THE RISE OF ARTIFICIAL PHOTOSYNTHESIS AS A RESOURCEFUL SOURCE OF ALTERNATIVE ENERGY

Abstract

Artificial photosynthesis, the scientific effort to replicate the chemistry of a living leaf using synthetic materials, is undergoing its most consequential period of advancement. This article examines recent breakthroughs from 2023 to 2025 in water splitting, CO_2 reduction, catalyst design, and photoelectrochemical device design. The focus is on landmark results from research teams at the University of Chicago, Lawrence Berkeley National Laboratory, and South Korea's Daegu Gyeongbuk Institute of Science and Technology. Key breakthroughs include a tenfold improvement in CO_2 to methane conversion efficiency, a copper nanoflower catalyst achieving over 40% efficiency for high value C_2 chemicals, and a rhodamine based photocatalyst producing hydrogen at 18.4 millimoles per hour per gram under visible light. The principal engineering challenges that remain between current laboratory prototypes and commercially deployable systems, include the efficiency gap, catalyst durability, materials cost, and scalability. Accelerating government investment across the United States, China, Japan, South Korea, and Europe make artificial photosynthesis one of the most strategically significant frontiers in clean energy research.

Section 1: Introduction- What is Artificial Photosynthesis?

Everyday trillions of leaves are performing a subtle but complex chemical process. Plants take in CO_2 and release oxygen. They do this by taking CO_2 from the atmosphere, water from the soil, and with nothing but sunlight as their engine; they can convert those products into clean energy in a process called photosynthesis. No emissions, no carbon footprint, and no extra waste are created [1, 2].

To truly grasp artificial photosynthesis (AP), you first must understand natural photosynthesis, and what it does. Every green leaf has organelles called chloroplasts which have a green pigment called chlorophyll. This acts as a light harvesting antenna. When it meets sunlight, the energy causes electrons to enter the excited state and causes a set of chemical reactions. Water molecules are split which release oxygen into the atmosphere as a byproduct, which is the same oxygen humans breathe. CO_2 is taken from the atmosphere where it is broken down and converted into glucose, a sugar the plant uses as fuel to grow and survive. The system can convert 1 to 6% of sunlight into stored chemical energy. Although this number may seem low, it is high enough to have fueled plant life on Earth for billions of years [2, 3].

Figure 1 shows this process, comparing the light driven chemistry of a natural lead with the synthetic equivalent in an AP device.

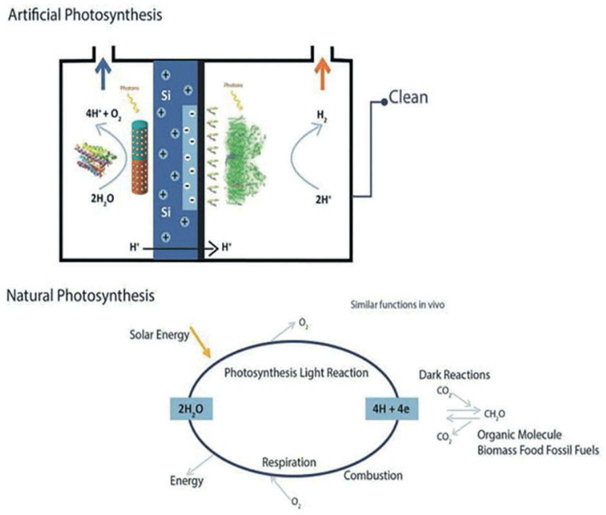


Figure 1: Diagram comparison of natural and AP illustrating how both systems use light driven electron transfer to oxidize water and produce chemical energy [2].

Scientists have watched this process for decades trying to mimic the efficiency of the natural world. They wonder what if we could create a device that performs the same process, but instead of making glucose sugar, it makes clean fuel. Laboratories in Chicago, Berkeley, Seoul, and Tokyo are building synthetic devices that absorb sunlight and use it to split water into hydrogen gas or convert CO_2 into usable fuels such as methane or ethanol. This process is called AP and after years of slow progression, it is having a scientific breakthrough [1, 2, 3].

AP takes the blueprint from its natural counterpart and recreates it using synthetic materials including semiconductors, metal oxide catalysts, and photoelectrochemical cells It has two main functions: first, splitting water molecules to produce clean hydrogen fuel, and second, to reduce atmospheric CO_2 by converting it to more useful chemicals such as methane, ethanol, or ethylene. Successfully doing either of these goals solves two of humanities' largest and most urgent problems. Being able to simultaneously produce clean hydrogen fuel, while reducing atmospheric CO_2 [1, 2].

The urgency for solving these problems comes from fossil fuels supplying 80% of global energy. Atmospheric CO_2 is currently at 421 ppm [4, 5]. Figure 2 shows the rapid growth of AP funding from governments all around the: the U.S. Department of Energy has promised $100 million over five years, positioning AP at technology readiness levels of roughly three to five. AP has moved beyond basic discovery into early proof on concept validation but is still several steps short of deployment. Germany, Japan, China, and the European Union have collectively directed hundreds of millions into national and collaborative programs [6, 7, 8]. In 2025, laboratories at the University of Chicago, Berkeley, and South Korea's DGIST published findings that shattered former performance record and standards, with one system performing ten times better than any earlier testing. The stage is currently being set for AP research and testing, and governments around the world are not hesitating to be the first to successfully implement this technology in their countries [9, 10].

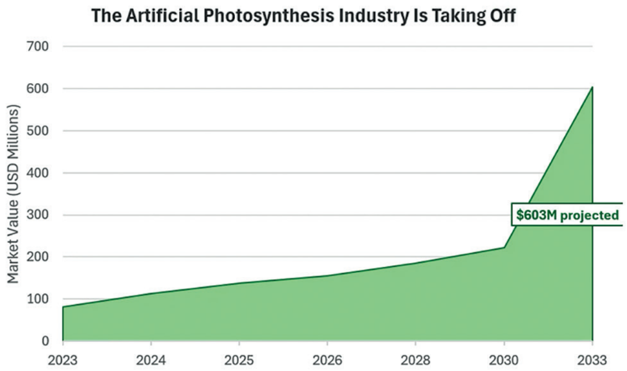
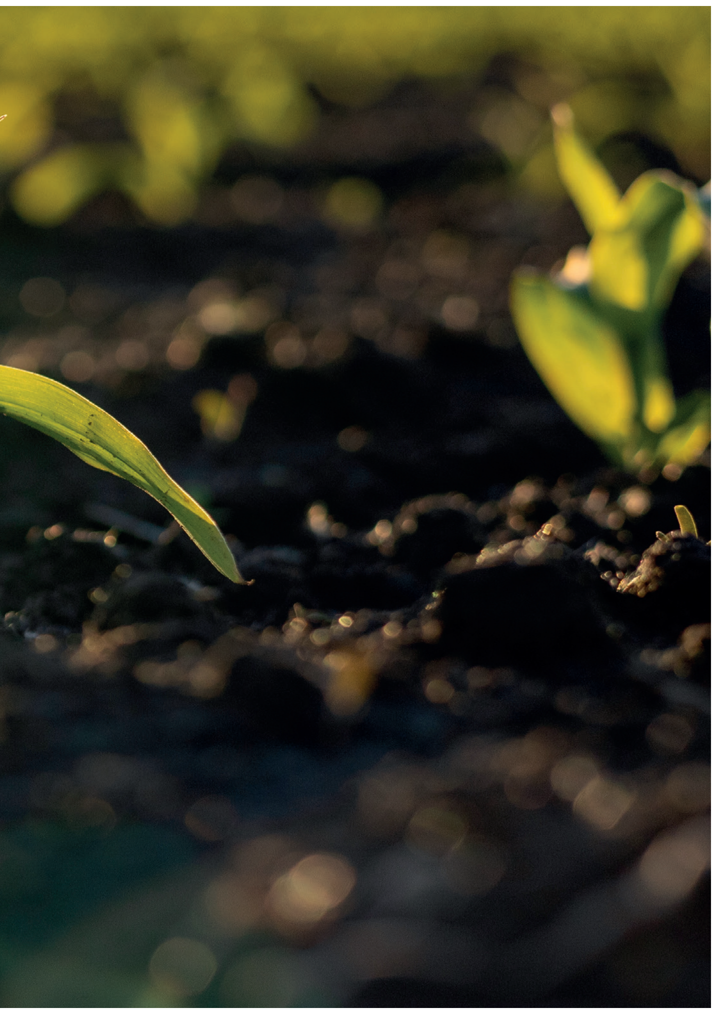


Figure 2: Projected global market growth for AP from 2023 to 2033, reflecting increasing government and private sector investment across major research economies [6, 7, 8].



The scale of ambition among AP research is well known. "We will have to do better than nature," said Wenbin Lin, one of the leading chemists on the University of Chicago research team whose 2025 system achieve a tenfold improvement in CO_2 to methane conversion, "and that's scary." The comment reflects a realistic of what the field is up against, natural photosynthesis has had three billion years of evolution to reach its current efficiency and surpassing it using a synthetic device is a massive engineering challenge [9].

This article documents the significant advances in AP in the last three years. From water splitting and CO_2 reduction to breakthroughs in catalyst design and physics device architecture. It will examine the remaining engineering challenges between current laboratory prototypes and technology capable of contributing to the global energy supply [1, 2, 3].

> *Artificial photosynthesis, the scientific effort to replicate the chemistry of a living leaf using synthetic materials, is undergoing its most consequential period of advancement.*

Section 2: Water Splitting- making hydrogen fuel from sunlight

There are multiple ways to turn sunlight into clean fuel; however, splitting water is the most direct. The reaction is shockingly simple and consists of taking a water molecule, inserting enough energy into the system, and then breaks apart into hydrogen gas and oxygen. The transformation into hydrogen fuel involves storing the hydrogen gas, transporting it, and then burning it in a fuel cell to generate electricity, which releases nothing but water vapor. In theory, this is the cleanest fuel cycle possible. Simple and effective, exactly what is needed for large scale adoption and implementation [1, 11].

Today, about 54 million tonnes of hydrogen are consumed each year and almost all of it is produced from fossil fuels [12]. The largest share, 43%, goes to ammonia and fertilizer manufacturing, the process that feeds a large portion of the world's population. Petroleum refining accounts for 27%, consuming hydrogen to turn crude oil into gasoline, diesel, and jet fuel. Methanol production takes 11%, steel manufacturing takes 7%, and the last 12% is distributed across other industrial processes. All the hydrogen in those processes is produced by steam methane reforming, a process that releases substantial amounts of CO_2 into the atmosphere. Replacing even a fraction of that supply with hydrogen made from AP would represent one of the single largest reductions in industrial carbon emissions to the global economy [1, 12].

Additionally, we must consider chemistry, which unfortunately is complex. Water splitting involves separating half-reactions that happen simultaneously. At one electrode, called the cathode, protons from the water get reduced into hydrogen gas. This is a straightforward process called the hydrogen evolution reaction. On the other electrode, the anode, water molecules are oxidized to release oxygen, which is the oxygen evolution reaction. This step is where the system usually fails because pulling four electrons and protons from two water molecules at the same time is one of the most challenging chemical processes. The oxygen evolution reaction is kinetically sluggish by nature. Each of the four electron removals must happen in a precise sequence, and a small mismatch in timing causes the intermediates to collapse or degrade the catalyst rather than completing the reaction. This is the bottleneck that has halted advancement of AP for decades. The reaction carries a high activation energy and demands four electron transfers in a concerted process. Getting past this challenge is one of the main issue researchers are investigating currently [2, 3, 11].

Figure 3 shows the traditional process of AP: having an efficient light absorber, an efficient water oxidation catalyst, and an efficient proton reduction catalyst.

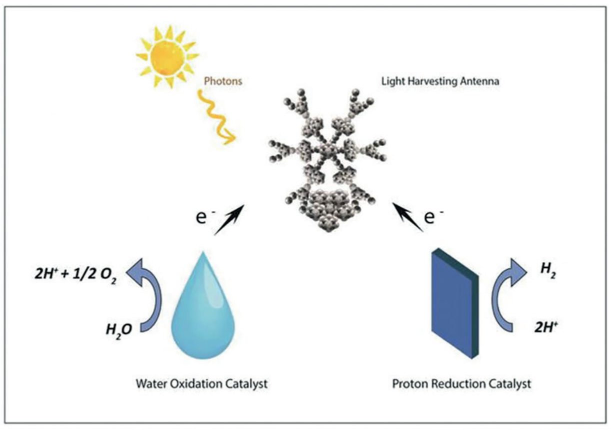


Figure 3: Fundamental architecture of an AP system, showing the three core components: a light absorber, a water oxidation catalyst, and a proton reduction catalyst [2].

Traditional electrolysis overcomes this problem by using electricity to power the reaction. However, AP tries to do the entire process only using sunlight as an energy input. Getting this to work at practical efficiency has proven almost impossible until recently [2, 11].

In December 2024, researchers at South Korea's Daegu Gyeongbuk Institute of Science and Technology, DGIST, published results that took the AP community by storm [10]. The team engineered a new photocatalyst. A photocatalyst is the material responsible for taking the light in and powering the chemical reaction. The DGIST team changed a common industrial dye called rhodamine into a structure that could position itself into ordered assemblies in water. This unique property they were able to make is amphiphilicity. After that they coated the structure with a thin layer of metal polyphenol compounds, copying the way natural proteins wrap around and stabilize biological molecules. The outcome was a system that effectively replicated the electron transfer process that chlorophyll does inside a leaf.

As a result, in visible light conditions the catalyst produced approximately 18.4 millimoles of hydrogen per hour per gram of materials. That figure is an astonishing 5.6 times higher than the earlier best result using the same class of material [10]. For context, industrial alkaline electrolysis produces hydrogen at 100 to 1,000 millimoles per hour per gram of catalyst. The DGIST result of 18.4 millimoles is still 5 to 50 times lower in terms of raw output. The difference is electrolysis requires grid electricity to operate, the majority of which is generated from fossil fuels. The DGIST catalyst runs on sunlight alone, with no external power. The gap in raw output is large, but the comparison is not the same. At 18.4 millimoles per hour per gram of catalyst, this marks the first solar only photocatalyst to produce hydrogen at rates that make a conversation about scaling up practical.

The material's ability to work under visible light, rather than just ultraviolet light, is crucial because UV radiation only makes up 5% of sunlight that hits the Earth's surface, and specifically plants, while visible light accounts for 43% and infrared accounts for the remaining 52% [13, 14, 15]. If the catalyst cannot run on visible light, then it will not work outdoors which completely ruins the idea of AP being a fully autonomous process.

Figure 4 shows the increasing rate at which AP is converting sunlight into usable energy compared with the target conversion rate of 10%.

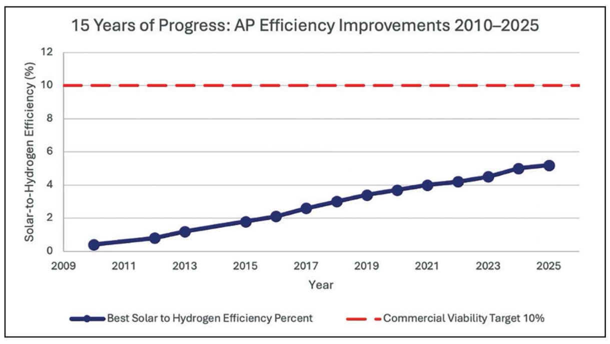


Figure 4: Solar to hydrogen efficiency progress in photocatalytic water splitting research, plotted against the commercially viable target of 10% [11, 16].

In 2025 chemists from the University of Basel in Switzerland were able to design a single molecule capable of something that had never happened. They simultaneously stored two positive and negative charges under light exposure [16, 17, 18]. The importance of this lies in the numbers behind water splitting. The reactions require the specific movement of four electrons, and most molecules involved in photochemistry can only compensate for one or two charge transfers before they reset. A molecule having the ability to store four charges at once could drive the entirety of the water splitting reaction from one burst of light as shown in Figure 5. This would drastically improve all earlier numbers behind AP and would increase the ability for wide scale adoption and ease of use [16, 17].

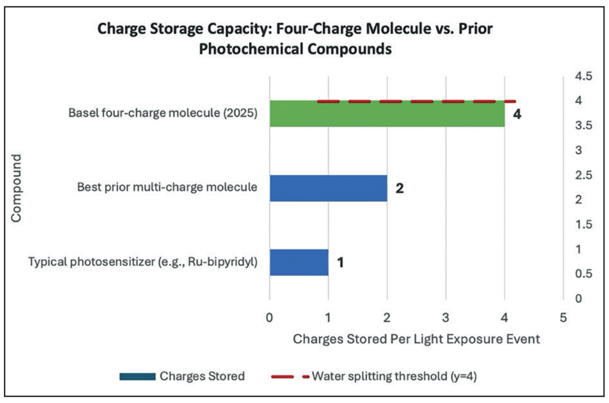


Figure 5: Molecular architecture of four charge storage compound, capable of simultaneously accumulating two oxidizing and two reducing equivalents under a single light exposure event [17].

A novel approach to the scaling problem of AP has been gaining traction through photocatalyst sheets. Instead of building multilayered devices, these new systems coat photocatalytic powder directly onto flat substrates using industrial screen-printing techniques. This is like the process used to make printed circuit boards [9, 28]. The sheets can be manufactured cheaply, which adds to the attractiveness of AP to companies and governments. They have great scalability and unlike previous artificial leaf designs, they avoid difficult engineering problems that come up when different parts of the device operate using different acid-base conditions. Panels using this method have been tested in Japan without using external energy input and they have been shown to successfully split water. This is a massive milestone for the autonomy of AP and water splitting. These advancements provide positive outlooks on fully autonomous water splitting devices that can fully function using only sunlight [19].

The commercial target for solar energy to clean hydrogen fuel is around 10%. This number comes from what analysts believe is the necessary efficiency these systems need to economically compete with fossil fuel alternatives [3, 11]. Currently, the most advanced labs are at around 3-5%. The gap may seem large, but at researchers' current pace the gap is decreasing quickly. Figure 6 puts this gap in perspective, comparing AP efficiency against solar power, wind turbines, and other leading energy technologies. AP currently underperforms on raw efficiency; however, it is the only technology on the chart capable of simultaneously absorbing sunlight, splitting water, and storing the result as chemical energy. All the other technologies require multiple steps and separate systems to accomplish the same final product as AP. This is the main reason why governments and institutions continue to put AP research as a top priority [20, 21].

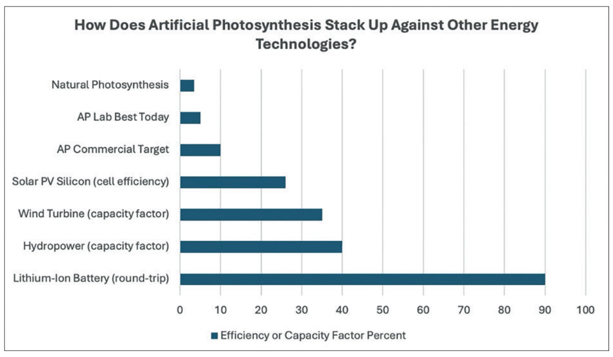


Figure 6: Efficiency comparison of AP against conventional solar panels, wind turbines, and electrolysis [11, 20, 21, 22, 23].

Closing the gap to 10% will require progress on multiple fronts. Light absorbers need to capture a broader section of the solar spectrum; current devices still leave a lot of energy on the table. The most effective catalysts still depend on expensive materials: iridium and platinum [1, 3]. These materials are too expensive for global deployment. Devices must also demonstrate sustained operation outdoors for thousands of hours, and not solely for a few hours in a controlled lab. Research proposes that reaching 7-8% efficiency would be high enough to spark commercial investment, and at the current rate of progress this goal is plausible within the next decade [11, 22].

Section 3: CO_2 reduction- turning pollution into fuel

Combustion is the process that has powered human civilizations for decades. It takes fuel and combines it with oxygen to release CO_2 and energy. CO_2 reduction does the exact opposite; it takes CO_2 and energy from the environment and transforms them into fuel. This closes the loop that combustion opened and did it solely using sunlight [1, 23].

Figure 7 demonstrates rising atmospheric CO_2 compared with increasing AP research. On one axis, atmospheric CO_2 is at 421 ppm while on the other global AP research publications are rising in parallel. The two lines show that the problem and solution are growing at the same time. Atmospheric CO_2 has become one of the defining environmental problems of the past century, currently sitting at 421 ppm and rising [4, 5]. The traditional carbon reduction and capture techniques require pulling CO_2 out of the atmosphere and burying deep underground which is a costly and ineffective method that does not solve any significant issues. AP offers a new method that is more cost effective and beneficial. It would take the same amount of CO_2 that is going to waste and combine it with sunlight and water to create clean fuel sources such as methane, methanol, ethanol, and ethylene. These compounds are worth billions of dollars in a global market and turn a pointless carbon reduction process into one that can power the world autonomously [3, 23, 24].

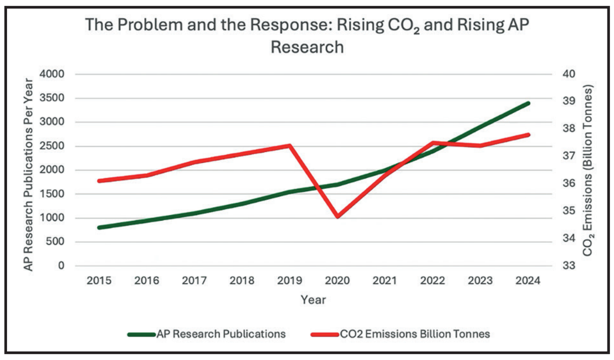


Figure 7: Parallel trends in rising atmospheric CO_2 concentration and growing global AP research output [3, 4, 5].

AP can power anything with its diverse range of potential products. It is different from water splitting which has one output, hydrogen, while CO_2 reduction can produce a variety of products depending on the catalyst used, the number of electrons transferred, and the conditions present during the reaction. Two electron reductions produce simpler compounds, such as carbon monoxide or formic acid. While more complex reactions with four electrons reductions produce more complex compounds such as methane, methanol, or a variety of C_2 chemicals [3, 23]. Figure 8 shows that more complex compounds are more valuable because they are needed to make feedstocks for plastics, polymers, and aviation fuels.

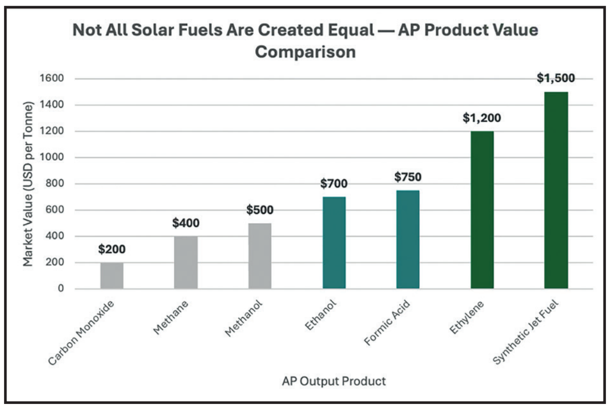


Figure 8: Product distribution from CO_2 reduction as a function of electron transfer complexity [24, 25, 26].

The main challenge is controlling the products. Having the ability to produce a specific compound on demand rather than a random mix of several is one of the unsolved issues in AP. A solid control of product production and the future will be quickly upon us.

The central challenge of CO_2 reduction has been understanding the reaction well enough to optimize it. The problem is that the intermediate chemical processes are not precisely known and improving the system has been guesswork. In 2025, the University of Chicago published results in Nature Catalyst that addressed this problem [9]. Their system converted CO_2 and water into methane fuel using sunlight at a rate ten times greater than any previous experiments. The CO_2 to methane selectivity exceeded 80% meaning most of the carbon entering the reaction was converted into methane rather than unwanted byproducts such as carbon monoxide or formic acid. The reaction was powered by a ruthenium-based photosynthesizer paired with a cobalt based catalyst. The ruthenium compound absorbed the incoming light and passed electrons to the cobalt catalyst, which used the energy to break the bonds in the CO_2 molecule and reform them into methane. The team used ultrafast spectroscopy to map out the short term lived intermediate compounds that formed during the reaction. They also were able to characterize the reaction mechanism at a molecular level. Understanding the underlaying mechanisms opens a clear path toward optimization in the field that previously was not there. This discovery gives the broader research community a target for improvement. They need to design better molecular interfaces between light absorbers and catalysts. Every future CO_2 reduction system can be designed around this new mechanistic discovery rather than being optimized through trial and error.

"We will have to do better than nature," said Wenbin Lin, lead author of the University of Chicago Nature Catalysis study, "and that's scary." This statement captures the scale of the AP field. Although natural photosynthesis seems inefficient, it is the product of billions of years of evolution and matching its efficiency is no small feat. Making a synthetic device that does around double the natural process is a logistical and engineering challenge that is on the edge of discovery [9].

Across the country at Lawrence Berkely National Laboratory, a separate team was researching an architecturally driven approach. Creating a device, with the size of a postage stamp, using a lead halide perovskite crystal as a light absorber, and a copper electrocatalyst [25, 26]. The lead halide perovskite crystal mimics the role of chlorophyll in a leaf. The copper electrocatalyst serves as the catalyst to drive the reaction of CO_2 into products and must be manufactured at the nanoscale to replicate tiny flowers within a plant. As shown in Figure 9, the device splits its work across two sides by a Neosepta membrane. The left side handles water oxidation, taking electrons from water and releasing oxygen. Those electrons can cross the membrane and drive CO_2 reduction on the right. The membrane is the key behind the system because it keeps the reactions separated, preventing recombining of the products. The result was an efficiency of over 40% for C_2 chemicals, ethylene and ethanol.

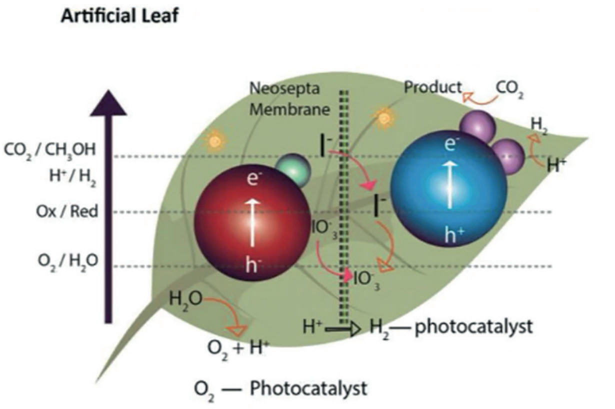


Figure 9: Cross sectional diagram of an artificial leaf device, showing the Neosepta membrane separating water oxidation on the left from CO_2 reduction on the right [2].

The advantage of the device developed at the Berkely lab was its selectivity for C_2 chemicals, specifically ethylene and ethanol. These products are significantly harder to produce, and more valuable than their simpler carbon counterparts. Producing C_2 chemicals is considered one of the largest challenges in the field, and the device developed by Berkely was proof of concept to many researchers in the field [25, 26].

Another advancement came from a DGIST team in 2025. They combined silver sulfide and amorphous titanium oxide in a single photocatalyst, deliberately making structural imperfections [27, 28]. Figure 10 demonstrates the structural makeup of the photocatalyst used in the experiment. The imperfections are defects in the crystal lattice that allow CO_2 molecules to preferentially bind. This method showed highly selective products including methane. The defect approach used in this experiment shows a broad approach used in modern materials science; researchers are learning to use defects to their advantage.

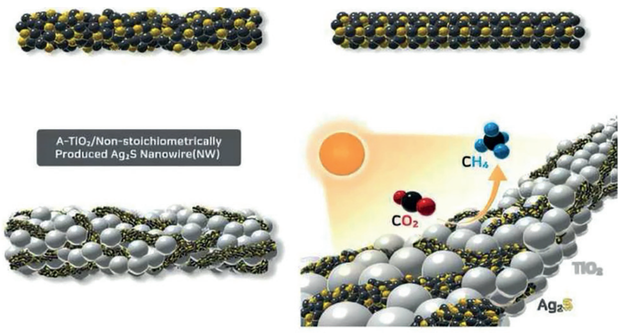


Figure 10: Scanning electron microscope diagram of Ag_2S/TiO_2 photocatalyst [27].

Section 4: The power of AP- catalyst innovation

Imagine a car, if AP were this car, then the catalyst would be the engine. The power behind the system. The light absorbing materials collect energy, the sunlight, the device keeps everything in place, but the catalyst is what causes chemistry to happen. In water splitting a viable catalyst must sustain hydrogen production rates on the order of millimoles per hour per gram of material. A threshold that many early systems could not meet, but the DGIST photocatalyst exceeded was a rate of 18.4 millimoles of hydrogen per hour per gram [10].

A catalyst is viable if it satisfies a criterion of four features. It must be active enough to power the reaction at a useful rate. It must be selective, producing the target compound without producing a mixture of unwanted byproducts. It must be stable enough to operate for thousands of hours under outdoor conditions without breaking. It must be made from materials that are cheap and abundant in scale. A catalyst that performs well in two or three of these areas but fails in one of them is not commercially viable. Finding a system that meets the requirements of all four categories is one of the most researched problems in the field [1, 3, 22].

A catalyst is a material that speeds up a chemical reaction without being consumed in the process. The challenge of catalysts in AP is not just finding one that can make the reaction happen at the desired rate but finding one that can survive in an outdoor environment for thousands of hours without breaking down.

The cost difference is large. Platinum, one of the most effective catalysts for the hydrogen evolution reaction, currently costs about $30,000 per kilogram, while iron and nickel, the abundant alternatives, cost less than $1 per kilogram [3, 22]. A technology that depends on platinum at a large scale cannot compete economically with fossil fuels. This is why replacing precious metals with cheap earth abundant alternatives is one of the most researched problems in the field.

The main problem currently is that the most effective catalysts currently depend on precious palatium group metals. Replacing platinum with nickel, or iridium with cobalt while not making any efficiency or performance sacrifices is an active area of research.

Catalysts are classified into one of four categories. Figure 11 illustrates how the catalyst sits at the heart of the entire AP process [2, 3]. Photons hit the photosensitizer, which absorbs lights and separates the charges, pushing electrons in the direction of the catalyst. The catalyst uses those electrons together with the protons from water oxidation to drive one of a few possible reactions. The catalyst can produce simple hydrogen gas with just 2H+, to reduce CO_2 into carbon monoxide, methanal, or methane. The number of protons involved in the given reaction determines both the product and difficulty. The first catalyst type is molecular catalysts, also referred to as homogeneous catalysts, are directly dissolved in the reaction solution. They often show high activity because every molecule is in contact with the reactants, and increased surface area increases reaction rate. They can be precisely engineered at the atomic level to make their behavior predictable [2, 3]. The drawback is recovering them from solutions on a large scale, and they tend to degrade over extended periods of time.

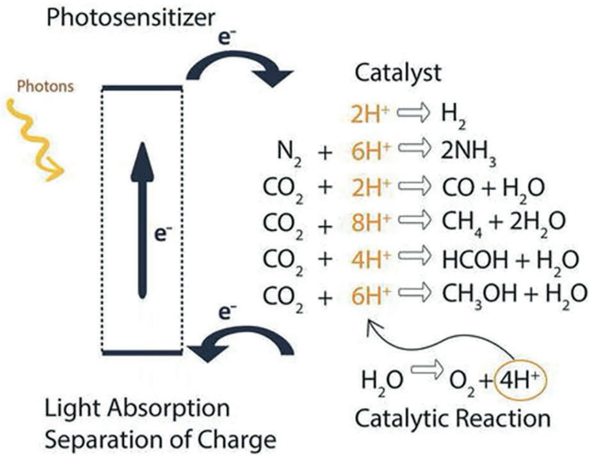


Figure 11: Reaction pathway diagram showing how a photosensitizer absorbs incoming photons and transfers electrons to a catalyst which drives reduction of protons or CO_2 into hydrogen gas, carbon monoxide, methane, or methanol [2].

The second are heterogeneous catalysts which are solids including metal oxides, sulfides, and nitrides. They stay separate from liquid reaction and are more practical for real world use. This is because they are easier to recover and more stable. The DGIST Ag_2S/TiO_2 system is in this category [27, 28].

The third type are biocatalysts. They are enzymes such as hydrogenases; bacteria use this to process hydrogen, which are highly selective and efficient because they have been refined through millions of years of evolution. Researchers either attach these to synthetic electrodes or incorporate the entire microorganisms to take advantage of the precision that evolution has provided us. The problem is that enzymes are sensitive to pH, temperature, and a lot of other environmental factors which make it difficult to keep running for years at a time without maintenance needed. Without autonomy, AP will only go so far [3].

The fourth category is nanomaterials. Nanomaterials behave differently on the nanoscale compared to when they are in mass quantities. A nanoparticle can have up to 30% of its atoms exposed to the surface compared to a fraction of a percent for a traditional material of the same composition. Catalytic reactions occur at surface sites causing this massive increase in surface area to volume ratio. This leads to higher reaction rates per gram of material. One of the most promising materials is called MXenes, which are two-dimensional sheets of titanium carbide, which are only a few atoms thick. They have high electrical conductivity and surfaces that are easily altered chemically. All these groundbreaking features of nanomaterials make specific ones such as MXenes, some of the most actively researched catalysts in the AP field [3].

Of the four catalyst categories, heterogeneous catalysts are the closest to commercialization because they are stable, recoverable, and manufacturable at scale. The DGIST photocatalyst has attracted a lot of industrial attention because it falls into the heterogeneous category. Molecular catalysts lead on precision and activity but fall behind in terms of durability. Biocatalysts are selective but are too environmentally sensitive for outdoor usage. Nanomaterials are the most promising frontier but remain at early research stages.

In 2025, the Berkely Lab developed a copper nanoflower catalyst. They are made to have a fractal, flower-like structure at the nanoscale and they have enormous surface area to the reaction while their crystal structure stabilizes the intermediates that lead to the production of C_2 chemicals rather than more basic compounds. Selectively producing ethylene and ethanol has been one of the main barriers in AP advancement and the Berkeley Lab breakthroughs show huge promises for rapid advancement and adoption.

Figure 12 shows a depiction of a tree with copper nanoflowers wired to perovskite crystals.

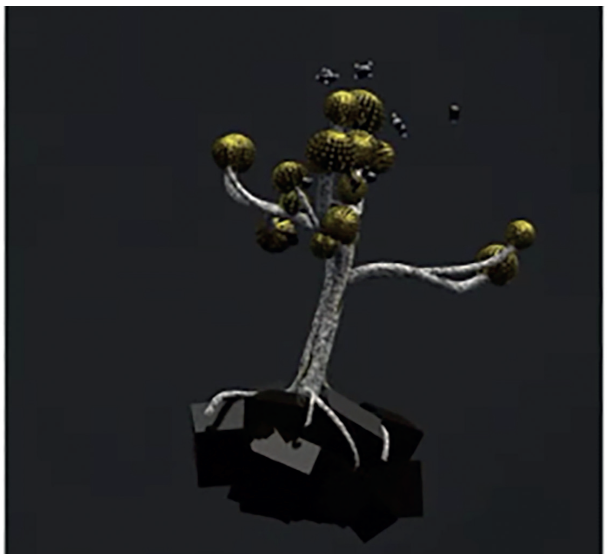


Figure 12: Scanning electron microscope moving diagram of copper nanoflower catalysts, showing the fractal surface architecture responsible for stabilizing C_2 reaction intermediates and enabling selectivity [26].

Section 5: Artificial leaves and photoelectrochemical cells

Remember that car analogy from earlier, imagine an engine without the body of a car; that is just like having a catalyst without a device. Chemistry must be incorporated into a practical physical device that has light absorbing capabilities. The device must also be able to manage the flow of electrons and protons, keep the products separated, and do all of this without stopping for years without needing maintenance. This is the intersection of chemistry and engineering in AP. This is a large area of research where chemists and engineers must come together to produce a practical product that satisfies all the needs of the industry [2, 29].

The main device used in the industry is a photoelectrochemical cell (PEC). Figure 13 shows the steps it takes for this process to work. Sunlight hits the photoanode on the left where water is oxidized. The electrons released travel up and though an external circuit to the electrode on the right. The protons are simultaneously moving across the solution and in the right electrode the electrons and protons recombine. This produces hydrogen gas bubbles out of the solution. The entire process is driven by sunlight, and no external power source is needed. In a PEC, the light absorbing part, a semiconductor, is integrated with the catalyst in a single part. When light meets the surface, it excites the electrons in the semiconductor, causing a voltage that powers two half reactions at once. Water oxidation at one electrode and hydrogen production or CO_2 reduction at the other end. This method is both simple and cost effective. The PEC ends the need to use a solar panel to generate electricity and then feed it into an electrolyzer. In traditional electrolysis, those two systems operate independently, each with its own energy loses at every intermediate step. This results in an efficiency of 60% to 80%. A PEC eliminates the intermediate electrical step, converting sunlight directly to chemical fuel in a singular device. This system can reduce errors because of its simplicity. Every arrow in the figure represents a step that in conventional energy processes requires separate hardware, while a PEC collapses it into a single device [2, 11, 29].

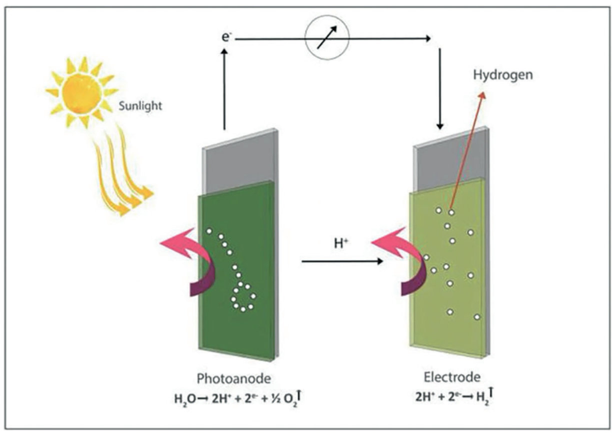


Figure 13: Working principle of a PEC, showing sunlight driven water oxidation at the photoanode, electron flow through an external circuit, and hydrogen gas evolution at the electrode [2].

An artificial leaf is a specified PEC. It is lightweight, flat, and directly exposed to the sun, the same way a real leaf is. The term was coined by Daniel Nocera in 2011 when he showed the first functional artificial leaf. It was a silicon water coated with catalysts that had water splitting capabilities when meeting sunlight. However, this original device was fragile and inefficient and the progressions since the original have been massive and made artificial leaves more than just an afterthought [2, 3].

The postage stamp device, displayed in Figure 14, created by the Berkely Lab shows off the most ultramodern CO_2 reduction systems. It uses a lead halide perovskite light absorber. Perovskites are used because they have a tunable bandgap that can be engineered to absorb a wide range of the solar spectrum. They can also be deposited as thin films at a low cost compared to traditional silicon semiconductors. The perovskites are then layered with copper nanoflower catalyst to convert CO_2 and water into C_2 chemicals using nothing but sunlight. The value of the device is because it is a fully functioning light driven system that produces high value C_2 chemicals under standard conditions [25, 26].

Figure 14: The Berkeley Lab postage stamp sized artificial leaf device [26].

Photocatalyst sheets have been the most scalable approach to water splitting. The manufacturing process goes hand in hand with industrial printing. Photocatalytic powder is placed onto a flat substrate using screen printing techniques, then dried and fried at temperatures between 400 to 600 degrees Celsius. The purpose is to bond the catalyst layer to the substrate surface and establish the required electronic contact between the particles. The sheets can be made in square meter panels and tested outdoors in natural sunlight. They have shown unassisted water splitting, which is huge for the autonomy of AP. Currently Japan is producing the most up to date tests for these devices and are paving the way for real world adoption [11, 19].

The main devices addressing the efficiency problem are tandem absorber systems. They do not rely on just one light absorbing layer to capture the entire solar spectrum, but these devices stack at least two layers on top of each other with different absorption characteristics. The top layer tends to capture higher energy light with shorter wavelength while the lower layer captures what goes through, normally being longer wavelength and lower energy light. The combination of different light absorbers allows a greater array and percentage of the light spectrum to be captured, which improves efficiency. They receive the same amount of sunlight as other devices but absorb more energy, seeming simple [11, 29].

Biology involves the most counterintuitive approach. Biohybrid artificial leaves combine inorganic semiconductors with living microorganisms. One example is a silicon photovoltaic base that generates electricity from light. Then it is fed to bacteria living in a solution. The bacteria use electrical energy to power their metabolic chemistry, which conveniently converts CO_2 to liquid fuels, which is the exact goal of AP. Biology is doing the same process that scientists are trying to do. The microorganisms serve as the catalyst in this reaction; a feat of evolution and biology being used for humanity's benefit and desire for clean fuel production [30].

Figure 14 shows a biohybrid electrode that combines living biology with synthetic materials. Photosystem I complexes from the red microalga C. merolae are embedded into a mesoporous hematite scaffold. When light encounters the device, the biological photosystem absorbs it and drives electrons through an FTO conductive layer toward the platinum cathode. Evolution handles the light absorption while synthetic materials handle the rest [2, 3].

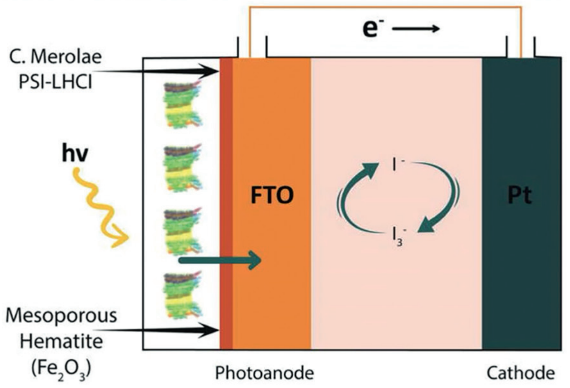


Figure 15: Biohybrid electrode architecture combining complexes from the red microalga C. merolae with a mesoporous hematite scaffold, an FTO conductive layer, and a platinum cathode to drive light powered chemical conversion [3].

These devices are not yet ready for commercial use. The highest performing PEC has an efficiency of 3-5%, roughly halfway to the economically practical 10%. Most of these results are measured in labs over hours, but real devices would need to run in the environment for years without need for repair. Most devices are also not cost competitive with alternative energy sources. Even with all this, the trajectory of improvement is extraordinary with the rapid development of advanced systems. All remaining engineering challenges in principle are solvable with the right minds and resources [3, 11, 29].

Section 6: Real world applications and the global race

The science of AP doesn't live in a vacuum. Every catalyst formation and device efficiency improvement is a group of practical questions: What will this process replace? Who will create it? Who will pay for it? And the most pressing question of them all: Who will get there first?

The final applications of AP are not just minor improvements made to the energy industry, but they are entire transformations of the entire global energy sector. Flipping the energy sector upside down and flipping the script of depending on fossil fuels.

The first target in site is green hydrogen. Currently an overwhelming majority of the world's hydrogen is produced from natural gas through a process called steam methane reforming. This process, as you would expect, releases a large amount of CO_2. The result of this process is called grey hydrogen, and it powers everything from steel production to fertilizer manufacturing to petroleum refining. Using AP to replace this grey hydrogen with green hydrogen using only sunlight and water would reduce a substantial amount of CO_2 emissions. By the year 2050, the global hydrogen economy is projected to hit $2.5 trillion, and the market share of green hydrogen is expected to increase rapidly as scientists are on the brink of discovery [12, 31].

On the other hand, aviation proves to be a more challenging problem. Planes cannot run on hydrogen stored in tanks without large redesigns. Figure 15 demonstrates this because it shows the large differences between energy densities of the fuel sources. Additionally, battery technology is not where it needs to be to power passenger jets. Using synthetic liquid fuels is currently the most probable path for decarbonizing the aviation industry. The research done on C_2 chemicals at the Berkeley Lab is directly targeting this issue. Ethylene and ethanol are the two main products of their artificial leaf, and those are the precursors needed for the same exact type of synthetic jet fuel that the aviation industry needs [25, 26, 32, 33, 34].

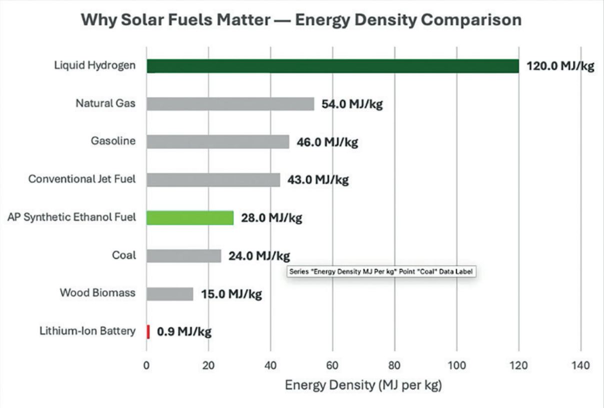


Figure 16: Energy density comparison across hydrogen, battery, and liquid hydrocarbon fuel sources [32, 33, 34].

The applications do not just stop at energy. In 2022, a team shows that a biohybrid AP system could convert CO_2 into acetate, a simple two carbon compound. Acetate could be used to serve as food for yeast, fungi, and algae growing in dark environments. Compared to traditional agriculture, solar-to-food energy conversion was about four times better. In the current world where the population is growing, farmable land is shrinking, and the climate is becoming increasingly unstable the ability to produce food from sunlight would be extremely valuable. This method could solve food insecurity for people all over the world, especially those in unstable and harsh climates [30].

Currently, every carbon capturing technique treats CO_2 as a waste product, which is inefficient and generates no economic return. AP completely flips the script and makes CO_2 become the raw material. The more CO_2 you have, the more fuel and feed stocks you can produce. The financial case for AP does not depend on regulatory matters, but it depends on the value of the output it produces [1, 23, 35].

The global scale of AP projects has taken countries like Japan by storm with them called their AP mission an "Apollo-like mission," [35] in the words of the World Economic Forum. They are doing this to gain energy independence and position themselves as energy leaders in a post fossil fuel landscape. Their program involves a government back consortium of universities and corporations, with multiple real-world applications currently in progress. The United States Department of Energy's Fuels from Sunlight Hub funds coordinated with research from Berkeley, Caltech, MIT, and the University of Chicago [9, 25]. China has invested in solar fuels research and now makes some of the highest yielding devices in the world. South Korea's DGIST has produced two world record catalyst results in a single year [10, 27, 28]. The Netherlands and Germany are leading efforts in Europe under the EU Horizon program. Figure 16 summarizes the total investments made by the leading countries [36].

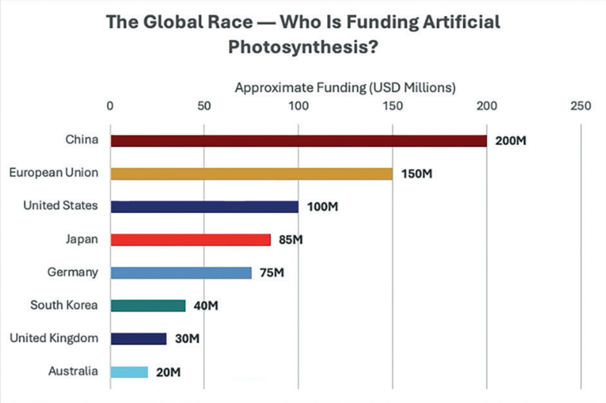


Figure 17: Chart showing AP research investment by country [33, 35, 36, 39].

Section 7: What is still in the way?

Progress in AP has been rapid in recent years. Honesty about realistic timelines in the field still needs to be understood even with the advancements made in recent years. Building technology that can be implemented across the entire human civilization is far from the same thing as making groundbreaking lab discoveries. The obstacles range from economic, to logistical, and in some cases even fundamental.

The most quantifiable challenge is the efficiency gap between AP and alternative energy methods. Current solar to hydrogen efficiencies range from around 3-5% and for large scale commercial viability that number needs to be about 10% [3, 11]. The losses occur at every step of the process. Incomplete light absorption across the solar spectrum, voltage losses at the semiconductor catalyst interface, and energy wasted driving the competing side reaction rather than the target chemistry. Every loss mechanism is an active area of research. That is the price for green hydrogen to be produced at competitive costs with fossil fuels. For reference, natural photosynthesis sits around 1-6% efficiency, which means the process humans have developed has yet to consistently surpass that of nature.

Materials and cost present a similar problem. Most of the highest performing catalysts use platinum, iridium, and ruthenium, elements that are scarce and expensive [3, 22]. The switch to iron, copper, nickel, or cobalt has not happened yet without sacrificing efficiency. Although this switch is possible, it has yet to be achieved. The system will never achieve commercial viability if the cost of the materials is higher than the fuel produced. Figure 17 demonstrates when green hydrogen will become cheaper than grey hydrogen. The graph shows how quickly until clean hydrogen becomes the more cost-efficient product.

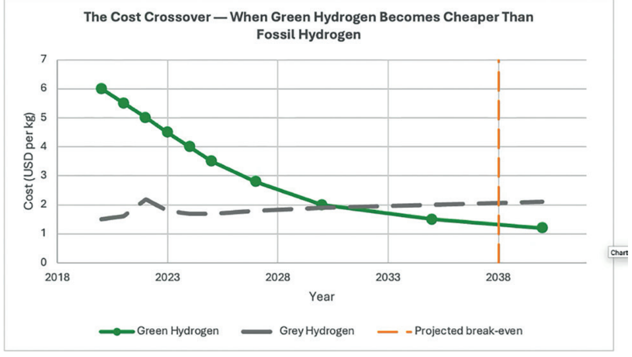


Figure 18: Projected cost trajectories for green hydrogen verses grey hydrogen, showing a crossover point at which solar produced hydrogen becomes cost competitive with fossil fuel derived hydrogen [12, 31, 33].

Where many other promising systems fail is durability. Many catalysts can perform perfectly in a lab for a couple of hours; however, that is not the capability needed by these materials. They must sustain perfect function for years in outdoor environments with varying weather conditions, temperature fluctuations, and biological contamination. Two mechanisms cause the most decay in practice. Photocorrosion is where the light absorbing semiconductor is chemically attacked by the reaction it is driving which slowly dissolves overtime. The second is catalyst poisoning which is where trace contaminants in water bind to the active surface sites and permanently block the reaction. Both are largely absent in controlled lab conditions which explains why published performance figures rarely survive when the device is tested outdoors. The other Many results are published over hours or days. For real adoption, these systems will have to run for at least a decade. The testing timelines and operational timelines are far from in the same league currently [3, 11, 29].

The main challenge of engineering and infrastructure is scalability. The Berkeley Lab device is the size of a postage stamp, and a meaningful contribution to global energy infrastructure would require a device to cover square kilometers. The manufacturing techniques, the storage and transportation system for gaseous hydrogen, safety regulations, and grid integration do not yet exist at the necessary scale to make any meaningful impact on global energy.

Product selectivity remains another open scientific problem for CO_2 reduction systems. While water splitting has one output, hydrogen, CO_2 reduction can produce a variety of products depending on minor changes in the system and process used. The ability to make a system that can consistently and solely produce a desired compound at a practical yield under real world conditions is a challenge that has not been totally solved by any researchers.

Although these obstacles may seem like a lot to overcome, they are all solvable with the right commitment. Every challenge currently has researchers working to solve it and pave the way for the future of energy. But these road bumps are 100% real, and history teaches us that the distance between positive lab results and deployable cost-effective systems is always longer than expected. With all the recent breakthroughs there is more than enough promise to trust the smartest minds by solving the challenges that lie ahead [1, 2, 3].

Section 8: Conclusion- The leaf we build tomorrow

The difference between a regular old leaf and an artificial leaf is rapidly shrinking.

Three years ago, the most effective AP systems were barely able to keep up with biological processes. Right now, there is one that is ten times better than anything else created before it [6]. A device that is so small you can hold it between your fingers is converting CO_2 from the air into chemical precursors for jet fuel and feedstock while only needing to be in the presence of sunlight [7, 24]. A molecule designed in a Swiss laboratory can manage four charges that can drive the entire water splitting reaction [16, 17, 39]. In Japan there are photocatalyst sheets the size of dining tables that are running autonomously [11, 19].

The pace is just as important as the results. More progress has been made for the advancement of AP in the last three years than in the previous ten years [1, 2, 3]. The reasons range from technological advancements such as advances in nanomaterials, catalyst design, and film fabrication to institutional adoption. Governments and corporations in the United States, China, Japan, South Korea, and Europe have committed themselves to advancing the field [6, 7, 8, 35, 36, 39].

Laboratories around the world are building technology to make a platform for AP. They are making a new way of thinking about how solar energy can be stored and used. The current prototype is a postage-stamp sized device that produces a few nanoliters of ethylene per hour. The outlook is a device that can work at scale to produce clean hydrogen used for steel and fertilizer manufacturing, synthetic jet fuel, feedstocks for plastics and polymers, and if we are being optimistic then even food. All of this is made from just sunlight, water, and CO_2 that industrialization has been releasing into the atmosphere for the last 200 years [1, 9, 25, 30].

AP will not fix climate change by itself. The transition of energy is too large and complex for a single technology to completely change everything. However, it can give us a powerful tool to fight the effects, and the device could fit in your hand and run on nothing but sunlight.

The natural leaf took over three billion years to come to fruition. Scientists are on the brink of building a more efficient one in less than a generation. If the last three years of advancement told us anything, it is that they might just do it.

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Biographies

Dr. Raj Shah, is a Director at Koehler Instrument Company in New York, where he has worked for the last 25 plus years. He is an elected Fellow by his peers at ASTM, IChemE, ASTM,AOCS, CMI, STLE, AIC, NLGI, INSTMC, Institute of Physics, The Energy Institute and The Royal Society of Chemistry. An ASTM Eagle award recipient, Dr. Shah recently coedited the bestseller, "Fuels and Lubricants handbook", details of which are available at ASTM's Long-awaited Fuels and Lubricants Handbook https://bit.ly/3u2e6GY. He earned his doctorate in Chemical Engineering from The Pennsylvania State University and is a Fellow from The Chartered Management Institute, London. Dr. Shah is also a Chartered Scientist with the Science Council, a Chartered Petroleum Engineer with the Energy Institute and a Chartered Engineer with the Engineering council, UK. Dr. Shah was recently granted the honorific of "Eminent engineer" with Tau beta Pi, the largest engineering society in the USA. He is on the Advisory board of directors at Farmingdale university (Mechanical Technology), Auburn Univ (Tribology), SUNY, Farmingdale, (Engineering Management) and State university of NY, Stony Brook (Chemical engineering/ Material Science and engineering). An Adjunct Professor at the State University of New York, Stony Brook, in the Department of Material Science and Chemical Engineering, Raj also has over 700 publications and has been active in the energy industry for over 3 decades.


Nate Polishook

Mr. Nate Polishook is a member of a thriving petroleum research internship at Koehler Instrument Company, where he regularly contributes to the petroleum and energy research industry.


Gavin Thomas

Mr. Gavin Thomas is part of a thriving internship program at Koehler Instrument Company in Holtsville, NY and is a recent graduate of the Chemical and Molecular Engineering program at Stony Brook University. He also works as a process engineer at Mill-Max in Oyster Bay, NY where he becomes hands-on with various production processes to ultimately improve safety, efficiency, and cost-effectiveness.


Kate Marussich

Ms. Kate Marussich is part of a thriving internship program at Koehler Instrument Company in Holtsville, NY underneath Dr. Raj Shah. Marussich is also a student in the department of Material Science and Chemical Engineering at Stony Brook University, where Dr. Shah serves on the External Advisory Board.


William Chen

Mr. William Chen is part of a thriving internship program at Koehler Instrument Company in Holtsville, NY and is a student of Chemical Engineering at State University of New York Stony Brook, NY.

Author Contact Details

Dr. Raj Shah, Koehler Instrument Company

- Holtsville, NY11742 USA
- **Email: rshah@koehlerinstrument.com**
- **Web: www.koehlerinstrument.com**