on the expansion of the universe.

Measurements of the cosmic microwave background (CMB) around these galaxies were made by the Atacama Cosmology Telescope (ACT) in Chile, which made the most accurate measurements to date of the CMB before it was decommissioned in 2022.

The analysis was done in collaboration with Bernardita Ried Guachalla, a graduate student at Stanford University; Emmanuel Schaan, a staff scientist at the SLAC National Accelerator Laboratory in Menlo Park; and the DESI and ACT teams.



A map of the cosmic microwave background radiation obtained by the Atacama Cosmology Telescope. The two circles highlight spots where ionized hydrogen gas has scattered the radiation, leaving a signature that can be used to estimate the amount of gas surrounding galaxies. Credit: ACT; *Journal of Cosmology and Astroparticle Physics* (2017). DOI: 10.1088/1475-7516/2017/06/031

Galactic feedback

Astronomers have generally thought that massive black holes at the centers of galaxies expel gas in jets of material only during their formative years, when the central black hole is gobbling up gas and stars and producing lots of radiation. This makes them stand out as what astronomers call active galactic nuclei (AGN), or quasars.

If, as the new study suggests, the ionized hydrogen halo around galaxies is more diffuse, but also more extensive, than thought, this implies that the central black holes may actually become active at other times in their lives.

"One problem we don't understand is about AGNs, and one of the hypotheses is that they turn on and off occasionally in what is called a duty cycle," said Hadzhiyska.

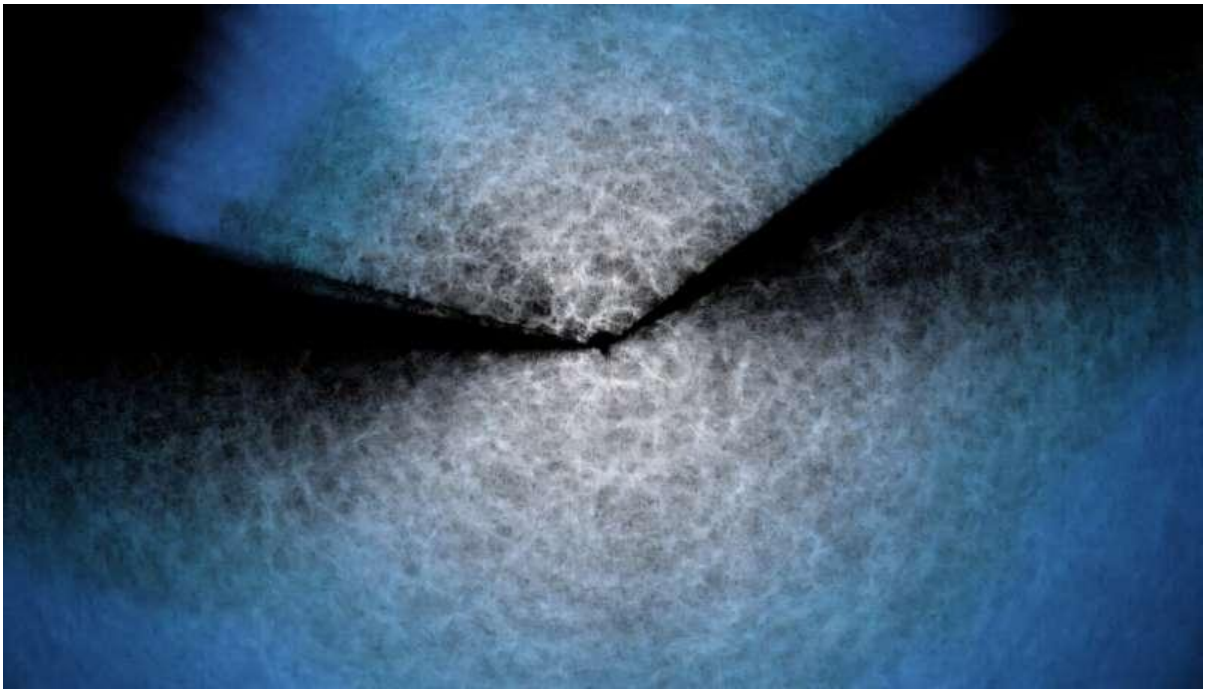
Astronomers refer to the expulsion of gas and its subsequent fall back into the galactic disk as feedback that regulates the formation of new stars throughout the galaxy. Ferraro, Schaan and their colleagues reported hints of more extended feedback in previous work in 2020, when Schaan was a postdoctoral fellow at Berkeley Lab.

But the new work incorporates more galaxies and produces a more precise measurement. Subsequent work by Ried Guachalla confirmed the findings with the DESI spectroscopic sample, and was able to study the gas in more nearby galaxies, highlighting that the gas is not distributed uniformly around them, but follows "cosmic filaments" that permeate the universe.

Hadzhiyska noted that current simulations of galaxy evolution will need to incorporate this more vigorous feedback in their models. Some new models are already doing so to produce stronger simulations in better agreement with the new data.

The identification of the missing matter, or baryons, in the universe also has implications for other aspects of cosmic evolution.

"Knowing where the gas is has become one of the most serious limiting factors in trying to get cosmology out of current and future surveys. We've kind of hit this wall, and this is the right time to address these questions," Ferraro said. "Once you know where the gas is, you can ask, 'What's the consequence for cosmological problems?'"



The DESI collaboration made the largest 3D map of our universe to date and uses it to study dark energy. In this visualization, Earth is at the center, and every dot is a galaxy. Credit: DESI collaboration and KPNO/NOIRLab/NSF/AURA/R. Proctor

For one, the expulsion of gas from the cores of these massive galaxies challenges the assumption that gas follows dark matter, Hadzhiyska said. Underestimating this gas expulsion can introduce inconsistencies into cosmological models, while the new results may actually resolve some issues about how clumpy the universe is.

"There are a huge number of people interested in using our measurements to do a very thorough analysis that includes this gas," she said. "People in astronomy care a lot about it for understanding galaxy formation and evolution."

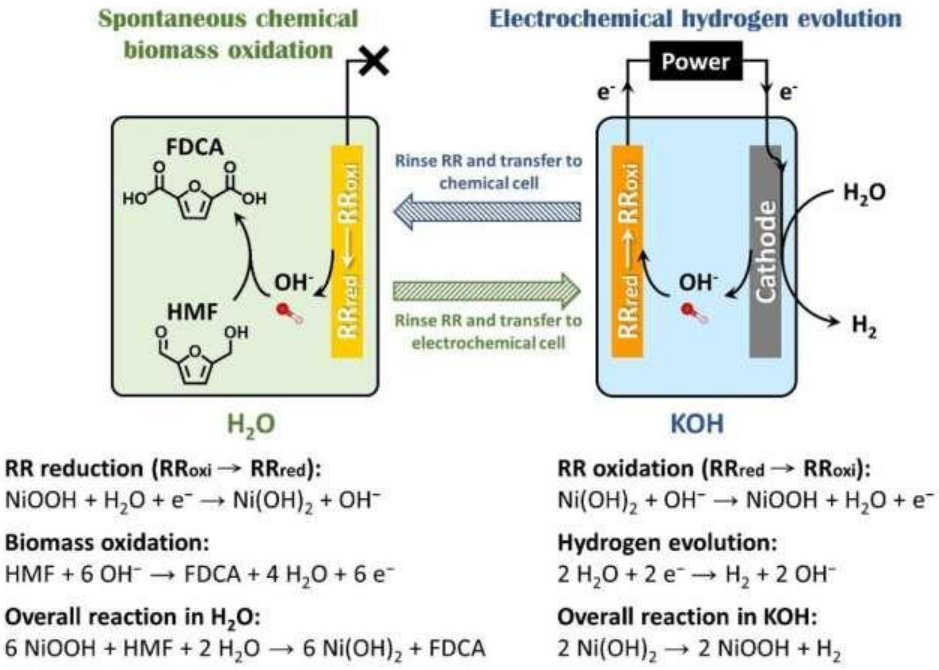
The technique the team used, the kinematic Sunyaev-Zel'dovich effect, could also be used to probe the early universe, Hadzhiyska said. This could provide insight into the large-scale structure of the universe and the laws of physics in the early universe and allow scientists to test gravity and general relativity.

More information: B. Hadzhiyska et al, Evidence for large baryonic feedback at low and intermediate redshifts from kinematic Sunyaev-Zel'dovich observations with ACT and DESI photometric galaxies, *arXiv* (2024). DOI: 10.48550/arxiv.2407.07152
Journal information: Physical Review Letters , arXiv
Provided by University of California - Berkeley

APRIL 15, 2025

Unlocking a greener pathway for biomass conversion and hydrogen production

by National Taiwan University



Schematics of the chemical-electrochemical cycles for decoupling 5-hydroxymethylfurfural oxidation reaction (HMFOR) and hydrogen evolution reaction (HER) through a redox reservoir (RR). The RR electrode transitions between oxidative (NiOOH) and reductive [$Ni(OH)_2$] states, denoted as RRoxi and RRred respectively. Credit: National Taiwan University

A research team from National Taiwan University, led by Prof. Chih-Jung Chen has developed an innovative electrochemical platform capable of efficiently converting biomass into high-value chemicals while simultaneously generating hydrogen fuel—without the use of conventional electrolytes or ion-exchange membranes.

This advancement offers a promising solution to longstanding challenges in sustainable chemical production and clean energy technologies.

In their study published in the *Chemical Engineering Journal*, the team introduced a "redox reservoir" (RR) system that decouples the oxidation of 5-hydroxymethylfurfural (HMF)—a key biomass-derived compound—from the hydrogen evolution reaction (HER).

By separating these two half-reactions both spatially and temporally, the system minimizes undesirable side reactions and allows greater control over each process.

Traditionally, HMF oxidation is carried out in strongly alkaline electrolytes to enhance reaction rates. However, such environments often trigger unwanted side reactions like Cannizzaro disproportionation and humin formation, reducing product yield and carbon efficiency. Moreover, the cathodic HER process can further destabilize HMF molecules, leading to significant carbon loss.

To address these limitations, the researchers designed a reusable RR electrode composed of nickel oxyhydroxide (NiOOH), which serves as a solid-state oxidant.

In pure water, the RR chemically oxidizes HMF without the need for electrolyte salts or external voltage, undergoing conversion to nickel hydroxide [$Ni(OH)_2$]. This reduced form of the RR can then be electrochemically regenerated during HER, thereby completing the redox cycle.

"The concept is similar to pumped hydro storage, but implemented at the microscale," explained lead author Shih-Wei Lin. "Energy is stored electrochemically in the RR electrode during HER and later released chemically to drive biomass oxidation—efficiently and cleanly."

The platform demonstrated remarkable performance, achieving a 97.4% yield of 2,5-furandicarboxylic acid (FDCA)—a key monomer for bioplastics—from HMF concentrations as high as 300 mM, approaching industrially relevant levels.

During the HER step, the regeneration of NiOOH maintained a Faradaic efficiency of 96.0%, while the overall process achieved a high voltage efficiency of 94.8%.

"Our findings open new avenues for green chemical synthesis," said Prof. Chih-Jung Chen. "The system is also capable of oxidizing other organic molecules containing aldehyde or alcohol groups, such as furfural, underscoring its versatility."

By eliminating supporting electrolytes and membrane components, the approach reduces energy demands, lowers material costs, and simplifies downstream purification. It also minimizes carbon losses and enhances product purity, offering a scalable and sustainable pathway for producing bio-based chemicals and clean hydrogen.

This breakthrough represents a critical step toward decarbonizing the chemical industry and leveraging renewable electricity for environmentally responsible chemical transformations.

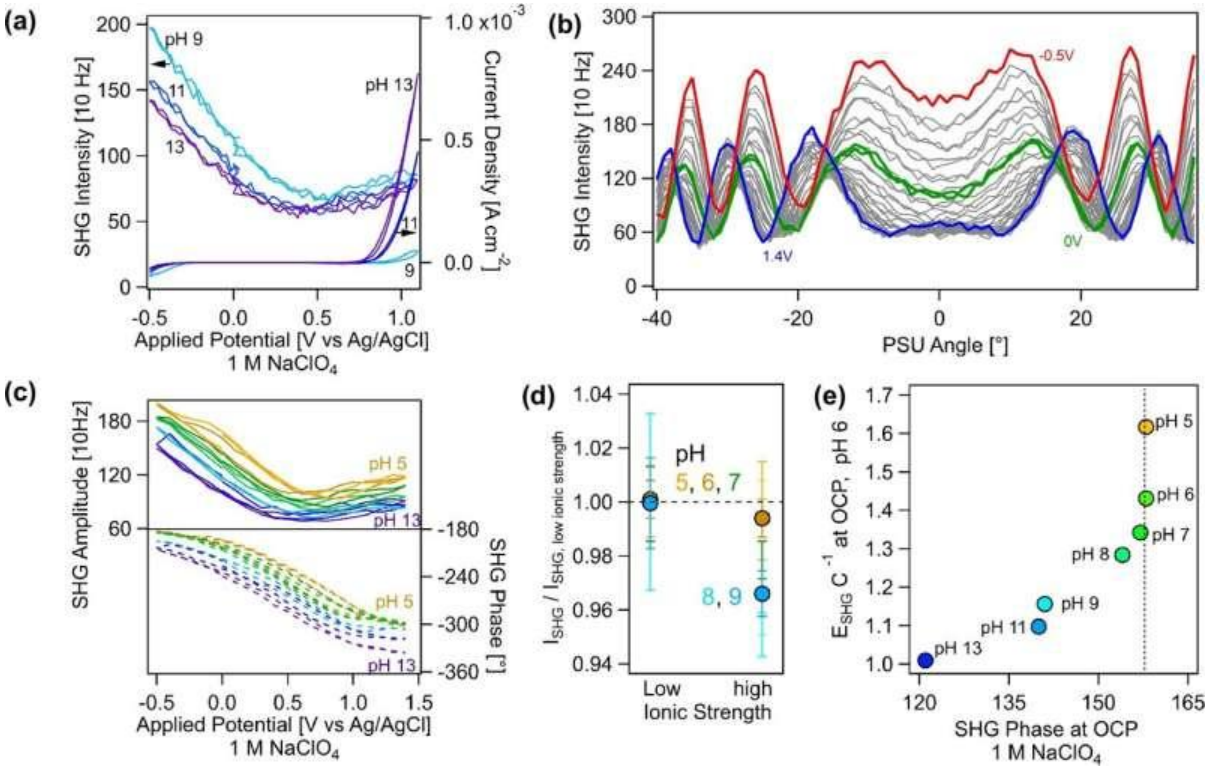
More information: Shih-Wei Lin et al, Stepwise chemical-electrochemical cycles for decoupling modular biomass oxidation and hydrogen evolution, *Chemical Engineering Journal* (2024). DOI: 10.1016/j.cej.2024.158764

Journal information: Chemical Engineering Journal
Provided by National Taiwan University

APRIL 15, 2025

Uncovering the hidden cost of water splitting: Study paves the way for more efficient clean energy production

by Amanda Morris, Northwestern University



SHG Phase and Amplitude Measurements. Credit: *Nature Communications* (2025). DOI: 10.1038/s41467-025-58842-y

As the global pursuit for sustainable energy solutions intensifies, water splitting remains a promising avenue for producing clean hydrogen fuels. But the process of splitting water into hydrogen and oxygen is inherently inefficient—requiring significantly more energy than theoretically predicted.

Now, Northwestern University chemists have found a molecular-level explanation for this discrepancy. In the crucial moment before giving up oxygen atoms, the water molecules perform an unexpected trick: They flip.

After observing the water molecules flip, the team quantified the precise energy cost associated with that critical step. They discovered the acrobatic act is a major contributor to water splitting's efficiency bottleneck. But, in yet another discovery, they found increasing the pH of water lowers that energy cost and thereby contributes to making the process more efficient.

This new knowledge could help researchers find new ways to reduce the energy barrier for generating clean hydrogen fuel and for producing breathable oxygen during future missions to Mars.

The study is published in the journal *Nature Communications*.

"When you split water, two half-reactions occur," said Northwestern's Franz Geiger, who led the study. "One half-reaction produces hydrogen and the other produces oxygen. The half-reaction that produces oxygen is really difficult to perform because everything has to be aligned just right. It ends up taking more energy than theoretically calculated. If you do the math, it should require 1.23 volts. But, in reality, it requires more like 1.5 or 1.6 volts. Providing that extra voltage costs money, and that's why water splitting hasn't been implemented at a large scale.

"We argue that the energy required to flip the water is a significant contributor to needing this extra energy. By designing new catalysts that make water flipping easier, we could make water splitting more practical and cost-effective."

Geiger is the Charles E. and Emma H. Morrison Professor of Chemistry at Northwestern's Weinberg College of Arts and Sciences and member of the International Institute for Nanotechnology and the Paula M. Trienens Institute for Energy and Sustainability. The study's lead author is Raiden Speelman and the second author is Ezra J. Marker, who are both members of Geiger's lab. Other co-authors include Alex Martinson from Argonne National Laboratory and Mavis Boamah, Jacob Kupferberg, Mark Engelhard, Yatong Zhao and Kevin Rosso—all from the Pacific Northwest National Laboratory.

Water splitting's promise and challenges

As the climate continues to warm, scientists have become increasingly interested in water splitting as a way to produce clean hydrogen energy as an alternative to fossil fuels. To perform the process, scientists add water to an electrode and then apply a voltage. This electricity splits water molecules into two components—hydrogen and oxygen—without any unwanted byproducts. From there, researchers can collect hydrogen for fuel or repurpose the hydrogen and oxygen into energy-efficient fuel cells.

While water splitting could play a significant role in a future clean-energy economy, it faces several challenges. The main issue is that the oxygen part of the reaction, called the oxygen evolution reaction (OER), can be difficult and inefficient. Although it's most efficient when iridium is used as the electrode, Geiger said scientists need more affordable alternatives.

"Iridium only comes to Earth from meteoric impact, like the famous iridium anomaly at the Cretaceous-Paleogene boundary, so there's a limited amount," he said. "It's very expensive and certainly not going to help solve the energy crisis any time soon. Researchers are looking at alternatives, like nickel and iron, and we're hoping to find ways to make these materials just as efficient—if not more efficient—than iridium."

'Optical equivalent to noise-canceling headphones'

In the new study, Geiger and his team focused on hematite, an inexpensive and earth-abundant iron oxide mineral. Although hematite is a promising material for performing the OER, it suffers from inefficiency—much like other inexpensive metals. To explore the reason why, the researchers applied a sophisticated new light-based technique called phase-resolved second harmonic generation (PR-SHG).

Previously developed in Geiger's laboratory, PR-SHG enables researchers to observe how water molecules interact with the metallic electrode in real time. To conduct the experiment, the team first placed a hematite electrode into a special container with water. Then, they shined a laser onto the electrode's surface and measured the light intensity at half the wavelength. Using multiple optical components—including lenses, mirrors and crystals—the researchers manipulated the laser beam to gain detailed information.

"Our technique is the optical equivalent to noise-canceling headphones," Geiger said. "We can essentially control constructive and deconstructive interference—the photon's phase—and from that, we can precisely quantify how many water molecules are pointing to the surface and how many rearrange to point away from it."

By analyzing the amplitude and phase of the signal photons, Geiger's team inferred the water molecules' arrangement. Before applying the voltage, the researchers noticed the water molecules were randomly positioned. As they applied a precise voltage to the electrode, however, they watched the water molecules reorient themselves.

Quantifying the energy hurdle

Directly observing the water molecules flip enabled the researchers to measure how many water molecules flipped as well as the energy associated with that flipping. They found the flipping happens immediately before OER starts, indicating this is a necessary, non-negotiable step in the process.

"These electrodes are negatively charged, so the water molecule wants to put its positively charged hydrogen atoms toward the electrode's surface," Geiger said. "In that position, electron transfer—from water's oxygen atoms to the electrode's active site—is blocked. We find that when the electric field becomes strong enough, it causes the molecules to flip, so

the oxygen atoms point toward the electrode's surface. Then, the hydrogen atoms are out of the way, and the electrons can move from water's oxygen to the electrode."

When quantifying the amount of energy used, Geiger and his team discovered that the energy required to align the water molecules closely matches the energy that holds liquid water together. They also found that water's pH level influences the orientation of water molecules. While low pH levels required more energy to flip the water molecules into the correct alignment, higher pH levels, by contrast, made the process more efficient.

"When you go below a pH level of nine, there's little-to-no electrical current produced at all," Geiger said. "So, while the water molecules still flip, the work associated with doing so is so high that there's no electrochemistry happening."

Confirmed conclusions

These findings confirm a previous study from Geiger's laboratory, published in March in the journal *Science Advances*. In that study, Geiger's team watched OER on a nickel electrode. The researchers witnessed the same behavior: water molecules flipped immediately before the reaction started.

"We now know that water flipping happens on both metal and semiconductor electrodes," Geiger said. "So, this is probably a more general behavior than we initially thought. Now, we can optimize the conditions where water flipping is easiest."

Although nickel and hematite are both inexpensive and abundant materials, hematite, which is a semiconductor, has potential applications as a photoanode and therefore solar water oxidation.

"A key goal is to move away from fossil fuels and toward a hydrogen economy," Geiger said. "One long-pursued idea is to use a material with the right electrocatalytic and optical properties. Through solar radiation, it generates catalytically active sites that do the electrochemistry. You still need to apply a current to perform the electrochemistry, but the sun's photons allow you to apply less voltage. And the less voltage you apply, the cheaper the fuel becomes.

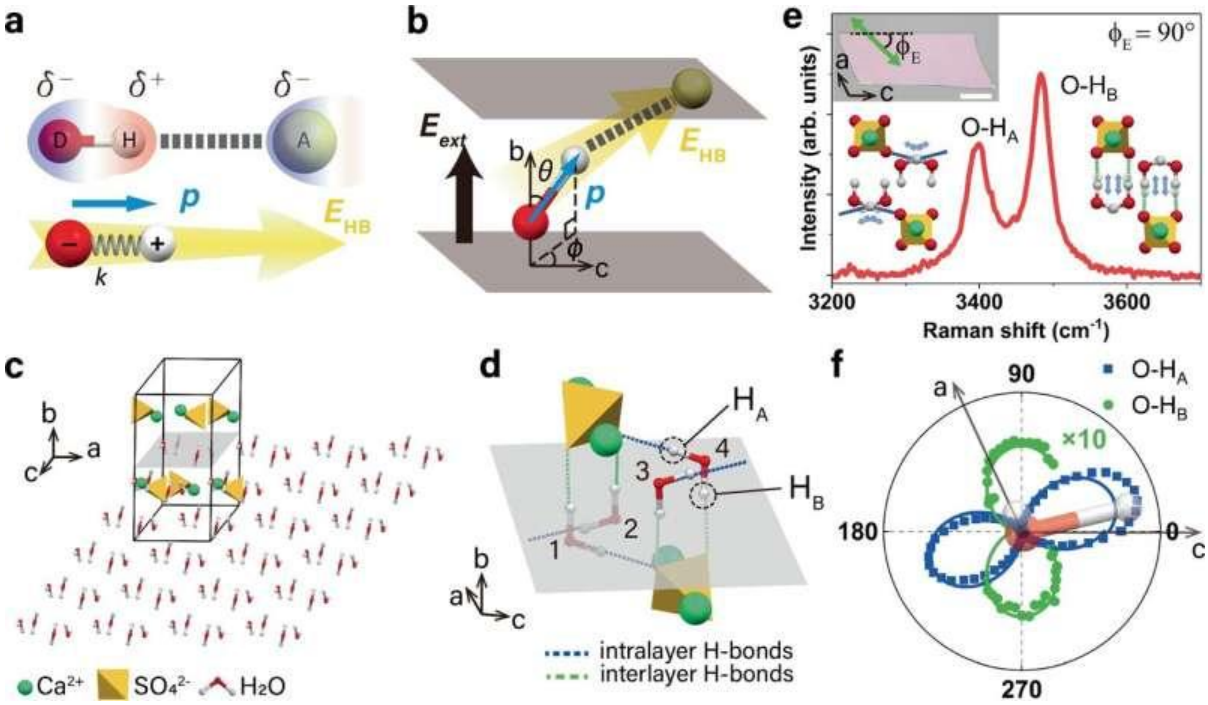
"Our study shows that the catalyst surfaces need to be tailored to facilitate water flipping so the electron transfer can initiate."

More information: Raiden Speelman et al, Water flipping and the oxygen evolution reaction on Fe2O3 nanolayers, *Nature Communications* (2025). DOI: 10.1038/s41467-025-58842-y
Journal information: Nature Communications , Science Advances
Provided by Northwestern University

APRIL 15, 2025

Scientists develop new method to measure and predict hydrogen bond strength in confined water

by University of Manchester



Hydrogen bond model and gypsum system. Credit: *Nature Communications* (2025). DOI: 10.1038/s41467-025-58608-6

A breakthrough by researchers at The University of Manchester sheds light on one of nature's most elusive forces, with wide-reaching implications for medicine, energy, climate modeling and more. The researchers have developed a method to precisely measure the strength of hydrogen bonds in confined water systems, an advance that could transform our understanding of water's role in biology, materials science, and technology.

The work, published in *Nature Communications*, introduces a fundamentally new way to think about one of nature's most important but difficult-to-quantify interactions.

Hydrogen bonds are the invisible forces that hold water molecules together, giving water its unique properties, from high boiling point to surface tension, and enabling critical biological functions such as protein folding and DNA structure. Yet despite their significance, quantifying hydrogen bonds in complex or confined environments has long been a challenge.

"For decades, scientists have struggled to measure hydrogen bond strength with precision," said Professor Artem Mishchenko, who led the study with Dr. Qian Yang and Dr. Ziwei Wang. "Our approach reframes hydrogen bonds as electrostatic interactions between dipoles and an electric field, which allows us to calculate their strength directly from spectroscopic data."

The team used gypsum ($CaSO_4 \cdot 2H_2O$), a naturally occurring mineral that contains two-dimensional layers of crystalline water, as their model system. By applying external electric fields to water molecules trapped between the mineral's layers, and tracking their vibrational response using high-resolution spectroscopy, the researchers were able to quantify hydrogen bonding with unprecedented accuracy.

"What's most exciting is the predictive power of this technique," said Dr. Yang. "With a simple spectroscopic measurement, we can predict how water behaves in confined environments that were previously difficult to probe, something that normally requires complex simulations or remains entirely inaccessible."

The implications are broad and compelling. In water purification, this method could help engineers fine-tune membrane materials to optimize hydrogen bonding, improving water flow and selectivity while reducing energy costs.

In drug development, it offers a way to predict how water binds to molecules and their targets, potentially accelerating the design of more soluble and effective drugs. It could enhance climate models by enabling more accurate simulations of water's phase transitions in clouds and the atmosphere.

In energy storage, the discovery lays the foundation for "hydrogen bond heterostructures," engineered materials with tailored hydrogen bonding that could dramatically boost battery performance. And in biomedicine, the findings could help create implantable sensors with better compatibility and longer lifespans by precisely controlling water-surface interactions.

"Our work provides a framework to understand and manipulate hydrogen bonding in ways that weren't possible before," said Dr. Wang, first author of the paper. "It opens the door to designing new materials and technologies, from better catalysts to smarter membranes, based on the hidden physics of water."

More information: Ziwei Wang et al, Quantifying hydrogen bonding using electrically tunable nanoconfined water, *Nature Communications* (2025). DOI: 10.1038/s41467-025-58608-6
Journal information: Nature Communications
Provided by University of Manchester

Earth’s Secret Hydrogen Jackpot: Enough Clean Power for 170,000 Years

BY UNIVERSITY OF OXFORDMAY 18, 2025

Scientists may have found a clean hydrogen jackpot underground, with a new recipe to find and tap it.

Natural hydrogen trapped in the Earth’s crust could power humanity for millennia, and without emissions. A new strategy maps out how to find it.

- Scientists from the University of Oxford, Durham University, and the University of Toronto have identified the key geological ingredients needed to find natural clean hydrogen beneath the Earth’s surface.
- This natural hydrogen is produced by the Earth over millions of years and can accumulate underground in the right rock formations.
- The study shows that the conditions for trapping hydrogen exist in many parts of the world, making this a truly global opportunity.
- Hydrogen is already a $135 billion global industry, used to produce fertilizer and other essential chemicals that support modern life.
- It is also a cornerstone for future clean energy systems, with the market expected to grow to as much as $1 trillion by 2050.

- This new research could help industries discover and tap into natural hydrogen reserves, offering a cleaner alternative to current hydrogen production methods that rely on fossil fuels.
- The findings were published on May 13 in *Nature Reviews Earth & Environment*.

Natural hydrogen naturally released at the Earth's surface from groundwater in rocks of the Canadian Shield. Credit: Stable Isotope Lab University of Toronto

Hydrogen's Critical Role in Modern Life

Hydrogen is more than just a clean fuel option; it helps feed half the world by powering the production of fertilizer, and sits at the heart of most plans for a carbon-neutral future.

Yet almost all hydrogen today comes from hydrocarbons, releasing about 2.4 percent of global carbon dioxide emissions. Demand is expected to soar from 90 million metric tons in 2022 to about 540 million metric tons by 2050, so finding a way to make hydrogen without adding more CO_2 is critical. Carbon sequestration and renewable-powered electrolysis can help, but they are not yet cost-competitive.

A Natural Hydrogen Solution Beneath Our Feet

A research team from the University of Oxford, Durham University, and the University of Toronto points to an overlooked answer: Earth's own crust. Over the past billion years, the

continental crust has generated enough hydrogen to meet human energy needs for roughly 170,000 years. Much of that gas remains locked underground, untouched and emission-free.

Until now, scientists had only scattered measurements of where natural hydrogen collects. The new study outlines a clear "exploration recipe"—the rock types, temperatures, fluids, and geological histories that allow hydrogen to form, migrate, and become trapped in reservoirs we can reach. With that blueprint in hand, industry can start hunting for clean hydrogen reserves worldwide, offering a potential game-changer for energy and climate goals.

First Principles and the Hydrogen System Blueprint

Study co-author Professor Jon Gluyas (Durham University) notes: "We have successfully developed an exploration strategy for helium, and a similar 'first principles' approach can be taken for hydrogen."

This research outlines the key ingredients needed to inform an exploration strategy to find different 'hydrogen systems.' This includes how much hydrogen is produced and the rock types and conditions these occur in, how the hydrogen migrates underground from these rocks, the conditions that allow a gas field to form, and the conditions that destroy the hydrogen.

Abandoned water well, Montana, USA. Measurement of gases dissolved in groundwater may help discover natural hydrogen. Credit: Chris Ballentine, University of Oxford

Microbes, Rocks, and Hydrogen’s Hidden Challenges

Study co-author Professor Barbara Sherwood Lollar (University of Toronto) said: “We know, for example, that underground microbes readily feast on hydrogen. Avoiding environments that bring them into contact with the hydrogen is important in preserving hydrogen in economic accumulations.”

The authors outline where understanding of these ingredients is strong, and highlight areas that need more work, such as rock reaction efficiencies and how geological histories can bring the right rocks together with the water that reacts with it.

Crust-Based Hydrogen: Young, Old, and Everywhere

Some sources of hydrogen gas, such as from the Earth’s mantle, have fueled much speculation and hyperbole, but this research shows that these are not viable sources. Instead, the authors showed that the ingredients for a complete hydrogen system can be found in a range of common geological settings within the crust. Some of these can be geologically quite young, forming hydrogen ‘recently’ (millions to tens of millions of years), others truly ancient (hundreds of millions of years old) – but critically are found globally.

Cooking Up Hydrogen: The Exploration Recipe

Lead author Professor Chris Ballentine (University of Oxford, Department of Earth Sciences) said: “Combining the ingredients to find accumulated hydrogen in any of these settings can be likened to cooking a soufflé – get any one of the ingredients, amounts, timing, or temperature wrong and you will be disappointed. One successful exploration recipe that is repeatable will unlock a commercially competitive, low-carbon hydrogen source that would significantly contribute to the energy transition – we have the right experience to combine these ingredients and find that recipe.”

The potential for natural geological hydrogen has motivated the authors to form Snowfox Discovery Ltd., an exploration company with a mission to find societally significant natural hydrogen accumulations.

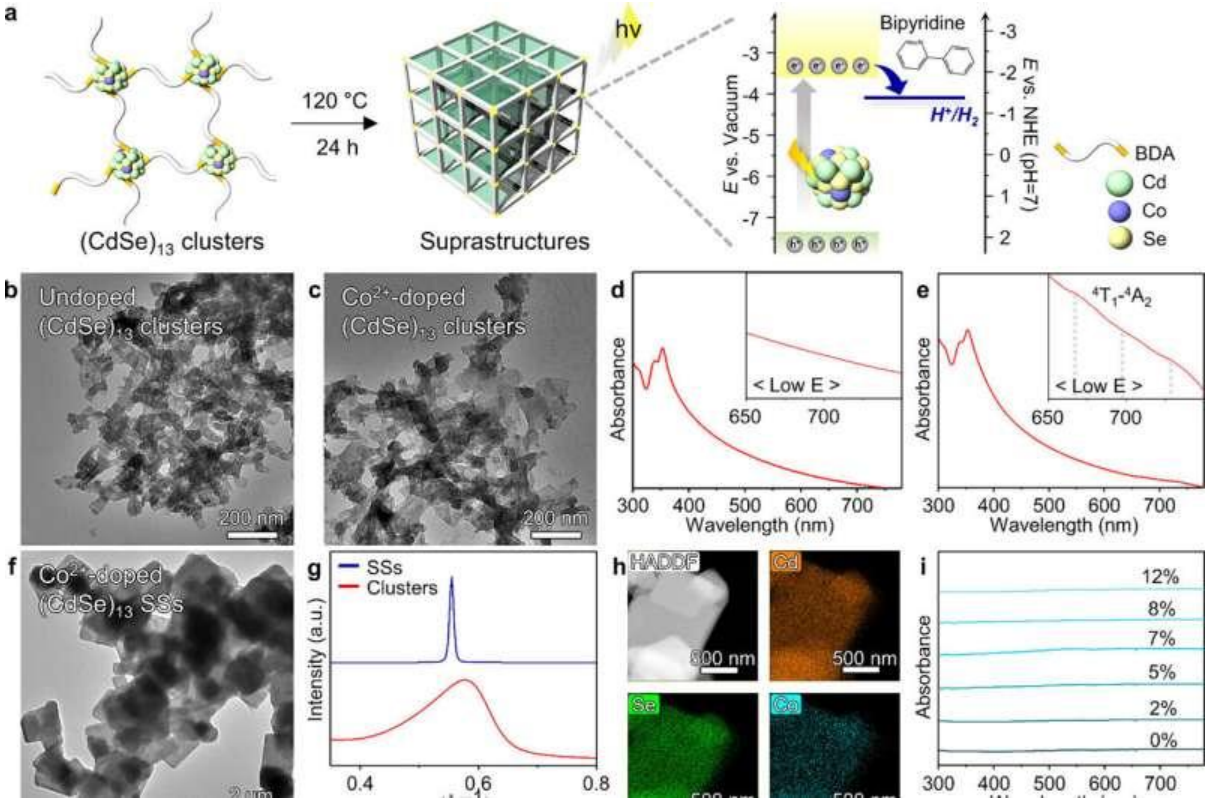
Reference: “Natural hydrogen resource accumulation in the continental crust” by Chris J. Ballentine, Rūta Karolytė, Anran Cheng, Barbara Sherwood Lollar, Jon G. Gluyas and Michael C. Daly, 13 May 2025, *Nature Reviews Earth & Environment*.
DOI: 10.1038/s43017-025-00670-1

MAY 19, 2025

Smallest inorganic semiconductor enables eco-friendly hydrogen production

by Daegu Gyeongbuk Institute of Science and Technology

edited by Gaby Clark, reviewed by Robert Egan



Credit: *Nano Letters* (2025). DOI: 10.1021/acs.nanolett.5c00529

A research team has successfully produced eco-friendly solar hydrogen for the first time based on a quantum semiconductor nanocluster, which is the world's smallest inorganic semiconductor material.

The research is published in the journal *Nano Letters*. The research was a collaboration with Professor Yoonjung Jang at the Department of Chemistry, Hanyang University, and Professor Stefan Ringe at the Department of Chemistry, Korea University, and Professor Jiwoong Yang at the Daegu Gyeongbuk Institute of Science & Technology (DGIST).

Professor Yang's research team has achieved a stable nanocluster of cadmium selenide consisting of 26 atoms ($(CdSe)_{13}$), a sub-1-nm ultrasmall quantum semiconductor material

that has never been previously used as a photocatalyst, in a water environment, applied it as a photocatalyst to successfully produce hydrogen, and suggested its potential for new applications across various fields, including not only energy and environment but also quantum science.

The quantum semiconductor nanocluster consisting of a specific number of atoms is a unique material located at the boundary between molecules and nanocrystals. While high reactivity as a catalyst is expected because most of its atoms are exposed on the surface, it is difficult to use it in practical applications due to its structural instability and poor electrical properties.

In this context, his research team designed and fabricated a superstructure in which a quantum nanocluster is self-arranged and bonded three-dimensionally, and obtained structural stability.

By cross-linking between ligands on the surface of the cluster, they achieved a stable structure while maintaining the properties of individual clusters. In addition, his team doped cobalt ions (Co^{2+}) within the cluster to enhance electrical properties and effectively induced photocatalytic hydrogen evolution.

"This study is the first of its kind to demonstrate that a quantum semiconductor nanocluster, known as the smallest inorganic semiconductor structure in existence, can be used as a photocatalyst," said Professor Yang at DGIST. "In the future, it is expected to expand into various possibilities in not just energy and environment but also quantum science."

More information: Soyeon Lee et al, Photocatalytic Hydrogen Production Using Semiconductor (CdSe)13 Clusters, *Nano Letters* (2025). DOI: 10.1021/acs.nanolett.5c00529
Journal information: Nano Letters
Provided by Daegu Gyeongbuk Institute of Science and Technology

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JUNE 10, 2025

Offshore hydrogen production affects the North Sea: Study offers strategies for environmentally friendly expansion

by Torsten Fischer, Helmholtz Association of German Research Centres

edited by Lisa Lock, reviewed by Robert Egan

Simulations of possible production platforms for offshore hydrogen. Centralized production on a single platform (left) and decentralized production on individual wind turbines (right). Credit: Aquaventus Förderverein e.V.
Green hydrogen is a key part of the energy transition. In the coming years, it'll be made in wind farms in the German Bight. With recent technology, this process creates waste heat and brine, which are both dumped into the sea.

A new study by Helmholtz-Zentrum Hereon shows for the first time that the waste heat of 500-megawatt plant can increase the water temperature locally by up to 2°C, thereby influencing the stratification of the sea.

The authors provide new recommendations for the environmentally friendly expansion of the planned offshore hydrogen production in the North Sea in a study recently published in *npj Ocean Sustainability*.

Almost 80% of the energy used worldwide currently comes from fossil fuels such as oil, coal, and gas. As part of the energy transition, these are to be increasingly replaced by environmentally friendly energy sources such as climate-neutral hydrogen.

The German Offshore Wind Energy Act (WindSeeG) lays the foundation for producing hydrogen using wind energy in the North Sea in the future. The goal is to install offshore hydrogen plants with a capacity of 10 gigawatts in offshore wind farms in the German Bight. The technologies are currently being tested.

Until now, the focus has been primarily on questions of technical feasibility and economic viability. The impact on the environment has only been considered to a limited extent. Using a computer model developed in-house, the new Hereon study analyzes for the first time the potential footprint of offshore hydrogen production in the North Sea and shows how the planned expansion can be achieved in an environmentally friendly manner.

In offshore hydrogen production, seawater is first desalinated and then split into hydrogen and oxygen through a process called electrolysis. This produces waste heat and brine. According to the current state of technology, both are returned to the sea near the surface.

The authors of the Hereon study based their calculations on a thermal process in which the water is desalinated through evaporation. The results of their modeling show that, compared to brine, waste heat has a significantly greater impact on seawater. It causes the water temperature within a 10-meter radius around a 500-megawatt hydrogen plant to rise by up to 2°C on average over the course of a year.

The researchers expanded the scenario and calculated the impact for several hydrogen plants located close to each other with a total capacity of 10 megawatts. Even within a radius of 1,000 meters, there was still an average annual temperature increase of 0.1°C to 0.2°C. At a distance of 50 kilometers, it was still 0.01°C.

"The decisive temperature changes occur mainly locally and, depending on the scale of production, have an impact on the stratification of the water body," says lead author Dr. Nils Christiansen from the Hereon Institute of Coastal Systems—Analysis and Modeling.

Stratification is the vertical division of the ocean into different water layers with varying density, temperature, and salinity. Colder, denser water with a higher salinity and many nutrients is found at the bottom. Above this is warmer, lighter water with a lower salinity. The warmer layer acts as a barrier and also influences the transport of nutrients from the bottom to the top.

The findings of the study show that this stratification intensifies when the water temperature at the surface rises due to the input of waste heat. This can alter nutrient transport and thus also the productivity of phytoplankton. Phytoplankton is found near the surface and forms the basis for the entire food chain in the sea. In order to reproduce and carry out photosynthesis, it needs nutrients from the deeper layers.

Solutions for environmentally friendly hydrogen production

To minimize the impact of hydrogen production on stratification, the authors of the study recommend distributing the input of by-products spatially, for example through decentralized solutions. This involves several small electrolyzers producing hydrogen at different locations instead of one large electrolyzer on a single platform. It also makes sense to distribute the input across the water column, from near the surface to the seabed, or to reduce waste heat through technological solutions.

"Our findings help to better understand the impact of green hydrogen production on the oceans and to develop solutions for a sustainable and nature-friendly energy transition at sea at an early stage," says Christiansen. "Further studies are now needed to investigate other technologies, such as chemical processes, and the exact impact on ecosystems."

More information: Nils Christiansen et al, Offshore hydrogen production leaves a local hydrographic footprint on stratification in the North Sea, *npj Ocean Sustainability* (2025). DOI: 10.1038/s44183-025-00121-w
Journal information: npj Ocean Sustainability
Provided by Helmholtz Association of German Research Centres

JUNE 11, 2025

From plastic waste to clean hydrogen: A scalable solar-powered solution

by Institute for Basic Science edited by Sadie Harley, reviewed by Robert Egan

How a newly developed floatable nanocomposite system produces hydrogen gas by using sunlight to break down everyday plastic waste. Credit: Institute for Basic Science

A team of Korean scientists has developed an innovative green technology that transforms plastic waste into clean hydrogen fuel using only sunlight and water.

Researchers at the Institute for Basic Science (IBS) Center for Nanoparticle Research, led by Professor KIM Dae-Hyeong and Professor Hyeon Taeghwan of Seoul National University, have developed a photocatalytic system that produces hydrogen from PET bottles. The work has been published in *Nature Nanotechnology*.

The key innovation lies in wrapping the photocatalyst in a hydrogel polymer, which helps it float on water and stay active even under harsh environmental conditions.

Hydrogen is gaining attention as a next-generation clean energy source. However, the most common method for producing it—methane steam reforming—consumes large amounts of energy and releases significant greenhouse gas emissions.

Photocatalytic hydrogen production, which relies on sunlight, is a cleaner alternative but faces challenges in maintaining stability under strong light and chemical stress.

To overcome these limitations, the IBS research team introduced a strategy that stabilizes the catalyst within a polymer network while placing the reaction site at the interface between air and water.

This setup allows the system to avoid common problems such as catalyst loss, poor gas separation, and reverse reactions. The system breaks down plastics like PET into useful byproducts such as ethylene glycol and terephthalic acid, while releasing clean hydrogen into the air.

This figure shows how a one-square-meter outdoor system can turn plastic waste into hydrogen using sunlight. (a) displays the actual setup of the steel reactor, where a sponge-like catalyst material (Pt-DSA/TiO_2 nanocomposites) floats in a plastic waste solution. (b) provides a top-down schematic view of the reactor, which includes four quartz windows that let sunlight in. (c) tracks the system's performance over two separate days, showing a steady rise in hydrogen production (green) as sunlight intensity (orange) increases throughout the day. Credit: Institute for Basic Science

"The key was engineering a structure that works not only in theory but also under practical outdoor conditions," explained Dr. LEE Wanghee, a postdoctoral researcher at MIT and co-first author of the study. "Every detail—from material design to the water-air interface—had to be optimized for real-life usability."

The researchers demonstrated that their system remained stable for over two months, even in highly alkaline conditions. The floatable catalyst system also works in diverse real-world water environments, including seawater and tap water.

In tests using a one-square-meter device placed outdoors under natural sunlight, the system successfully produced hydrogen from dissolved PET bottle waste. Additional economic and scale-up simulations showed that the technology can be expanded to 10 or even 100 square meters, offering a pathway toward cost-effective, carbon-free hydrogen production.

"This research opens a new path where plastic waste becomes a valuable energy source," said Professor KIM Dae-Hyeong. "It's a meaningful step that tackles both environmental pollution and clean energy demand."

Professor Hyeon Taeghwan added, "This work is a rare example of a photocatalytic system that functions reliably in the real world—not just the lab. It could become a key stepping stone toward a hydrogen-powered, carbon-neutral society."

More information: Wang Hee Lee et al, Polymeric stabilization at the gas–liquid interface for durable solar hydrogen production from plastic waste, *Nature Nanotechnology* (2025). DOI: 10.1038/s41565-025-01957-6
Journal information: Nature Nanotechnology
Provided by Institute for Basic Science

JUNE 11, 2025

High-performance water electrolysis without platinum brings hydrogen economy closer

by The Korea Advanced Institute of Science and Technology (KAIST)

edited by Lisa Lock, reviewed by Robert Egan

Electron transport resistance at the catalyst layer/diffusion layer interface. Credit: *Energy & Environmental Science* (2025). DOI: 10.1039/D4EE05816J
Hydrogen is gaining attention as a clean energy source that emits no carbon. Among various methods, water electrolysis, which splits water into hydrogen and oxygen using electricity, is recognized as an eco-friendly hydrogen production method.

Specifically, proton exchange membrane water electrolysis (PEMWE) is considered a next-generation hydrogen production technology due to its ability to produce high-purity hydrogen at high pressure. However, existing PEMWE technology has faced limitations in commercialization due to its heavy reliance on expensive precious metal catalysts and coating materials. Korean researchers have now proposed a new solution to address these technical and economic bottlenecks.

A research team led by Professor Hee-Tak Kim of the Department of Chemical and Biomolecular Engineering, in a joint study with Dr. Gisu Doo of the Korea Institute of Energy Research (KIER), has developed a next-generation water electrolysis technology that achieves high performance without the need for expensive platinum (Pt) coating. Their paper is published in *Energy & Environmental Science*.

The research team focused on the primary reason why iridium oxide (IrO_x), a highly active catalyst for water electrolysis electrodes, fails to perform optimally. They found that this is due to inefficient electron transfer and, for the first time in the world, demonstrated that performance can be maximized simply by controlling the catalyst particle size.

In this study it was revealed that the reason iridium oxide catalysts do not exhibit excellent performance without platinum coating is due to electron transport resistance that occurs at the interface between the catalyst, the ion conductor (hereinafter referred to as ionomer), and the Ti (titanium) substrate—core components inherently used together in water electrolysis electrodes.

Specifically, they identified that the "pinch-off" phenomenon, where the electron pathway is blocked between the catalyst, ionomer, and titanium substrate, is the critical cause of reduced conductivity. The ionomer has properties close to an electron insulator, thereby hindering electron flow when it surrounds catalyst particles. Furthermore, when the ionomer comes into contact with the titanium substrate, an electron barrier forms on the surface oxide layer of the titanium substrate, significantly increasing resistance.

To address this, the research team fabricated and compared catalysts of various particle sizes. Through single-cell evaluation and multiphysics simulations, they experimentally demonstrated, for the first time globally, that when iridium oxide catalyst particles with a size of 20 nanometers (nm) or larger are used, the ionomer mixed region decreases, ensuring an electron pathway and restoring conductivity.

Moreover, they successfully optimized the interfacial structure through precise design, simultaneously ensuring both reactivity and electron transport. This achievement demonstrated that the previously unavoidable trade-off between catalyst activity and conductivity can be overcome through meticulous interfacial design.

This breakthrough is expected to be a significant milestone not only for the development of high-performance catalyst materials but also for the future commercialization of proton exchange membrane water electrolysis systems that can achieve high efficiency while drastically reducing the amount of precious metals used.

Professor Hee-Tak Kim stated, "This research presents a new interface design strategy that can resolve the interfacial conductivity problem, which was a bottleneck in high-performance water electrolysis technology." He added, "By securing high performance even without expensive materials like platinum, it will be a stepping stone closer to realizing a hydrogen economy."

More information: Jeesoo Park et al, On the interface electron transport problem of highly active IrO_x catalysts, *Energy & Environmental Science* (2025). DOI: 10.1039/D4EE05816J
Journal information: Energy & Environmental Science
Provided by The Korea Advanced Institute of Science and Technology (KAIST)

JUNE 12, 2025

Tunable nanosheet catalyst promises cheaper green hydrogen production

by Hanyang University edited by Sadie Harley, reviewed by Robert Egan

The novel electrocatalysts, developed using metal-organic frameworks, feature excellent electrocatalytic performance and high efficiency, while also having a low cost. These electrocatalysts have the potential to enable large-scale hydrogen production, which can help in reducing greenhouse gas emissions. Credit: Prof. Seunghyun Lee / Hanyang University ERICA, South Korea

To reduce greenhouse gas emissions and combat climate change, the world urgently needs clean and renewable energy sources. Hydrogen is one such clean energy source that has zero carbon content and stores much more energy by weight than gasoline.

One promising method to produce hydrogen is electrochemical water-splitting, a process that uses electricity to break down water into hydrogen and oxygen. In combination with renewable energy sources, this method offers a sustainable way to produce hydrogen and can contribute to the reduction of greenhouse gases.

Unfortunately, large-scale production of hydrogen using this method is currently unfeasible due to the need for catalysts made from expensive rare earth metals. Consequently, researchers are exploring more affordable electrocatalysts, such as those made from diverse transition metals and compounds.

Among these, transition metal phosphides (TMPs) have attracted considerable attention as catalysts for the hydrogen generating side of the process, known as hydrogen evolution reaction (HER), due to their favorable properties.

However, they perform poorly in the oxygen evolution reaction (OER), which reduces overall efficiency. Previous studies suggest that boron (B)-doping into TMPs can enhance both HER and OER performance, but until now, making such materials has been a challenge.

In a recent breakthrough, a research team led by Professor Seunghyun Lee, including Mr. Dun Chan Cha, from the Hanyang University ERICA campus in South Korea, has developed a new type of tunable electrocatalyst using B-doped cobalt phosphide (CoP) nanosheets.

Prof. Lee explains, "We have successfully developed cobalt phosphide-based nanomaterials by adjusting boron doping and phosphorus content using metal-organic frameworks. These materials have better performance and lower cost than conventional electrocatalysts, making them suitable for large-scale hydrogen production."

Their study was published in the journal *Small*.

The researchers used an innovative strategy to create these materials, using cobalt (Co) based metal-organic frameworks (MOFs). "MOFs are excellent precursors for designing and synthesizing nanomaterials with the required composition and structures," notes Mr. Cha.

First, they grew Co-MOFs on nickel foam (NF). They then subjected this material to a post-synthesis modification (PSM) reaction with sodium borohydride ($NaBH_4$), resulting in the integration of B. This was followed up by a phosphorization process using different amounts of sodium hypophosphite (NaH_2PO_2), resulting in the formation of three different samples of B-doped cobalt phosphide nanosheets (B-CoP@NC/NF).

Experiments revealed that all three samples had a large surface area and a mesoporous structure, key features that improve electrocatalytic activity. As a result, all three samples exhibited excellent OER and HER performance, with the sample made using 0.5 grams of NaH2PO2 (B-$CoP_{0.5}$@NC/NF) demonstrating the best results. Interestingly, this sample exhibited overpotentials of 248 and 95 mV for OER and HER, respectively, much lower than previously reported electrocatalysts.

An alkaline electrolyzer developed using the B-$CoP_{0.5}$@NC/NF electrodes showed a cell potential of just 1.59 V at a current density of 10 mA cm^{-2}, lower than many recent electrolyzers. Additionally, at high current densities above 50 mA cm^{-2}, it even outperformed the state-of-the-art RuO_2/NF(+) and 20% Pt-C/NF(−) electrolyzer, while also demonstrating long-term stability, maintaining its performance for over 100 hours.

Density functional theory (DFT) calculations supported these findings and clarified the role of B-doping and adjusting P content. Specifically, B-doping and optimal P content led to effective interaction with reaction intermediates, leading to exceptional electrocatalytic performance.

"Our findings offer a blueprint for designing and synthesizing next-generation high-efficiency catalysts that can drastically reduce hydrogen production costs," says Prof. Lee.

"This is an important step towards making large-scale green hydrogen production a reality, which will ultimately help in reducing global carbon emissions and mitigating climate change."

More information: Dun Chan Cha et al, Tunable B-Doped Cobalt Phosphide Nanosheets Engineered via Phosphorus Activation of Co-MOFs for High Efficiency Alkaline Water-Splitting, *Small* (2025). DOI: 10.1002/smll.202500334
Journal information: Small
Provided by Hanyang University

JULY 7, 2025

Decoupled electrolysis method paves way for industrial-scale green hydrogen production

by Technion - Israel Institute of Technology edited by Gaby Clark, reviewed by Robert Egan

The bromide/bromate decoupled water electrolysis process. Credit: *Nature Reviews Clean Technology* (2025). DOI: 10.1038/s44359-025-00061-1
A recent review in *Nature Reviews Clean Technology* presents, for the first time, a pathway for scaling up decoupled water electrolysis (DWE) technologies to produce industrial-scale green hydrogen.

Hydrogen, a key chemical feedstock, is usually produced from fossil fuels, generating high CO_2 emissions. Water electrolysis powered by renewable energy emits oxygen rather than CO_2 and offers a clean alternative. Green hydrogen production on an industrial scale is one of the holy grails of the energy transition, as it would unlock the potential of replacing the world's dependency on fossil fuels.

Conventional electrolysis uses two electrodes separated by a membrane to split water into hydrogen and oxygen. This approach is expensive, suffers from internal hydrogen leakage, and is incompatible with intermittent solar and wind power.

DWE overcomes these issues by separating the hydrogen and oxygen production in time or space, eliminating the need for membranes. Rather, it uses redox materials that can absorb and release ions from which oxygen or hydrogen are produced.

The article reviews different DWE methods and, for the first time, presents feasible scale-up pathways. The authors include leading experts from all over the world: Prof. Avner Rothschild of the Technion Faculty of Materials Science and Engineering, Prof. Mark D. Symes of the University of Glasgow, Prof. Jens Oluf Jensen of the Technical University of Denmark, Dr. Tom Smolinka of the Fraunhofer Institute for Solar Energy Systems ISE, Rotem Arad and Gilad Yogev from the company H2Pro, Technion postdoctoral fellow Dr. Guilin Ruan, and University of Glasgow doctoral student Fiona Todman.

Prof. Mark Symes and his collaborators at the University of Glasgow pioneered the original embodiment of decoupled electrolysis in 2013, using solution-phase redox mediators. He has continued his work on decoupled electrolysis using a variety of liquid-based systems and is actively trying to commercialize this technology through the company Clyde Hydrogen Systems.

In 2015, Prof. Avner Rothschild pioneered a new technology together with Technion colleagues Prof. Gideon Grader, Dr. Hen Dotan, and Dr. Avigail Landman, using nickel-based redox electrodes. Their breakthrough led to the founding of H2Pro in 2019.

Prof. Jens Oluf Jensen and Dr. Tom Smolinka are world-renowned experts on state-of-the-art electrolyzer technologies. Their work in proton exchange membranes (PEM), anion exchange membranes (AEM), electrode materials, and their application in cell stacks for large capacity PEM and AEM electrolyzers provided valuable insight into the challenges of scale-up and operation of commercial electrolyzers, and a sound base for comparison of disruptive decoupled and membrane-less electrolyzer concepts. Rotem Arad and Gilad Yogev provide insights into transforming these concepts into technologies for green hydrogen production at scale.

This review is the first to detail feasible scale-up strategies for DWE. While lab-scale DWE experiments produce less than a gram of hydrogen per day, industrial systems must generate about a ton daily—a million times more.

Indeed, meeting current hydrogen demand would require around a million full-scale electrolyzers. Conventional industrial electrolyzers, on the other hand, require a stable grid supply and can only be used to a limited extent with highly dynamic power fluctuations such as those caused by solar and wind energy.

DWE's unique advantage lies in its energy storage capability via redox materials, functioning like an electrolyzer with a built-in battery. This allows it to buffer energy fluctuations from renewable sources, making it highly compatible with solar and wind systems, thereby offering a critical pathway to low-cost, green renewable hydrogen production.

The potential impact of scaling up green hydrogen production is huge. The hydrogen market is currently worth about $250 billion annually. Once it becomes available on an industrial scale, the market for green hydrogen is expected to reach $550 billion within ten years.

"Green hydrogen is expected to account for 10% of the future energy market. Once it becomes possible to produce green hydrogen at large-scale and sell it at reasonable prices, hydrogen will replace a large part of the energy used in industry, heavy transportation, and other sectors," Prof. Rothschild predicted.

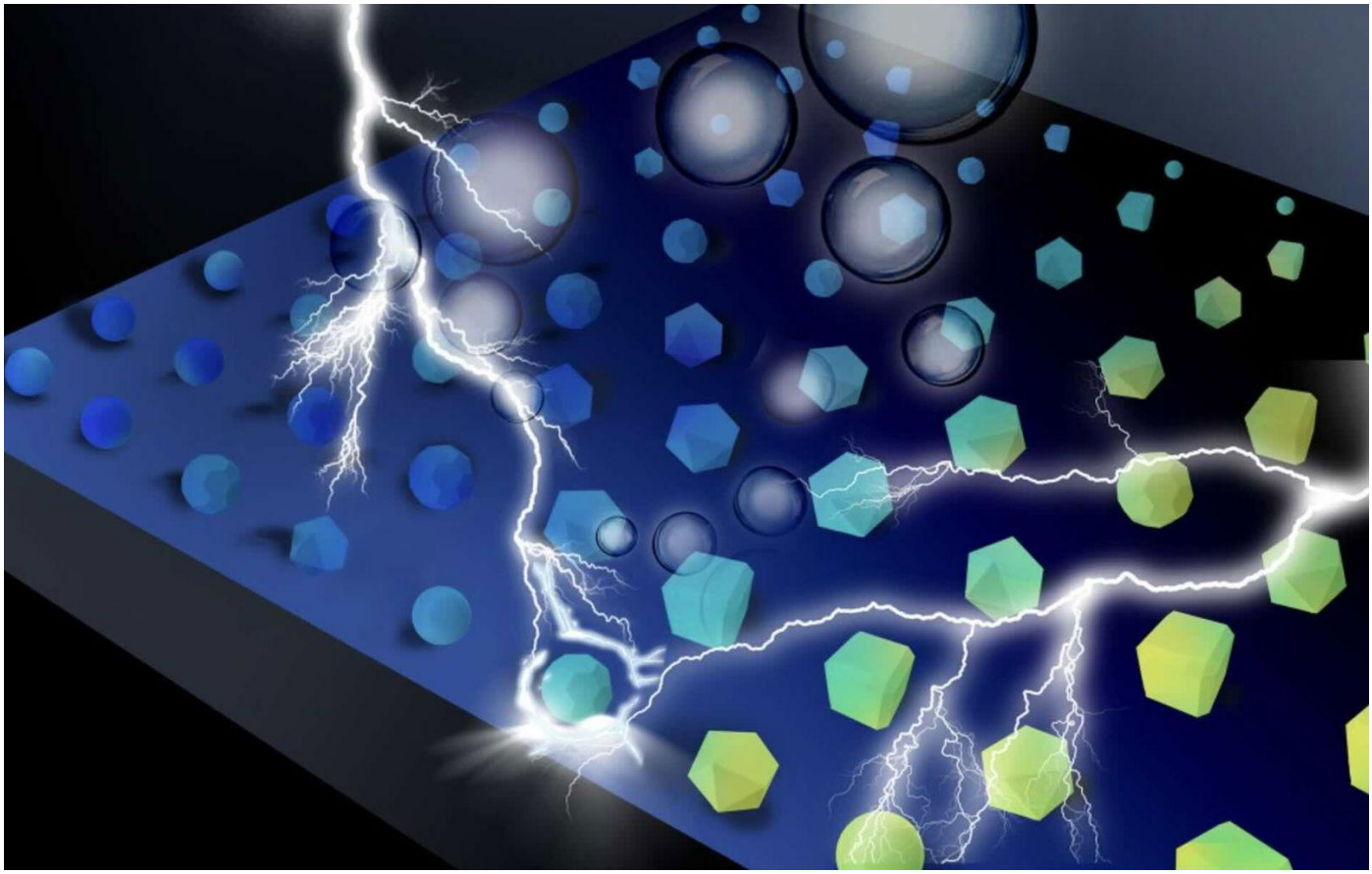
"Traditional electrolyzers should evolve to fit this market and, as noted by Darwin, it is not the strongest species that survives through evolution but, rather, the one that is best able to adapt and adjust to the changing environment in which it finds itself. I believe DWE would be it."

"Decoupled electrolysis is only about 12 years old. More conventional technologies, such as alkaline and proton-exchange membrane cells, have had decades (if not centuries) for development. This gives some context to the rate of scaling of some of the new decoupled systems starting to emerge," elaborated Prof. Symes.

"On the current trajectory, I expect that the next decade will see decoupled electrolysis systems becoming serious competitors to more conventional electrolyzers, especially for the conversion of renewable energy to green hydrogen."

The new ideas presented in the review article are compelling and shed light on the long-term prospects of scaling up DWE technologies for the benefit of all humanity.

More information: Guilin Ruan et al, Technologies and prospects for decoupled and membraneless water electrolysis, *Nature Reviews Clean Technology* (2025). DOI: 10.1038/s44359-025-00061-1
Provided by Technion - Israel Institute of Technology



MOVE OVER IRIDIUM: NORTHWESTERN BREAKTHROUGH SOLVES DECADES-OLD CLEAN HYDROGEN FUEL PROBLEM IN A SINGLE AFTERNOON

MICAH HANKS·AUGUST 20, 2025

The decades-long search for an alternative to iridium, one of the rarest and most expensive metals on Earth, may finally be over, with a new discovery that could accelerate the push for affordable clean hydrogen technologies.

Remarkably, researchers at Northwestern University behind the discovery say they found a viable substitute in just a single afternoon.

By leveraging a powerful new nanomaterial data factory that researchers call a “megalibrary,” the team was able to screen millions of nanoparticles on a single chip at record speeds. Through a

collaboration with the Toyota Research Institute (TRI), the team's powerful new tool helped them uncover a new catalyst made from abundant metals that performs in ways on par with, or even better than, commercial iridium-based materials.

The discovery could help facilitate less expensive green hydrogen production and highlights the promise of the megascale library approach in significantly advancing materials discoveries across various industries.

REINVENTING MATERIALS DISCOVERY

In the past, identifying new materials has often been a painstaking process of trial and error.

To combat this, nanotechnology pioneer Chad Mirkin created megalibraries—a novel platform where each individual chip contains up to millions of nanoparticles printed with arrays of pyramid-shaped structures that deposit precise mixes of metallic salts.

Mirkin, the senior author of a new study published in the Journal of the American Chemical Society, which describes the team's findings, said that each pyramid-shaped tip can be thought of as a tiny lab unto itself. When heated, the mixtures they deposit form nanoparticles with tightly controlled compositions and sizes.

"Instead of having one tiny person make one structure at a time, you have millions," Mirkin explained in a statement. "So, you basically have a full army of researchers deployed on a chip."

SEARCHING FOR AN IRIDIUM ALTERNATIVE

Armed with this innovative technology, the team decided to apply it toward a major hurdle in the production of green hydrogen energy: the oxygen evolution reactor (OER), which involves a step in water splitting that currently relies on iridium as a catalyst.

One of the major issues with the use of iridium is its cost. Currently, this rare Earth metal is valued at close to $5,000 per ounce and is mined only as a byproduct of another rare Earth metal: platinum. This makes it both too rare and too costly to support global clean energy demands.

“There’s not enough iridium in the world to meet all of our projected needs,” said Ted Sargent, a Northwestern researcher and co-author of the recent paper.

However, with help from Mirkin’s megalibrary, the Northwestern team was able to screen combinations of four metals—ruthenium, cobalt, manganese, and chromium—with remarkable speed. The chip used as the sample for this screening contained 156 million nanoparticles, and a robotic scanner evaluated their performance in terms of OER.

A WINNING CATALYST

Following the team’s analysis, a clear winner stood out among the compositions they examined: a multi-metal oxide with the formal designation of $Ru_{52}Co_{33}Mn_9Cr_6$. This specific blend not only appeared to be an almost perfect match for iridium’s activity, but remarkably, it appeared to exceed it in at least a few tests.

Additionally, the novel multi-metal oxide showed promising indications of offering long-term stability that also exceeded that of iridium.

“Our catalyst actually has a little higher activity than iridium and excellent stability,” Mirkin said. “That’s rare because oftentimes ruthenium is less stable. But the other elements in the composition stabilize it.”

Furthermore, durability tests demonstrated that the new catalyst could operate for over 1,000 hours under extremely harsh, acidic conditions without experiencing significant efficiency loss. Best of all,

it's production cost clocks in at close to one-sixteenth that of iridium, making it a far more commercially viable alternative.

Although additional research is still required, the team says the results are extremely promising.

"There's lots of work to do to make this commercially viable, but it's very exciting that we can identify promising catalysts so quickly — not only at the lab scale but for devices," said TRI's Joseph Montoya, a co-author of the study.

ADVANCING BEYOND HYDROGEN

Even beyond the team's most recent achievement, their study demonstrates how megalibraries can be leveraged to assemble massive datasets that can be paired with artificial intelligence and machine learning to provide new avenues for discovery in materials science.

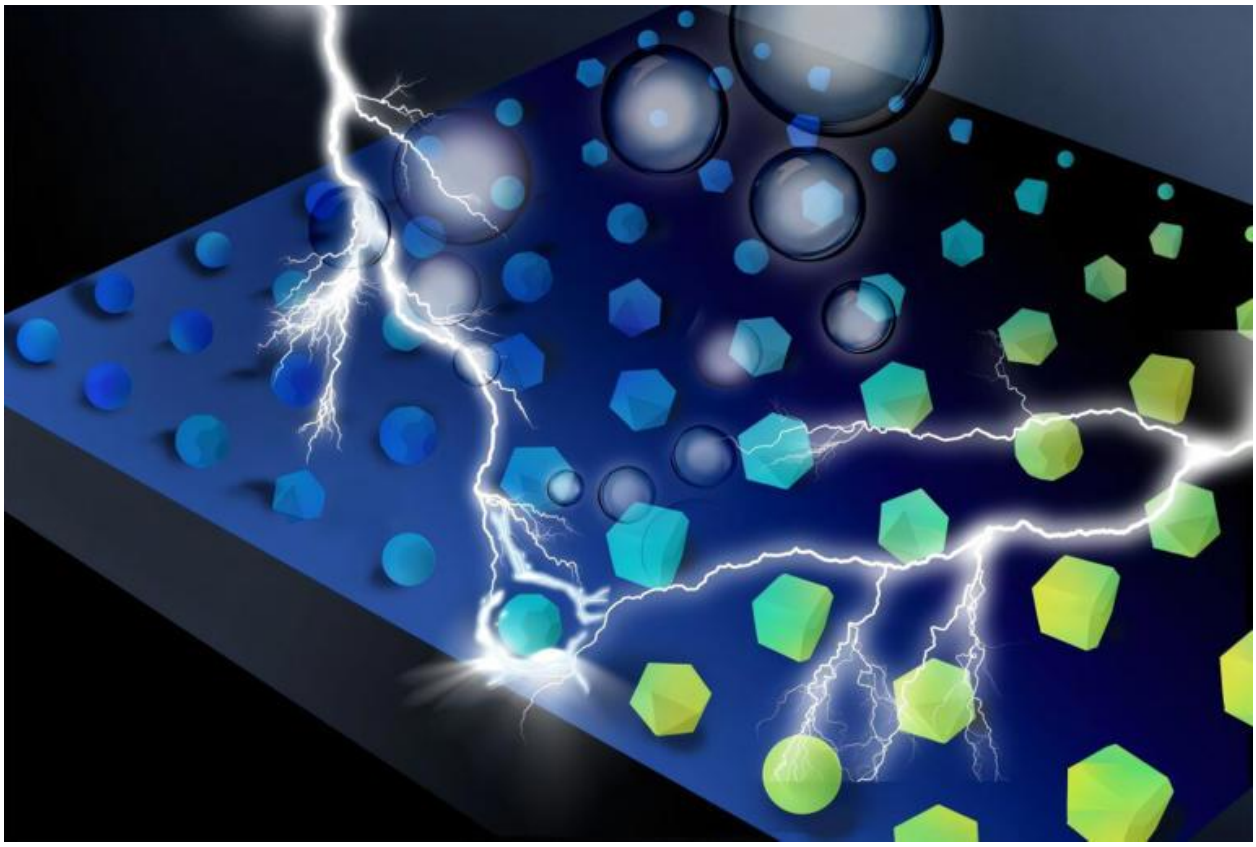
Mirkin believes what his team has achieved is really is just the beginning of more exciting discoveries to come.

"The world does not use the best materials for its needs," he said. "People found the best materials at a certain point in time, given the tools available to them."

"We want to turn that upside down," Mirkin added. "It's time to truly find the best materials for every need — without compromise."

The team's discovery was detailed in the recent paper, "Accelerating the Pace of Oxygen Evolution Reaction Catalyst Discovery through Megalibraries," published in the *Journal of the American Chemical Society*.

Clean hydrogen's iridium problem? Solved in an afternoon with a new mega-library



New material rivals iridium for water splitting reaction at a fraction of the cost. Credit: Jin Huang and Siyuan Zuo

For decades, researchers around the world have searched for alternatives to iridium, an extremely rare, incredibly expensive metal used in the production of clean hydrogen fuels.

Now, a powerful new tool has found one—within a single afternoon.

Invented and developed at Northwestern University, that tool is called a megalibrary. The world's first nanomaterial "data factory," each megalibrary contains millions of uniquely designed nanoparticles on one tiny chip.

In collaboration with researchers from the Toyota Research Institute (TRI), the team used this technology to discover commercially relevant catalysts for

hydrogen production. Then, they scaled up the material and demonstrated it could work within a device—all in record time.

With a megalibrary, scientists rapidly screened vast combinations of four abundant, inexpensive metals—each known for its catalytic performance—to find a new material with performance comparable to iridium. The team discovered a wholly new material that, in laboratory experiments, matched or in some cases even exceeded the performance of commercial iridium-based materials, but at a fraction of the cost.

This discovery doesn't just make affordable green hydrogen a possibility; it also proves the effectiveness of the new mega-library approach, which could completely change how researchers find new materials for any number of applications. The study is published in the *Journal of the American Chemical Society*.

"We've unleashed arguably the world's most powerful synthesis tool, which allows one to search the enormous number of combinations available to chemists and materials scientists to find materials that matter," said Northwestern's Chad A. Mirkin, the study's senior author and primary inventor of the megalibrary platform.

"In this particular project, we have channeled that capability toward a major problem facing the energy sector. That is: How do we find a material that is as good as iridium but is more plentiful, more available, and a lot cheaper? This new tool enabled us to find a promising alternative and to find it rapidly."

A nanotechnology pioneer, Mirkin is the George B. Rathmann Professor of Chemistry at Northwestern's Weinberg College of Arts and Sciences; professor of chemical and biological engineering, biomedical engineering and materials science and engineering at the McCormick School of Engineering; and executive director of the International Institute for Nanotechnology.

Mirkin co-led the work with Ted Sargent, the Lynn Hopton Davis and Greg Davis Professor of Chemistry at Weinberg, professor of electrical and computer engineering at McCormick and executive director of the Paula M. Trienens Institute for Sustainability and Energy.

'Not enough iridium in the world'

As the world moves away from fossil fuels and toward decarbonization, affordable green hydrogen has emerged as a critical piece of the puzzle. To produce clean hydrogen energy, scientists have turned to water splitting, a process that uses electricity to split water molecules into their two constituent components—hydrogen and oxygen.

The oxygen part of this reaction, called the oxygen evolution reaction (OER), however, is difficult and inefficient. OER is most effective when scientists use iridium-based catalysts, which have significant disadvantages. Iridium is rare, expensive and often obtained as a byproduct from platinum mining. More valuable than gold, iridium costs nearly $5,000 per ounce.

"There's not enough iridium in the world to meet all of our projected needs," Sargent said. "As we think about splitting water to generate alternative forms of energy, there's not enough iridium from a purely supply standpoint."

'Full army deployed on a chip'

Mirkin, who introduced the megalibraries in 2016, decided with Sargent that finding new candidates to replace iridium was a perfect application for his revolutionary tool. While materials discovery is traditionally a slow and daunting task filled with trial and error, megalibraries enable scientists to pinpoint optimal compositions at breakneck speeds.

It's time to truly find the best materials for every need—without compromise."

Each megalibrary is created with arrays of hundreds of thousands of tiny, pyramid-shaped tips to print individual "dots" onto a surface. Each dot contains an intentionally designed mix of metal salts. When heated, the metal salts are reduced to form single nanoparticles, each with a precise composition and size.

"You can think of each tip as a tiny person in a tiny lab," Mirkin said. "Instead of having one tiny person make one structure at a time, you have millions of people. So, you basically have a full army of researchers deployed on a chip."

And the winner is…

In the new study, the chip contained 156 million particles, each made from different combinations of ruthenium, cobalt, manganese and chromium. A robotic scanner then assessed how well the most promising particles could perform an OER. Based on these tests, Mirkin and his team selected the best-performing candidates to undergo further testing in the laboratory.

Eventually, one composition stood out: a precise combination of all four metals ($Ru_{52}Co_{33}Mn_9Cr_6$ oxide). Multi-metal catalysts are known to elicit synergistic effects that can make them more active than single-metal catalysts.

"Our catalyst actually has a little higher activity than iridium and excellent stability," Mirkin said. "That's rare because oftentimes ruthenium is less stable. But the other elements in the composition stabilize ruthenium."

The ability to screen particles for their ultimate performance is a major new innovation. "For the first time, we were not only able to rapidly screen catalysts, but we saw the best ones performing well in a scaled-up setting," said Joseph Montoya, a senior staff research scientist at TRI and study co-author.

In long-term tests, the new catalyst operated for more than 1,000 hours with high efficiency and excellent stability in a harsh acidic environment. It is also dramatically cheaper than iridium—about one-sixteenth of the cost.

"There's lots of work to do to make this commercially viable, but it's very exciting that we can identify promising catalysts so quickly—not only at the lab scale but for devices," Montoya said.

Just the beginning

By generating massive high-quality materials datasets, the megalibrary approach also lays the groundwork for using artificial intelligence (AI) and machine learning to design the next generation of new materials. Northwestern, TRI and Mattiq, a Northwestern spinout company, have already developed machine learning algorithms to sift through the megalibraries at record speeds.

Mirkin says this is only the beginning. With AI, the approach could scale beyond catalysts to revolutionize materials discovery for virtually any technology, such as batteries, biomedical devices and advanced optical components.

"We're going to look for all sorts of materials for batteries, fusion and more," he said. "The world does not use the best materials for its needs. People found the best materials at a certain point in time, given the tools available to them. The problem is that we now have a huge infrastructure built around those materials, and we're stuck with them.

"We want to turn that upside down. It's time to truly find the best materials for every need—without compromise."

More information: Jin Huang et al, Accelerating the Pace of Oxygen Evolution Reaction Catalyst Discovery through Megalibraries, *Journal of the American Chemical Society* (2025). DOI: 10.1021/jacs.5c08326

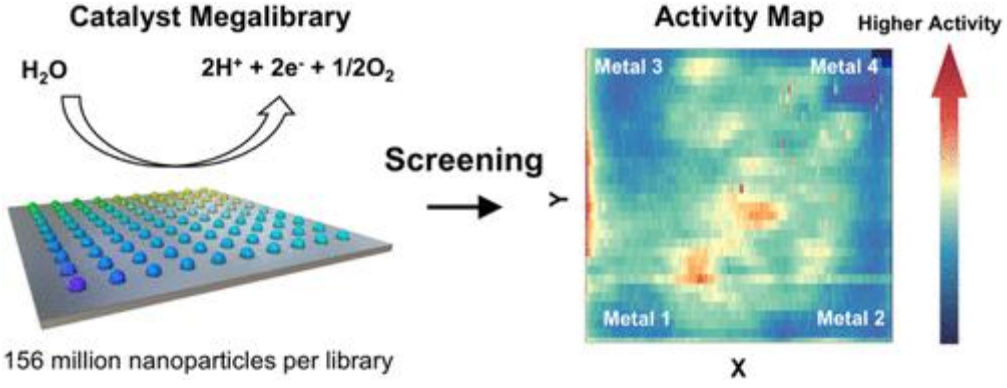
Provided by Northwestern University

Journal of the American Chemical Society Vol 147/Issue 34 August 19, 2025

Accelerating the Pace of Oxygen Evolution Reaction Catalyst Discovery through Megalibraries

- Jin Huang, Zhe Wang, Jiashun Liang, Xiao-Yan Li, Jacob Pietryga, Zihao Ye, Peter T. Smith, Alp Kulaksizoglu, Connor R. McCormick, Jaerim Kim, Bosi Peng, Zeyan Liu Ke Xie, Steven B. Torrisi, Joseph H. Montoya, Gang Wu, Edward H. Sargent*Chad A. Mirkin*

Abstract



Iridium (Ir) catalysts are essential for the acidic oxygen evolution reaction (OER) in proton-exchange membrane water electrolyzers (PEMWEs), but their high cost, scarcity, and geographical concentration limit large-scale adoption. In addition, the discovery of non-Ir alternatives is slow due to the vast design space possible. Here, a “megalibrary” is used to explore the catalytic activity of ∼156 million distinct nanostructures comprised of Ru, Co, Mn, and Cr to find alternatives to Ir catalysts for OER. Over 40 RuCoMnCr oxides, ranging from low to high activity, were selected, scaled to milligram levels, and studied for their catalytic performance. The activities measured within the megalibrary closely correlated (r = 0.84) with those of the macroscopic samples. In a PEMWE, the most active catalyst, $Ru_{52}Co_{33}Mn_9Cr_6$ oxide, demonstrated a voltage of 1.58 V at 1 A/cm^2 and 1.77 V at 3 A/cm^2. At 1 A/cm^2, it operated continuously for over 1000 h with an average voltage increase rate of 57 μV/h. This study establishes a roadmap to accelerate catalyst discovery for energy conversion, and the platform is a route to large data sets that will facilitate the development of AI and machine learning algorithms that can identify key catalyst design features.

Toyota’s water-powered engine could signal the fall of EVs

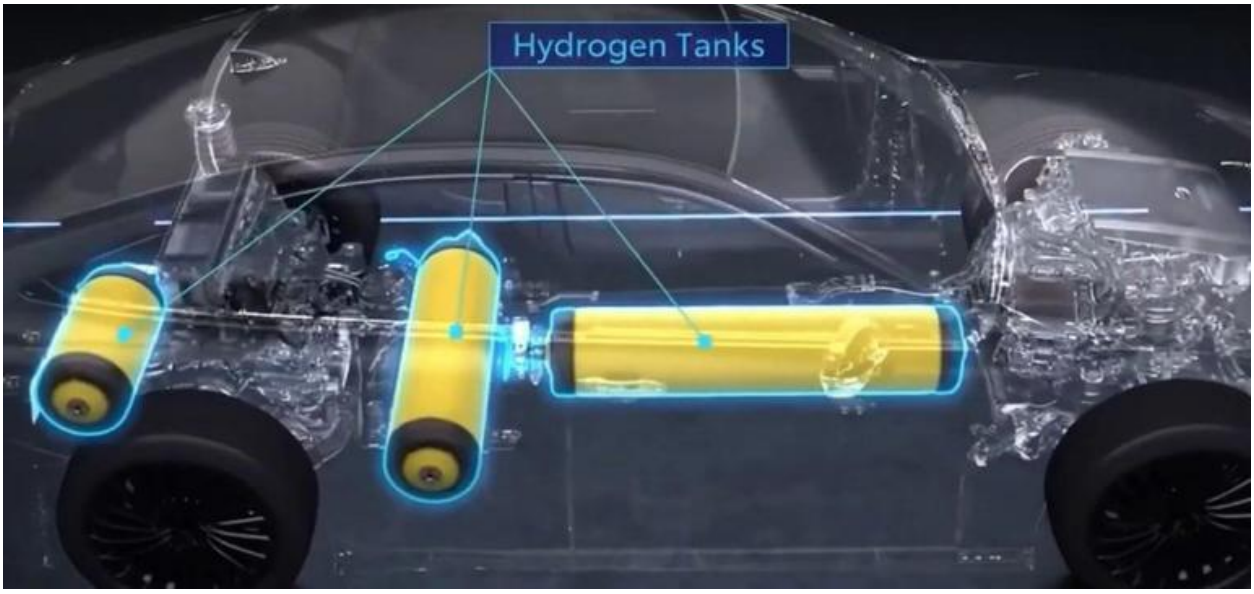
In a surprising turn of events, the automotive world has been rocked by Toyota’s announcement of a new engine technology that could challenge the dominance of electric vehicles. The CEO of Toyota has introduced a water engine, a potentially revolutionary innovation that raises questions about the future of electric cars and the broader implications for the industry. This article delves into the details of this groundbreaking announcement and what it could mean for the future of transportation.

The Announcement: A New Era of Engine Technology

Toyota's recent announcement has sent shockwaves through the automotive industry. The CEO detailed a new water engine that promises to revolutionize how we think about vehicle propulsion. This engine, according to Toyota, utilizes water as a primary component in its operation, potentially offering an alternative to traditional fossil fuels and electric power. The details, while still emerging, suggest a significant shift in Toyota's strategic direction, emphasizing sustainability and innovation.

The announcement has been met with a mix of excitement and skepticism across the automotive landscape. Industry insiders and tech enthusiasts have been quick to weigh in, with some praising Toyota for pushing the boundaries of what is possible, while others caution against the technological and logistical challenges such an innovation presents. Nevertheless, the announcement has positioned Toyota at the forefront of automotive innovation, potentially reshaping its market strategy and brand positioning as it embraces this new era.

Understanding the Water Engine



The concept of using water to power an engine is not entirely new, but Toyota's approach appears to be a novel iteration. Essentially, the water engine relies on a chemical reaction involving water to produce energy, which is then used to propel the vehicle. Unlike traditional internal combustion engines that burn fuel, this engine would theoretically use water as a medium to create energy, potentially making it more efficient and environmentally friendly.

When comparing the efficiency of the water engine to traditional combustion and electric engines, several factors need to be considered. While electric vehicles (EVs) have made significant strides in efficiency and reduced emissions, the infrastructure for widespread adoption is still developing. In contrast, a water engine could offer a more immediate and scalable solution if the technology proves viable. Environmental implications are also a critical consideration; if the water engine can deliver on its promises, it could offer a greener alternative to current technologies, reducing reliance on fossil fuels and lowering carbon emissions.

Implications for Electric Vehicles

The introduction of Toyota's water engine could represent a significant challenge to the burgeoning electric vehicle market. As it stands, EVs are rapidly gaining traction, supported by growing infrastructure investments and increasing consumer demand for sustainable transportation options. However, the water engine could disrupt this trend by offering a potentially more versatile and accessible alternative.

Electric vehicle manufacturers are likely to respond by accelerating their innovation cycles, perhaps focusing on enhancing battery technology and improving charging infrastructure to maintain their competitive edge. The current state of electric vehicle adoption, while robust, is still in its infancy compared to traditional vehicles. Should Toyota's water engine prove successful, it could force a reevaluation of the existing automotive landscape, prompting both established automakers and newcomers to rethink their strategic roadmaps.

Toyota’s water-powered engine could signal the fall of EVs

Despite the excitement surrounding Toyota’s announcement, skepticism abounds. Critics question the feasibility of a water-powered car, citing potential technical and logistical challenges that could hinder its development and widespread adoption. For instance, the infrastructure required to support a water engine ecosystem is not yet in place, posing a significant hurdle to overcome.

Moreover, experts in the field have expressed doubts about the viability of Toyota’s claims. Some argue that the energy required to extract usable power from water could offset any potential benefits, making it a less efficient solution than it appears. Insights from industry leaders suggest that while the water engine could indeed be revolutionary, significant research and development are needed before it can be considered a practical alternative to existing technologies. As Forbes points out, there are many hurdles to clear before this concept can reach the consumer market.

The Future of Automotive Innovation

Toyota’s announcement of the water engine is a bold step within the broader trend of automotive innovation. As automakers worldwide race to develop sustainable and efficient transportation solutions, the introduction of new

technologies like the water engine could catalyze further advancements across the sector. The potential ripple effects on global energy policies and automotive regulations are profound, with governments potentially incentivizing or mandating the adoption of such technologies in pursuit of environmental goals.

Speculating on the future landscape of transportation, it's intriguing to consider whether water engines might become mainstream. If Toyota manages to overcome the challenges associated with this technology, it could pave the way for a new class of vehicles that redefine how we think about mobility. While the road ahead is uncertain, one thing is clear: the quest for sustainable automotive solutions is far from over, and Toyota's water engine could play a pivotal role in shaping the future of transportation.