

Mimicking Nature to Replace Fossil Fuels: The Promise of Artificial Photosynthesis Systems

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ABSTRACT

Rapid anthropogenic warming has accelerated climate risks beyond historical precedent, underscoring the necessity of replacing fossil fuels, which account for nearly 90% of global CO₂ emissions. This perspective argues that artificial photosynthesis, particularly the Si-perovskite tandem photoelectrochemical (PEC) system, represents the most promising pathway for large-scale energy-system decarbonization. Recent breakthroughs enabling sunlight-driven conversion of CO₂ into multicarbon liquid fuels mark a pivotal advance, offering storable, energy-dense alternatives uniquely suited for hard-to-electrify sectors such as aviation, shipping, and heavy industry. The Si-perovskite tandem PEC overcomes long-standing challenges in photovoltage, light absorption, and material cost, and emerging solutions such as dual-skin ALD/SLIPS coatings show potential to address the critical instability of perovskites. However, translating laboratory success into global adoption requires targeted policy support, including early-stage capital subsidies, stringent recycling regulations for lead-based perovskites, expanded R&D funding, and international frameworks ensuring equitable technology transfer. Efficiency estimates and energy-supply projections suggest that artificial photosynthesis could meaningfully contribute to global fuel demand while reducing lifecycle emissions, though the paper acknowledges uncertainties related to land use, intermittency, and commercial scalability. Alternative decarbonization pathways, such as green hydrogen, offer valuable context but face infrastructure and energy-density limitations. Ultimately, this paper contends that with coordinated technological innovation and policy action, artificial photosynthesis can become a cornerstone of a just, scalable, and carbon-neutral global energy system.

Keywords: si-perovskite; photoelectrochemical cells; electrocatalysis; artificial photosynthesis; climate change

INTRODUCTION

Although Earth's climate has fluctuated throughout history, the present rate of warming has been unprecedented in the last 10,000 years (1). In 2024, the

global surface temperature soared to $1.55 \pm 0.13^\circ\text{C}$ above the 1850–1900 pre-industrial average, the hottest year in the 175-year observational record (2). This escalation is not just a statistic; it signals an escalating catastrophe. Rising global temperatures drive increasingly destructive and frequent weather disasters, intensify food insecurity and malnutrition worldwide, and push ecosystems toward collapse and potential mass extinction (3). With that said, NASA states that these future outcomes ultimately depend on global CO₂ emissions (4). Considering fossil fuels account for nearly 90% of all CO₂ emissions (2),

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urgent action is needed to transition toward sustainable energy alternatives. Among emerging solutions, one novel technology stands out for its potential to eliminate the need for fossil fuels: artificial photosynthesis.

This technology has been in the works for the past 20 years (5); however, just months ago, a breakthrough discovery found a way to produce multicarbon liquid fuels (6). Unlike conventional renewable energy sources which only generate electricity, artificial photosynthesis offers a direct route to clean liquid fuels, capable of decarbonizing hard-to-abate sectors such as aviation and shipping, where the potential climate benefits are significant (7). Thus, this paper argues that artificial photosynthesis represents the most promising solution for decarbonizing the global energy system in the current literature.

SI-PEROVSKITE TANDEM PHOTOELECTROCHEMICAL CELL

Artificial photosynthesis technology mimics natural photosynthesis by using sunlight, water, and atmospheric CO₂ to produce storable, carbon-neutral fuels (5). The present and most efficient artificial photosynthesis device is an Si-Perovskite tandem photoelectrochemical cell (PEC), a stacked structure with a variety of layers.

Now, mimicking a natural biological process with only inorganic, economically scalable materials presents a complex series of steps, as visualized in Figure 1. Here is a condensed summary of this complex process. First, photons from the sun enter the system and strike the perovskite photocathode layer. These entering photons excite the electrons in perovskite, creating an electron-hole pair (8), with the holes traveling to the silicone (Si) layer via the PTAA layer (9) while the electrons travel to the Cu catalyst layer via the PEIE and PCBM layers (10). Si is the photoanode where the photons will also generate an electron-hole pair. The electrons from this electron-hole pair generation will flow to the Cu catalyst through PEIE and PCBM layers, and the holes from both Si and perovskite's electron-hole pair drive the GOR, producing C₃H₆O₃ (glyceraldehyde), electrons (e⁻), and protons (H⁺) (Eq. 1). Glyceraldehyde, although not further used in the artificial photosynthesis process, is a valuable product that has market value in pharmaceuticals, cosmetics, and more (11). The protons from this equation are transported to the Cu catalyst through the electrolyte solution consisting of 0.1M KHCO₃ (aq) with C₃H₈O₃ (glycerol) additive. At the Cu catalyst, the CO₂ reduction reaction (CO₂RR) occurs, utilizing the electrons from

the perovskite and Si's electron-hole pair, as well as the protons from the Si GOR (Eq. 2) (12). The product of this CO₂RR is usable liquid fuel and water as a byproduct.

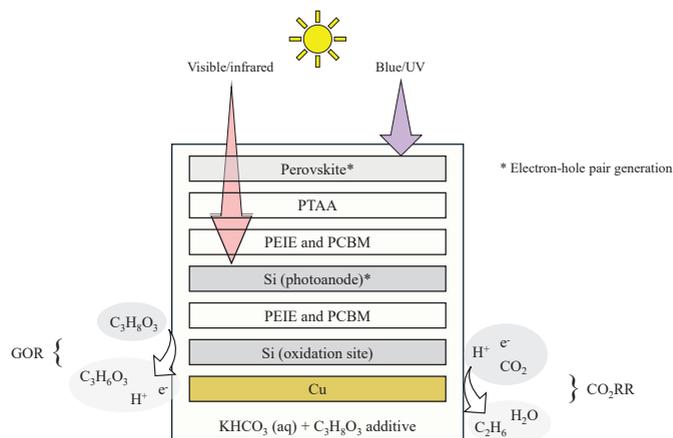


Figure 1. Stacked Si-Perovskite tandem PEC visualization. Incident solar photons are depicted by red and purple arrows. The GOR is shown at the Si layer (oxidation site), and the CO₂RR proceeds at the Cu layer. Reactants are highlighted within a dark grey oval, and products within a light grey oval. The white curved arrows represent the progression of the respective reactions (6, 13, 14).



By enabling sunlight-driven CO₂ conversion into liquid fuels within a compact, tunable device architecture, the Si-Perovskite tandem PEC embodies why artificial photosynthesis stands out as a uniquely scalable decarbonization pathway. These architectures significantly improve economic feasibility by boosting solar-to-fuel efficiency, meaning less land, material, and capital are required per unit of energy produced. Likewise, the choice of catalysts, such as earth-abundant copper versus rare metals, directly affects whether these systems can be deployed at global scale rather than remain laboratory curiosities. Its ability to integrate photon absorption, charge separation, and catalytic fuel formation in one self-sustaining system illustrates why artificial photosynthesis is the most promising technology for transforming the global energy system.

CURRENT TECHNICAL LIMITATIONS AND DESIGN RESPONSES

The materials in this system build on existing PEC literature. Previous trials struggled with insufficient light absorption, failing to harvest enough sunlight (16); low photovoltage ($<1.2V$), below the energy required for CO₂RR (17); too wide/narrow bandgaps, with too-wide bandgaps unable to absorb lower wavelengths of light (18) and too-narrow bandgaps reducing the photocurrent and consequently overall efficiency (19); and scalability issues, where translating lab performance to industrial-scale reactors presented major economic barriers (20). This system utilizes perovskite, specifically lead halide perovskite (CH₃NH₃PbI₃), mitigating the insufficient light absorption limitation because of its turnability, high absorption coefficient, and long carrier diffusion length (21). By pairing perovskite with the underlying Si layer, the system combines their photovoltages to achieve $>1.8V$ in practice, sufficient to drive both the CO₂RR and GOR simultaneously without an external bias (5). The two of these layers also have unique bandgaps, maximizing overall solar absorption while providing sufficient photovoltage (11, 12). Moreover, Si is already mass-produced (22), perovskite fabrication is low cost (23), Cu is Earth-abundant (24), and KHCO₃ is a common electrolyte (25). Together, these advances demonstrate why artificial photosynthesis is emerging as a highly promising decarbonization pathway: the Si–Perovskite tandem architecture not only overcomes long-standing efficiency and photovoltage barriers but does so using materials that are inexpensive, scalable, and already aligned with global manufacturing capacity. By converting CO₂ into liquid fuels using only sunlight and abundant resources, this system points toward an energy infrastructure that can grow without expanding carbon emissions. In this way, the device exemplifies how artificial photosynthesis can realistically supply clean, storable fuels at the scale required to decarbonize the global energy system.

A pressing challenge for the commercial viability of this device is perovskite stability. PCBM and PEIE layers attempt to address this by shielding perovskite from the electrolyte and moisture, which lessens degradation, corrosion, and delamination (26). However, they do not effectively prevent heat, light, and oxygen from contacting the perovskite. Thus, the overall device lifespan is shortened, posing a major barrier to real-world scalability. Current research has yet to mitigate this limitation, however there is a forward-looking solution

that shows great promise in perfecting this system.

One proposal is a ‘dual-skin’ protective coating, consisting of an atomic layer deposition (ALD)-grown TiO₂ nanolaminate barrier overlaid with a slippery liquid-infused porous surface (SLIPS) composed of fluoropolymers (27). The ALD nanolaminate provides a conformal barrier that slows water and ion ingress, stabilizing buried interfaces in harsh electrolytes (28). Pairing that with a SLIPS layer, which is anti-wetting and highly corrosion-resistant in aqueous solutions, further reduces the likelihood of water, oxygen, light, or heat from reaching the perovskite (29, 30, 31). These layers maintain ionic conductivity to the Cu, a crucial aspect for the GOR, while still minimizing water activity at the perovskite interface (32), an issue previously researched hermetic caps struggled with (33, 34, 35, 36). While this solution is still under researched, it presents a promising proposal for addressing perovskite instability, and ultimately strengthening the pathway toward durable, grid-relevant fuel production. Enhancing device longevity directly improves economic feasibility, allowing artificial photosynthesis systems to operate reliably under real-world conditions and ultimately produce carbon-neutral fuels at competitive costs. In this way, stability-focused innovations like the dual-skin coating accelerate the transition from promising concept to deployable clean-energy technology, reinforcing the potential of artificial photosynthesis to support global energy-system decarbonization.

CURRENT LIMITATIONS AND FUTURE STEPS

Artificial photosynthesis addresses a central policy challenge: decarbonising sectors that are otherwise intractable through electrification. International agreements require not only rapid solar and wind expansion, but also scalable production of carbon-neutral fuels for aviation, shipping, and heavy industry (37). Unlike passenger vehicles or residential heating which can transition toward electrification and batteries, these sectors rely on high energy-density liquid fuels to operate over long distances without frequent refueling, making them persistent sources of CO₂ emissions (6, 38). As an example, cargo shipping alone accounts for nearly 3% of global CO₂ emissions, yet the scale of ocean freight and the limited space onboard make large-scale battery storage impractical (39). The Si–Perovskite PEC described in this viewpoint produces storable multicarbon fuels which provide a drop-in

replacement compatible with existing infrastructure, avoiding the prohibitively high costs of retrofitting entire global fleets and industrial plants (40). However, translating laboratory prototypes into commercial adoption will require supportive government policy frameworks, including targeted research funding, pilot project incentives, and carbon pricing or subsidies to make artificial photosynthesis fuels competitive in early markets (41).

Science policy and Deployment Considerations

Effective policy must also anticipate risks and enable the specific conditions required for artificial photosynthesis to scale. Because early artificial-photosynthesis reactors will initially face high capital costs and uncertain lifetimes, targeted subsidies, loan guarantees, and production tax credits—similar to those used for solar PV and green hydrogen—will be essential to help early commercial plants reach cost parity with fossil fuels. Additionally, this technology relies on lead-based perovskites, which poses environmental and public-health risks; therefore, strict recycling standards, mandatory take-back programs, and protocols for safe handling and encapsulation must accompany deployment to prevent leakage throughout the device lifecycle (42). The heavy material demands of large-scale CO₂-to-fuel systems also justify increased federal R&D funding for catalyst durability, perovskite stability, and tandem-cell manufacturing, accelerating the transition from laboratory prototypes to industrial reactors.

At the global level, artificial photosynthesis offers a geographically flexible decarbonization strategy, but equitable deployment requires policy mechanisms that ensure access to manufacturing techniques, maintenance expertise, and financial support. Equity considerations must ensure that developing nations, often most vulnerable to climate impacts (43), benefit from technology transfer, open licensing, and capacity-building programs rather than being excluded by restrictive patents or high-cost import dependencies. Integrating these guardrails with broader climate policies such as carbon pricing, clean-fuel mandates, and international financing frameworks will align economic incentives with the attributes of artificial photosynthesis itself: modular, scalable reactors capable of producing carbon-neutral fuels. Taken together, these policies not only support successful commercialization but also help ensure that artificial photosynthesis contributes to a more just and decarbonized global energy system, rather than replicating existing inequities.

Because national contexts vary widely, the policies needed to support artificial-photosynthesis deployment will differ substantially from one country to another. High-income countries with mature research ecosystems and established clean-energy industries are positioned to prioritize R&D funding, early-stage capital subsidies, robust safety and waste-management regulations for perovskites, and large demonstration projects. These nations can absorb early financial risk and set stringent environmental standards that shape global best practices. In contrast, middle-income countries may focus on technology transfer, joint-venture manufacturing, and workforce training, using international partnerships to build domestic production capacity without bearing the full cost of initial innovation. Meanwhile, low-income countries, many of which face severe climate vulnerabilities, often require concessional financing, multilateral grants, and open-access licensing to ensure affordable access to the technology, along with support for grid integration and maintenance infrastructure. A coordinated approach, anchored by institutions like the UNFCCC, Mission Innovation, or multilateral development banks, can align these differing needs. Such an approach would pair stringent global safety and recycling standards with flexible national implementation pathways, ensuring that artificial photosynthesis develops in a way that is technologically sound, economically viable, and globally equitable.

Predicted System-Level Impacts

Successful translation to commercial adoption could enable a large-scale transition away from fossil fuels. This system has demonstrated ~19 % solar-to-fuel conversion efficiency in controlled settings (44), which means that if such efficiency could be maintained at scale, the amount of solar power required to produce fuels is substantially reduced compared to lower-efficiency approaches. Earth receives on the order of 170,000 TW of solar irradiance at the top of the atmosphere (45), but only a fraction of that (after atmospheric losses and land-use constraints) is practically harvestable. That said, even harvesting 0.05 % of incoming solar energy (~85 TW) would yield 16.2TW of fuel power, assuming idealized continuous operation and no intermittency losses. In comparison, global primary energy consumption is roughly 17 TW on average (46), demonstrating that this system would theoretically nearly meet the entire world's energy demand. Furthermore, global CO₂ emissions from fossil fuel combustion exceed ~35–40 billion tonnes annually, which drives climate change and underscores the

urgency of low-carbon replacements (47). Replacing just 1% of fossil fuel energy use with artificial photosynthesis would correspond to on the order of hundreds of millions of tonnes of CO₂ avoided per year (a rough scale based on proportional substitution). It is important to note that these figures mask variations in demand, conversion inefficiencies, and the fact that energy consumption is not all directly replaceable by solar fuels without infrastructure changes. Real-world impacts also depend on lifecycle emissions, deployment pace, and competition with other mitigation technologies. However, these estimated calculations still demonstrate the profound effect artificial photosynthesis can have on global energy consumption and climate change.

Alternative options

Considering an alternative pathway is essential because no single technology can address the full complexity of global decarbonization. Energy systems differ widely in geography, infrastructure, economic capacity, and sectoral needs, meaning that a solution that excels in one context may underperform in another. An alternative option to consider is green hydrogen, produced through water electrolysis powered by renewable electricity (48). Green hydrogen already benefits from rapidly falling electrolyzer costs, strong policy support in regions like the EU and Japan, and growing applications in heavy industry, ammonia production, and long-duration energy storage (49). However, despite these advantages, green hydrogen faces significant challenges: its low volumetric energy density requires costly compression or liquefaction, long-distance transport is still inefficient, and end-use infrastructure, such as pipelines, fuel cells, and industrial retrofits, remains underdeveloped (50). Compared to this pathway, artificial photosynthesis offers a distinct advantage by producing energy-dense liquid fuels that can be transported, stored, and used within existing global fuel infrastructure. Considering green hydrogen alongside artificial photosynthesis highlights that while multiple decarbonization strategies are emerging, the ability of artificial photosynthesis to directly convert CO₂ and sunlight into drop-in fuels positions it as a uniquely compelling solution for global energy-system decarbonization.

CONCLUSION

As the Earth approaches critical climate tipping points, the urgency to replace fossil fuels with sustainable

alternatives has never been greater (2, 4). Artificial photosynthesis technology, particularly the Si-perovskite tandem PEC, shows promise in just that, offering a transformative pathway to carbon-neutral, storable liquid fuels. By mimicking natural photosynthesis with scalable, low-cost materials, this system addresses long-standing barriers in artificial photosynthesis, with significant future projections. While perovskite instability remains a current limitation, the proposed dual-skin ALD/SLIPS coatings show promise in extending device lifetimes. Further policy frameworks, including funding, pilot incentives, carbon pricing, and equitable access, will be essential to guide commercialization while managing environmental risks like lead toxicity. With coordinated innovation and policy, artificial photosynthesis could shift from laboratory prototype to the cornerstone of a sustainable global energy system.

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CONFLICT OF INTEREST

The author declares that there are no conflicts of interest related to this work.

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