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Photoelectrochemical solar fuels from carbon dioxide, water and sunlight

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The production of fuels from renewable sources is one of the most promising alternatives to the current dominant position of fossil fuels in the energy market. Environmental, socio-economic, and geo-political issues make a fast and sustainable transition of high importance. One plausible opportunity for the generation of renewable fuels would be the capture of sunlight and the utilisation of this energy to reduce carbon dioxide, a pollutant, into energy rich molecules, mimicking natural photosynthesis. Here, we describe the challenge and the few successful examples able to produce fuels, exclusively from carbon dioxide, water and sunlight.

Introduction

The search for solar fuels is becoming a major driving force in energy-related research.^{1,2} The excessive and continuous consumption of fossil fuels has caused high emissions of greenhouse gases, including CO₂, into the atmosphere resulting in a global energy crisis. A sustainable, alternative, close energy cycle based on renewable resources is urgently needed. The opportunity to combine the most widely available renewable energy source (sunlight) with the most

preferred energy storage vectors (fuels) offers unparalleled possibilities to meet the present and future energy needs,^{3,4} while offering highly attractive opportunities from a socio-economic perspective.⁵⁻⁷ The combustion of these fuels would return them to their starting materials, in a complete, circular and environmentally friendly process.

Most of the promising strategies reported to date deal with water splitting, where the energy of the incident light is stored as molecular hydrogen, pointing towards a hydrogen economy.^{8,9} Despite their advantages,¹⁰ it is reasonable to state that liquid green fuels would be much preferred for a faster and easier transition from fossil fuels to a new environmentally friendly and carbon neutral energy cycle. If energy-rich molecules such as methane, ethanol, or small hydrocarbons could be obtained from a carbon source (CO₂) and water, their implementation as fuels or fuel additives for industrial applications should be quite straightforward.¹¹⁻¹³

Indeed, CO₂ recycling into fuels is expected to become a key technology for the introduction of renewable sources in the energy cycle.^{14,15} However, intensive research is still needed to apply such technologies to viable and scalable processes.¹⁶

CO₂ reduction is a complex reaction (see eqn (1)–(6)), where selectivity is difficult to achieve. The problem resides in the high number of different products that can be obtained, which are also prone to further reactivity. To make things worse, most of them require very similar energy input, precluding selectivity control by electrochemical potential, for example. Additionally, the simplest reduction products, such as carbon monoxide, are the most demanding in terms of energy. Meanwhile, the most interesting products, such as methane or alcohols, thermodynamically require less energy. However, the higher number of electrons and protons involved in those reactions generates a prohibiting activation energy. Such high overpotentials benefit the simpler reactions, that are not necessarily desired. This is particularly

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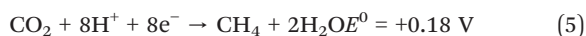


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true for the hydrogen evolution reaction (HER), the most important side-reaction diffculting high CO₂ selectivity, since protons are needed for CO₂ reduction. The high complexity of the surface mechanisms for CO₂ reduction makes the establishment of helpful computational models also difficult. Some recent developments in the theory of (photo) electrochemical CO₂ fixation are shedding light on the problem, and bring appealing strategies to the table for future development.^{17,18} Good selectivity (>80%) has only been described for CO or HCOOH¹⁹ Probably, because of this reason, many strategies are targeting a mixture of H₂ and CO as products, since this syngas can be converted to gasoline or diesel by the Fischer–Tropsch synthesis.^{20,21}



Green plants and algae are extremely selective to reducing CO₂ to sugars. Their enzymatic mechanism is an inspiration and valuable information can be extracted,^{22–25} despite their very low solar to biomass efficiency.²⁶ One strategy would be to utilise solar H₂ as feedstock for the reduction of CO₂ as a second step, which could be attained by industrial methods or new approaches, including the use of microorganisms engineered to produce biomass and fine chemicals.^{27,28} Such a scheme, as any CO₂ valorisation strategy, will need to be combined with CO₂ producing processes (combustion, fermentation), needing additional concentration and purification steps.²⁹ It is worthy to mention that CO₂, despite its damaging effects on the climate, is not readily available in the atmosphere (still <500 ppm), and any strategies based on atmospheric CO₂ purification would be cost-prohibitive.

Several comprehensive reviews have been published in recent years regarding the production of CO₂-based fuels, including future perspectives.^{30–37} In this review, we will focus exclusively on photoelectrochemical (PEC) strategies, where fuels are obtained using sunlight energy, CO₂ as feedstock and H₂O as a source of protons and electrons, highlighting the light absorption requirements and schemes, along with catalyst integration. The combination of water oxidation with CO₂ reduction is arguably the most appealing strategy, given its simplicity. It is also the most advantageous, since no additional power or sacrificial chemicals would be needed, allowing immediate product separation. In contrast, for example, in the so-called homogeneous Z-schemes, where products and reagents are present, oxidation and reduction occur in a one pot architecture.^{38,39}

Light absorption by semiconductors with the right band alignment could drive both reactions, but they will need cocatalysts for high selectivity.^{40–45} This integrated approach that combines light absorbers and electrocatalysts allows for fine tuning their features and minimizing losses. The interface engineering is the key for the suitable function of these composite electrodes, since the properties of both semiconductors and catalysts can be severely affected by these surface modifications. Unfortunately, few absorbers can generate the required potential difference between cathodes and anodes. Thus, typical PEC devices need a combination of them, as a photocathode and photoanode, or addition of an external power supply (photovoltaic or not). This comes with a current limitation, since the current density is limited by the photocurrent of the lesser unit when connected in series. Because of this difficult implementation, from a technological perspective, a modular approach has been also proposed by simply wiring a photovoltaic device to a CO₂ electrolyser in the dark. Despite being not so elegant, this approach has provided the highest solar to hydrogen efficiency in water splitting, reaching a spectacular 30% yield.^{46,47} The separation of the two modules avoids the complex interface engineering, and also the limitations of each component, since they can be individually scaled to match performance without the restrains of direct surface contact. The major disadvantage of this approach is the functional integration of both sub-systems that are currently individually optimised, whereas the integration of their respective function is still a must for successful and long-term application. For example, industrial electrolysers lose performance when working under dynamic operation conditions.^{48,49} The intermittent nature of sunlight will force the electrolyser part to follow continuous start/stop cycles, inducing random changes in potential, and favouring back-reactions at open circuit voltage causing fast deterioration of catalysts, supports and membranes. Systems engineering becomes a major requirement to mitigate these effects under intermittent operation conditions.

Photoelectrocatalytic CO₂ conversion: photovoltaics plus electrolysers

As mentioned above, the combination of photovoltaics (PV) with electrolysers has become closer to technological development, since independent optimisation of each system appears to be an easier task. This modular approach allows taking advantage of highly efficient photovoltaic modules, encapsulated for long term stability and wired to an electrolyser. State-of-the-art PV devices easily reach over 20% solar to electricity efficiency,^{50–52} and new multi-junction technologies are reaching over 30%.⁵³ One of the limitations comes from the voltage window, since CO₂ electrolysers need well over a 2 volt difference, due to the large overpotential required by the catalysts. PV modules offering such power are formed by the combination of multiple cells, in series, with the corresponding limitations in current density. The

second key parameter for this approach to be successful is the selectivity of the electrocatalysts that must minimise side-reactions, such as the HER.

A record high solar to fuel (STF) efficiency was reported using a GaInP/GaInAs/Ge photovoltaic cell (Fig. 1a), reaching a 13.4% STF efficiency towards CO with bifunctional electrodes made of SnO₂-modified CuO, which act as a cathode and anode.⁵⁴ Bifunctionality and high selectivity of these electrodes was achieved by atomic layer deposition of the SnO₂ decoration. Long term stability required each electrode to work at different pH levels.

A remarkable 6.5% efficiency towards CO was obtained using an electrolyser equipped with a nanostructured Au cathode and an IrO₂ anode in bicarbonate neutral media, powered by three perovskite solar cells connected in series.⁵⁵ The major drawback of this set-up (Fig. 1a) is the need for noble metal-based cathodes and anodes, both being key components. The gold cathode offers an excellent Faradaic efficiency of over 80%. The IrO₂ anode offers good kinetics and, more importantly, good stability in neutral pH.

Currently, no low cost alternatives are available to reach comparable performance under these conditions.

In a single compartment reactor, and exclusively using earth abundant elements, CO was obtained with a 3.4% STF efficiency.⁵⁶ This was achieved by the combination of a homogeneous Mn catalyst on the cathode and a Ni-Fe oxo-hydroxide as an anode, both working in alkaline media. This study also included an interesting comparison of efficiencies when using different PV modules (Fig. 1a).

A first step towards integrated devices was reported by combination of four encapsulated silicon heterojunction solar cells (SHSCs)⁵⁷ in series wired to a Ni foam electrode to build a self-standing photoanode (Fig. 1c). In combination with a cathode made from Cu foam decorated with Zn nanoflakes, a 16% Faradaic efficiency towards CO was reported, for a total of 4.3% STF production. As in previous examples, two different electrolytes were used to avoid noble metal catalysts as anodes.⁵⁸

Beyond CO, only formate production has been reported with this modular configuration with the implementation of selective catalysts, such as Bi metal. Highly porous Bi electrodes were used to reach an impressive 8.5% STF efficiency for formate when combined with an IrO₂ anode (Fig. 1a), both working in bicarbonate media.⁵⁹ It is worthy to mention that when powered by a polycrystalline Si solar cell, this set-up works at currents over 10 mA cm⁻¹, resulting in one of the highest STF production rates reported. Arguably, this probably comes from the relative high surface area of the cathode, and not necessarily from a higher electrocatalytic activity. The authors also present a computational analysis of the cathode selectivity, along with the influence of electrolytes.

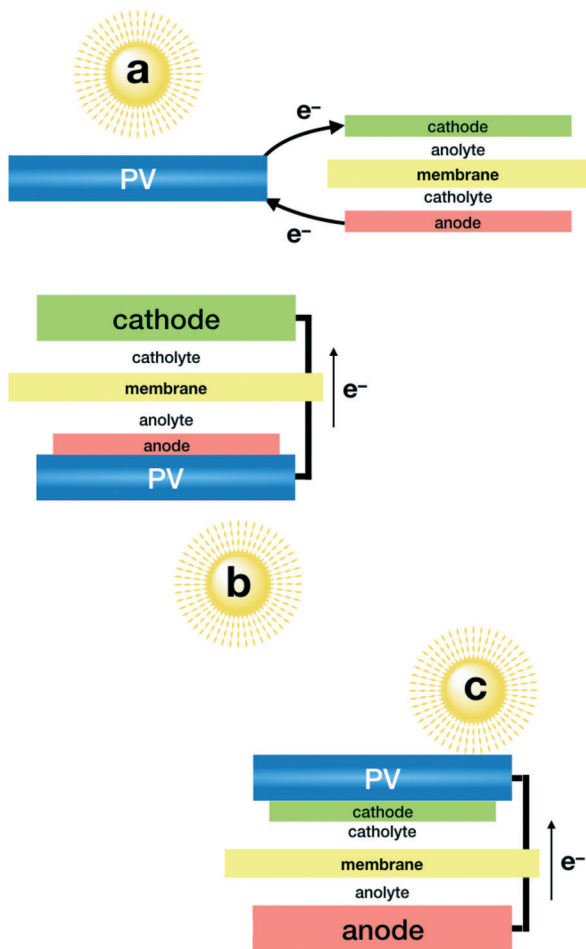


Fig. 1 Plausible schemes for the conversion of sunlight, CO₂ and H₂O to fuels based on a PV plus unbiased electrolyser architecture: a) simple wired PV plus an electrolyser; b) and c) integration of the PV module as a support for a cathode or an anode, to drive both reactions through the wired counter electrode.

Integrated photoelectrocatalytic CO₂ conversion

Wireless decoration of PV cells appears to be the second step towards integrated systems. Following this strategy, two amorphous Si triple-junction cells in series were decorated with a WSe₂ cathode and a CoO_x anode to yield a 4.6% STF efficiency for CO.⁶⁰ This system minimises the HER side-reaction, reaching a 10:1 CO₂/H₂ ratio with the help of an ionic liquid catholyte, while the anode works in neutral phosphate buffer to stabilise the cobalt oxide catalyst.

Most examples from an integrated approach are built from monolithic semiconductors as photoelectrodes, decorated with catalysts, looking for optimum synergy by interface engineering. However, only a few common semiconductors are able to promote the right potential difference and band alignment to promote both the reactions, CO₂RR and OER, such as TiO₂, SiC, ZnO, or CdS.⁶¹ TiO₂ has been the most studied material for photoelectrodes with inconsistent results during the last years.⁶² A photocathode built from a combination of CuFeO₂ and CuO is another one of the very few examples of single absorber PEC electrode. This photocathode drives formate production and oxygen evolution at a Pt anode with a 1% efficiency.⁶³

Given that single absorbers are very scarce, most integrated PEC devices need to combine two absorbers when working unbiased. This combination may come from heterostructured photoelectrodes; from two photoelectrodes in series: photoanode + photocathode; or by addition of an external photovoltaic device to provide the extra power needed to run both semi-reactions. An interesting compromise deals with the parallel combination of the two photoelectrodes, or one photoelectrode and a PV cell to absorb light from complementary regions in the solar light spectrum to improve photocurrent generation efficiency. All the possibilities are shown in Fig. 2.

A single photoanode, built from a tandem Ni/TiO₂/InGaP/GaAs architecture, delivered a record 10% STF efficiency for formate with the assistance of a highly selective Pd/C/Ti cathode. In this case, the implementation of a low resistance bipolar membrane allowed to minimise voltage losses and product crossover. This set-up works at a high current density under unbiased conditions, thanks to the nanostructuration and optimisation of all the parts, including the large pH difference between the anolyte and catholyte maintained with the membrane.⁶⁴

Combination of a hybrid Ru-metal complex/zinc-doped InP photocathode with a reduced SrTiO₃ photoanode yielded a maximum of 0.14% for formate when both photoelectrodes are connected with wires, working in different compartments.⁶⁵ Taking advantage of the high selectivity of

the photoanode towards water oxidation, the authors also explored a one-compartment cell, using back-to-back configuration (Fig. 2a). In this case, the yield was reduced to 0.08%. This difference was assigned to the pH difference that can be maintained in different compartments, which occurs because CO₂ is bubbled only into the catholyte, decreasing the pH by about 1.5.

Previously, the same photocathodes were combined with TiO₂ photoanodes in parallel (Fig. 2c).⁶⁶ Since TiO₂ only absorbs UV light, the visible light passing through the photoanode reached the photocathode. This light absorption scheme did not yield a better STF efficiency though, which was limited to 0.04%.

This parallel architecture also works with SrTiO₃ photoanodes when combined with a more elaborated photocathode incorporating an analogous Ru complex.⁶⁷ This combination with a Ru complex/TiO₂/N,Zn-Fe₂O₃/Cr₂O₃ photocathode delivered a 0.15% STF efficiency, albeit at very low current densities.

A cobalt molecular catalyst has been used as a selective cathode catalyst to produce syngas (H₂/CO₂ = 3) from a perovskite-BiVO₄ PEC tandem cell working in bicarbonate buffer, when irradiated from the photoanode side.⁶⁸ Multiple protective layers on the photoabsorbers confer moderate stability to this architecture for at least 10 h when working completely immersed in the solution.

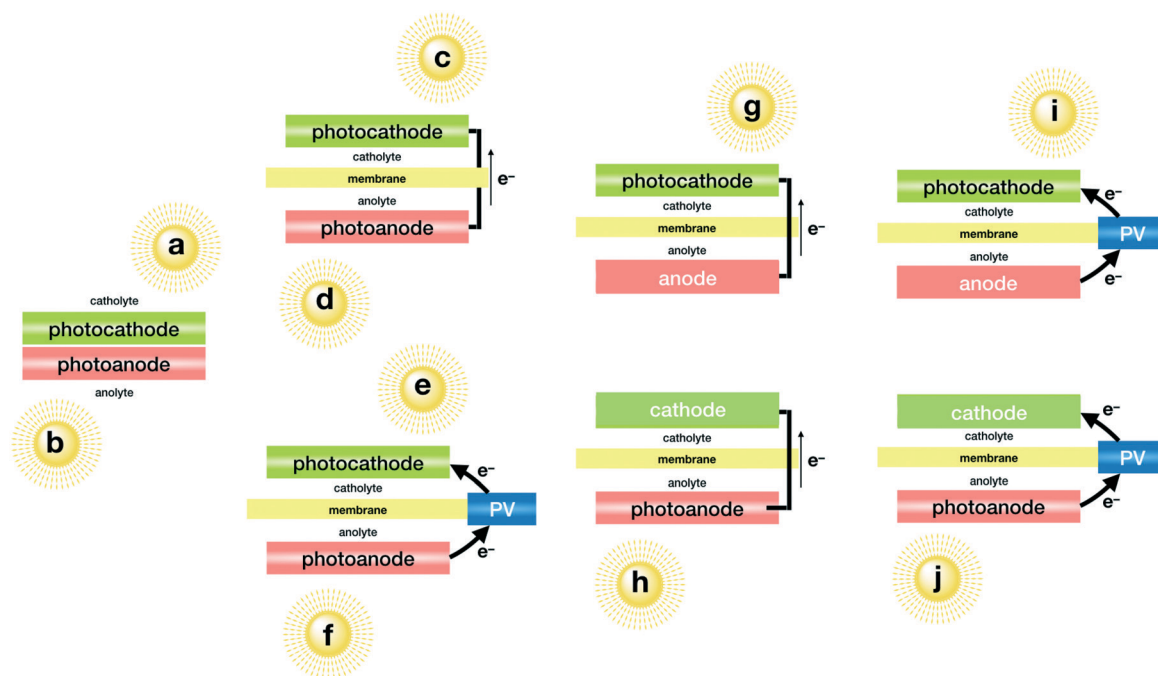


Fig. 2 Plausible schemes for the conversion of sunlight, CO₂ and H₂O to fuels based on integrated, unbiased photoelectrochemical (PEC) architecture: a) and b) simple coupling of a photocathode and photoanode, irradiated from only one side (a or b) or from both sides (a and b). c) and d) Wired coupling of two complementary photoelectrodes, when irradiated from only one side (c or d) or from both sides (c and d); e) and f) wired coupling of two complementary photoelectrodes, assisted by an external PV cell, when irradiated from only one side (e or f) or from both sides (e and f); g) single photocathode architecture; h) single photoanode architecture; i) and j) single photoelectrode architectures assisted by an external PV cell. In the cases of two photoelectrodes irradiated only from one side, both should ideally absorb complementary regions of the solar spectrum to maximise solar to fuel efficiency.

The rest of the examples incorporate an external PV cell (Fig. 2e–f and i–j) to reach the required potential for both reactions. This comes with a STF efficiency penalty, since this external PV cell is connected in series with the rest of the semiconductors. Such architecture results in voltage addition, but the current is limited by the photocurrent of the weakest photoabsorber, since it is constant throughout the whole circuit.⁶⁹

A record high efficiency was achieved with this strategy with a tandem system of Cu/Ag/TiO₂ photocathodes that yielded a 60% FE for C₂₊ products under illumination. These cathodes have been successfully combined with water oxidation when coupled to a series of perovskite solar cells, reaching a total of 3.5% STF efficiency.⁷⁰ This also represents the only example of CO₂-reduction PEC devices that produce carbon–carbon bonds.

An interesting combination of a photocathode/photovoltaic tandem assembly was designed to harvest a wide energy range of incident light and to power the CO₂ to CO conversion at the photocathode (>0.35%), which was composed of gold-decorated ZnO/ZnTe/CdTe nanorods, while oxidising water into oxygen at the anode, powered by the tandem photocathode + CH₃NH₃PbI₃ (MAPI) perovskite device.⁷¹

FeOOH-decorated BiVO₄ photoanodes have been combined with a large surface area 3D TiN electrode able to transfer electrons to CO₂-selective loaded enzymes to obtain formate in a very high FE. Reasonable currents need the additional power from a photovoltaic cell to deliver 0.08% STF conversions.⁷²

Despite being less appealing from an application point of view, many attempts to combine metal complexes as chromophores with semiconductors to boost the performance of such hybrid photoelectrodes have been incorporated into CO₂ reduction PEC devices.⁷³ Again, few examples have been able to work unbiased.

Another molecular photocatalyst/semiconductor hybrid photocathode was reported from the impregnation of CuGaO₂ with a mixed Ru–Re complex. This photocathode is able to produce CO and H₂ operating at <75% selectivity when combined with an oxygen evolution CoO_x/TaON photoanode.⁷⁴ This architecture required an additional PV unit to achieve significant photocurrent.

Discussion

Despite the great technological and industrial interest on the direct storage of sunlight power into energy rich chemicals from CO₂ reduction, this field is still in its infancy. Fortunately, many studies and reports on the optimisation of the needed parts are available. Surprisingly, the key step of implementation into working systems is missing. Unbiased transformation is scientifically demanding, but all problems derived from implementation can only be solved when tackled. Compared to the hundreds of results on photoelectrodes under biased conditions, and on

photocatalysts with the help of ancillary chemicals (as an energy source), the focus of this review resulted in a very short list. Shorter than what we expected, indeed.

Beyond the limited number, just looking at Tables 1 and 2, several additional conclusions can be derived from these promising results, obtained by a few research groups. Starting on the positive side, some research teams have already achieved over 10% STF efficiency, a common minimum required to receive industrial interest. All are based on different materials and architectures, with their own advantages and disadvantages. Most of them are fuelled by the authors' previous expertise. There has not been a sustained, rational stepwise progress. Given the importance of the challenge, a consistent, collaborative, multidisciplinary effort will be needed as soon as possible.

Another interesting conclusion is the clear superiority of the modular approach, combining a photovoltaic cell with an electrolyser. An over 3% STF efficiency has been reached with earth abundant, low-cost materials following this scheme, and a record high >13% using more complex, unscalable approaches. This approach is more promising to reach reasonable success in the near future, thanks to the better synergy between both parts. Photovoltaic cells can only deliver <30 mA cm⁻²,^{75–77} but industrial electrolysers can work at much higher currents, >0.5 A cm⁻².⁷⁸ The challenge here is the implementation of CO₂RR cathodes, and the corresponding product separation and management into industry-ready systems. In the meantime, it does not make much sense to limit the electrolytic capabilities to low current densities offered by PV devices by matching the area and geometry of both parts, when a reduced-size electrolyser could efficiently do the same work. Furthermore, in the near future, when the grid becomes predominantly renewable, the “simple” development of appropriate electrolysers, associated with CO₂ sources, will emerge as a plausible strategy, and an economically attractive one for industrial CO₂ emitters.

On the integrated approach, too many examples yield marginal efficiencies (<0.5%), restricted by two major issues. On one end, the limited voltage offered by monolithic semiconductors combined with the very high overpotentials required by the catalysts hampers their productivity. This can be solved by using two photoelectrodes, but this limits the current and also STF efficiency. Ideally, both should absorb light from complementary regions of the solar spectrum to maximise efficiency, which is not a simple achievement. Using *n* external photovoltaic cells in series has been the most successful solution, and the only one yielding STF efficiencies over 1%. The other solution explored has been the decoration of heterojunction photovoltaics with catalysts to build photoelectrodes, but this approach does not improve the wired analog technology, although it could be preferred given some restrictions (space, costs, implementation, *etc.*). The second major issue comes from the interface that must protect the light absorber, while facilitating fast and energy efficient charge transfer. This complicates the processing and architecture, since the high efficiency of PV also depends on

Table 1 Modular PEC devices

| Cathode | Anode | PV | j (mA cm ⁻²) | FE _{CO} (%) | FE _{COOH} (%) | STF ^a (%) | Ref. |
|-----------------------|------------------------------------|-------------------------|----------------------------|----------------------|------------------------|----------------------|------|
| SnO ₂ /CuO | SnO ₂ /CuO | GaInP/GaInAs/Ge (2.4 V) | 0.1 | 81 | — | 13.8 | 54 |
| Anodised Au | IrO ₂ | Perovskite (3.1 V) | ? | 90 | — | 6.5 | 55 |
| Mn complex | FeO _x /NiO _x | Si (2.2 V) | 1 | 80 | — | 3.4 | 56 |
| Cu–Zn | Ni | Si (2.7 V) | 5 | 16 | — | 4.3 | 58 |
| Porous Bi | IrO ₂ | Si (2.7 V) | 10 | — | 95 | 8.5 | 59 |

^a All efficiencies are quoted as reported, although not all the reports used identical methods for their estimation.

Table 2 Integrated PEC devices

| (photo)Cathode | (photo)Anode | j (mA cm ⁻²) | FE _{CO} (%) | FE _{COOH} (%) | FE _{others} (%) | STF (%) ^b /PV ^a | Ref. |
|---|-------------------------------------|----------------------------|----------------------|------------------------|--------------------------------------|---------------------------------------|------|
| WSe ₂ /PV-a-si-3jn | CoO _x /PV-a-si-3jn | ? | 24 | — | — | 4.6 | 60 |
| CuFeO ₂ /CuO | Pt | <0.2 | — | 90 | — | 0.7–1.2 | 63 |
| Pd/C/Ti | Ni/TiO ₂ /InGaP/GaAs | 8.7 | — | >94 | — | >10 | 64 |
| Ru complex/InP | Reduced SrTiO ₃ | 0.1 | — | >71 | — | 0.14 | 65 |
| Ru-complex/InP | TiO ₂ | ? | — | >70 | — | 0.04 | 66 |
| Ru-complex/TiO ₂ /Fe ₂ O ₃ /Cr ₂ O ₃ | TiO ₂ | >0.1 | 16 | >79 | — | 0.15 | 67 |
| Co-complex/perovskite | CoO _x /BiVO ₄ | >1 | 25 | — | — | 0.08 | 68 |
| Cu/Ag/TiO ₂ | IrO ₂ | — | — | — | 60 (C ₂ /C ₃) | 3.5/perovskite | 70 |
| ZnO–ZnTe@CdTe–Au | Co–HCO ₃ /Ni foam | 0.85 | 80 | — | — | 0.43/MAPI | 71 |
| Bio/TiN | FeO _x /BiVO ₄ | <1 | — | 77 | — | 0.08/perovskite | 72 |
| RuRe-complex/CuGaO ₂ | CoO _x /TaON | <0.05 | 41 | — | — | ? | 74 |

^a All efficiencies are quoted as reported, although not all the reports used identical methods for their estimation. ^b External photovoltaic cell, if any.

the perfect encapsulation and optimum definition of the current collector layers, that must be modified. Modifications on these key parts have necessarily a detrimental effect on PV efficiency. Finally, the same current density limitation applies to this approach, as fixed by the weakest photoabsorber.

With all these in mind, we can summarise the major challenges that prevent sunlight-to-CO₂-based fuel technology. From a basic science perspective, the lack of selectivity towards the desired product is without a doubt the major drawback. With rare exceptions, only CO/H₂ (syngas) and formate have been obtained in significant yields. These are interesting chemicals, but higher value products would be certainly preferred, like methane. Methane could be directly used as a fuel in current technologies, complementing natural gas, in a real sustainable cycle. Other products, like alcohols, would also be useful as additives for liquid fuels. There is a huge margin of improvement. On the development end, the field will need to follow the same route that water splitting electrolyzers followed decades ago. The mitigation of losses in the electrolyser part (membrane, electrolyte, interface, reagent and product dynamics, *etc.*) must be optimised to exploit the excellent capabilities of electrode supports and catalysts. On the application end, the target should be adapted to industry standards. Scalability and economic feasibility should be taken into account, and not just scientific excellence. The latter is a must, but if we all, as a community, are discussing about contributing to solve a societal challenge, we better put our words into action. Finally, scientific cooperation will be fundamental to

overcome all these hurdles. It is difficult to envision a successful solution coming from a single research team. Multiple disciplines and multiple points of view will be needed to deliver. This is why multi-institutional and multi-national programs are so important to move this field forward.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

- 1 N. S. Lewis, *Science*, 2016, **351**, aad1920.
- 2 S. Chu, Y. Cui and N. Liu, *Nat. Mater.*, 2017, **16**, 16–22.
- 3 D. Gust, T. A. Moore and A. L. Moore, *Acc. Chem. Res.*, 2009, **42**, 1890–1898.
- 4 H. B. Gray, *Nat. Chem.*, 2009, **1**, 7.
- 5 R. J. Detz, J. N. H. Reek and B. C. C. van der Zwaan, *Energy Environ. Sci.*, 2018, **11**, 1653–1669.
- 6 J. Newman, P. G. Hoertz, C. A. Bonino and J. A. Trainham, *J. Electrochem. Soc.*, 2012, **159**, A1722–A1729.
- 7 A. Harriman, *Philos. Trans. R. Soc., A*, 2013, 20110415.

- 8 I. Staffell, D. Scamman, A. V. Abad, P. Balcombe, P. E. Dodds, P. Ekins, N. Shah and K. R. Ward, *Energy Environ. Sci.*, 2019, **12**, 463–491.
- 9 S. Ardo, D. F. Rivas, M. A. Modestino, V. S. Greiving, F. F. Abdi, E. Alarcon Llado, V. Artero, K. Ayers, C. Battaglia, J. P. Becker, D. Bederak, A. Berger, F. Buda, E. Chinello, B. Dam, V. Di Palma, T. Edvinsson, K. Fujii, H. Gardeniers, H. Geerlings, S. M. H. Hashemi, S. Haussener, F. Houle, J. Huskens, B. D. James, K. Konrad, A. Kudo, P. P. Kunturu, D. Lohse, B. Mei, E. L. Miller, G. F. Moore, J. Muller, K. L. Orchard, T. E. Rosser, F. H. Saadi, J. W. Schuttauf, B. Seger, S. W. Sheehan, W. A. Smith, J. Spurgeon, M. H. Tang, R. van de Krol, P. C. K. Vesborg and P. Westerik, *Energy Environ. Sci.*, 2018, **11**, 2768–2783.
- 10 A. Saeedmanesh, M. A. Mac Kinnon and J. Brouwer, *Curr. Opin. Electrochem.*, 2019, **12**, 463–491.
- 11 G. Centi and S. Perathoner, *Catal. Today*, 2009, **148**, 191–205.
- 12 G. A. Olah, G. K. S. Pakash and A. Goepfert, *J. Am. Chem. Soc.*, 2011, **133**, 12881–12898.
- 13 A. Corma and H. Garcia, *J. Catal.*, 2013, **308**, 168–175.
- 14 G. Centi and S. Perathoner, *Energy Environ. Sci.*, 2013, **6**, 1711–1731.
- 15 G. Centi and S. Perathoner, *ChemSusChem*, 2010, **3**, 195–208.
- 16 H. L. Tuller, *Mater. Renewable Sustainable Energy*, 2017, **6**, 3.
- 17 S. Z. Xu and E. A. Carter, *Chem. Rev.*, 2018, **119**, 6631–6669.
- 18 R. Garcia-Muelas, F. Dattila, A. J. Shinagawa, T. Abd Martin, J. Pérez-Ramírez and N. López, *J. Phys. Chem. Lett.*, 2019, **9**, 7153–7159.
- 19 G. O. Larrazábal, A. J. Martín and J. Pérez-Ramírez, *J. Phys. Chem. Lett.*, 2017, **8**, 3933–3944.
- 20 S. Hernández, M. A. Farkhondehfar, F. Sastre, M. Makkee, G. Saracco and N. Russo, *Green Chem.*, 2017, **19**, 2326–2346.
- 21 C. Graves, S. D. Ebbesen, M. Mogensen and K. S. Lackner, *Renewable Sustainable Energy Rev.*, 2011, **15**, 1–23.
- 22 G. D. Scholes, G. R. Fleming, A. Olaya-Castro and R. van Grondelle, *Nat. Chem.*, 2011, **3**, 763–774.
- 23 X. J. Xie and E. Bakker, *Phys. Chem. Chem. Phys.*, 2014, **16**, 19781–19789.
- 24 Y. Kim, J. H. Lee, H. Ha, S. W. Im and K. T. Nam, *Nano Convergence*, 2014, **16**, 19781–19789.
- 25 N. Kornienko, J. Z. Zhang, K. K. Sakimoto, P. D. Yang and E. Reisner, *Nat. Nanotechnol.*, 2018, **13**, 890–899.
- 26 X. G. Zhu, S. P. Long and D. R. Ort, *Curr. Opin. Biotechnol.*, 2008, **19**, 153–159.
- 27 J. P. Torella, C. J. Gagliardi, J. S. Chen, D. K. Bediako, B. Colón, J. C. Way, P. A. Silver and D. G. Nocera, *Proc. Natl. Acad. Sci. U. S. A.*, 2015, **112**, 2337–2342.
- 28 D. K. Dogutan and D. G. Nocera, *Acc. Chem. Res.*, 2019, **52**, 3143–3148.
- 29 P. C. Psarras, S. Comello, P. Bains, P. Charoensawadpong, S. Reichelstein and J. Wilcox, *Environ. Sci. Technol.*, 2017, **51**, 11440–11449.
- 30 E. V. Kondratenko, G. Mul, J. Baltrusaitis, G. O. Larrazábal and J. Pérez-Ramírez, *Energy Environ. Sci.*, 2013, **6**, 3112–3135.
- 31 C. A. Trickett, A. Helal, B. A. Al-Maythaly, Z. H. Yamani, K. E. Cordova and O. M. Yaghi, *Nat. Rev. Mater.*, 2017, **2**, 17045.
- 32 S. C. Roy, O. K. Varghese, M. Paulose and C. A. Grimes, *ACS Nano*, 2010, **4**, 1259–1278.
- 33 W. G. Tu, Y. Zhou and Z. G. Zou, *Adv. Mater.*, 2014, **26**, 4607–4626.
- 34 Y. Izumi, *Coord. Chem. Rev.*, 2013, **257**, 171–186.
- 35 M. K. Brennaman, R. J. Dillon, L. Alibabaei, M. K. Gish, C. J. Dares, D. L. Ashford, R. L. House, G. J. Meyer, J. M. Papanikolas and T. J. Meyer, *J. Am. Chem. Soc.*, 2016, **138**, 13085–13102.
- 36 A. U. Pawar, C. W. Kim, M. Nguyen-Le and Y. S. Kang, *ACS Sustainable Chem. Eng.*, 2019, **7**, 7431–7455.
- 37 N. Vu, S. Kaliaguine and T. Do, *Adv. Funct. Mater.*, 2019, **29**, 1901825.
- 38 P. Zhou, J. G. Yu and M. Jaroniec, *Adv. Mater.*, 2014, **26**, 4920–4935.
- 39 A. J. Morris, G. J. Meyer and E. Fujita, *Acc. Chem. Res.*, 2009, **42**, 1983–1994.
- 40 X. Li, J. G. Yu, M. Jaroniec and X. B. Chen, *Chem. Rev.*, 2019, **119**, 3962–4179.
- 41 X. Chang, T. Wang, P. Yang, G. Zhang and J. Gong, *Adv. Mater.*, 2019, **31**, 1804710.
- 42 J. R. Ran, M. Jaroniec and S. Z. Qiao, *Adv. Mater.*, 2018, **30**, 1704649.
- 43 J. X. Low, B. Cheng and J. G. Yu, *Appl. Surf. Sci.*, 2017, **392**, 658–686.
- 44 S. Nahar, M. F. M. Zain, A. A. H. Kadhum, H. A. Hasan and M. R. Hasan, *Materials*, 2017, **10**, 629.
- 45 J. L. White, M. F. Baruch, J. E. Pander III, Y. Hu, I. C. Fortmeyer, J. E. Park, T. Zhang, K. Liao, J. Gu, Y. Yan, T. W. Shaw, E. Abelev and A. B. Bocarsly, *Chem. Rev.*, 2015, **115**, 12888–12935.
- 46 J. Jia, L. C. Seitz, J. D. Benck, Y. Huo, Y. Chen, J. W. D. Ng, T. Bilir, J. S. Harris and T. F. Jaramillo, *Nat. Commun.*, 2016, **7**, 13237.
- 47 J. S. Luo, J. H. Im, M. T. Mayer, M. Schreier, M. K. Nazeeruddin, N. G. Park, S. D. Tilley, M. Fan and H. J. Grätzel, *Science*, 2014, **345**, 1593–1596.
- 48 S. M. Alia, S. Stariha and R. L. Borup, *J. Electrochem. Soc.*, 2019, **166**, F1164–F1172.
- 49 A. Weiß, A. Siebel, M. Bernt, T.-H. Shen, V. Tileli and H. A. Gasteiger, *J. Electrochem. Soc.*, 2019, **166**, F487–F497.
- 50 G. Grancini and M. K. Nazeeruddin, *Nat. Rev. Mater.*, 2019, **4**, 4–22.
- 51 J. P. Correa-Baena, M. Saliba, T. Buonassisi, A. Grätzel, W. Tress Abate and A. Hagfeldt, *Science*, 2017, **358**, 739–744.
- 52 M. A. Green, *Science*, 2013, **371**, 20110413.
- 53 S. Essig, C. Allebe, T. Remo, J. F. Geisz, M. A. Steiner, K. Horowitz, L. Barraud, J. S. Ward, M. Schnabel, A. Descoeurdes, D. L. Young, M. Woodhouse, M. Despeisse, C. Ballif and A. Tamboli, *Nat. Energy*, 2017, **2**, 17144.
- 54 M. Schreier, F. Héroguel, L. Steier, S. Ahmad, J. S. Luterbacher, M. T. Mayer, J. Luo and M. Grätzel, *Nat. Energy*, 2017, **2**, 17087.
- 55 M. Schreier, L. Curvat, F. Giordano, L. Steier, A. Abate, S. M. Zakeeruddin, J. Luo, M. T. Mayer and M. Grätzel, *Nat. Commun.*, 2015, **6**, 7326.

- 56 T. Arai, S. Sato, K. Sekizawa, T. M. Suzuki and T. Morikawa, *Chem. Commun.*, 2019, **55**, 237–240.
- 57 C. Battaglia, A. Cuevas and S. De Wolf, *Energy Environ. Sci.*, 2016, **9**, 1552–1576.
- 58 F. Urbain, P. Tang, N. M. Carretero, T. Andreu, L. G. Gerling, C. Voz, J. Arbiol and J. R. Morante, *Energy Environ. Sci.*, 2017, **10**, 2256–2266.
- 59 G. Pia, S. H. Yoon, D. S. Han and H. Park, *ChemSusChem*, 2020, **13**, 698–706.
- 60 M. Asadi, K. Kim, C. Liu, A. V. Addepalli, P. Abbasi, P. Yasaei, P. Phillips, A. Behranginia, J. M. Cerrato, R. Haasch, P. Zapol, B. Kumar, R. F. Klie, J. Abiade, L. A. Curtiss and A. Salehi-Khojin, *Science*, 2016, **353**, 467–470.
- 61 T. Inoue, A. Fujishima, S. Konishi and K. Honda, *Nature*, 1979, **277**, 637–638.
- 62 S. Xie, Q. Zhang, G. Liu and Y. Wang, *Chem. Commun.*, 2016, **52**, 35–59.
- 63 U. Kang, S. K. Choi, D. J. Ham, S. M. Ji, W. Choi, D. S. Han, A. Abdel-Wahab and H. Park, *Energy Environ. Sci.*, 2015, **8**, 2638–2643.
- 64 X. Zhou, R. Liu, K. Sun, Y. Chen, E. Verlage, S. A. Francis, N. S. Lewis and C. Xiang, *ACS Energy Lett.*, 2016, **1**, 764–770.
- 65 T. Arai, S. Sato, T. Kajino and T. Morikawa, *Energy Environ. Sci.*, 2013, **6**, 1274–1282.
- 66 S. Sato, T. Arai, T. Morikawa, K. Uemura, T. M. Suzuki, H. Tanaka and T. Kajino, *J. Am. Chem. Soc.*, 2011, **133**, 15240–15243.
- 67 K. Sekizawa, S. Sato, T. Arai and T. Morikawa, *ACS Catal.*, 2018, **8**, 1405–1416.
- 68 V. Andrei, B. Reuillard and E. Reisner, *Nat. Mater.*, 2020, **19**, 189–194.
- 69 T. J. Jacobsson, V. Fjällström, M. Edoff and T. Edvinsson, *Sol. Energy Mater. Sol. Cells*, 2015, **138**, 86–95.
- 70 J. W. Beeman Gurudayal, J. Bullock, J. Wang, H. nd Eichhorn, C. Towle, A. Javey, F. M. Toma, N. Mathews and J. W. Ager, *Energy Environ. Sci.*, 2019, **12**, 1068–1077.
- 71 Y. J. Jang, I. Jeong, J. Lee, J. Lee, M. J. Ko and J. S. Lee, *ACS Nano*, 2016, **10**, 6980–6987.
- 72 S. K. Kuk, Y. Ham, K. Gopinath, P. Boonmongkolras, Y. Lee, Y. W. Lee, S. Kondaveeti, C. Ahn, B. Shin, J. Lee, S. Jeon and C. B. Park, *Adv. Energy Mater.*, 2019, **9**, 1900029.
- 73 K. Maeda, *Adv. Mater.*, 2019, **31**, 1808205.
- 74 H. Kumagai, G. Sahara, K. Maeda, M. Higashi, R. Abe and O. Ishitani, *Chem. Sci.*, 2017, **8**, 4242–4249.
- 75 P. Tonui, S. O. Oseni, G. Sharma, Q. Yan and G. Tessema Mola, *Renewable Sustainable Energy Rev.*, 2018, **91**, 1025–1044.
- 76 S. Q. Zhang, L. Ye and J. H. Hou, *Renewable Sustainable Energy Rev.*, 2016, **6**, 1502529.
- 77 H. P. Shen, D. Walter, Y. L. Wu, K. C. Fong, D. A. Jacobs, T. Duong, J. Peng, K. Weber, T. P. White and K. R. Catchpole, *Adv. Energy Mater.*, 2019, **6**, 1902840.
- 78 O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson and S. Few, *Int. J. Hydrogen Energy*, 2019, **6**, 1902840.