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Translating insights from progress in photovoltaics to accelerate industrial-scale CO_2 electroreduction

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CO_2 electroreduction (CO_2E) uses electricity to produce valuable chemicals and fuels. Although much fundamental progress has been made, industrial adoption will rely on an appropriate combination of CO_2E energy efficiency, capital cost and lifetime, as well as electricity and carbon price, to achieve a competitive levelized cost of chemicals/fuels. Here we discuss how a consistent set of testing conditions, third-party accreditation and intersectoral partnerships can prepare CO_2E for its transition from bench-scale prototypes to industrial deployment. Drawing on lessons from photovoltaics—which progressed from the laboratory to globally deployed product once the levelized cost of electricity reached grid parity—we recommend establishing robust, transparent testing procedures, as well as objective certification frameworks. We also discuss disanalogies to photovoltaics—how standardizing CO_2E feedstocks, product analysis and device configurations may be more challenging and multivariate than in photovoltaics. By quantifying technological maturity, we can better target research efforts and accelerate innovation, which will enable transparent technology comparisons, increasing investment and manufacturing readiness.

Electrochemical CO_2 conversion seeks to contribute to lowering the carbon intensity of fuels and chemicals by converting CO_2 into fuels and commodity products using renewable electricity[1–3]. There is now a substantial body of research reporting improved catalyst selectivity and reactor designs, as well as new chemical products. CO_2 electroreduction (CO_2E) nevertheless has a long way to go before it is on the path to commercial deployment[4]. Even with a projected energy efficiency for electricity-to-ethylene conversion (lower heating value basis) of 50%, as well as US\$50 MWh^{-1} electricity, the electricity cost alone corresponds to approximately US\$1,300 per ton of C_2H_4—well above today's fossil ethylene market price. Thus, the main focus of CO_2 electrolysis research and development today—lowering the energy burden—remains the correct top priority for the field. Increasing productivity, improving durability and achieving high selectivity are all crucial to ensure that the capital cost of CO_2 electrolysers becomes acceptable. These technical advances must converge with two major external developments: further increases in the abundance of low-carbon-intensity electricity at lower price, and policy and/or carbon-pricing mechanisms that reward CO_2-reducing technologies.

Once these conditions align, the field must be ready to transition efficiently from sound scientific foundations to industrial and climate relevance. To understand what will enable such a transition

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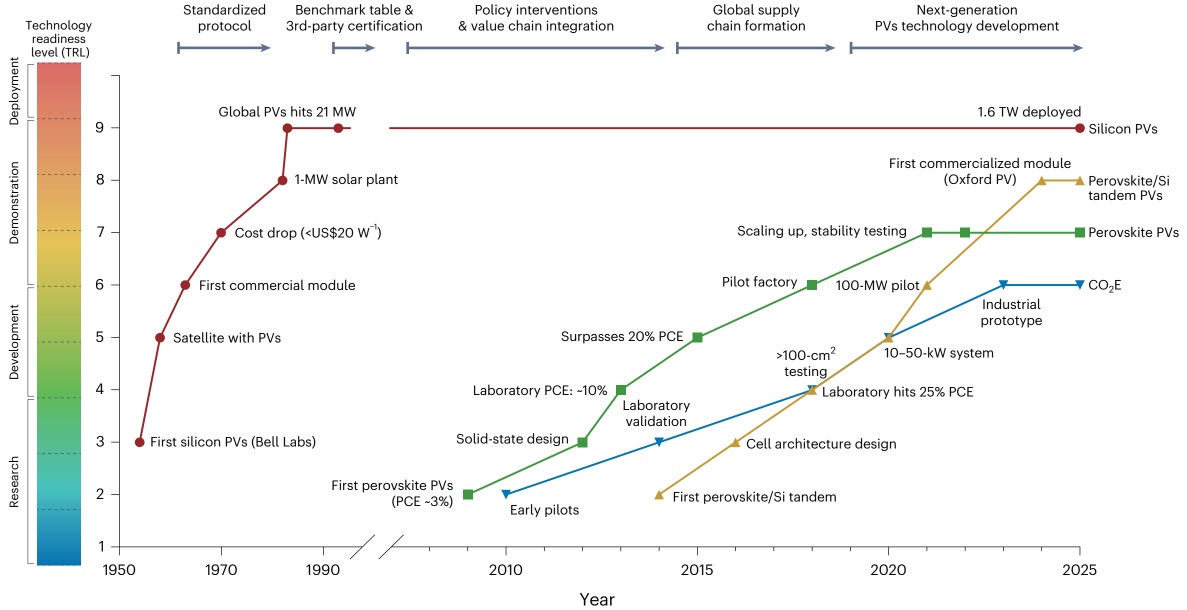


Fig. 1 | Comparative timeline of TRL advancement in solar cells and CO_2E. A multi-trajectory timeline comparing the TRL progress of photovoltaics (PVs; silicon PVs, perovskite PVs and perovskite/silicon tandem PVs) and CO_2E (refs. 4,37,38). The figure highlights milestone events in the development of PVs, such as the first demonstrations, commercial modules, scaling efforts and key drivers of adoption—including protocol standardization, benchmark table publication, policy interventions, global supply chain formation and next-generation technology development. PCE, power conversion efficiency.

from laboratory success to deployment, we examine how lessons from a more developed allied sector—solar photovoltaics—can inform this transition.

In photovoltaics, the levelized cost of electricity (LCOE) reached grid parity with major legacy alternatives (such as natural gas) only by 2014, in approximately 20 countries worldwide. In the five years leading up to 2014, solar accounted for ~10–15% of new US electricity-generating capacity additions. In the decade that followed, it accounted on average for 40% of annual capacity additions. Indeed, 2024 was record-setting, at 66% (ref. 5).

The establishment of consistent testing and reporting protocols, third-party certification and defined interfaces among ecosystem tiers proved conducive to rapid technological and industrial growth. In this Perspective, by analysing how such measures enabled photovoltaics to progress from laboratory innovation to global deployment, we identify transferable principles that could inform CO_2E in its own evolution towards industrial relevance. We discuss both parallels and distinctions between the two technologies, emphasizing that consistent benchmarking, accreditation and intersectoral collaboration will be needed to accelerate CO_2E from scientific promise to industrial impact.

Standardized protocols and external certification in photovoltaics

Early research on photovoltaics faced major reproducibility issues due to different simulated sunlight spectra, intensities and uncontrolled ambient conditions, which made efficiency reports difficult to compare. To address this, the photovoltaics community adopted standardized test protocols, such as AM1.5G (air mass 1.5 global) and fixing irradiance (1,000 W m^{-2}) and temperature (25 °C), to enable global benchmarking. This uniformity allowed independent certification bodies, including NREL and Fraunhofer ISE, to validate new devices and later expand into product-level standards (for example, IEC 61215, UL 61730) that address durability, safety and reliability—factors essential for investor confidence and large-scale adoption[6].

Another hallmark of the photovoltaics community's approach is collective coordination. For instance, the publication *Progress in Photovoltaics* has published benchmark tables of record cell efficiencies since 1993, updating them every six months under the same test conditions[6]. In doing so, the field set a precedent for open data sharing and ongoing performance tracking, creating a dynamic environment that rewarded incremental improvements and facilitated the translation of laboratory gains into commercial products[7].

Although the certification of silicon-based photovoltaics has traditionally focused on efficiency metrics, the rise of emerging technologies—particularly perovskites and organic photovoltaics—has increasingly addressed operating stability. Stability testing protocols such as The International Summit on Organic and Perovskite Solar Cells Stability (ISOS)[8,9], and more recently initiatives like PV Accelerator for Commercializing Technologies (PACT), further extended this framework by adding long-term durability as a tracked performance criterion[10,11]. These evolving protocols and verification platforms are playing an essential role in advancing the technology readiness level (TRL) of perovskite and perovskite/silicon tandem photovoltaics by enabling credible, standardized demonstrations of long-term performance (Fig. 1)[12,13].

We note that these successes in photovoltaics were made possible by the relatively controlled and finite nature of its inputs and outputs. In the following we go on to discuss how CO_2E requires accounting for more complex chemistry, variable feedstocks and a broad product spectrum.

Barriers to standardization in CO_2E

CO_2E development is increasingly building on component-level qualification practices from adjacent fields—such as thermocatalysis, water electrolysis and fuel cells—but the CO_2E field continues to lack standardized testing protocols and accreditation systems[4,14]. This is hindering an objective comparison of reported performances and slowing the translation of laboratory-scale discoveries into scalable technologies. Two structural challenges are particularly central to this issue: the variability in CO_2 feedstocks and the diversity of possible products.

CO_2E experiments are conducted using a wide spectrum of feed gases, ranging from ultrapure CO_2 cylinders to dilute flue-gas mixtures, each with different impurity profiles and moisture contents. These are further modulated by varying flow rates, humidification levels and cell operating temperatures. As a result, reported data often reflect laboratory-specific set-ups rather than broadly representative system behaviour. The absence of harmonized CO_2 feed definitions is impeding the creation of a universally accepted benchmarking protocol and complicating reproducibility across institutions and geographies.

In contrast with photovoltaics, which has a main single performance metric (power conversion efficiency, PCE), CO_2 electrolysis yields a wide range of products, including C_1, C_2 and C_{3+} species, each with distinct reaction pathways, with each system and catalyst having a complex interplay with microenvironment engineering, and with key roles for operating voltages and separation requirements[15–20]. Attempting to capture this diversity within a unified testing framework imposes conflicting requirements and contributes to fragmented performance benchmarks. This product-level divergence is further hindering the development of cohesive accreditation frameworks and shared certification standards. Even systems with relatively simple chemistries and single-product outputs—such as water electrolysis and fuel cells—have experienced slow commercialization due to persistent challenges in integration, durability and cost. This reinforces the need for structured, product-specific performance frameworks in CO_2E, where the underlying reaction networks and downstream processing requirements are substantially more complex.

A path towards CO_2E standardization

The path towards commercial impact for CO_2E begins with clearly identifying which products warrant industrial focus, how their performance is assessed, and how standardized protocols can accelerate scalable deployment. Here we propose a product-driven standardization framework grounded in techno-economic viability and aligned with industrially relevant conditions. Given the inherent diversity and analytical challenges of CO_2E, a one-size-fits-all benchmarking approach may not be viable. In this context, it is instructive to note that the EU has recently introduced harmonized test protocols for low-temperature water electrolysis, providing standardized operating conditions and durability metrics. Such frameworks can serve as a practical reference point for CO_2E, complementing the broader ecosystem lessons drawn from photovoltaics[21]. In addition, industrial precedents such as oxygen-depolarized cathodes (ODCs) in the chlor-alkali industry—commercialized at the multi-m^2 scale with multi-year durability—illustrate that gas diffusion electrode architectures can achieve long-term industrial deployment[22]. These experiences provide instructive parallels for scaling CO_2E beyond laboratory demonstrations. A product-specific standardization framework offers a practical path forward, tailored to the unique performance and measurement needs of each CO_2-derived product.

Given the present stage of technology readiness, concentrating research efforts on a smaller number of techno-economically relevant products represents one of the most promising ways to accelerate progress towards deployment. Here we narrow the scope of evaluation to four CO_2E products that exhibit both technical maturity and market potential: carbon monoxide (CO), formic acid (HCOOH), ethylene (C_2H_4) and ethanol (EtOH)[3,14]. These span from two-electron C_1 species to multi-carbon C_2 compounds, each with distinct production pathways, performance profiles and commercialization challenges. Although syngas is also an industrially relevant pathway, its value depends on subsequent thermochemical upgrading (for example, Fischer–Tropsch, methanol synthesis)[23,24]. For this reason, in this Perspective, we focus on CO, HCOOH, C_2H_4 and EtOH, which can be regarded as closer to final products and for which clearer techno-economic benchmarks and sufficient data are available for standardized comparison. To link laboratory performance with market relevance, we introduce economically viable windows—multidimensional thresholds of key performance metrics (for example, partial current density, Faradaic efficiency, cell voltage, energy efficiency and stability) that define the minimum requirements for competitiveness (Fig. 2a–d). The economically viable regions are defined relative to market price targets, without accounting for system-level factors such as the recycling of CO_2E products or the generation of additional revenue streams. CO and HCOOH already demonstrate performance metrics approaching these thresholds, with partial current densities >200 mA cm^{-2}, Faradaic efficiency above 90%, and energy efficiencies exceeding 60%. In contrast, C_2H_4 and EtOH remain constrained by low selectivity and high voltage penalties, leading to subpar energy efficiency and limited operational stability.

Building on this product-wise assessment, we next visualize the gap between academic progress and industrial readiness by mapping laboratory- and pilot-scale data against these viability criteria (Fig. 3). C_1 products appear increasingly aligned with techno-economic targets, whereas C_2 products remain further from feasibility. These distinctions suggest two strategies: for CO, improving long-term stability may suffice to catalyse near-term deployment, whereas C_2 products require substantial advances in catalyst design and product selectivity under industrial conditions. This gap partly reflects the greater complexity of the industrial systems, where factors such as variations in catalysts, cell components, electrolyte handling and by-product management make it harder to identify operating conditions that are both effective and economically viable.

Before discussing standardized CO_2 testing protocols, it is important to consider the source and composition of the CO_2 feedstock used in experiments. The type of feedstock used can greatly influence reactor behaviour, system efficiency and the relevance of performance data. Most laboratory studies rely on high-purity CO_2 gas, which simplifies system behaviour but does not reflect the conditions encountered in industrial applications. In practice, CO_2 feedstocks vary depending on the application, such as direct air capture, amine-based post-combustion capture, or flue-gas utilization, each with distinct chemical compositions and impurity profiles. Therefore, feedstock selection should be guided by the target deployment context.

To support consistent benchmarking, we classify feedstocks into three categories based on deployment relevance: high-purity CO_2 recovered from carbon capture, utilization and storage (CCUS) processes (for example, amine or carbonate-based solutions), flue gas from coal-fired power plants, and flue gas from cement and steel plants. The two flue gas categories reflect major CO_2-emitting industries, each with distinct impurity profiles and gas compositions relevant to different CO_2E deployment scenarios. At present, purified CO_2 streams remain the most practical basis for achieving stable and selective electrolysis performance. In the longer term, however, deployment will also require strategies for less purified sources such as flue gas, biogas or direct air capture, where reducing purification energy becomes critical[24–26]. Figure 4 (bottom table) summarizes the typical characteristics of each type and their alignment with different CO_2E applications. Standardized reporting of feedstock composition will enhance comparability across studies and promote more realistic system evaluations. As CO_2 electrolysis technologies mature, carbon streams derived from biomass or plastic waste should also be considered as realistic alternative inputs, underscoring the importance of developing flexible pathways that can accommodate diverse feedstocks in future deployment scenarios[27].

To bridge the gap between laboratory research and industrial deployment, we outline a stepwise protocol for evaluating CO_2 electrolysis systems under practically relevant conditions (Fig. 4). The process includes material screening, electrode engineering, single-cell testing and evaluation, viability mapping, stack-level demonstration and industrial-scale validation. Each stage should reflect the intended application environment, including appropriate CO_2 feedstocks such as CCUS-derived or flue-gas sources.

Materials screening should consider both the catalytic performance and the scalability of the synthesis routes, including raw material cost and process maturity. Electrode engineering must establish industry-relevant specifications in terms of composition, density, areal

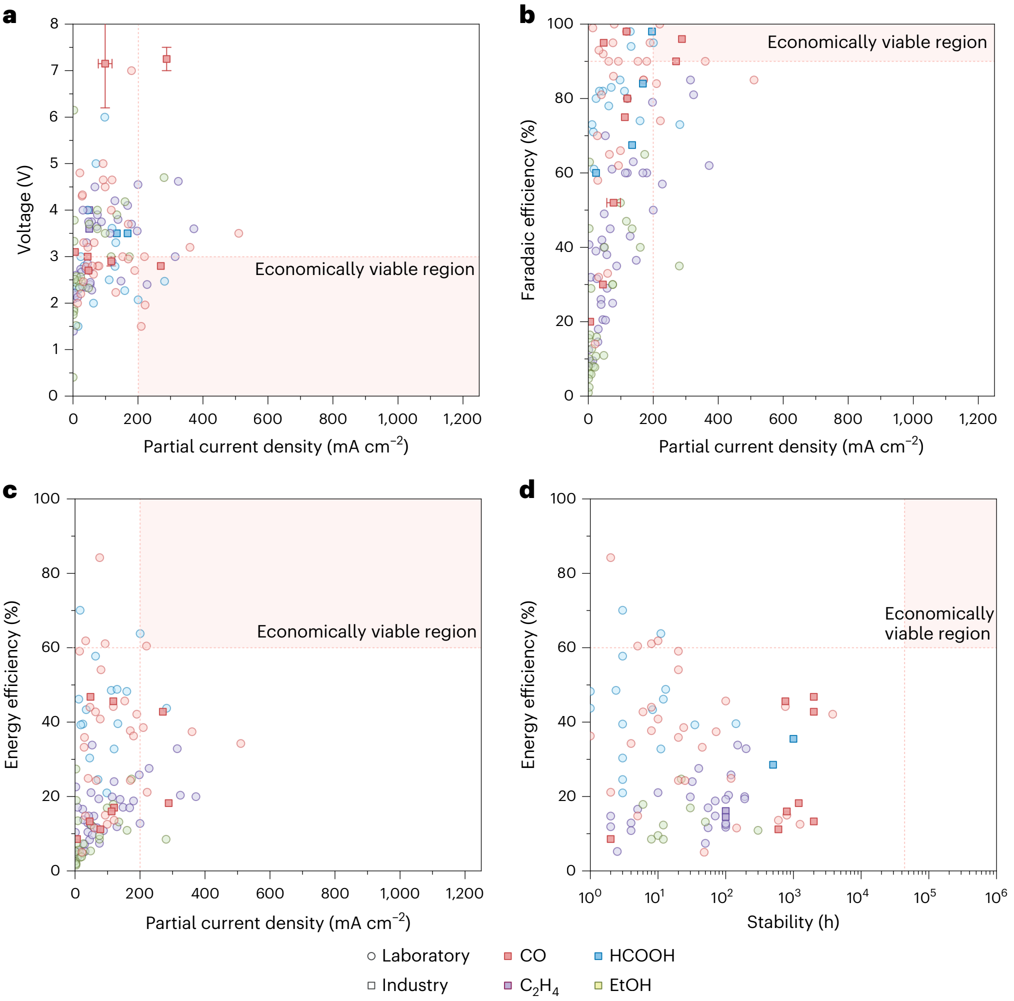


Fig. 2 | Comparison of reported performance metrics for C_1 (CO and HCOOH) and C_2 (C_2H_4 and C_2H_5OH) production in laboratory and industrial settings. **a**–**c**, Voltage (**a**), Faradaic efficiency (**b**), and energy efficiency (**c**) as a function of partial current density. **d**, Energy efficiency as function of stability. Reported values are assessed against commercialization benchmarks, highlighting the need for standardized protocols and guiding the development of product-specific roadmaps for industrial deployment. The techno-economic benchmarks were defined using common assumptions across products, including an electricity price of US\$0.03 kWh^{-1}, a CO_2 feedstock cost of US\$40 ton^{-1}, a water cost for the oxygen evolution reaction (OER) of US\$0.005 gal^{-1}) and a plant lifetime of 20 years, consistent with published techno-economic analysis studies[3,4,17,39]. Product benchmarks were set relative to prevailing market values or incumbent production routes (~US\$600 ton^{-1} for CO, ~US\$730 ton^{-1} for formic acid, ~US\$1,300 ton^{-1} for ethylene and ~US\$1,000 ton^{-1} for ethanol)[16,18]. Beyond these shared parameters, product-specific considerations such as separation and concentration penalties (formic acid, ethanol) or cryogenic requirements (ethylene) are further considered. Boundaries are indicative and context-dependent. Actual viability will vary with upstream capture, downstream utilization pathways and product-specific penalties.

capacity and loading strategy. Early-stage single-cell testing should assess key parameters such as Faradaic efficiency, overpotential, electrochemical surface area, turnover frequency and Tafel slope. These metrics help identify promising catalysts before transitioning to more holistic evaluations.

Subsequent single-cell evaluation should simulate realistic operating conditions, incorporating metrics aligned with techno-economic analysis, life-cycle assessment, long- and short-term stability, energy efficiency, and product selectivity and purity. To estimate long-term performance efficiently, accelerated durability testing (ADT) is recommended, using standardized conditions and evaluation metrics inspired by US Department of Energy (DOE) protocols for proton-exchange membrane (PEM) fuel cells[28,29]. Although PEM-derived ADT protocols provide a useful starting point, CO_2 electrolysers exhibit additional degradation pathways. Table 1 compares conventional water electrolysis ADT metrics with CO_2-specific factors that must also be considered to establish meaningful and transferable durability benchmarks. These assessments should be benchmarked against the viability thresholds outlined in Figs. 2 and 3 to identify performance-limiting factors. Standardized single-cell evaluation thus serves as a common baseline, ensuring that only catalysts with demonstrated feasibility advance to stack-level validation and engineering optimization (such as pressure control, wettability/microstructure tuning), which in turn enhances the efficiency of the overall development pathway.

At the scale-up stage, stack-level demonstrations are essential to validate performance consistency and robustness. Repeatability tests should be conducted under application-relevant conditions. In this process, parallel to water electrolysis, the chlor-alkali industry provides transferable lessons for CO_2 electrolysis. The chlor-alkali industry faced similar challenges related to the loss of hydrophobicity of a gas diffusion electrode during prolonged operation, which were ultimately mitigated through the adoption of ODCs capable of more than 10,000 hours (>1,100 days) of stable performance. The long-term stability of ODCs demonstrates how gas diffusion electrodes can be industrially engineered for year-scale durability. Design

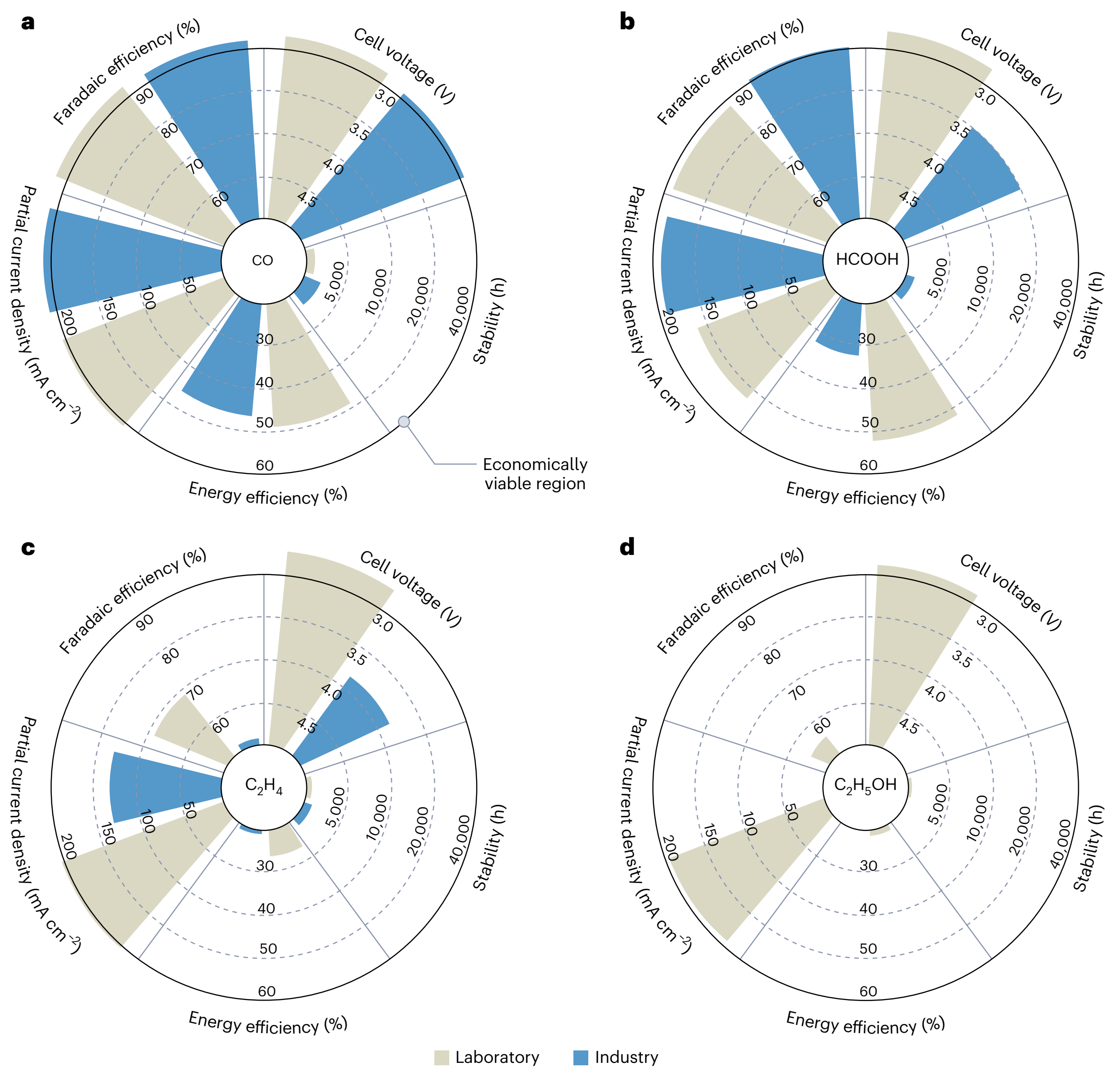


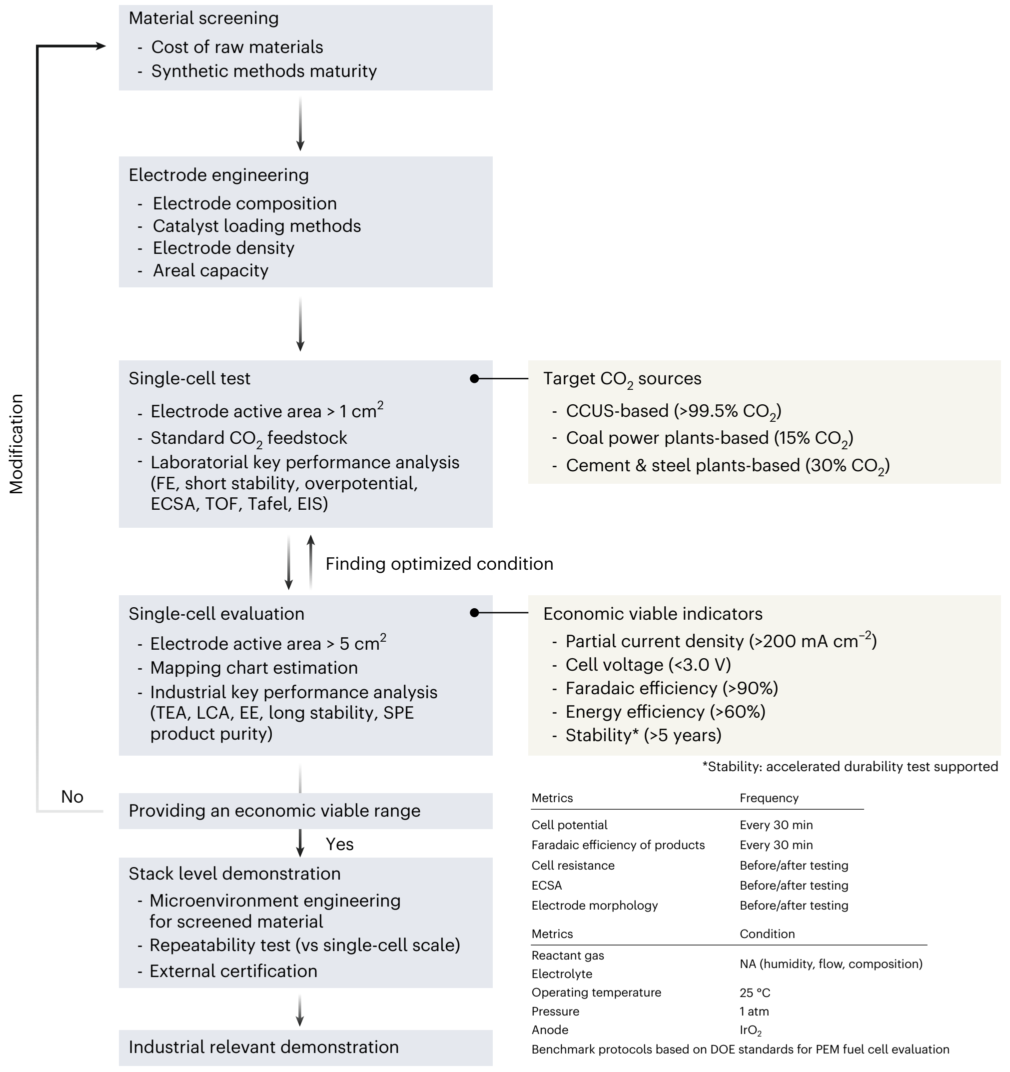
Fig. 3 | Comparison of reported performance metrics. a–d, C_1 products for CO (**a**) and HCOOH (**b**), and C_2 products for C_2H_4 (**c**) and C_2H_5OH (**d**) in laboratory and industrial contexts. The metrics represent the top 50% of reported values in Fig. 2, providing a representative view of current progress towards commercialization. The outermost line of each circle indicates the minimum value to achieve economic viability (viz. Fig. 2).

strategies such as pressure-differential control, hydrophobic/hydrophilic microstructure management, and the use of a metal-supported gas diffusion electrode provide a potential roadmap for improving the stability—particularly for C_1 products—and reliability of CO_2E systems, both of which are key prerequisites for industrial deployment[22]. Finally, third-party certification—drawing from frameworks used in the photovoltaics and fuel-cell industries—will support market readiness by ensuring transparent, credible evaluation. By structuring the development of CO_2E systems around this protocol, the field can more effectively align academic innovation with industrial deployment targets.

Although protocol harmonization is a critical step towards standardizing CO_2 electrolysis, challenges remain in the quantification of products—especially liquid-phase and multi-carbon species—due to intrinsic complexities in the electrochemical system. Unlike photovoltaics, where the output is a single, continuous electrical metric (that is, power), CO_2E generates a range of gas- and liquid-phase products with different volatilities, solubilities and transport behaviours. Quantitative analysis is often complicated by membrane crossover (for example, for formate, acetate, ethanol), product evaporation, and losses due to sampling delays or gas stripping. These effects are further exacerbated under high-current-density operation, where rapid gas evolution and local pH shifts dynamically alter species transport.

Even in systems such as gas diffusion electrodes, uncorrected gas outlet flow rates—particularly in alkaline conditions where CO_2 reacts with OH^- to form carbonate—can cause the Faradaic efficiency for gas products to be substantially overestimated or underestimated. Additionally, product quantification using high-performance liquid chromatography, gas chromatography or NMR is highly sensitive to internal standard selection, electrolyte matrix effects, and dilution factors—a concern that has led to recent recommendations for cross-validation using multiple analytic techniques to enhance measurement reliability. Notably, gas temperature and humidity—often underreported—can cause up to 10% error in outlet flow-rate measurements, directly distorting Faradaic efficiency calculations unless corrected volumetric flowmeters are used[30,31].

Although this Perspective primarily focuses on identifying what to test in pursuit of standardization, we acknowledge that how to measure rigorously, reproducibly and transparently is equally important. Although a detailed discussion on measurement protocols is beyond the scope of this work, we recognize it as a critical parallel effort needed to ensure the reliability and comparability of CO_2E performance data across the field.



Metrics	Frequency
Cell potential	Every 30 min
Faradaic efficiency of products	Every 30 min
Cell resistance	Before/after testing
ECSA	Before/after testing
Electrode morphology	Before/after testing

Metrics	Condition
Reactant gas	NA (humidity, flow, composition)
Electrolyte	
Operating temperature	25 °C
Pressure	1 atm
Anode	IrO_2

Benchmark protocols based on DOE standards for PEM fuel cell evaluation

Types of standardized CO_2 feed gas	CO_2 feed sources[24–26]	CO_2	O_2	N_2	H_2O	NO_x	SO_x
	CCUS-based sources	>99.5%	<100 ppm	<500 ppm	<50 ppm	<5 ppm	<5 ppm
	Flue gas-based source 1 (coal power plants)	15%	<3%	Balanced	<3%	<300 ppm	<150 ppm
	Flue gas-based source 2 (cement & steel plants)	30%	<3%	Balanced	<3%	<1,000 ppm	<400 ppm

Fig. 4 | CO_2 testing protocol from the laboratory to an industrially relevant demonstration. Flowchart outlining a protocol for evaluating cathodic catalysts from laboratory conditions to industrially relevant demonstrations. Suggested durability metrics are adapted from the US DOE ADTs used in PEM fuel cell evaluation. Reactant gas composition[24–26], electrolyte and reactor conditions may vary depending on the catalyst's optimized operating parameters. FE, faradaic efficiency; ECSA, electrochemical surface area; TOF, turnover frequency; EIS, electrochemical impedance spectroscopy; TEA, techno-economic analysis; LCA, life-cycle assessment; EE, energy efficiency; SPE, single-pass efficiency.

Photovoltaics ecosystem and key drivers of photovoltaics growth

The remarkable growth of the photovoltaics field from laboratory innovation to the fastest contributor to growth in electricity generation technology offers a compelling example of how a technology-centred ecosystem can take shape and flourish. The photovoltaics ecosystem as we know it today—comprising material suppliers, cell and module manufacturers, system integrators, equipment providers, research institutions, government agencies, financiers, certification bodies and service providers—was not assembled overnight (Table 2). Rather, it developed through decades of cumulative efforts across research, policy and industry.

Standardized protocols and third-party certification created trust among investors and policymakers, enabling capital mobilization and regulatory support. Policy interventions were equally critical: Germany's feed-in-tariff (FiT) programmes and renewable portfolio standards in the United States and South Korea established guaranteed demand, and China's strategic support in the 2010s drove massive expansions in manufacturing capacity[32–34]. These measures supported massive expansions in production capacity across the value chain, from polysilicon and ingot casting to wafer slicing, cell manufacturing and module assembly. The result was a steep decline in the LCOE for photovoltaics, allowing it to outcompete fossil fuels in many markets.

Research and development institutions and industry partnerships played a central role in scaling photovoltaics innovations. Laboratories such as NREL and Fraunhofer not only advanced fundamental research, but also worked with manufacturers to accelerate the adoption of architectures such as passivated emitter rear contact (PERC) cells—a low-cost and commercially dominant architecture for silicon solar

Table 1 | Comparative ADT consideration for PEM water electrolysis versus CO_2 electrolysis

Metrics	PEM/water electrolysis (typical ADT focus)	CO_2 electrolysis (additional CO_2E-specific consideration)
Operating environment	Temperature, pressure, humidity	Local pH shifts, CO_2 supply/transport limitations, (bi)carbonate precipitation
Catalyst degradation	Catalyst dissolution, ECSA loss	Poisoning (for example, CO adsorption), selectivity degradation and product change
Membrane/ electrode	Conductivity and chemical stability	Membrane diversity: AEM/CEM chemical degradation, BPM delamination, salt deposition
Side reactions	Minor impact beyond main products (H_2/O_2)	HER competition, side-product crossover and re-oxidation, (bi)carbonate crossover and CO_2 generation
Product-related	Gas product purity	Diluted liquid products; separation energy penalty, product crossover
Impurity effects	Impurities in electrolyte (for example, ions, metals)	SO_x/NO_x/O_2 tolerance (impurity-stress testing under flue gas)
Operating mode	Intermittent renewable cycling, on/off loop	Added stress: CO_2 feed stabilization, selectivity hysteresis
System integration	Single-cell durability focus	Stability with CO_2 recycle, downstream separation/purification coupling

PEM/water electrolysis ADT considerations generally apply to CO_2E as the baseline. AEM, anion exchange membrane; CEM, cation exchange membrane; BPM, bipolar membrane; HER, hydrogen evolution reaction.

cells—through coordinated roadmaps that set efficiency, cost and durability targets[35]. At the same time, firms such as First Solar, LONGi and Hanwha Q CELLS combined multiple steps of the value chain, from materials to deployment, streamlining innovation cycles and enabling quality control. Horizontal standardization in modules and systems enabled installers and balance of system (BoS) providers to operate at scale, further driving cost reductions[36].

Taken together, these elements—standardization, policy support, large-scale manufacturing, collaborative research and development, and value chain integration—formed the foundation of the photovoltaics ecosystem. They transformed solar energy from a niche scientific curiosity to the backbone of global decarbonization efforts. For emerging technologies such as CO_2 electrolysis, this evolution offers both a roadmap and a challenge: how to replicate the conditions that turned photovoltaics from potential into practice.

Current state of the CO_2E ecosystem

CO_2E is in its nascency. At present, the CO_2E ecosystem consists of research groups developing electrocatalysts, membrane materials and cell configurations; startups and a few established players building prototype electrolysers; and a small number of early adopters experimenting with deployment at sub-megawatt scales. However, this structure lacks the industrial coordination, supply chain maturity and commercial validation that underpin today's photovoltaics industry.

Key actors in the current CO_2E ecosystem include raw material and catalyst suppliers; electrolyser manufacturers and system developers, academic and national laboratories conducting fundamental and applied research; early-stage investors and climate-focused venture funds; and government and policy institutions exploring support mechanisms (Table 2). Despite this emerging structure, the field is not yet supported by shared infrastructure, production standards or independent certification frameworks. Most CO_2E systems are built in-house, operate under laboratory-specific conditions, and demonstrate highly varied performance across institutions. Moreover, long-term reliability data are limited, and few systems have undergone third-party durability testing. As a result, knowledge transfer, performance comparison, and ecosystem-wide learning remain slow.

Key gaps between the CO_2E and photovoltaics ecosystems

The disparity between the photovoltaics and CO_2E ecosystems stems from fundamental differences in maturity and integration. Addressing these disparities is critical to enabling CO_2E to transition from promising laboratory technologies to scalable climate solutions. The following gaps are especially salient. For supply chain maturity, the photovoltaics industry benefits from a vertically integrated, global supply chain capable of producing gigawatt-scale capacity annually. In contrast, CO_2E lacks standardized component suppliers, industrial-scale stack fabrication, and contract manufacturers. Most devices are custom-built and pilot-scale. For standardization and certification, photovoltaics technologies are supported by widely adopted testing protocols (for example, IEC and ISOS) and third-party verification (for example, NREL and Fraunhofer). CO_2E, by contrast, lacks universal performance benchmarks. Variations in feedstock, device design and testing parameters complicate cross-laboratory comparisons. For durability and reliability, photovoltaics modules routinely demonstrate 25+-year operational lifetimes with minimal degradation. CO_2E devices, however, often show performance decay within hundreds to thousands of hours. Catalyst deactivation, membrane breakdown and gas crossover are unresolved challenges. For economic viability, photovoltaics has achieved grid parity in many regions, whereas CO_2-derived products are not yet ready to compete with fossil counterparts without subsidies or carbon pricing. High electricity consumption and low current densities inflate production costs, especially for multi-carbon targets. For policy and market incentives, the photovoltaics sector benefited from coordinated policy support, including FiTs and renewable portfolio standards. CO_2E has yet to see comparable instruments. The US Inflation Reduction Act and EU e-fuel mandates provided early momentum, but consistent demand signals remain absent. For downstream infrastructure, photovoltaics electricity can be directly fed into existing grids. CO_2E products, however, require new infrastructure for capture, purification, distribution and end-use integration (for example, aviation fuel logistics). The lack of these systems hinders market entry.

To bridge these gaps, the CO_2E field must develop shared standards, reliable components and a robust project finance ecosystem, much like photovoltaics did over the past two decades. With coordinated research, policy alignment and industrial investment, CO_2 electrolysis can evolve into a foundational pillar of the decarbonized energy economy.

Conclusion

The journey of photovoltaics from early laboratory discoveries to the backbone of today's clean electricity generation offers a powerful blueprint for how emerging technologies can mature through coordinated innovation, standardization and ecosystem development. By establishing universal testing protocols, embracing third-party certification, and building vertically integrated supply chains, the photovoltaics field unlocked pathways to low-cost, high-reliability solutions at a global scale. Yet, applying this blueprint to CO_2E must go hand in hand with recognizing the fundamental differences in system complexity, product variability and measurement ambiguity. Addressing these head-on is essential to building a comparably credible and scalable ecosystem.

CO_2 electrolysis now stands at a similar inflection point. Decades of research have yielded promising catalysts, membranes and device architectures, but the field still lacks the infrastructure, coordination

Table 2 | Value chain maturity comparison between photovoltaics and CO_2E

Photovoltaic value chain	Maturity	CO_2E value chain	Maturity
Raw material supply	◆◆◆◆◆	CO_2 capture and feedstock preparation	◆◆◆
Ingot and wafer production	◆◆◆◆◆	Catalyst and membrane production	◆◆
Solar cell manufacturing	◆◆◆◆◆	Electrolyser stack manufacturing	◆ ◆ ◆ ◆◆
Module assembly	◆◆ ◆◆◆◆	System integration and balance of plant	◆◆ ◆
System installation	◆◆◆◆◆	Electrochemical conversion	◆◆
Electricity generation and sale	◆◆◆◆◆	Production separation and purification	◆
Operation and maintenance	◆◆◆◆◆	Storage and distribution	◆
Recycling and disposal	◆◆◆◆	End-use application (fuel, chemicals)	◆

Diamonds represent the relative maturity of each process step, from upstream raw material supply to downstream deployment and disposal. While photovoltaics benefits from a globally integrated and standardized industrial ecosystem, CO_2E lags across most stages of the value chain due to fragmentation and limited commercialization.

and market support to transition from potential to practice. Drawing on the experience of photovoltaics, we identify three critical enablers for CO_2E: standardized protocols and accreditation systems that allow transparent, quantitative benchmarking; shared roadmaps and milestone frameworks to coordinate innovation and target economic viability; and public–private partnerships to catalyse supply chain development, scale up manufacturing, and build downstream integration pathways.

If these elements are adopted and adapted to the unique challenges of CO_2 electrolysis—particularly the diversity of feedstocks and products—the field can accelerate its trajectory towards commercial deployment. Doing so will not only enable the valorization of captured CO_2, but also position electrochemical conversion as a cornerstone of the net-zero energy economy. Looking further ahead, CO_2 electrolysis is expected to contribute to supplying low-carbon intermediates to the refinery of the future, an approach expected to integrate with complementary thermochemical upgrading (for example, Fischer–Tropsch synthesis and hydrocracking) and thereby extend its impact beyond standalone devices to the broader energy and chemical ecosystem. By combining structured learning from photovoltaics and deliberate ecosystem-building, CO_2 electrolysis can move from fragmentation to impact.

References

1. Wakerley, D. et al. Gas diffusion electrodes, reactor designs and key metrics of low-temperature CO_2 electrolysers. *Nat. Energy* **7**, 130–143 (2022).
2. Masel, R. I. et al. An industrial perspective on catalysts for low-temperature CO_2 electrolysis. *Nat. Nanotechnol.* **16**, 118–128 (2021).
3. Küngas, R. Review—Electrochemical CO_2 reduction for CO production: comparison of low- and high-temperature electrolysis technologies. *J. Electrochem. Soc.* **167**, 044508 (2020).
4. Belsa, B., Xia, L. & García de Arquer, F. P. CO_2 electrolysis technologies: bridging the gap toward scale-up and commercialization. *ACS Energy Lett.* **9**, 4293–4305 (2024).
5. Solar Energy Industries Association (SEIA) and Wood Mackenzie. *U.S. Solar Market Insight Report 2024 Year-in-Review* https://seia.org/research-resources/solar-market-insight-report-2024-year-in-review/ (SEIA, 2025).
6. Green, M. A. et al. Solar cell efficiency tables (Version 64). *Prog. Photovolt. Res. Appl.* **32**, 425–441 (2024).
7. Jacobsson, T. J. et al. An open-access database and analysis tool for perovskite solar cells based on the FAIR data principles. *Nat. Energy* **7**, 107–115 (2022).
8. Reese, M. O. et al. Consensus stability testing protocols for organic photovoltaic materials and devices. *Sol. Energy Mater. Sol. Cell* **95**, 1253–1267 (2021).
9. Khenkin, M. V. et al. Consensus statement for stability assessment and reporting for perovskite photovoltaics based on ISOS procedures. *Nat. Energy* **5**, 35–49 (2020).
10. Zhang, D., Li, D., Hu, Y., Mei, A. & Han, H. Degradation pathways in perovskite solar cells and how to meet international standards. *Commun. Mater.* **3**, 58 (2022).
11. Zhu, H. et al. Long-term operating stability in perovskite photovoltaics. *Nat. Rev. Mater.* **8**, 569–586 (2023).
12. Aydin, E. et al. Pathways toward commercial perovskite/silicon tandem photovoltaics. *Science* **383**, eadh3849 (2024).
13. Pescetelli, S. et al. Integration of two-dimensional materials-based perovskite solar panels into a stand-alone solar farm. *Nat. Energy* **7**, 597–607 (2022).
14. Guerra, O. J., Almajed, H. M., Smith, W. A., Somoza-Tornos, A. & Hodge, B. M. S. Barriers and opportunities for the deployment of CO_2 electrolysis in net-zero emissions energy systems. *Joule* **7**, 1111–1133 (2023).
15. Gao, T. et al. Techno-economic analysis and carbon footprint accounting for industrial CO_2 electrolysis systems. *Energy Fuels* **37**, 17997–18008 (2023).
16. Shin, H., Hansen, K. U. & Jiao, F. Techno-economic assessment of low-temperature carbon dioxide electrolysis. *Nat. Sustain.* **4**, 911–919 (2021).
17. Lee, H. et al. Scalable low-temperature CO_2 electrolysis: current status and outlook. *JACS Au* **4**, 3383–3399 (2024).
18. Deng, W. et al. Techno-economics of polymer-membrane-based CO_2 electrolysers. *Nat. Rev. Clean Technol.* **1**, 255–268 (2025).
19. Nzotcha, U., Sanz, S., Tempel, H. & Eichel, R. A. Technoeconomic perspective on the electroreduction of CO_2 to formic acid: scale-up strategies toward industrial viability. *Angew. Chem. Int. Ed.* **64**, e202418114 (2025).
20. Sun, Q. et al. Ampere-level electroreduction of CO_2 and CO. *Chem. Soc. Rev.* **54**, 6973–7016 (2025).
21. Tsotridis, G., Pilenga, A., De Marco, G. & Malkow, T. *EU Harmonised Test Protocols for PEMFC MEA Testing in Single Cell Configuration for Automotive Applications* https://doi.org/10.2790/54653 (Publications Office of the European Union, 2015).

22. Hernandez-Aldave, S. & Andreoli, E. Oxygen depolarised cathode as a learning platform for CO_2 gas diffusion electrodes. *Catal. Sci. Technol.* **12**, 3412–3420 (2022).
23. Hou, X. et al. Syngas production from CO_2 and H_2O via solid-oxide electrolyzer cells: fundamentals, materials, degradation, operating conditions and applications. *Chem. Rev.* **124**, 5119–5166 (2024).
24. Kumar De, S., Won, D. I., Kim, J. & Kim, D. H. Integrated CO_2 capture and electrochemical upgradation: the underpinning mechanism and techno-chemical analysis. *Chem. Soc. Rev.* **52**, 5744–5802 (2023).
25. Wen, X., Gao, D. & Wang, G. Direct electrochemical conversion of CO_2 from industrial flue gases. *ChemSusChem* **18**, e202402438 (2025).
26. Chen, B. et al. Molecular enhancement of direct electrolysis of dilute CO_2. *ACS Energy Lett.* **9**, 911–918 (2024).
27. Vogt, E. T. C. & Weckhuysen, B. M. The refinery of the future. *Nature* **629**, 295–306 (2024).
28. Nwabara, U. O. et al. Towards accelerated durability testing protocols for CO_2 electrolysis. *J. Mater. Chem. A* **8**, 22557–22571 (2020).
29. Lickert, T. et al. Advances in benchmarking and round robin testing for PEM water electrolysis: reference protocol and hardware. *Appl. Energy* **352**, 121898 (2023).
30. Dutta, N., Bagchi, D., Chawla, G. & Peter, S. C. A guideline to determine faradaic efficiency in electrochemical CO_2 reduction. *ACS Energy Lett.* **9**, 323–328 (2024).
31. Ma, M. et al. Insights into the carbon balance for CO_2 electroreduction on Cu using gas diffusion electrode reactor designs. *Energy Environ. Sci.* **13**, 977–985 (2020).
32. Krewitt, W. & Nitsch, J. The German Renewable Energy Sources Act—an investment into the future pays off already today. *Renew. Energy* **28**, 533–542 (2003).
33. Wiser, R., Namovicz, C., Gielecki, M. & Smith, R. The experience with renewable portfolio standards in the United States. *Electr. J.* **20**, 8–20 (2007).
34. Li, J. & Huang, J. The expansion of China's solar energy: challenges and policy options. *Renew. Sustain. Energy Rev.* **132**, 110002 (2020).
35. Green, M. A. Commercial progress and challenges for photovoltaics. *Nat. Energy* **1**, 15015 (2016).
36. Basore, P. & Feldman, D. *Solar Photovoltaics: Supply Chain Deep Dive Assessment* https://www.osti.gov/biblio/1871588 (OSTI, 2022).
37. Biçer, Ü. I. & Krebs, F. C. Lost in transition? Perspective on research versus commercialization of organic and perovskite solar cells. *Adv. Energy Mater.* **15**, e02426 (2025).
38. Wagner, L. et al. The resource demands of multi-terawatt-scale perovskite tandem photovoltaics. *Joule* **8**, 1142–1160 (2024).
39. Jouny, M., Luc, W. & Jiao, F. General techno-economic analysis of CO_2 electrolysis systems. *Ind. Eng. Chem. Res.* **57**, 2165–2177 (2018).

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