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# **Solar-Driven Reduction of Aqueous CO<sub>2</sub> with a Co Bis(terpyridine)-based Photocathode**

Jane J. Leung<sup>‡</sup>, Julien Warnan<sup>‡</sup>, Khoa H. Ly, Nina Heidary, Dong Heon Nam, Moritz F. Kuehnel and Erwin Reisner\*

Christian Doppler Laboratory for Sustainable SynGas Chemistry, Department of Chemistry, University of Cambridge, Lensfield Road, Cambridge CB2 1EW, United Kingdom

Email: [reisner@ch.cam.ac.uk](mailto:reisner@ch.cam.ac.uk)

<sup>‡</sup>These authors contributed equally.

## ABSTRACT

The selective reduction of CO<sub>2</sub> with inexpensive solar-driven photoelectrochemical devices is a contemporary challenge in the quest for renewable fuel production. Here we report a molecular catalyst-based photocathode assembled from precious-metal-free components that is active towards solar-driven, aqueous CO<sub>2</sub> reduction. The reported photocathode is based on a phosphonated cobalt bis(terpyridine) catalyst that is interfaced *via* a mesoporous TiO<sub>2</sub> scaffold with a light-harvesting *p*-type silicon electrode. The hybrid photoelectrode reduces CO<sub>2</sub> to CO in both organic-water and purely aqueous conditions, achieving a turnover number of ~330 and maintaining stable activity for more than one day. Critically, in-depth electrochemical and *in situ* resonance Raman and infrared spectroelectrochemical investigations alluded to a catalytic mechanism that differs to that reported for the soluble metal bis(terpyridine) catalyst as the consequence of the immobilisation. In addition, it further unlocks an earlier catalytic onset and better electrocatalytic performance while enabling aqueous CO<sub>2</sub> reduction with the reported photocathode.

## INTRODUCTION

The solar-driven conversion of CO<sub>2</sub> and water into renewable fuels and chemicals offers a promising route to storing the Sun's intermittent and diffuse energy.<sup>1</sup> However, achieving scalable and selective photoelectrodes for aqueous CO<sub>2</sub> conversion without generating hydrogen from competing proton reduction has yet to be accomplished.<sup>2</sup> CO<sub>2</sub>-reducing molecular catalysts offer a distinct advantage over heterogeneous materials as they often combine high product selectivity with high efficiency, and their transparency ensures light penetration to allow for absorption by the supporting semiconductor.<sup>3</sup> On the other hand, photoelectrodes based on precious-metal-free heterogeneous catalysts for CO<sub>2</sub> reduction suffer from low selectivity, low Faradaic efficiencies (FE), and the inability to avoid competing hydrogen evolution in aqueous solution.<sup>4</sup> The immobilisation of molecular catalysts onto light-harvesting semiconductor photoelectrodes is an emerging approach in artificial photosynthesis to overcome these obstacles.<sup>5</sup> In contrast to most homogeneous photocatalytic systems, molecular photocathodes require no sacrificial electron source and only a minimal amount of catalyst, while utilising photoexcited electrons without the kinetic limitations of catalyst diffusion. However, only precious-metal-containing molecular photocathodes have been reported for aqueous CO<sub>2</sub> reduction to date,<sup>6-10</sup> the majority with formate (HCOO<sup>-</sup>) over carbon monoxide (CO) as the predominant product.

This study reports a precious-metal-free molecular catalyst-based photocathode for aqueous CO<sub>2</sub> reduction. The photoelectrochemical hybrid system consists of a *p*-silicon (Si) photoelectrode modified with a mesoporous titania (mesoTiO<sub>2</sub>) layer and adsorbed Co catalyst. Silicon is ubiquitous in the Earth's crust and its utilisation in the photovoltaic industry has resulted in a substantial price drop for crystalline Si in recent years.<sup>11</sup> Its conduction band (CB) energy delivers approximately 0.4 V for the reduction of CO<sub>2</sub> to CO and the small energy band gap ( $E_g$ ) of 1.12 eV enables panchromatic light harvesting in the ultraviolet (UV), visible and near infrared (IR) region. The pivotal mesoTiO<sub>2</sub> interlayer provides a high surface area scaffold to enable high loading with a phosphonated cobalt(II)

bis(terpyridine) catalyst, **CotpyP** (Figure 1), as well as a substantial surface for contact with the electrolyte solution. Upon solar light irradiation, Si is able to inject electrons into TiO<sub>2</sub>, which then shuttles them to the anchored Co catalyst. The hybrid photocathode performed CO<sub>2</sub> reduction in aqueous acetonitrile and purely aqueous electrolyte solution. The importance of the photocathode environment on the photoelectrocatalytic performance and mechanism was investigated by spectroelectrochemical IR and resonance Raman studies.

## RESULTS

### Photocathode Assembly

The CO<sub>2</sub>-reduction catalyst **CotpyP** was synthesised by self-assembly of Co(BF<sub>4</sub>)<sub>2</sub>·6H<sub>2</sub>O with two equivalents of phosphonated terpyridine (tpy), 2,2':6',2''-terpyridine-4'-phosphonic acid (**tpyP**). Full synthetic details and characterisation (<sup>1</sup>H and <sup>31</sup>P nuclear magnetic resonance (NMR) spectroscopy, high-resolution mass spectrometry, IR and elemental analysis) are available in the Methods section and Supplementary Information. NMR spectroscopy is in agreement with previous reports of cobalt(II) bis(terpyridine) complexes, and no peaks for a potential Co mono(terpyridine) by-product were observed.<sup>12</sup> Attenuated total reflectance Fourier-transform IR (ATR-FTIR, Figure 2a) of the isolated **CotpyP** displayed bands at 1604, 1475, 1413 cm<sup>-1</sup> (assigned to stretching vibrations of aromatic rings).<sup>13</sup> The UV-visible spectrum of **CotpyP** displays three absorption maxima ( $\lambda = 448, 510$  and 555 nm in methanol), which have been previously attributed to metal-to-ligand charge (MLCT) transfer transitions for low-spin cobalt(II) bis(terpyridine) species (Supplementary Figure 1a-b).<sup>14</sup>

The Si|mesoTiO<sub>2</sub>|**CotpyP** photocathode is assembled by first depositing a stabilising mesoporous, anatase TiO<sub>2</sub> scaffold (TiO<sub>2</sub> particle size ~15–20 nm, film thickness ~6  $\mu$ m) on Si as previously reported (Supplementary Figure 2).<sup>15</sup> The Si|mesoTiO<sub>2</sub> electrodes were

subsequently modified with the catalyst by immersion in a methanol solution of **CotpyP**. UV-visible spectroscopic features for the adsorbed **CotpyP** were comparable to the isolated catalyst (Supplementary Figure 1b), suggesting that its structure is preserved upon immobilisation. Although the ATR-FTIR fingerprint region indicates the same catalyst core structure of the free and immobilised **CotpyP** (Figure 2a and Supplementary Figure 1c), the decrease in the intensity of bands near 1230 and 915  $\text{cm}^{-1}$  (commonly attributed to  $\nu(\text{P}=\text{O})$  and  $\nu(\text{P}-\text{OH})$ , respectively), together with shifts of the  $\nu(\text{P}-\text{Ar})$  at 1165  $\text{cm}^{-1}$  and  $\nu(\text{P}-\text{O})$  bands around 1100-1000  $\text{cm}^{-1}$  suggest the chemisorption of phosphonic acid upon adsorption on  $\text{TiO}_2$ .<sup>16,17</sup> X-ray photoelectron spectroscopy (XPS) showed binding signals in the  $\text{Co}_{2p}$ ,  $\text{P}_{2p}$  and  $\text{N}_{1s}$  regions with elemental atomic concentration ratios in general agreement with the catalyst structure (Figure 2b-d, Supplementary Table 1). As a result of the  $\text{TiO}_2$  scaffold's mesoporosity, a high loading of  $45.0 \pm 7.4 \text{ nmol cm}^{-2}$  of chemisorbed **CotpyP** was achieved and quantified via inductively coupled plasma optical emission spectrometry after desorption (see Methods section for details).

## Photoelectrocatalytic $\text{CO}_2$ Reduction

Controlled potential photoelectrolysis (CPPE) of  $\text{Si}|\text{mesoTiO}_2|\text{CotpyP}$  was conducted under a  $\text{CO}_2$  atmosphere at an applied potential ( $E_{\text{app}}$ ) of  $-1.0 \text{ V vs. Fc}^+/\text{Fc}$  under continuous UV-filtered simulated solar irradiation (AM1.5G,  $100 \text{ mW cm}^{-2}$ ,  $\lambda > 400 \text{ nm}$ ) at room temperature.  $\text{CO}$  and  $\text{H}_2$  were quantified by gas chromatography, whereas  $\text{HCOO}^-$  was quantified by ion chromatography. Different electrolyte solution compositions were studied to identify optimal conditions for the system. No  $\text{CO}_2$  reduction products were detected with  $\text{Si}|\text{mesoTiO}_2|\text{CotpyP}$  in anhydrous acetonitrile (MeCN) containing 0.1 M tetrabutylammonium tetrafluoroborate ( $\text{TBABF}_4$ ) after several hours of CPPE. Addition of water into the electrolyte solution resulted in catalytic  $\text{CO}_2$  reduction with the turnover number ( $\text{TON}_{\text{CO}_2} = \text{TON}_{\text{CO}} + \text{TON}_{\text{HCOO}^-}$ ) rising from 13 (9:1 v:v MeCN: $\text{H}_2\text{O}$ ) to 108 (7:3

MeCN:H<sub>2</sub>O) after 8 h CPPE upon increasing the H<sub>2</sub>O content. The product selectivity for CO was favoured over H<sub>2</sub> and formate in all cases and the overall FE (FE<sub>H<sub>2</sub></sub> + FE<sub>CO</sub> + FE<sub>HCOO<sup>-</sup></sub>) increased from 12% (9:1 MeCN:H<sub>2</sub>O) to 53% (7:3 MeCN:H<sub>2</sub>O) (Figure 3 and Supplementary Table 2). The modest FE under these conditions can be partially attributed to initial parasitic reductive processes (as evidenced by an initial increase in the FE over time, see below), and ineffective catalyst reduction.<sup>18</sup> The latter is implied by the steadily decreasing turnover frequency for CO production (TOF<sub>CO</sub>) over time (Supplementary Figure 3). Additionally, bare mesoTiO<sub>2</sub> electrodes are known to produce significant charging currents that do not translate into H<sub>2</sub> evolution in the absence of a catalyst.<sup>15</sup>

Further increase in water content increased the activity up to an optimal point of 40% water. In 6:4 MeCN:H<sub>2</sub>O, a remarkably stable photocurrent as well as an overall FE of 77% (with FE<sub>CO</sub> = 48%) and a TON<sub>CO<sub>2</sub></sub> of 159 were achieved after 8 h CPPE (Figures 3 and 4a). The photocathode maintained activity during 24 h of operation and achieved a TON<sub>CO<sub>2</sub></sub> of 381 (TON<sub>CO</sub> = 334, TON<sub>HCOO<sup>-</sup></sub> = 47, Supplementary Figure 4). An initial increase in the FE over time may once again be attributed to reduction of trapped O<sub>2</sub> in the mesoTiO<sub>2</sub> architecture,<sup>19</sup> while a gradual drop in FE over this long-term experiment may be a result of progressive desorption leading to unproductive transfer pathways. Bringing the water content to 50% also allowed for robust CPPE with a constant TOF<sub>CO</sub> over time (Supplementary Figure 3), but a slightly reduced TON<sub>CO<sub>2</sub></sub> and FE. Thus, increasing the water content in the electrolyte solution from 10-30% to 40-50% is beneficial for the photocathode performance.

The Si|mesoTiO<sub>2</sub>|**CotpyP** photocathode was even found to display catalytic CO<sub>2</sub> reduction activity in pure CO<sub>2</sub>-saturated water (0.1 M KHCO<sub>3</sub>) at pH 6.7, reaching a TON<sub>CO<sub>2</sub></sub> of 21 with a Faradaic efficiency for CO and HCOO<sup>-</sup> at 9.5% and 13% respectively after 8 h CPPE (Figure 3). Control experiments in the absence of either catalyst or CO<sub>2</sub> afforded no CO<sub>2</sub> reduction products and only minimal quantities of H<sub>2</sub> (Supplementary Figures 5 and 6). The catalytic selectivity changed from CO as the main product in hydro-organic media to proton-

containing formate and H<sub>2</sub> in purely aqueous electrolyte solution. Despite the TOF<sub>CO</sub> being low, it remains constant during CPPE in water (Supplementary Figure 3), again implying good catalyst stability with an increasing presence of water. The latter is also supported by unaltered redox waves during repetitive cyclic voltammetry (CV) scans on a conductive oxide (*i.e.* indium tin oxide, ITO; Supplementary Figure 7 and more detailed discussion below).

Linear sweep voltammograms (LSVs) with chopped illumination in the optimal electrolyte solution (6:4 MeCN:H<sub>2</sub>O) reveal a photocurrent onset potential at -0.44 V vs. Fc<sup>+</sup>/Fc for Si|mesoTiO<sub>2</sub>|**CotpyP**, compared to -0.56 V vs. Fc<sup>+</sup>/Fc for the bare Si|mesoTiO<sub>2</sub> electrode (Figure 4b). **CotpyP**-functionalised photoelectrodes showed approximately double the photocurrent and an onset that occurs ~120 mV earlier. Note that the majority of charges in the **CotpyP**-free photoelectrode are charging of TiO<sub>2</sub> without promoting catalysis in the short timescale of LSVs (Supplementary Figure 8).<sup>15</sup>

Switching the Si photoelectrode for a supporting Ti foil substrate yields the equivalent dark Ti|mesoTiO<sub>2</sub>|**CotpyP** electrode, whose LSVs (also recorded in CO<sub>2</sub>-saturated 6:4 MeCN:H<sub>2</sub>O conditions) display a current onset at approximately -1.0 V vs. Fc<sup>+</sup>/Fc. This suggests that the photoabsorber delivers a photovoltage of ~550 mV (Supplementary Figure 9), in line with previous reports of Si photoelectrodes.<sup>20</sup> Controlled potential electrocatalysis (CPE) performed on the Ti|mesoTiO<sub>2</sub>|**CotpyP** electrode at -1.0 V vs. Fc<sup>+</sup>/Fc yielded no detectable products, further demonstrating the need for the light-absorbing Si electrode to operate at such a positive potential. Interestingly, the catalytic performances (current intensity, TON and selectivity) reached by the Si photoelectrodes at -1.0 V vs. Fc<sup>+</sup>/Fc (Figures 3 and 4a) are matched only by the dark Ti-based electrodes when -1.3 V vs. Fc<sup>+</sup>/Fc is applied during CPE (Supplementary Figure 10). Applying more positive or more negative potentials ( $E_{app} = -1.2$  or  $-1.4$  V vs. Fc<sup>+</sup>/Fc, respectively) dramatically affect the CPE outcome, resulting in lower activity or selectivity towards CO (Supplementary Figure 10a). This potential dependency in product selectivity is in agreement with previous reports,<sup>21</sup> and

highlights the need for synergy between molecular catalyst and the photovoltage provided by the electrode. Furthermore, the comparable performances reached by Si|mesoTiO<sub>2</sub>|**CotpyP** and Ti|mesoTiO<sub>2</sub>|**CotpyP** at -1.0 and -1.3 V vs. Fc<sup>+</sup>/Fc, respectively, suggest that kinetic limitations of the molecular catalyst **CotpyP** are the main factor determining performances, irrespective of the supporting electrode (Supplementary Figure 10b-c). Indeed, conducting light intensity dependent LSVs with Si|mesoTiO<sub>2</sub>|**CotpyP** revealed a non-linear relationship between photocurrent density and light intensity (Supplementary Figure 11), further alluding to **CotpyP** being the kinetic bottleneck.

Several control experiments were conducted in 6:4 MeCN:H<sub>2</sub>O solution to ascertain that CO<sub>2</sub> reduction catalysis originates from **CotpyP** (Figure 4c and Supplementary Figure 12). Product analysis following CPPE with both bare Si|mesoTiO<sub>2</sub> under CO<sub>2</sub> and Si|mesoTiO<sub>2</sub>|**CotpyP** under N<sub>2</sub> revealed only traces of H<sub>2</sub> and no CO<sub>2</sub>-reduction products (Supplementary Figures 13 and 14). Isotopic labelling experiments conducted with Si|mesoTiO<sub>2</sub>|**CotpyP** in a <sup>13</sup>CO<sub>2</sub>-saturated solution confirmed that CO originated from CO<sub>2</sub> and not another carbon source (determined by gas-phase IR analysis; Supplementary Figure 15). CPPE was also conducted on a photoelectrode modified with the catalyst metal salt precursor, Co(BF<sub>4</sub>)<sub>2</sub>·6H<sub>2</sub>O (Si|mesoTiO<sub>2</sub>|Co(BF<sub>4</sub>)<sub>2</sub>; Supplementary Figure 16) to determine that CO<sub>2</sub> reduction was not being performed by Co salt released from the degrading molecular catalyst. The production of mostly H<sub>2</sub> at a FE of 84% and minimal CO and formate can be ascribed to catalysis carried out by a heterogeneous deposit.<sup>22</sup> Analyses by ATR-FTIR and XPS were further employed to confirm the post-CPPE molecular integrity of **CotpyP**. The FTIR fingerprint spectrum remained largely unchanged (Figure 2a), whereas the XPS spectra show clear signals at pre-CPPE binding energies and the absence of one at 778.2 eV in the Co<sub>2p</sub> region that would indicate metallic Co (Figure 2b-d and Supplementary Table 1).<sup>23</sup> Only a small change in the atomic concentration ratios was observed, suggesting a small loss of the metal centre.

The inability of the immobilised **CotpyP** catalyst to turn over under anhydrous conditions implies a proton-dependent mechanism, but the substantial rate enhancements for CO<sub>2</sub> reduction up to 40% water content suggest an additional role of H<sub>2</sub>O. Firstly, the enhanced catalytic rate with increasing H<sub>2</sub>O content (TOF<sub>CO</sub>, Supplementary Figure 3) is due to a changing thermodynamic landscape as  $E^{\circ}(\text{CO}_2/\text{CO})$  becomes less negative, resulting in a more exergonic reaction upon addition of protons (from water) to MeCN.<sup>24</sup> This change in  $E^{\circ}(\text{CO}_2/\text{CO})$  is most pronounced when the volume percentage of water ( $x$ ) is  $0 < x < 16$ , and plateaus at  $16 < x < 45$ ; our optimal conditions ( $x = 40$ ) lies within this latter region. Secondly, (photo)electrocatalytic CO<sub>2</sub> reduction is commonly limited by its low solubility in solutions with high water content, partially explaining a performance maximum at a median water concentration.<sup>25</sup> This limited availability of CO<sub>2</sub> and the correspondingly higher concentration of protons would also favour H<sub>2</sub> evolution. Finally, as the water concentration increases in aprotic solvents, the proton adsorption-desorption equilibrium at the metal oxide electrode-solution interface favours proton adsorption.<sup>26,27</sup> This results in (i) a shift of the CB of TiO<sub>2</sub> to more positive potentials and (ii) changes in the surface hydrophilicity and local pH.<sup>26,28,29</sup> Consequently, the further addition of water in our system causes less thermodynamic driving force for both proton and CO<sub>2</sub> reduction and a more protic environment with a lower CO<sub>2</sub> concentration, resulting in less driving force for charge transfer to the catalyst as well as lower overall activity with reduced selectivity for CO<sub>2</sub> reduction.

## Comparison with State of the Art

To date, reported molecule-based photocathodes performing CO<sub>2</sub> reduction remain scarce, whether in organic or water-containing media, and continue to rely on precious metal-containing components (Supplementary Table 3).<sup>6-10,30-32</sup> Moreover, even in anhydrous conditions where enhanced photocathode and/or catalyst stability may be expected, only a

few reports exist, and all depend on Re-based catalysts.<sup>30-32</sup> For instance, a Re-bipyridine catalyst on a Cu<sub>2</sub>O photoelectrode protected by atomic layer deposited coatings has been reported to achieve a TON<sub>CO</sub> of 70 in anhydrous MeCN.<sup>32</sup> Another benchmark system consists of a Ru-Re dye-catalyst dyad immobilised on NiO that evolves CO in dry dimethylformamide (DMF) solution.<sup>30</sup> Systems reported in water continue to face activity issues and favour H<sub>2</sub> and HCOO<sup>-</sup> over CO production. Apart from one that produces CO,<sup>10</sup> the few reports on narrow band gap semiconductors in water produce only formate with a TON<sub>HCOO<sup>-</sup></sub> that does not exceed ~20,<sup>6,7</sup> and are all based on Ru-centred metal complex catalysts. Photoelectrochemical production of CO in aqueous solutions was achieved with Re- and Ru-centred catalysts, in dye-catalyst dyads on wide band gap semiconductors<sup>8,9</sup> or immobilised on a hematite photoelectrode,<sup>10</sup> respectively, with the maximum TON<sub>CO</sub> in these systems reaching 125. In these CO-producing systems, H<sub>2</sub> and HCOO<sup>-</sup> also occurred as co-products – the former in quantities above half the amount of CO,<sup>9</sup> and the latter at similar proportions of CO<sup>10</sup> – demonstrating a continued struggle with product selectivity even with molecule-catalysed systems.

Despite not containing precious metals, the performance of our **CotpyP**-functionalised silicon photocathode exceeds all previous reports in both TONs towards CO<sub>2</sub>-reduction products and stability.<sup>6-10,30-32</sup> Although the potential of Si as an earth-abundant light harvester has been recognised to drive homogeneous molecular catalysts for solar CO<sub>2</sub> reduction,<sup>33-35</sup> our work demonstrates the successful immobilisation of such a molecular catalyst onto Si to yield a discrete, functional photocathode from which CO<sub>2</sub> reduction products have been verified. This also allowed us to demonstrate CO production in pure water, which is an important milestone for precious-metal-free, synthetic molecular catalysts immobilised on a photocathode. Demonstrating aqueous CO<sub>2</sub> conversion for more than one day with the Co-centred molecular catalyst photo-driven by Si is an excellent basis for further improvement towards high-performance and scalable systems.

Notably, the performance of **CotpyP** in this photocathode also far exceeds that of any previously reported Co bis(terpyridine) catalyst – whether in solution or immobilised on dark electrodes – in terms of stability and activity.<sup>36</sup> This is even more remarkable when one recognises that the thermodynamic potential offered by the Si|mesoTiO<sub>2</sub> electrode ( $E_{CB(TiO_2)}$  ~ -0.1 V vs. NHE) is rather small, especially when considering the significant overpotential previously reported for cobalt bis(terpyridine) complexes in solution (~ -2.0 V vs. Fc<sup>+</sup>/Fc ≈ -1.4 V vs. NHE).<sup>21,36</sup> In order to gain a deeper understanding of the unexpected activity of our hybrid photocathode (*i.e.*, apparent mismatch of driving force provided by the photoelectrode and literature reports of the catalytic onset of cobalt bis(terpyridines)) and to provide an explanation for the strong solvent-dependent behaviour, detailed mechanistic investigations were executed by (spectro)electrochemical experiments.

### **Mechanistic Studies of Immobilised CotpyP**

CV as well as potential-controlled ATR-IR and confocal resonance Raman (RR) studies were conducted on **CotpyP**-modified mesoporous ITO (mesoITO; particle size < 50 nm, film thickness 3 μm) electrodes. The complementarity of the two spectroscopic techniques delivers a global (ATR-IR) and specific (RR) monitoring approach to elucidate structural changes of the **CotpyP** catalyst under an applied potential. Thin mesoporous ITO electrodes (mesoITO) were elected to perform these experiments due to their conductivity, transparency and high molecular loading abilities that enable access to stronger (spectro)electrochemical signals across a wide potential range. A mechanistic interpretation is provided after presenting the results from these three techniques.

CV of mesoITO|**CotpyP** electrodes were recorded in 9:1 MeCN:H<sub>2</sub>O (0.1 M TBABF<sub>4</sub>) electrolyte solution under N<sub>2</sub> (Figure 5a and Supplementary Figure 17). An anodic sweep displays a reversible redox wave at  $E_{1/2} = -0.12$  V vs. Fc<sup>+</sup>/Fc ( $E_1$ ) that can be assigned to the Co<sup>III</sup>/Co<sup>II</sup> redox couple.<sup>21</sup> Upon scan reversal towards negative potentials, a quasi-reversible

wave emerges at  $E_{1/2} = -1.36$  V vs.  $\text{Fc}^+/\text{Fc}$  ( $E_2$ ). The current density of this wave at  $E_2$  decreases upon consecutive scan cycles with the concomitant appearance of a new reversible redox wave at  $E_{1/2} = -1.10$  V vs.  $\text{Fc}^+/\text{Fc}$  ( $E_3$ ). In agreement with previous reports,<sup>21</sup> waves at  $E_2$  are assigned to the  $\text{Co}^{\text{II}}/\text{Co}^{\text{I}}$  redox couple and the emerging wave at  $E_3$  is therefore attributed to the formation of a  $\text{Co}^{\text{II}}/\text{Co}^{\text{I}}$  couple belonging to a new species that is more easily reduced than the original complex. Notably, although the anodic wave at  $E_3$  can already be observed in the first scan, the corresponding cathodic wave only appears in the second scan (Supplementary Figure 17). In contrast, the  $\text{Co}^{\text{III}}/\text{Co}^{\text{II}}$  couple at  $E_1$  remains largely unchanged throughout cycling. A comparable voltammetric behaviour is observed in 9:1 DMF:H<sub>2</sub>O instead of MeCN:H<sub>2</sub>O (Supplementary Figure 18), indicating that the organic solvent does not seem directly responsible for the couple at  $E_3$ .

Increasing the water content of the electrolyte solution sequentially from 9:1 to 6:4 (MeCN:H<sub>2</sub>O mixtures) results in faster growth of the  $E_3$  redox couple (Figure 5b), which points towards a water/proton-involving process for the formation of the new species. Notably, running CV after removing the applied potential (at an open circuit potential of  $\sim -0.5$  V vs.  $\text{Fc}^+/\text{Fc}$ ) following an initial set of consecutive scans in 9:1 MeCN:H<sub>2</sub>O showed the same voltammetric response as the original 1<sup>st</sup> scan (Figure 5a, compare scans 7 and 8). The latter behaviour suggests that the process is only accessible in 9:1 MeCN:H<sub>2</sub>O if certain conditions induced by electrode polarisation are met; these are discussed further below.

CV of mesoITO|**CotpyP** under a CO<sub>2</sub> atmosphere show a catalytic onset reduction wave ( $E_{\text{cat}} \sim -1.3$  V vs.  $\text{Fc}^+/\text{Fc}$ ) that is more pronounced in 6:4 MeCN:H<sub>2</sub>O compared to 9:1 MeCN:H<sub>2</sub>O (Supplementary Figure 19b), which is consistent with its better activity in our CPPE results above. Notably, the catalytic onset potential occurs  $\sim 700$  mV earlier than those generally reported for Co bis(terpyridine) catalysts in solution.<sup>21</sup>

Confocal RR spectroelectrochemistry was employed to investigate the potential-dependent features of the adsorbed catalyst at a molecular level *in situ* using 413, 458, and 514 nm

excitation wavelengths ( $\lambda_{ex}$ ) to match the strong MLCT transitions of Co bisterpyridine complexes, including those of **CotpyP** (Supplementary Figure 1a-b). The RR spectra of dry mesoITO|**CotpyP** (in absence of solution) were dominated by bands located at 1345, 1473 and 1603  $\text{cm}^{-1}$  with altered relative intensities depending on the employed excitation wavelength (Supplementary Figure 20; characteristic frequencies given in Supplementary Table 4) and are consistent with previous reports for terpyridine-based complexes.<sup>37,38</sup> The high RR intensities are attributed to the high effective surface area resulting from the mesoporous electrode architecture,<sup>37,39</sup> and the strong electronic absorption of the complex in the visible spectrum.<sup>40</sup> The spectrum of the dry mesoITO|**CotpyP** electrode matches that of the **CotpyP** powder and not a cobalt mono(terpyridine) (Supplementary Figure 21a and Supplementary Table 4). Conservation of the structural bis-ligation upon placing the electrode in 9:1 MeCN:H<sub>2</sub>O solution (0.1 M TBABF<sub>4</sub>) is indicated by an unchanged RR band pattern (Supplementary Figure 21b). Potential-dependent confocal RR spectra of mesoITO|**CotpyP** were subsequently recorded at  $E_{app}$  between 0.5 and -1.6 V vs. Fc<sup>+</sup>/Fc (Figure 6a). At positive potentials, a weakly pronounced spectral pattern with major bands located at 1561 (not specifically labelled) and 1611  $\text{cm}^{-1}$  was observed (Supplementary Table 5). Lowering  $E_{app}$  below 0.0 V vs. Fc<sup>+</sup>/Fc caused the disappearance of these bands with a concomitant rise of intense bands at 1345, 1483, 1542 and 1603 (not specifically labelled)  $\text{cm}^{-1}$ , which are in good agreement to those for the native [Co<sup>II</sup>] state in the **CotpyP** powder (Supplementary Figure 21a). Further lowering  $E_{app}$  below -1.0 V vs. Fc<sup>+</sup>/Fc resulted in bands rising at 1466, 1556 and 1593  $\text{cm}^{-1}$  attributed to the [Co<sup>I</sup>] state, with the simultaneous disappearance of the aforementioned **Co<sup>II</sup>tpyP** bands. As these changes were all fully reversible upon changing the potential-step direction, they do not suggest irreversible alteration of the complex over the broad potential window.

The potential-dependent RR spectra of mesoITO|**CotpyP** over the full potential window could be fitted accurately using three component spectra (Supplementary Figure 22; see Methods section for a detailed description). One of the component spectra fully resembles

the RR spectrum obtained for the dry mesoITO|**CotpyP** electrode (in absence of solution; Supplementary Figures 20 and 21b). To confirm that the spectral components can indeed be assigned to three Co oxidation states, relative intensities of the components were plotted against  $E_{app}$ . This approach resulted in matching sigmoidal curves that indicate complete interconversion from one oxidation state to another (Figure 6b). The apparent redox potentials can be estimated from the inflection points of the sigmoidal curves ( $-0.18$  and  $-1.32$  V vs.  $Fc^+/Fc$ ), and match those determined for  $Co^{III}/Co^{II}$  ( $E_1$ ) and  $Co^{II}/Co^I$  ( $E_2$ ) from voltammetric experiments (Figure 5).

Measurements recorded in  $CO_2$ -saturated conditions revealed the same spectral patterns as observed under  $N_2$  (Supplementary Figure 23). Lowering  $E_{app}$  to the catalytic region of  $-1.6$  V vs.  $Fc^+/Fc$ , followed by stepping back to  $0.5$  V vs.  $Fc^+/Fc$  once again demonstrated full reversibility of the spectral features. Holding  $E_{app}$  at  $-1.4$  V vs.  $Fc^+/Fc$  for 10 min resulted in no significant alteration of the **CotpyP** spectrum. Both observations point to preservation of the complex's overall molecular structure and its metal's first coordination sphere, as either loss of a terpyridine ligand or changes in the hapticity of the complex would have afforded significant alterations of the RR spectral pattern and relative intensities (see Supplementary Figure 21a). This highlights the maintained structural integrity of **CotpyP** even after catalytic turnover, which is consistent with the CV and post-CPPE XPS and ATR-IR measurements above. It is however noted that catalytic intermediates that involve opening the coordination sphere are unlikely to be detectable in our experiment's timeframe due to their transient nature.

Interestingly, we noted a singular band at  $1546\text{ cm}^{-1}$  that exhibits altered intensities at potentials more negative than  $-1.0$  V vs.  $Fc^+/Fc$  (*i.e.*  $[Co^I]$ -affording) under  $N_2$  and  $CO_2$  atmospheres (Supplementary Figure 24). Component fit analysis showed that this band exhibits a different potential-dependence to that of **CotpyP**, suggesting that it involves a vibrational mode that is sensitive to a potential-coupled process other than mere reduction. Further, this band was more pronounced in anhydrous MeCN electrolyte solution, while

adding H<sub>2</sub>O (9:1 MeCN/H<sub>2</sub>O, 0.1 M TBABF<sub>4</sub>) resulted in a strong decrease in its intensity. In contrast, replacing H<sub>2</sub>O with D<sub>2</sub>O afforded only minor changes in this band compared to spectra recorded in anhydrous MeCN. Isotopically induced shifts were not observed in the marker band (Supplementary Figure 25a, b, d). On the other hand, adding DCI (95 μM) to the 9:1 MeCN:D<sub>2</sub>O solvent induced a decrease in the band's intensity analogous to that observed when H<sub>2</sub>O was added to MeCN (Supplementary Figure 25c-d). Overall, it is evident that the band at 1546 cm<sup>-1</sup> is sensitive to the apparent acidity of the solution, and would suggest a dependence on a proton-containing function. From these observations and due to the frequency of the band, it appears likely that the 1546 cm<sup>-1</sup> band reflects  $\nu(\text{C}=\text{N})$  and  $\nu(\text{C}=\text{C})$  pyridine ring modes sensitive to the electronic density at the cobalt atom and is therefore also affected by the electronic effect induced by the phosphonic acid group's protonation state. Substituents in the *para* position in pyridine-coordinated complexes have been shown to exert a strong effect on the electron density at the coordinated metal atom.<sup>41</sup> In this respect, the retained intensity of the band at 1546 cm<sup>-1</sup> in the case of these D<sub>2</sub>O experiments could be explained by a lack of shift of the protonation equilibrium of the phosphonic acid groups as a result of the lesser acidity of D<sub>2</sub>O compared to H<sub>2</sub>O.

ATR-IR spectroelectrochemical measurements were also conducted under varying applied potentials, beginning at  $E_{\text{app}} = -0.5 \text{ V vs. Fc}^+/\text{Fc}$  ([Co<sup>II</sup>]-affording potential) and proceeding step-wise from  $E_{\text{app}} = -1.0 \text{ V}$  through to  $-1.5 \text{ V vs. Fc}^+/\text{Fc}$  ([Co<sup>I</sup>]-affording potential; Supplementary Figure 26). In agreement with RR experiments, ATR-IR measurements in dry N<sub>2</sub>, wet N<sub>2</sub> and wet CO<sub>2</sub> conditions likewise did not detect changes in **CotpyP**'s primary coordination sphere. This is indicated by the similar spectral changes under non-catalytic and catalytic conditions as observed in the second derivative and difference spectra of the absorbance in the aromatic terpyridine spectral region (blue regions of Supplementary Figures 27 and 28, respectively). More specifically, additional new bands do not arise in the aromatic region upon applying potentials in different solvent media. The spectra display only mild intensity changes and the few band shifts (e.g., at 1458 cm<sup>-1</sup> and 1390 cm<sup>-1</sup>

characteristic of pyridine ring modes) cannot account for either changes in the hapticity or complete loss of the terpyridine ligands.

Nonetheless, spectroelectrochemical ATR-IR allowed us to probe media-dependent changes specifically in the phosphonate spectral region, affording a qualitative means to monitor their role *in situ* under applied potentials. As can be seen from the absorbance spectra, addition of H<sub>2</sub>O (Supplementary Figure 26b) and, further, CO<sub>2</sub> (Supplementary Figure 26c) results in broadening of the band features in the phosphonate region – shown between 1250 and 900 cm<sup>-1</sup>, corresponding to contributions from the acid's stretching frequencies<sup>42</sup> – indicating a change at the phosphonate group that would be in line with protonation at this site, as previously reported in ATR-IR studies.<sup>42,43</sup> Nevertheless, the broad band features of the phosphonate region are best deconvoluted into their discrete components by computing the second derivatives (Figure 7) of the absorbance spectra. While only a few minor changes in band intensities within this phosphonate region were observed upon reducing **Co<sup>II</sup>tpyP** to **Co<sup>I</sup>tpyP** under dry MeCN conditions (Figure 7a), the addition of water in 9:1 MeCN:H<sub>2</sub>O, N<sub>2</sub>-purged electrolyte solution led to large spectral changes at [Co<sup>I</sup>]-affording potentials across the entire phosphonate region (Figure 7b).<sup>42,43</sup> For instance, changing intensities of bands reflective of  $\nu(\text{P-O})$  and  $\nu(\text{P-OH})$  phosphonate vibrational modes are observed (decrease at 1126, 1082 and 965 cm<sup>-1</sup>; increase at 1168 and 1011 cm<sup>-1</sup>). Under CO<sub>2</sub>, similar but significantly weaker changes to that found under wet N<sub>2</sub>-purged conditions were also observed when lowering  $E_{\text{app}}$  down to catalytic conditions (Figure 7c). Overall, these observed trends are supportive of a change in protonation of the phosphonate group upon addition of water under N<sub>2</sub>, which is later revoked during catalysis in presence of CO<sub>2</sub> due to a difference in the protonation state of the observed steady-state species.

Spectroscopic and electrochemical evidence suggests that the complex's bis(terpyridine) ligation is preserved under (photo)electrocatalytic CO<sub>2</sub> reduction, and that catalysis does not involve irreversible structural alteration to the metal's first coordination sphere (Figures 2, 5a, 6a and Supplementary Figure 23). Considering that the immobilised **CotpyP** displays an

onset for CO<sub>2</sub> reduction at a much more positive potential than that previously observed in solution, and that formate has previously been the only product from cobalt bis(terpyridine)-catalysed CO<sub>2</sub> reduction in water,<sup>44</sup> we propose that the mechanism in our system proceeds differently to that commonly reported for metal bis(terpyridine) complexes.<sup>21,36</sup> Specifically, the catalytic mechanism of our immobilised **CotpyP** species involves retention of the bis-tpy ligation, whereas previous reports of homogeneous Co bis(terpyridine)s suggested that they proceed *via* the irreversible loss of one terpyridine ligand to generate a Co(I) mono(terpyridine).<sup>21</sup> This difference is depicted in Figure 8, which presents structures of both (spectro)electrochemically-supported (**A**, **B**, **C**) and speculated (**D**) molecular species, as discussed below.

The existence of an alternative mechanism for immobilised **CotpyP** is also indicated by the emergence of waves at **E**<sub>3</sub>, which has not been previously reported for cobalt bis(terpyridine)s. Moreover, the latter occurs at a potential just prior to that of the CO<sub>2</sub>-reduction catalytic onset (Figure 5 and Supplementary Figure 19), suggesting that the **E**<sub>3</sub>-related species is non-innocent towards CO<sub>2</sub> reduction. In light of the nature of the changes observed in the RR and ATR-IR spectra, it is probable that all chemical processes resulting from the redox steps at **E**<sub>1</sub>, **E**<sub>2</sub> and **E**<sub>3</sub> occur without major disruption of the Co coordination sphere, thereby ruling out ligand exchange possibilities. Rather, CV, RR and ATR-IR measurements suggest a proton-involving pathway that likely involves the unbound phosphonate group of the [Co<sup>I</sup>] complex. From these observations, we propose that the species formed at **E**<sub>3</sub> is a [Co<sup>I</sup>] complex bearing a diprotonated phosphonic acid (Figure 8, species **C**). We deduce that species **C** can be generated either *via* a proton-coupled electron transfer process (PCET) from **A** or *via* a chemical step from **B**, depending on the water content of the electrolyte solution. The former mechanism was observed at **E**<sub>3</sub> in early CV scans in water-rich solution, whereas **C** required several CV scans to become significantly apparent in water-deficient medium. The promotion of **C**'s formation by the presence of protons can be further supported by: (i) the diminishing of the RR band at 1546 cm<sup>-1</sup> for [Co<sup>I</sup>]

(typically observed in anhydrous MeCN conditions) and (ii) changes in phosphonate group IR frequencies upon addition of water or acid as a result of the protonation of the unbound phosphonate. This can be rationalised in two ways: (i) by the presumed increased basicity of the phosphonate group in the [Co<sup>I</sup>] state as the  $\pi$ -symmetry of the filled Co d-orbital is suggested to allow the electronic density to spread on the  $\pi^*$  levels of the terpyridine (a relatively good  $\pi$ -acceptor)<sup>13</sup> and diminish its electron-withdrawing effect on the phosphonate group, and (ii) by the phosphonic acid's increasing  $pK_a$  or decreasing local pH with negative polarisation of the electrode from the surface potential effect.<sup>45,46</sup>

We attribute the slow growth of **E**<sub>3</sub> in water-poor media to a steady increase of the local proton concentration at the electrode-solution interface upon cycling (as previously observed for metal oxides), which favours the PCET mechanism and further allows for the observed cycle-dependent behaviour in Supplementary Figure 17.<sup>47,48</sup> This hypothesis is supported by the disappearance of wave **E**<sub>3</sub> upon restoring the electrode to its initial state by allowing equilibration at open-circuit conditions (Figure 5a). As such, in such a water-poor medium, we attribute the origin of the oxidation wave of **C** seen in the first scan to the protonation of **B**.

On the other hand, the formation of species **C** is promoted upon increasing the acidity of the medium (by increasing water content and/or purging with CO<sub>2</sub>), with the catalytic potential towards CO<sub>2</sub> reduction close to the potential of the formation of species **C** (Figure 5 and Supplementary Figure 19). These observations ultimately suggest that **C** is involved in the CO<sub>2</sub> reduction mechanism and we thus postulate that, upon reduction of the complex and coordination of CO<sub>2</sub>, **D** is a plausible CO-releasing intermediate. Its formation would involve the de-coordination of one or two pyridines to create a vacant coordination site and, subsequently, the oxidative addition of CO<sub>2</sub>.<sup>49</sup> In fact, the d<sup>8</sup> configuration of [Co<sup>I</sup>] species is likely to favour a square planar or tetrahedral geometry, as well as increase the lability of the ligand.<sup>50,51</sup> Moreover, the pyridine de-coordination is likely to be stabilised by protonation of its nitrogen atom from the diprotonated phosphonic acid due to the latter's lower  $pK_a$  value.<sup>52</sup>

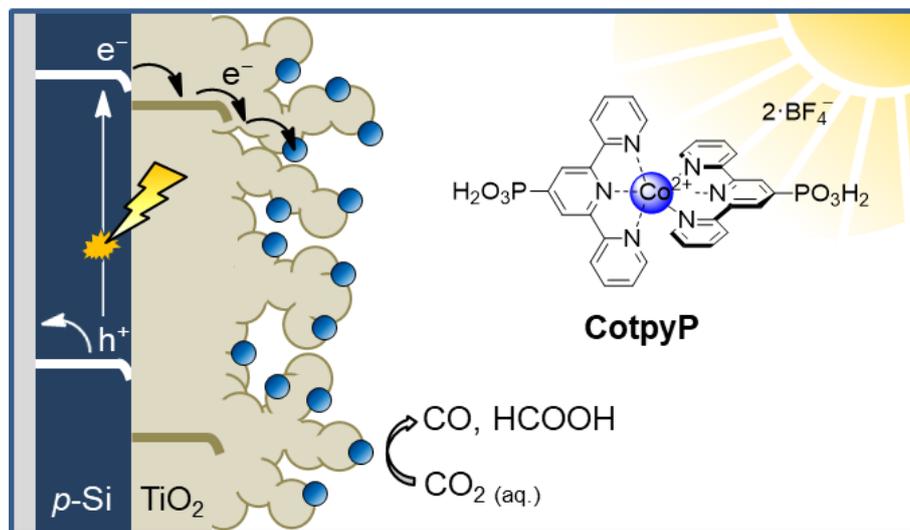
As a result, the deprotonated phosphonic acid could in effect act as a proton relay or H-bond source, facilitating C-O bond cleavage during catalysis. The formation of such a stabilising intermediate would also explain why CO is formed as the major catalytic product at the expense of formate (the only previously-observed CO<sub>2</sub> reduction product in analogous homogeneous conditions) and H<sub>2</sub>, both of which would have required the stabilisation of a Co-H intermediate instead. At this stage, it is difficult to adjudicate whether CO<sub>2</sub> insertion would occur in **C** or only after further reduction of **C**. It is also worth noting that, in the absence of time-resolved experiments, this interpretation does not rule out the possibility that **B** could, upon further reduction, permit CO<sub>2</sub> reduction without necessarily involving **C** and **D** in the mechanism, and the suggested mechanism remains tentative. Nevertheless, the suggested mechanistic pathway contrasts overall with previous reports and suggests exciting benefits of immobilising a metal complex (such as the opportunity to operate in an aqueous solution) that are not accessible in analogous homogeneous systems.<sup>44,50,53</sup>

## CONCLUSIONS

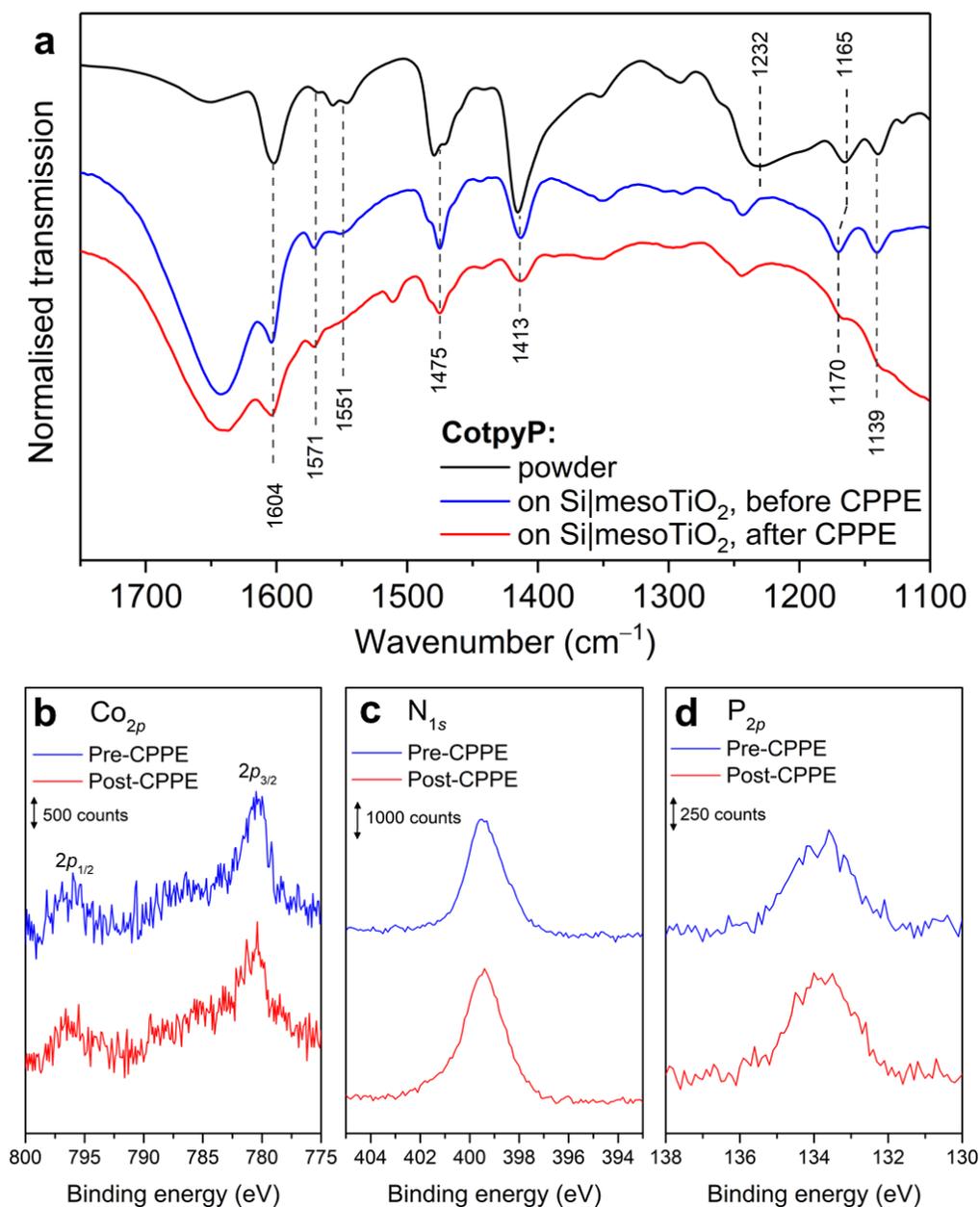
We report a precious-metal-free molecular photocathode towards solar-driven CO<sub>2</sub> reduction. This Si|mesoTiO<sub>2</sub>|**CotpyP** electrode is active towards CO and formate production in both hydro-organic and purely aqueous solution, achieving a TON for CO<sub>2</sub>-reduction products as high as 381 after 24 h – exceeding previously reported benchmarks for molecular photocathodes (including those containing precious metal complexes). Furthermore, with a selectivity towards CO making up ~75% of all gaseous products, our photocathode compares favourably with most reported precious-metal-free photocathodes based on heterogeneous catalysts that deliver state-of-the-art performances. Our results further highlight that altering the water content of the photoelectrocatalysis media has a pronounced effect on the stability, activity, and product selectivity of the photocathode.

Intriguing insights into how the catalyst is permitted to enter its reduced and pre-catalytic state were obtained by cyclic voltammetry as well as *in situ* ATR-IR and RR spectroelectrochemical experiments. The formation of a key intermediate (species **C**) is revealed that creates an alternative CO<sub>2</sub> reduction mechanism without requiring the loss of one terpyridine, which is in sharp contrast to the conventional understanding for metal bis(terpyridine) catalysts in solution. This unexpected mechanistic pathway enabled **CotpyP** to perform CO<sub>2</sub> reduction on Si/mesoTiO<sub>2</sub> thanks to a dramatically lower catalytic onset (700 mV), and consequently led to improved stabilities and a TON four times higher than previously reported for Co terpyridine complexes.<sup>36</sup> This unexpected performance enhancement was ultimately afforded by the synergy of having a phosphonic acid functional group alongside the possibility to operate the system under aqueous conditions – the latter having been conferred by the catalyst's immobilisation. In addition to shedding insight on the behaviour of the complex, these experiments also illustrate the power and precision offered by *in situ* vibrational spectroscopic techniques in the wider context of better understanding molecular catalyst-based solar fuel devices.

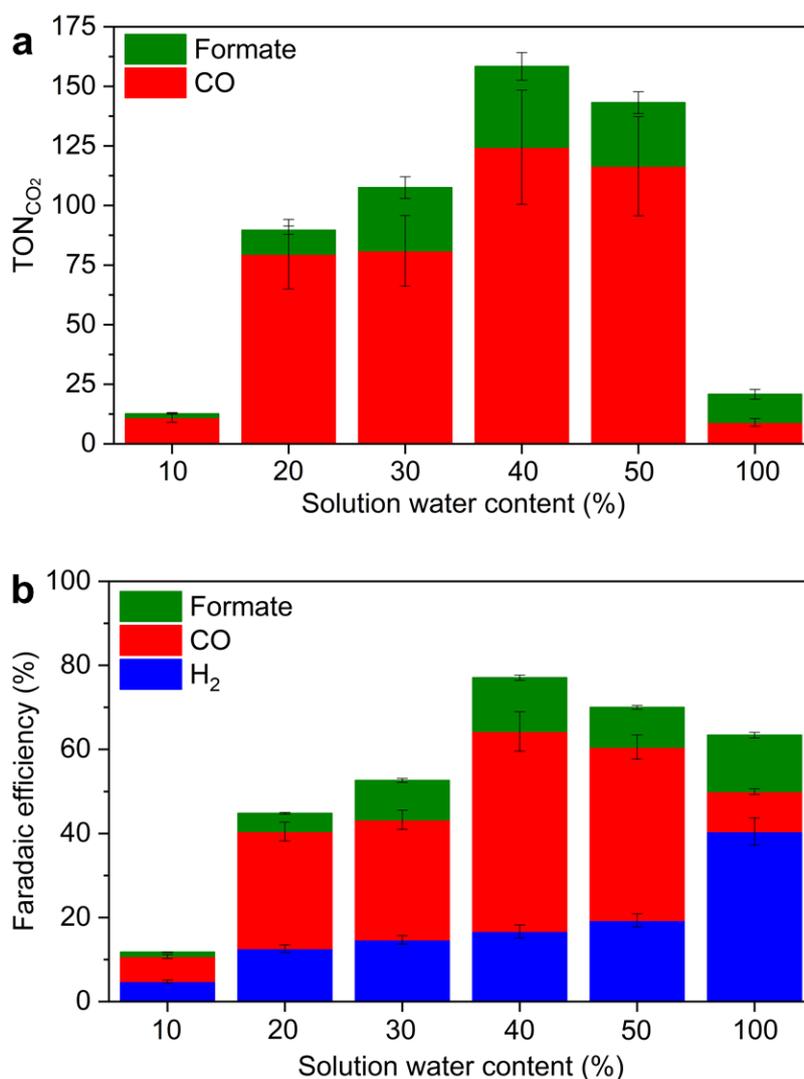
## FIGURES



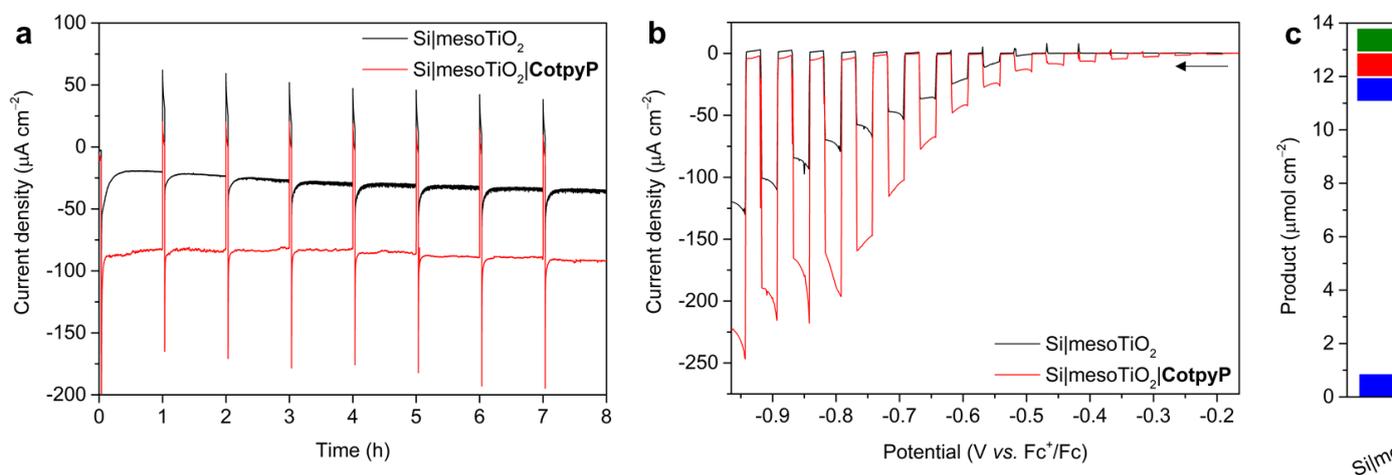
**Figure 1.** Schematic representation of Si|mesoTiO<sub>2</sub>|CotpyP photocathode (not drawn to scale).



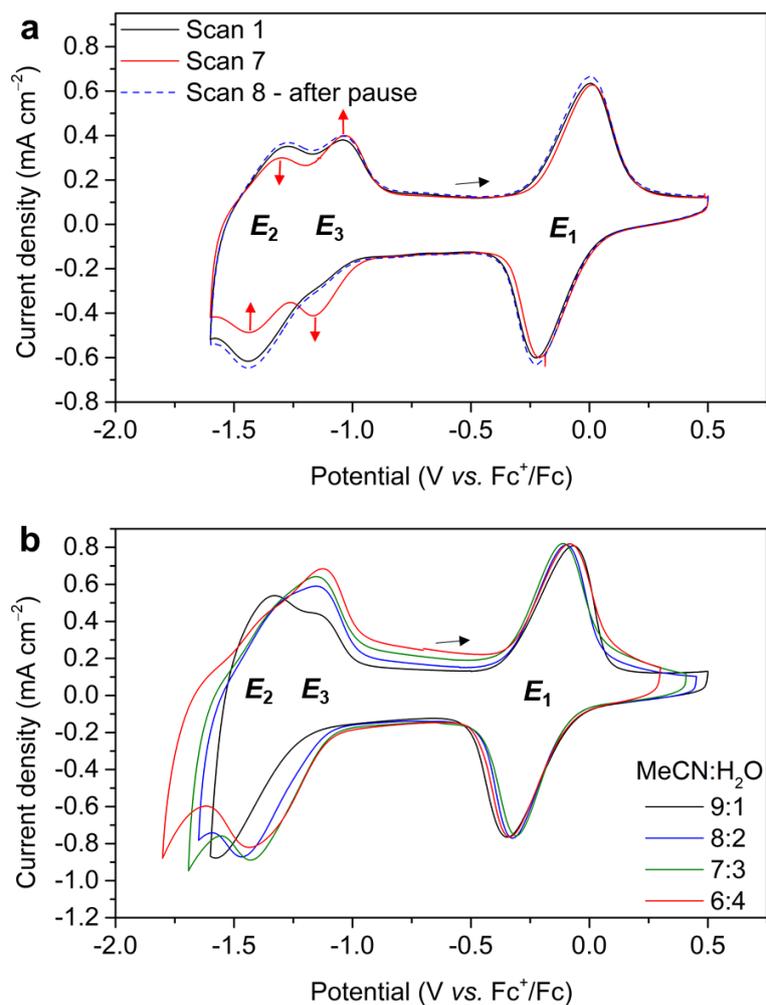
**Figure 2.** Characterisation spectra of **CotpyP** before and after CPPE. (a) ATR-FTIR spectra of **CotpyP** as powder (black trace), and after immobilisation on mesoTiO<sub>2</sub> before (blue trace) and after (red trace) 1 h of CPPE. (b-d) XPS spectra of Si|mesoTiO<sub>2</sub>|**CotpyP** in the Co<sub>2p</sub>, N<sub>1s</sub> and P<sub>2p</sub> regions showing peaks attributed to Co<sup>II</sup>-N, pyridine N and phosphonic acid groups, respectively, before (black traces) and after (red traces) 8 h of CPPE. CPPE conditions:  $E_{app} = -1.0$  V vs. Fc<sup>+</sup>/Fc, 1 Sun (AM1.5G, 100 mW cm<sup>-2</sup>,  $\lambda > 400$  nm), CO<sub>2</sub>-saturated conditions in 6:4 MeCN:H<sub>2</sub>O with 0.1 M TBABF<sub>4</sub> at room temperature.



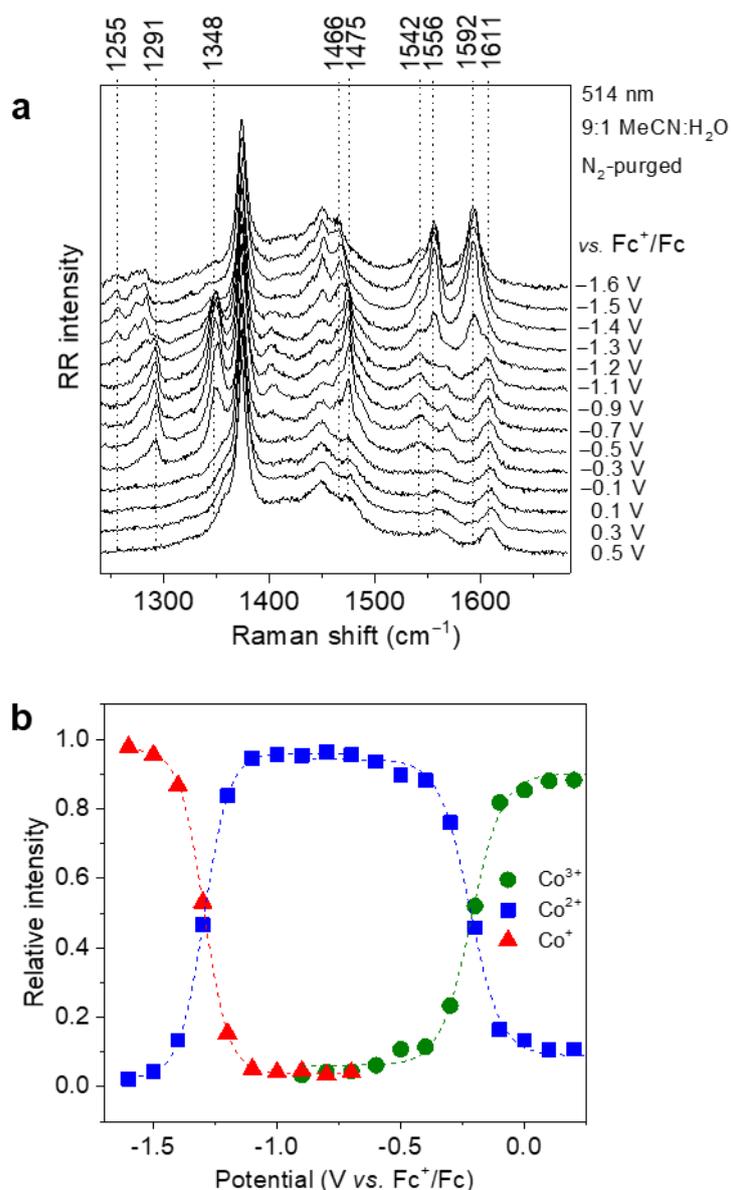
**Figure 3.** Performance of Si|mesoTiO<sub>2</sub>|CotpyP photocathodes in different electrolyte solutions after 8 h of CPPE. (a) TON for CO<sub>2</sub> reduction products (TON<sub>H<sub>2</sub></sub> not included as catalyst-free Si|mesoTiO<sub>2</sub> photoelectrode produces small amounts of H<sub>2</sub>; see Supplementary Figure 13) and (b) FEs (cumulative over the duration of the CPPE) for all products. Conditions:  $E_{app} = -1.0$  V vs. Fc<sup>+</sup>/Fc for MeCN:H<sub>2</sub>O mixtures,  $E_{app} = 0.0$  V vs. RHE for H<sub>2</sub>O; simulated solar light (AM1.5G, 100 mW cm<sup>-2</sup>,  $\lambda > 400$  nm); CO<sub>2</sub>-saturated solutions of TBABF<sub>4</sub> (0.1 M) in MeCN:H<sub>2</sub>O mixtures (solution water content 10-50%) or KHCO<sub>3</sub> (0.1 M) in pure water; room temperature. A tabulated summary of results is available in Supplementary Table 2. Error bars correspond to the standard deviation ( $n = 3$ ).



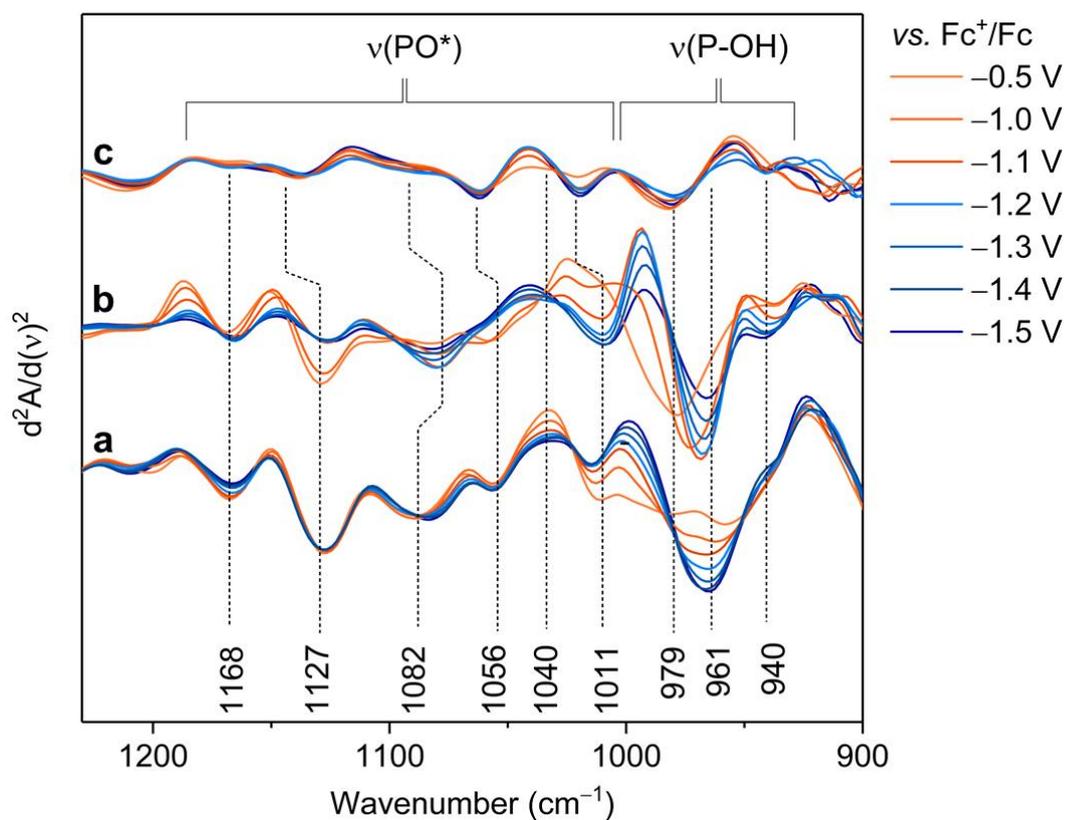
**Figure 4.** Photoresponse of  $\text{Si|mesoTiO}_2|\text{CotpyP}$  in catalytic conditions and control experiments. (a) CPPE ( $J-t$ ) (under photo-saturated conditions) with  $\text{Si|mesoTiO}_2$  (black trace) and  $\text{Si|mesoTiO}_2|\text{CotpyP}$  (red trace) photocathodes under continuous dark chop (for close-up see Supplementary Figure 8). (b) LSVs of  $\text{Si|mesoTiO}_2$  and  $\text{Si|mesoTiO}_2|\text{CotpyP}$  with continuous photo-saturated conditions); the arrow indicates scan start. (c) Product analysis from  $\text{Si|mesoTiO}_2|\text{CotpyP}$  and control experiments. Conditions: 6:4 MeCN:H<sub>2</sub>O with TBABF<sub>4</sub> (0.1 M); 1 Sun (AM1.5G, 100 mW cm<sup>-2</sup>,  $\lambda > 400$  nm); room temperature vs.  $\text{Fc}^+/\text{Fc}$ .



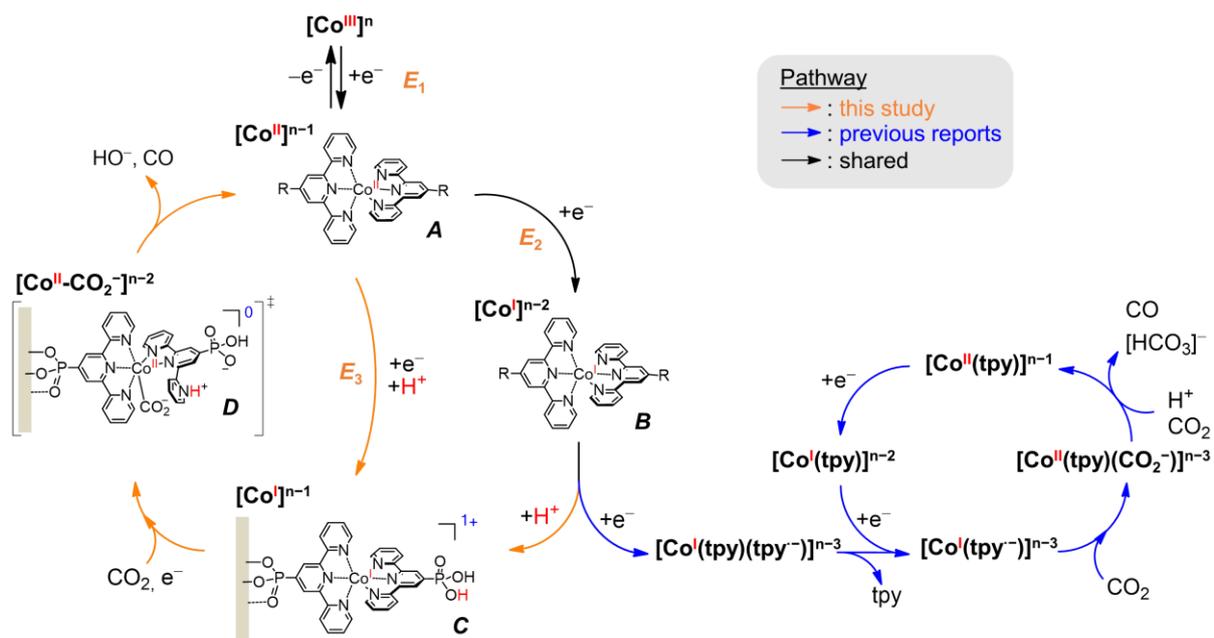
**Figure 5.** Cyclic voltammograms of mesoITO|CotpyP. (a) Consecutive CV scans of mesoITO|CotpyP in 9:1 MeCN:H<sub>2</sub>O (0.1 M TBABF<sub>4</sub>) with scans 1 and 7 being shown (red arrows indicate change in wave intensities); scan 8 was recorded after a pause at open circuit potential. (b) CV scans of mesoITO|CotpyP in MeCN:H<sub>2</sub>O ratios of 9:1, 8:2, 7:3 and 6:4 (0.1 M TBABF<sub>4</sub>), with scan 1 shown. Black arrows indicate scan start. Conditions:  $\nu = 50 \text{ mV s}^{-1}$ ; N<sub>2</sub> atmosphere; room temperature.



**Figure 6.** Confocal RR spectroelectrochemistry of mesoITO|CotpyP. (a) RR spectra at different  $E_{\text{app}}$ . (b) Relative intensities of the Co<sup>3+</sup>, Co<sup>2+</sup> and Co<sup>+</sup> redox species as a function of  $E_{\text{app}}$ , with inflection points at  $-0.18$  and  $-1.32$  V vs. Fc<sup>+</sup>/Fc. The relative intensities were derived using component fit analysis of the RR spectra (Supplementary Figure 22). Conditions: 9:1 MeCN:H<sub>2</sub>O (0.1 M TBABF<sub>4</sub>, N<sub>2</sub>) at room temperature,  $\lambda_{\text{ex}} = 514$  nm. Note that due to the intrinsically lower RR activity of Co<sup>3+</sup> and Co<sup>2+</sup> species causing an inaccuracy in the calculation procedure of about 10%, the relative intensities of Co<sup>2+</sup> and Co<sup>3+</sup> at positive potentials do not reach full redox conversion conditions, *i.e.* 0 and 1, respectively.



**Figure 7.** ATR-IR spectroelectrochemistry of immobilised **CotpyP**. Second derivatives of ATR-IR absorbance spectra in the phosphonate spectral region taken of mesoITO|**CotpyP** at different  $E_{app}$  (Supplementary Figure 26) in (a)  $N_2$ -purged MeCN, (b)  $N_2$ -purged 9:1 MeCN:H<sub>2</sub>O and (c)  $CO_2$ -purged 9:1 MeCN:H<sub>2</sub>O (0.1 M TBABF<sub>4</sub> in all cases) at room temperature. All spectra have been referenced to background spectra recorded from catalyst-free mesoITO for each of the above conditions. \* indicates contributions from all possible P–O single bonds.



**Figure 8.** Proposed CO<sub>2</sub> reduction catalytic mechanism for immobilised **CotpyP**. Proposed catalytic mechanism and postulated intermediates for CO<sub>2</sub>-to-CO reduction for immobilised **CotpyP** compared to the previously reported pathway for homogenous [Co(tpy)<sub>2</sub>]<sup>2+</sup> (adapted from ref. 23).  $E_1$ - $E_3$  refer to potentials recorded in 9:1 MeCN:H<sub>2</sub>O solutions of the indicated redox couples in this study. R in **A** and **B** is respective to individual reports (this work and ref. 24). It is noted that alternative CO<sub>2</sub>-reducing mechanisms with a bis(terpyridine) ligation cannot be entirely ruled out based on our data.

## METHODS

### Materials

Chemicals purchased for analytical measurements were of the highest available purity. Boron-doped Si wafers (resistivity of 1-10 ohm-cm; <100>; 500  $\mu\text{m}$  thickness; single-side polished) were purchased from University Wafer. Ti foil (0.25 mm thick, 99.5 %) was purchased from Alfa Aesar. The  $\text{TiO}_2$  paste was purchased from Solaronix (15-20 nm, Ti-Nanoxide T/SP, 100% anatase). Fluorine-doped tin oxide (FTO)-coated glass sheets were purchased from Sigma Aldrich ( $\text{SnO}_2/\text{F}$ ,  $7 \Omega \text{ sq}^{-1}$  sheet resistance,  $300 \times 300 \times 2 \text{ mm}$ ). ITO nanopowder (< 50 nm particle size; BET =  $27 \text{ m}^2 \text{ g}^{-1}$ ; 90%  $\text{In}_2\text{O}_3$ , 10%  $\text{SnO}_2$ ) was obtained from Sigma Aldrich.  $\text{KHCO}_3$  and  $\text{Co}(\text{BF}_4)_2 \cdot 6\text{H}_2\text{O}$  (96%) were purchased from Alfa Aesar and 2,2':6',2''-terpyridine-4'-phosphonic acid was purchased from HetCat, Switzerland (98%).  $\text{TBABF}_4$  was purchased from Sigma Aldrich ( $\geq 99.0\%$ , electrochemical grade). MeOH and MeCN were both distilled over calcium hydride before use. All aqueous experimental solutions were prepared with ultrapure water (DI water; Milli-Q<sup>®</sup>,  $18.2 \text{ M}\Omega \text{ cm}$ ).  $^{13}\text{CO}_2$  (> 99 atom %  $^{13}\text{C}$ ) was purchased from Sigma Aldrich. Mono(terpyridine) [ $\text{CoCl}_2(\text{tpy})$ ] was prepared following a previously-reported procedure.<sup>54</sup>

### Physical Characterisation

$^1\text{H}$  and  $^{31}\text{P}$  NMR spectra were recorded on a Bruker 500 MHz DCH cryoprobe spectrometer at room temperature. Chemical shifts are given in ppm and coupling constants in Hz. Chemical shifts for  $^1\text{H}$  NMR spectra are referenced relative to residual protium in the deuterated methanol (Eurisotop). High resolution-mass spectra were recorded using a ThermoScientific Orbitrap Classic mass spectrometer. UV-vis spectra were collected using a Varian Cary 50 Bio UV-vis spectrometer. For solution spectra, a quartz cuvette (Hellma, 1 cm path length) was used. ATR-FTIR spectra were recorded on a Nicolet iS50 spectrometer. Elemental analysis was carried out by the Microanalysis Service of the Department of Chemistry, University of Cambridge, using a Perkin-Elmer 240 Elemental Analyser.

Inductively coupled plasma optical emission spectrometry (ICP-OES) measurements were conducted by the Microanalysis Service of the Department of Chemistry, University of Cambridge, on a Thermo Scientific iCAP 7400 ICP-OES DUO spectrometer. XPS was performed on a Thermo Fisher Scientific K-alpha<sup>+</sup> spectrometer using a micro-focused monochromatic Al X-ray source (72 W) over an area of approximately 400 microns, with argon sputtering performed using a Thermo Scientific MAGCIS source operating in the monatomic mode at 4 kV over a raster area of approximately 2 mm<sup>2</sup>. Data analysis was performed in CasaXPS using a Shirley type background and Scofield cross sections, with an energy dependence of -0.6.

### Synthesis and Characterisation of CotpyP Catalyst

2,2':6',2''-terpyridine-4'-phosphonic acid (**tpyP**; 30.0 mg,  $9.6 \times 10^{-5}$  mol) and  $\text{Co}(\text{BF}_4)_2 \cdot 6\text{H}_2\text{O}$  (14.3 mg,  $4.2 \times 10^{-5}$  mol) were placed in a round bottom flask under  $\text{N}_2$  atmosphere and solubilised with 6 mL of MeOH (a few drops of water can be added to improve the solubility). The solution was stirred for 24 h at room temperature during which the colour gradually turned from colourless to red-brown, attesting to the formation of the cobalt bis(terpyridine) complex. 4 mL of ethanol was then added, followed by ethyl acetate to precipitate the complex. The solid was filtered off on Millipore and washed with ethyl acetate. The solid was dried under vacuum to afford 21 mg of **CotpyP** complex as a fine brown powder (58%). <sup>1</sup>H NMR (MeOD, 500 MHz):  $\delta_{\text{H}}$  (ppm) = 91.00 (bs, H<sup>5</sup>), 52.39 (s, H<sup>2</sup>), 38.82 (s, H<sup>4</sup>), 32.86 (s, H<sup>1</sup>), 9.74 (s, H<sup>3</sup>) (assignment based on ref. 12); <sup>31</sup>P NMR (MeOD, 202 MHz):  $\delta_{\text{P}}$  (ppm) = 34.25; FT-IR (ATR):  $\sigma$  (cm<sup>-1</sup>): 1604, 1558, 1480, 1416, 1166, 1140. HRMS (+ESI, m/z): calcd. for  $\text{C}_{30}\text{H}_{23}\text{O}_6\text{N}_6^{56}\text{Co}_1\text{P}_2$   $[\text{M}-\text{H}^+-2 \cdot \text{BF}_4^-]^+$ : 684.0481; found, 684.0472. Anal. calcd. for  $\text{C}_{30}\text{H}_{24}\text{B}_2\text{Co}_1\text{F}_8\text{N}_6\text{O}_6\text{P}_2$ : C, 41.95; H, 2.82; N, 9.78; P, 7.21; found: C, 41.76; H, 3.22; N, 9.57; P, 7.32. UV-vis. (MeOH):  $\lambda_{\text{max}}$  (nm) = 320, 448, 510, 555.

### **Fabrication of mesoITO Electrode**

FTO-coated glass sheets were cut into 1 cm × 3 cm pieces and cleaned by immersing them in a solution of water, ammonia (35%, Fisher Scientific) and hydrogen peroxide (30% w/v, Breckland Scientific Supplies) in a 5:1:1 v/v ratio at 70 °C for 30 min. The glass slides were subsequently sonicated in water and dried at room temperature. An ITO suspension consisting of 20 wt % of ITO nanopowder (particle size < 50 nm) in 5 M acetic acid in ethanol was prepared and sonicated well. This was spin-coated onto the cleaned FTO glass slides over a 1 × 0.8 cm area defined using Scotch<sup>®</sup> tape (3M) as spacers, using a volume of 200 μL per slide and a spin speed of 1000 rpm over 1 min. The solution was left to dry completely in air before removing the tape and annealing in a Carbolite furnace under atmospheric conditions using the following temperature program: heating from 25 °C to 400 °C (5 °C min<sup>-1</sup>), holding at 400 °C for 30 min before slowly cooling down to room temperature in the furnace chamber.

### **Fabrication of Si|mesoTiO<sub>2</sub> Electrode**

The preparation of the Si|mesoTiO<sub>2</sub> electrode (TiO<sub>2</sub> layer thickness ≈ 6 μm) was conducted following a previously reported procedure.<sup>15</sup> In brief, the Si wafer is etched with HF acid, followed by immediate deposition and sintering of a mesoTiO<sub>2</sub> film.

### **Fabrication of Ti|mesoTiO<sub>2</sub> Electrode**

The Ti foil (10 × 20 × 0.25 mm) was sonicated sequentially in isopropanol and ethanol for 30 min, and dried under a flow of N<sub>2</sub>. Subsequent deposition of the mesoTiO<sub>2</sub> film was conducted in the same manner as that on Si to make Si|mesoTiO<sub>2</sub> electrodes (above).

## Assembly of CotpyP mesoITO, Ti|mesoTiO<sub>2</sub> and Si|mesoTiO<sub>2</sub>

Immobilisation of **CotpyP** on mesoITO, Ti|mesoTiO<sub>2</sub> or Si|mesoTiO<sub>2</sub> was carried out by soaking the electrodes in a methanolic solution of **CotpyP** (prepared by the dropwise addition of a MeOH solution of **tpyP** to a MeOH solution of Co(BF<sub>4</sub>)<sub>2</sub>·6H<sub>2</sub>O to give a final concentration of 0.25 mM) for 16 h. The mesoITO|**CotpyP**, Ti|mesoTiO<sub>2</sub>|**CotpyP** and Si|mesoTiO<sub>2</sub>|**CotpyP** electrodes were rinsed with MeOH and dried prior to use. In the case of the control experiment using a Si|mesoTiO<sub>2</sub>|Co(BF<sub>4</sub>)<sub>2</sub> electrode, a solution of the Co(BF<sub>4</sub>)<sub>2</sub>·6H<sub>2</sub>O salt (0.25 mM) was used to sensitise the Si|mesoTiO<sub>2</sub> electrode instead of **CotpyP**.

In the case of Ti|mesoTiO<sub>2</sub>|**CotpyP** and Si|mesoTiO<sub>2</sub>|**CotpyP**, the photocathodes were subsequently back-contacted and insulated by an epoxy adhesive prior to further use. Sand paper was used to abrade the back of the electrodes (unpolished Si side for Si electrodes) before application of a conductive silver paint (RS<sup>®</sup> Components 186-3593), after which an electrical wire was connected to the dry silver using the same conductive silver paint. Upon drying, an off-white opaque epoxy adhesive (Loctite<sup>®</sup> EA 9466) was applied on both sides of the electrodes, leaving only the photoactive surface ( $S \approx 0.2 \text{ cm}^2$ ) exposed. The cells were allowed to dry thoroughly for 40 h in air before use.

## Quantification of Catalyst Loading

The quantification of the amount of immobilised **CotpyP** (mole per geometrical area) on the Si|mesoTiO<sub>2</sub>|**CotpyP** electrodes was evaluated in triplicate by inductively coupled plasma optical emission spectrometry (ICP-OES) after digestion of Si|mesoTiO<sub>2</sub>|**CotpyP** electrodes ( $\approx 1 \text{ cm}^2$  film area) in aqueous HNO<sub>3</sub> (70%) overnight and dilution to 2% v/v with MilliQ<sup>®</sup> water.

## Electrochemistry

Electrochemical experiments were performed with an Ivium CompactStat potentiostat. A three-electrode configuration was employed in airtight compartments, with a Pt mesh as the counter electrode (CE) and a Ag/AgCl electrode in either saturated  $\text{KCl}_{(\text{aq.})}$  for aqueous experiments or in a solution with the same composition as the electrolyte for organic-water mixture experiments as the reference electrode (RE). In organic-water mixtures, the RE was regularly referenced against the ferrocene couple ( $\text{Fc}^+/\text{Fc}$ ). Variations in the potential of the  $\text{Fc}^+/\text{Fc}$  couple in different solvent mixtures were taken into account.<sup>55</sup> The electrolyte was tetrabutylammonium tetrafluoroborate (0.1 M) in organic-water mixtures and  $\text{KHCO}_3$  (0.1 M) in aqueous solutions. All electrochemical measurements were performed at room temperature.

CV scans were recorded with mesoITO-based working electrodes (WE) in the dark in one-compartment cells. The electrolyte solution was purged with either  $\text{N}_2$  or  $\text{CO}_2$  for 15 min to remove atmospheric  $\text{O}_2$ .

LSVs and CP(P)E were performed on Ti|mesoTiO<sub>2</sub>- and Si|mesoTiO<sub>2</sub>-based electrodes as the working electrodes, the former in the dark and the latter under illumination. A Newport Oriel Xenon 150 W solar light simulator (100 mW cm<sup>-2</sup>, AM1.5G containing IR water and UV ( $\lambda < 400$  nm) filters) was used as the light source in the case of Si|mesoTiO<sub>2</sub>-based electrodes; an additional neutral density filter was used in the case of light intensity dependence LSV studies on Si|mesoTiO<sub>2</sub>|**CotpyP** to vary the light intensity between 0-100% of 1 Sun.

Custom-made airtight two-compartment photoelectrochemical cells were employed for all (photo)electrochemical measurements, where a glass frit or Nafion membrane was used to separate the compartments for organic-water mixtures or aqueous solutions, respectively. LSVs were conducted at a scan rate of 5 mV s<sup>-1</sup>, with chopped light alternating between dark and light every 5 s for Si|mesoTiO<sub>2</sub>|**CotpyP** electrodes.  $E_{\text{cat}}$  was defined as the potential at which a photocurrent density of  $|j| = 10 \mu\text{A cm}^{-2}$  was achieved by the respective

electrode. The applied potential during CPPE was  $-1.0$  V vs.  $\text{Fc}^+/\text{Fc}$  or  $0.0$  V vs. RHE in organic-water or pure water solutions, respectively. Continuous illumination was maintained, apart from hourly dark chops lasting for 2 min each. The applied potential during CPE in the dark on  $\text{Ti|mesoTiO}_2$ -based electrodes was varied between  $-1.0$ ,  $-1.2$ ,  $-1.3$  and  $-1.4$  V vs.  $\text{Fc}^+/\text{Fc}$ .

Prior to all (photo)electrochemical experiments, the electrolyte solution in both compartments of the photoelectrochemical cell was purged with  $\text{CO}_2$  containing 2%  $\text{CH}_4$  as an internal standard for gas chromatography measurements; the only exception was in the case of  $\text{N}_2$  atmosphere control experiments, where the solution was purged with  $\text{N}_2$  containing 2%  $\text{CH}_4$ . The amount of gaseous  $\text{CO}$  and  $\text{H}_2$  produced was analysed by headspace gas analysis using a Shimadzu Tracera GC-2010 Plus with a barrier discharge ionization detector (BID). The GC was equipped with a ShinCarbon micro ST column (0.53 mm diameter) kept at  $40$  °C using helium carrier gas. Aliquots ( $50$   $\mu\text{L}$ ) of the headspace gas were removed from the sealed photoelectrochemical vessel using a gastight syringe (Hamilton, GASTIGHT®) for GC analysis at hourly time intervals. Formic acid was analysed by ion chromatography using a Metrohm 882 compact IC plus ion chromatography system, with a solution of carbonate ( $4$  mM) containing acetone ( $50$   $\text{mL L}^{-1}$ ) as the eluent after calibration with solutions of different known formate concentrations. The FE of the photocathodes was calculated by comparing the expected amount of total product as indicated by the total charge passed through the electrode and the actual amount produced. Analytical measurements were performed in triplicate and the standard deviation of each data point is given in the supporting tables and denoted by error bars in the graphs.

### Isotopic Labelling

CPPE of the  $\text{Si|mesoTiO}_2|\text{CotpyP}$  electrode was performed under 6:4 MeCN:H<sub>2</sub>O conditions with  $^{13}\text{CO}_2$  as the headspace gas. After 4 h, the photoelectrochemical cell headspace was

transferred to an evacuated gas IR cell (SpecAc, 10 cm path length, equipped with KBr windows) and a high-resolution transmission spectrum was collected on a Thermo Scientific Nicolet iS50 FT-IR spectrometer.

### **Spectroelectrochemical Resonance Raman Spectroscopy**

RR measurements of mesoITO|**CotpyP** were carried out using the 413 nm line of a Kr ion laser (Sabre), and the 458 nm and 514 nm lines of an Ar ion laser (Coherent Innova 300c). A Horiba LabRamII confocal Raman spectrometer equipped with a liquid nitrogen-cooled CCD detector (Symphony) was employed. The laser light was focused onto the sample using a 20× objective (Nikon, 20×, NA 0.05). Potentials during the Raman spectroscopic experiments were applied using a multichannel potentiostat (Metrohm MicroAutoLab). Measurements were carried out in anhydrous MeCN or 9:1 MeCN:H<sub>2</sub>O/9:1 MeCN:D<sub>2</sub>O with 0.1 M TBABF<sub>4</sub> as electrolyte. As counter and reference electrodes, a hydrogen flame-cleaned Pt wire and a leak-free Ag/AgCl in 0.1 M H<sub>2</sub>SO<sub>4</sub> (DriRef, WPI) were used, respectively. To acidify the 9:1 MeCN:D<sub>2</sub>O mixture, DCl was added (final concentration: 95 μM). The samples were moved during measurements using an xy-stage (OWISoft) to avoid laser-induced sample degradation.

Analysis of the spectra was performed using a home-made software (Qipsi) and component fitting analyses were performed following published procedures.<sup>39,56</sup> To derive the component spectra, RR spectra of mesoITO|**CotpyP** using 514 nm excitation recorded at very positive (0.5 V vs. Fc<sup>+</sup>/Fc), intermediate (-0.5 V vs. Fc<sup>+</sup>/Fc) and very negative potentials (-1.5 V vs. Fc<sup>+</sup>/Fc) were considered first. These spectra were each expected to be spectrally dominated by the **CotpyP** species in only one oxidation state ([Co<sup>III</sup>], [Co<sup>II</sup>] and [Co<sup>I</sup>], respectively). The spectra were iteratively fitted using Lorentzian bands by iteratively varying their absolute intensity, half-width and frequency until a full reproduction of the spectra was achieved. The resulting bands were grouped to afford a component spectrum,

*i.e.* three spectra were derived in total. RR spectra measured at intermediate potentials were finally fitted using the so-derived component spectra allowing only a variation by a fitting parameter factor *GF*, *i.e.* varying spectral contribution of a respective component spectrum to overall RR spectrum.

Group intensities were obtained by multiplying *GF* with a prominent, highly intense band found in the respective component spectrum to obtain the intensity of the respective *i* component spectrum *I<sub>i</sub>*. Relative intensities *I<sub>i,rel</sub>* for a component spectrum *i* were calculated using:

$$I_{i,rel} = \frac{I_i}{(\sum_f I_f)}$$

### **Spectroelectrochemical Infrared Spectroscopy**

Spectroelectrochemical ATR-IR measurements were carried out on mesoITO|**CotpyP** prepared on a Si ATR prism. An ITO suspension consisting of 10 wt % of ITO nanopowder in 5 M acetic acid in ethanol was prepared and sonicated well. This was spin-coated onto the flat surface of the Si ATR-prism over the complete area of 3 cm<sup>2</sup>, using a volume of 50 μL and a spin speed of 1000 rpm over 1 minute. The solution was left to dry completely in air before annealing at 400 °C for 30 min (5 °C min<sup>-1</sup>) under atmospheric conditions. **CotpyP** was adsorbed from 1 mL of the catalyst stock solution in MeOH (0.25 mM) for 45 min at room temperature. After the adsorption process was completed, the catalyst solution was removed from the ATR cell and the electrode rinsed several times with MeOH.

Spectroelectrochemical ATR-IR measurements were performed in a single-reflection PIKE ATR-IR setup and a customised ATR -IR spectroelectrochemical cell using an angle of incidence of 60°. The electrochemical studies were carried out in a three-electrode system with the mesoITO|**CotpyP** film as WE, a Ag/AgCl electrode (in a solution with the same composition as the electrolyte) as RE, and a Pt wire as CE. Potentials were applied using an Ivium CompactStat potentiostat. The ATR-IR spectra were recorded in a spectral range from 4000 to 900 cm<sup>-1</sup> (note that the range below 900 cm<sup>-1</sup> is inaccessible due to strong

absorption by the Si ATR prism) with a spectral resolution of  $4\text{ cm}^{-1}$  on a Bruker Vertex 70 spectrometer equipped with a photovoltaic MCT detector. A total of 200 scans were co-added for one spectrum, requiring an accumulation time of 1.5 min. All measurements were carried out at room temperature under either  $\text{N}_2$  or  $\text{CO}_2$  overpressure.

ATR-IR spectra were evaluated using the OPUS 5.5 software. Absorbance spectra (A) were generated according to the Lambert–Beer equation:

$$A = -\log \frac{I_{\text{sample}}}{I_{\text{reference}}}$$

$I_{\text{sample}}$  denotes the sample spectrum and  $I_{\text{reference}}$  denotes the respective reference spectrum for absorbance spectra. Baseline corrections of the absorbance spectra and second derivative spectra were generated by means of the OPUS 5.5 software data analysis tools.

## DATA AVAILABILITY

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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## Competing Interests

The authors declare no competing interest.

## Author Contributions

J.J.L., J.W. and E.R. conceived the research. J.W. synthesised and characterised **CotpyP**. J.J.L., J.W. and D.H.N. prepared the electrodes. J.J.L. and J.W. carried out physical characterisation of the electrodes, J.J.L. the (photo)electrochemical experiments, K.H.L. the spectroelectrochemical RR measurements, and N.H. and J.J.L. the spectroelectrochemical ATR-IR measurements. J.J.L., J.W., K.H.L., N.H. and E.R. analysed the data. M.F.K. carried out initial preliminary investigations on **CotpyP**. J.J.L., J.W., K.H.L., N.H., M.F.K. and E.R. contributed to the creation of the manuscript. E.R. supervised the work.