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# Light-driven CO<sub>2</sub> reduction with substituted imidazole-pyridine Re catalysts favoring formic acid production†

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Removing carbon dioxide from the atmosphere is an attractive way to mitigate the greenhouse gas effect that contributes to climate change. A series of donor- $\pi$  (D- $\pi$ ), acceptor- $\pi$  (A- $\pi$ ), and  $\pi$  Re(I) pyridyl imidazole complexes have been synthesized and examined under photocatalytic conditions for the photocatalytic reduction of CO<sub>2</sub>. The catalytic activity of the complexes was further supported by cyclic voltammetry through the presence of a catalytic current under CO<sub>2</sub> atmosphere. The D- $\pi$ ,  $\pi$ , and A- $\pi$  complexes were studied to elucidate the effects of incorporating conjugated electron donating vs. withdrawing groups on the catalytic rates and product selectivity. The synthesized complexes were compared with Re(bpy)(CO)<sub>3</sub>Br (where bpy is 2,2'-bipyridine), the benchmark catalyst for this transformation. Remarkably, the complex with A- $\pi$  pendant (**RC4**) outperformed the  $\pi$  (**RC2–3**) and D- $\pi$  (**RC5**) complexes for the production of formic acid (HCO<sub>2</sub>H) in the presence of photosensitizer [Ru(bpy)<sub>3</sub>]<sup>2+</sup> and sacrificial electron donor BIH (1,3-dimethyl-2-phenyl-2,3-dihydro-1*H*-benzo[d]-imidazole). Among the investigated catalysts, **RC4** with the A- $\pi$  pendant showed the highest turnover number (TON) value of 844 for HCO<sub>2</sub>H production with 86% carbon selectivity. In stark contrast to the imidazole-pyridine based catalysts reported here that favor formic acid as a product, Re(bpy)(CO)<sub>3</sub>Br generated no formic acid under the same conditions. The imidazole-pyridine complexes also function as catalysts for CO<sub>2</sub> reduction without an added photosensitizer, however, the TON values under self-sensitized conditions are poor.

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## Introduction

Currently, CO<sub>2</sub> is the largest greenhouse gas emitted in the world.<sup>1</sup> There is a considerable effort to convert this relatively untapped waste product into renewable fuels. While the thermodynamic reduction potentials of transforming CO<sub>2</sub> to various products (CO, formic acid, methanol, methane, *etc.*) can be modest depending on the conditions,<sup>2</sup> the kinetics are slow and a catalyst is required to lower activation barriers and direct selectivity for the desired product.<sup>3</sup> Ideally, the energy required for catalysis is obtained directly from the sun or indirectly using solar photovoltaics to drive the electrochemistry. One reasonable goal for CO<sub>2</sub> valorization is to selectively reduce CO<sub>2</sub> to formic acid (HCO<sub>2</sub>H), which can be used directly in formic acid

fuel cells<sup>4</sup> or as a safe and easily transported H<sub>2</sub> storage material.<sup>5,6</sup> We note that CO is also a valuable product that can be transformed into hydrocarbon fuels *via* the Fischer–Tropsch process.<sup>7</sup>

The most well-studied mononuclear photocatalysts are derived from Lehn's original Re(bpy)(CO)<sub>3</sub>X (X = Cl, Br) catalyst,<sup>8–10</sup> which has been modified extensively with the goal to improve the catalytic performance.<sup>11–14</sup> Modification of the bidentate ligand has included introducing redox sites,<sup>15</sup> ancillary Lewis acids,<sup>16</sup> and other moieties to the second coordination sphere<sup>17</sup> (proton relays,<sup>18</sup> charged groups,<sup>19</sup> hydrogen bond donors<sup>20,21</sup>) to facilitate proton transfer events or stabilize intermediates,<sup>8</sup> change the local pH,<sup>22</sup> or increase the onset of visible light absorption.<sup>23</sup> Recently, Liang-Nian and coworkers reported an approach to increase the efficiency of the Re(bpy)-based photocatalyst by introducing chromophores onto the bipyridyl ligand, which yielded TONs as high as 1323 and  $\Phi_{\text{CO}}$  up to 55%.<sup>24</sup> Another approach by Jurss and coworkers studied the effect of pendant light absorbing anthracene chromophores in mono- and di-nuclear anthracenyl Re(bpy) catalysts and found that especially in di-nuclear catalysts the ligand-based triplet state was highly influential.<sup>25</sup> With these two works as a conceptual backdrop, we seek to improve the overall light

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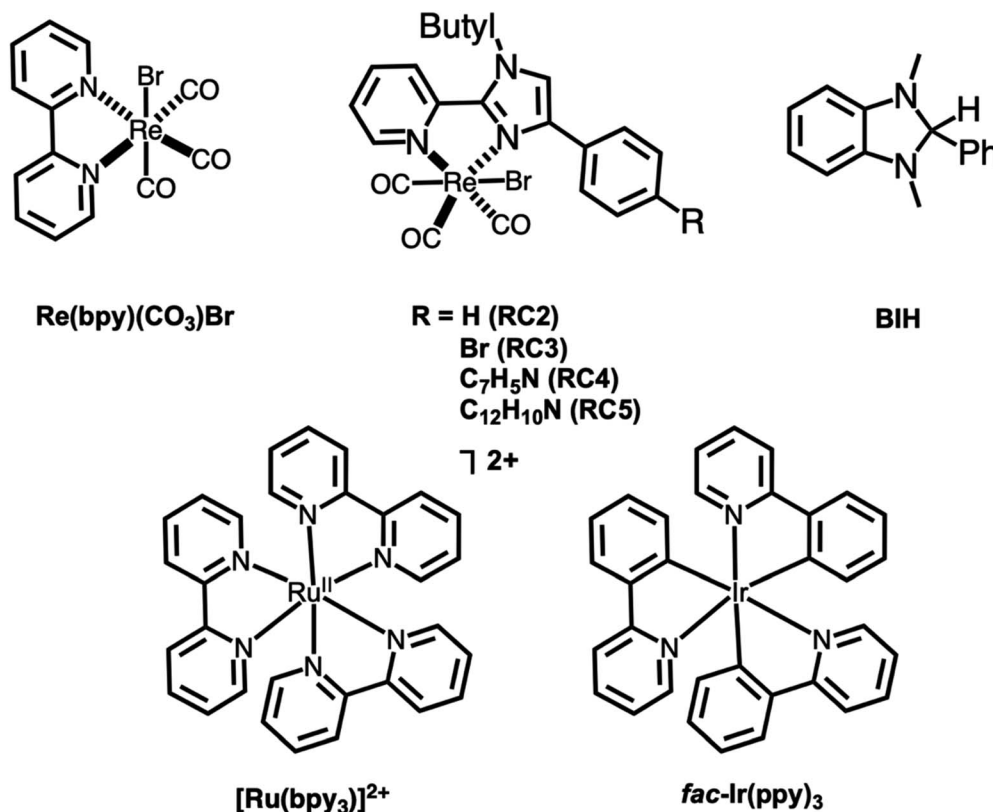


Fig. 1 Structures of complexes studied herein. The photosensitizers used and sacrificial electron donor (BIH) are also shown.

absorption and increase the activity for Re-based photocatalysts. We hypothesized that incorporating a ligand design with an enhanced charge transfer absorption, either in a donor-acceptor (D-A) or acceptor-donor (A-D) configuration would provide a strongly red-shifted charge transfer absorption.<sup>26</sup>

Herein, we report the synthesis, characterization, and catalytic activity of a series of novel Re(i) imidazolylpyridine complexes (Fig. 1). We were able to confirm two of the metal complex structures through single crystal X-ray diffraction. The electrocatalytic and photocatalytic trials indicated that the complexes are able to reduce CO<sub>2</sub> in sensitized photocatalytic reactions, and were modestly selective for HCO<sub>2</sub>H, which is rare for this class of Re photocatalysts.<sup>27–29</sup>

## Results and discussion

### Catalyst synthesis

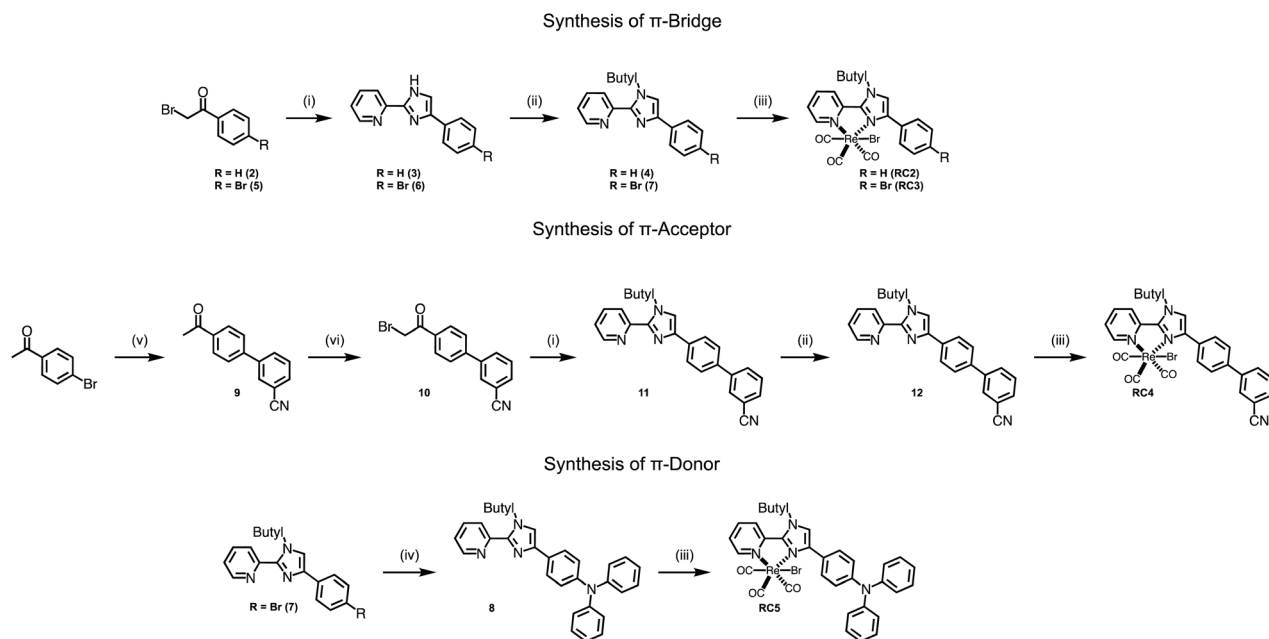
The synthesis of complexes **RC2** and **RC3** begin with an imidazole forming condensation between the alpha-brominated ketones **2**, **5**, or **10** and 2-amidinylpyridine to afford **3**, **6**, and **11** (Scheme 1).<sup>30</sup> Imidazole alkylation with 1-bromobutane using NaH afforded **4**, **7**, and **12** in moderate yields. Alkylation of the imidazole unit was crucial to the success of the synthesis as the non-alkylated pyridyl-imidazole ligand was observed to chelate the Re metal center using either of the imidazole N atoms due to tautomerization. This led to mixtures of the two possible isomers that were not separable.<sup>31</sup> Upon alkylation,

however, only one isomer was observed to form, and Nuclear Overhauser Effect (NOESY) spectroscopy was performed to confirm which isomer was present after purification (Fig. S4†). Refluxing Re(CO)<sub>5</sub>Br in toluene with **4**, **7**, or **12** afforded catalysts **RC2**, **RC3**, or **RC4**. Catalyst **RC5** was afforded with relative ease by Buchwald-coupling of diphenylamine with **7**, followed by metalation with Re(CO)<sub>5</sub>Br in refluxing toluene. Suzuki-coupling of 3-cyanophenylboronic acid and 4-bromoacetophenone was performed to afford **9** which was then brominated at the ketone α carbon with NBS and *p*-toluenesulfonic acid to give **10**. Detailed procedures for the synthesis of the ligands and their corresponding Re complexes is described in the ESI.†

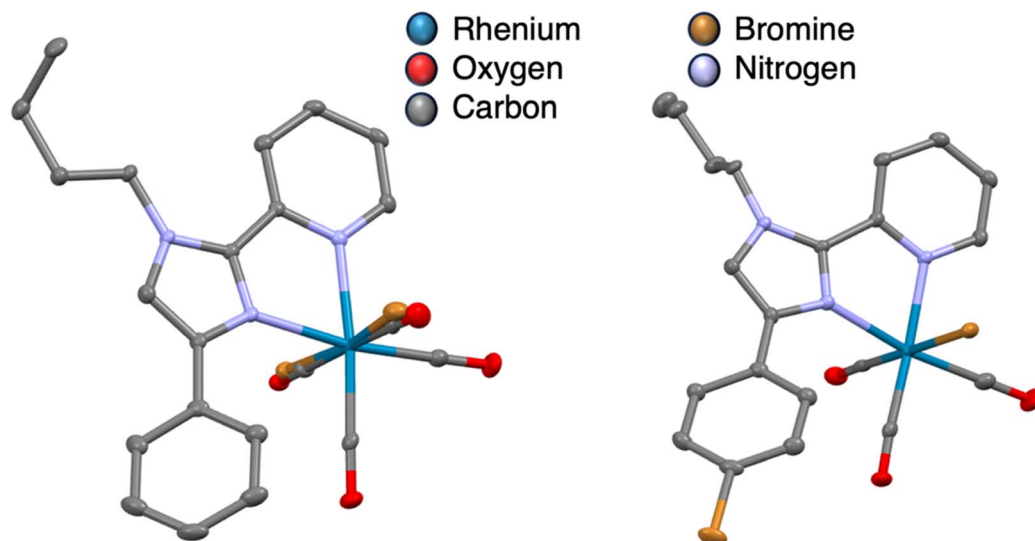
### Crystallographic data

Suitable single crystals of **RC2** and **RC3** were obtained *via* vial-in-vial vapor diffusion using methylene chloride in the inner vial and diethyl ether in the outer vial after allowing the set-up to stand overnight (Fig. 2). Both crystals were bright yellow in color. Other instances of diimine pyridyl-imidazole rhenium crystals have been reported in the literature and a comparison of the selected bond lengths with a reference complex can be found below. The crystallographic data are summarized in Table 1. The Re1–N<sub>imidazole</sub> and Re1–N<sub>pyridine</sub> bond lengths are slightly shorter (0.005 Angstroms) in **RC2** than **RC3**, likely owing to the electron withdrawing nature of the bromine substituent lengthening the Re–N bonds in **RC3**. The N<sub>imidazole</sub>–Re bond length in **RC2** (2.181(2) Å) is longer than an analogous bond





**Scheme 1** Synthetic steps to prepare complexes RC2–RC5. Reaction conditions: (i)  $\text{KHCO}_3$ ,  $\text{H}_2\text{O}$ , THF, amino(pyridin-2-yl)methaniminium chloride, reflux. Yields: **3**: 70%; **6**: 70%; **11**: 75%. (ii) 1-Bromobutane, DMF, NaH, 80 °C. Yields: **4**: 60%; **7**: 77%; **12**: 30%. (iii)  $\text{Re}(\text{CO})_5\text{Br}$ , toluene, reflux. Yields: **13**: 55%; **14**: 57%; **15**: 23%; **16**: 60%. (iv) Diphenyl amine, toluene,  $\text{KOtBu}$ ,  $\text{Pd}(\text{dba})_2$ , tri-*tert*-butylphosphonium tetrafluoroborate, reflux, 76%. (v) 3-Cyanophenylboronic acid,  $\text{Na}_2\text{CO}_3$ ,  $\text{Pd}(\text{PPh}_3)_4$ , 5 : 1 dioxane : water, 72%. (vi) *p*-TsOH, NBS, MeCN, reflux, 60%.



**Fig. 2** Crystal structures of RC2 (left) RC3 (right) omitting hydrogen atoms for clarity.

found in a benzimidazolypyridine  $\text{Re}(\text{I})$  complex (2.130(1) Å), indicating a weaker N–Re bond for the imidazole donor of **RC2**.<sup>32,33</sup> Similarly, in a Re–pyridylimidazole complex with a 4-(*N,N*-dimethylamino)pyridine group instead of a bromine substituent, the  $\text{N}_{\text{imidazole}}\text{-Re}$  bond length is shorter as well (2.118 Å). This indicates that in **RC2/RC3**, the bond lengths are longer than those observed for related Re(azoly)pyridine complexes.

### UV-Vis analysis

To characterize the light absorption properties of each complex, UV-visible absorption spectra were collected of the complexes dissolved in acetonitrile (MeCN) and are shown in Fig. 3. The optical properties of the complexes are summarized in Table 2. The data from these experiments revealed that the absorption onsets ( $\lambda_{\text{onset}}$ ) of **RC2–4** are blue-shifted compared to **1**, in contrast to our hypothesis. We reason the blue shifts are due to the increased basicity of the imidazole donor in comparison to



Table 1 Crystallographic data of catalysts RC2 and RC3

	RC2	RC3
Empirical formula	C <sub>21</sub> H <sub>19</sub> BrN <sub>3</sub> O <sub>3</sub> Re	C <sub>21</sub> H <sub>18</sub> Br <sub>2</sub> N <sub>3</sub> O <sub>3</sub> Re
Formula weight	627.50	706.40
Crystal system	Orthorhombic	Monoclinic
Space group (no.)	<i>Pbca</i>	<i>P2<sub>1</sub>/c</i>
<i>a</i> (Å)	14.4135 (6)	11.7322 (3)
<i>b</i> (Å)	13.9657 (5)	11.2485 (2)
<i>c</i> (Å)	19.9434 (9)	17.8809 (4)
$\alpha$ (deg)	90	90
$\beta$ (deg)	90	104.108
$\gamma$ (deg)	90	90
<i>V</i> (Å <sup>3</sup> )	4014.5 (3)	2288.56
<i>Z</i>	8	4
<i>F</i> (000) (e)	2400	1336
$\mu$ (Mo-K $\alpha$ ) (mm <sup>-1</sup> )	8.073	
Reflections collected	43 216	46 047
Independent reflections	4593 ( <i>R</i> <sub>int</sub> = 0.0474)	5254 ( <i>R</i> <sub>int</sub> = 0.0310)
Observed reflections	43 216	46 047
( <i>F</i> <sub>o</sub> $\geq$ 2 $\sigma$ ( <i>F</i> <sub>o</sub> ))		
Refined parameters	280	273
Goodness-of-fit on <i>F</i> <sup>2</sup>	1.163	1.057
<i>R</i> <sub>a</sub> , <i>R</i> <sub>wb</sub> ( <i>I</i> $\geq$ 2 $\sigma$ ( <i>I</i> ))	0.0195, 0.0434	0.0149, 0.0292
<i>R</i> <sub>a</sub> , <i>R</i> <sub>wb</sub> (all data)	0.0212, 0.0440	0.0179, 0.0299

pyridine, in addition to the lower degree of conjugation in the imidazole ring. Complex **RC5** shares a similar  $\lambda_{\text{onset}}$  to **1** at 425 nm. From the compounds, **RC5** possesses the largest molar absorptivity coefficient while also possessing the most red-shifted MLCT absorption band in the visible light region. Interestingly, complexes **RC2** and **RC3** differ considerably in their molar absorptivity ( $\Delta\epsilon = 5853 \text{ M}^{-1} \text{ cm}^{-1}$ ) with the substitution of just one hydrogen for a bromine atom.

### Electrochemical analysis

The redox properties of **RC2–5** were measured using cyclic voltammetry (CV) to examine whether the complexes could serve as CO<sub>2</sub> reduction catalysts under a CO<sub>2</sub> atmosphere and shown in Fig. 4 and summarized in Table 3. When CO<sub>2</sub> was sparged into each solution of dissolved complex, there was an increase in current associated with the first reduction potential, indicative

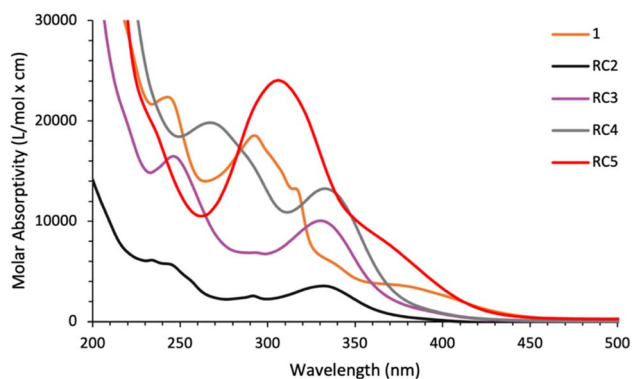


Fig. 3 UV-Vis absorption spectra for catalysts 1–RC5 dissolved in MeCN.

Table 2 Optical properties of catalysts 1 and RC2–5<sup>a</sup>

Catalyst	$\lambda_{\text{max}}$ (nm)	$\lambda_{\text{onset}}^c$ (nm)	$\epsilon$ (M <sup>-1</sup> cm <sup>-1</sup> )	$E_{\text{MLCT-GS}}^d$ (eV)
<b>1</b>	292, 384 <sup>b</sup>	420	18 951	2.95
<b>RC2</b>	248, 337 <sup>b</sup>	370	3718	3.35
<b>RC3</b>	246, 331 <sup>b</sup>	375	9571	3.31
<b>RC4</b>	267, 336 <sup>b</sup>	380	19 855	3.26
<b>RC5</b>	306, 371 <sup>b</sup>	425	23 381	2.92

<sup>a</sup> Measured in acetonitrile. <sup>b</sup> Indicates shoulder. <sup>c</sup> Estimated from the intercept of the baseline and a tangent line on the UV-Vis spectrum on the low energy side of the absorption. <sup>d</sup> Estimated from the onset of the low energy side of the absorption curve. The  $E_{\text{MLCT-GS}}$  was converted from nm to eV using the equation  $1240/E_{\text{MLCT-GS}} \text{ nm} = E_{\text{MLCT-GS}} \text{ eV}$ .

of catalytic CO<sub>2</sub> reduction activity. The increase in current for complexes **RC2** and **RC3** was also accompanied by shifts in the reduction wave to higher energy, while the current for **RC5** was accompanied by a shift in the reduction wave to a lower energy.

These measurements are also useful for determining whether the excited state reduction potentials of each complex are appropriately positioned for electron transfer from sacrificial electron donors like BIH or from photosensitizers (PS) such as Ir(ppy)<sub>3</sub> or [Ru(bpy)<sub>3</sub>]<sup>2+</sup>. An energy level diagram showing relevant reduction potentials associated with the rhenium catalysts, the aforementioned photosensitizers, the standard reduction potential of CO<sub>2</sub> to CO, and sacrificial electron donors BIH and TEA is given in Fig. 5. The reduction potentials of the dissolved complexes in nitrogen-sparged MeCN fall between -1.30 and -1.55 V vs. saturated calomel electrode (SCE), all of which are relatively higher in energy than the reduction potential of Re(bpy)(CO)<sub>3</sub>Br. The reduction potentials are also lower or very nearly lower in energy than both Ir(ppy)<sub>3</sub> or [Ru(bpy)<sub>3</sub>]<sup>2+</sup>, which suggests that either could serve as a PS for the complexes. The excited state reduction potential of each complex falls between 1.59 and 2.01 V vs. SCE, which are all substantially lower than the oxidation potentials of both BIH and triethanolamine (TEOA) or triethylamine (TEA), which indicates that each can serve as an electron donor.

### Photocatalytic CO<sub>2</sub> reduction

The Re complexes were applied to the photocatalytic reduction of CO<sub>2</sub> using anhydrous MeCN as the reaction solvent and a natural white light LED light source ( $\lambda > 400 \text{ nm}$ ) adjusted to 1 Sun intensity. Following initial optimization experiments (Table S2†) with catalyst **RC2** and **RC5**, [Ru(bpy)<sub>3</sub>]<sup>2+</sup> was selected as a PS due to its superior performance for photocatalytic CO<sub>2</sub> reduction compared to Ir(ppy)<sub>3</sub>. A sacrificial electron donor BIH was used with TEOA where TEOA plays a secondary role as a base in deprotonating the BIH radical cation generated in the initial electron transfer process to the excited PS to limit back electron transfer.<sup>39</sup> TEOA was chosen as the amine to pair with BIH as it gave better activity compared to another commonly used base, TEA. TEOA has been shown to react with CO<sub>2</sub> to form a zwitterionic alkylcarbonate adduct that serves to capture CO<sub>2</sub> in solution and facilitate proton transfer events.<sup>40</sup> Gaseous products such as carbon monoxide (CO), methane (CH<sub>4</sub>), and



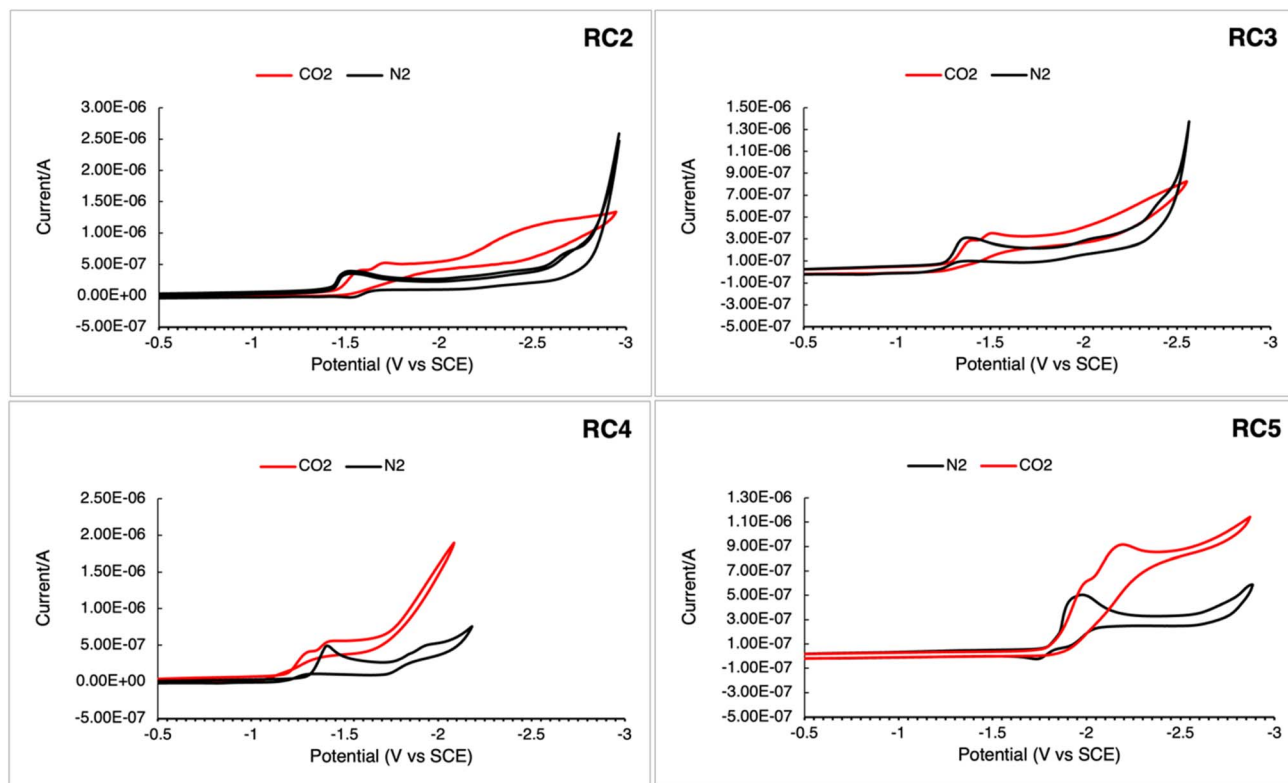


Fig. 4 Cyclic voltammograms of catalysts RC2–RC5. Spectra were recorded in dry MeCN, 0.1 M Bu<sub>4</sub>NPF<sub>6</sub> in MeCN using a Pt pseudo-reference, Pt counter, and glassy carbon working electrode using a scan rate of 0.1 V s<sup>-1</sup>. All spectra were referenced to ferrocene (Fc) as an internal standard using the Fc<sup>+</sup>/Fc = 0.4 V couple vs. SCE.<sup>38</sup>

Table 3 Electrochemical properties of catalysts RC2–RC5<sup>a</sup>

Catalyst	$E_{(S+/S)}$ <sup>b</sup> (V)	$E_{(S-/S)}$ <sup>c</sup> (V)	$E_{(S^*/S^-)}$ <sup>d</sup> (V)
1 (ref. 11)	1.26	-1.20	1.33
RC2	1.40	-1.35	2.00
RC3	1.45	-1.30	2.01
RC4	1.40	-1.35	1.91
RC5	0.85	-1.55	1.59
[Ru(bpy) <sub>3</sub> ] <sup>2+</sup> (ref. 34)	1.29	-1.33	0.31
fac-Ir(ppy) <sub>3</sub> (ref. 34)	0.73	-2.19	0.34

<sup>a</sup> Measured in dry MeCN. All values are reported vs. SCE and were measured by CV in 0.1 M Bu<sub>4</sub>NPF<sub>6</sub> in MeCN using a Pt pseudo-reference, Pt counter, and a glassy carbon working electrode. <sup>b</sup> Estimated as the onset of the oxidation peak due to irreversibility of the wave. <sup>c</sup> Estimated as the onset of the reduction peak due to irreversibility of the wave. <sup>d</sup> Estimated *via* the sum of the reduction potential and  $E_{MLCT-GS}$  using the equation:  $E_{(S^*/S^-)} = E_{(S-/S)} + E_{MLCT-GS}$ .

hydrogen (H<sub>2</sub>) were detected and quantified by gas chromatography (GC). Formic acid (HCO<sub>2</sub>H) as a solution-phase product of the photocatalytic reactions was quantified by <sup>1</sup>H NMR spectroscopy using ferrocene as an internal standard. The detailed procedure for quantifying HCO<sub>2</sub>H and a representative <sup>1</sup>H NMR spectrum for this measurement is given in the ESI (Fig. S7<sup>†</sup>).

The results of photocatalytic CO<sub>2</sub> reduction experiments are summarized and shown in Table 4 and Fig. 6. In the presence of

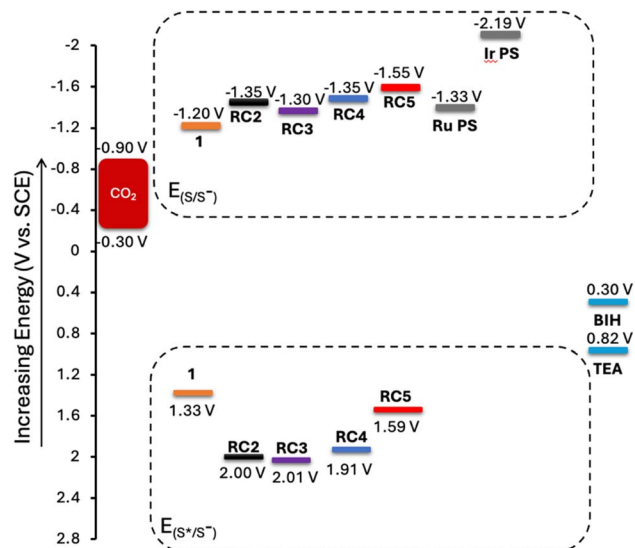


Fig. 5 Energy level diagram illustrating of catalyst reduction potentials, calculated excited-state reduction potentials from the  $E_{MLCT-GS}$  values, approximated range for the standard 2e<sup>-</sup>/2H<sup>+</sup> reduction potential of CO<sub>2</sub> to CO (and H<sub>2</sub>O) in acetonitrile based on the minimum and maximum pH range in the photocatalytic trials, and the oxidation potentials of BIH and TEA.<sup>35–37</sup>

PS [Ru(bpy)<sub>3</sub>]<sup>2+</sup> and electron donor BIH, Re-complexes RC2–5 were found to be active in light-driven CO<sub>2</sub> reduction with observed products HCO<sub>2</sub>H, CO, and H<sub>2</sub>. At a catalyst



Table 4 Performance comparison of the catalysts in the photocatalytic reduction of CO<sub>2</sub><sup>a</sup>

Entry	Catalyst	HCO <sub>2</sub> H (TON <sup>b</sup> )	CO (TON <sup>b</sup> )	H <sub>2</sub> (TON <sup>b</sup> )	CS <sup>c</sup> (%)
1	RC4	844	88	148	86
2	RC3	593	126	362	67
3	RC2	280	150	224	66
4	RC5	275	113	266	59
5	1 <sup>d</sup>	0	436	222	67

<sup>a</sup> Reactions were conducted in anhydrous MeCN with 1 μM catalyst/2 mL, 0.1 mM [Ru(bpy)<sub>3</sub>]<sup>2+</sup>, 50 mM BIH, and 5% (v/v) TEOA/MeCN. <sup>b</sup> Turnover number (TON) values are reported at 72 h after catalysis was no longer occurring. <sup>c</sup> Carbon-selective (CS) reduction percentage is calculated as CS% = [(CO TON + CH<sub>4</sub> TON + HCO<sub>2</sub>H TON)/total observed product TON × 100]. <sup>d</sup> Previously published; no HCO<sub>2</sub>H formation.

concentration of 1 μM, CO<sub>2</sub> is primarily reduced to HCO<sub>2</sub>H as the dominant product, accompanied by H<sub>2</sub> as a secondary byproduct from proton reduction. A smaller amount of CO was also formed. Interestingly, catalyst RC4, having resonance π-A group, exhibited the best catalytic performance for CO<sub>2</sub> reduction with a turnover number (TON) value of 844 for HCO<sub>2</sub>H production and the highest selectivity for CO<sub>2</sub> reduction products of 86% (Table 4, entry 1 and Fig. 6 (right)). Catalysts RC2 (TON for HCO<sub>2</sub>H = 280) and RC5 (TON for HCO<sub>2</sub>H = 275) with π-bridge and π-D group, respectively, showed lower catalytic activity overall than RC4, but similar activities and selectivities to one another with RC2 having a modestly higher carbon selectivity percentage (Table 4 and Fig. 6). Complex RC3 with Br-substituted π-bridge gave the second highest TON value for HCO<sub>2</sub>H of 593, which exceeds RC5 and the structurally similar complex RC2, but also produced the largest TON value for H<sub>2</sub> at 362. This photocatalytic study establishes a clear correlation between the electron withdrawing π-A (-PhCN) and electron donating π-D (-NPh<sub>2</sub>) substituents attached to the imidazole ring. Among the catalysts investigated, the best performance

was observed from the Re complex RC4 which contains a π-A group, followed by less electron withdrawing Br-substituted π-bridge RC3. Electronically neutral catalyst RC2 and π-D group substituted RC5 showed the lowest TON value for HCO<sub>2</sub>H generation. Notably, no HCO<sub>2</sub>H was observed for benchmark catalyst 1. A recent publication described that [Re(bpy)<sub>2</sub>(CO)<sub>2</sub>]<sup>+</sup> also selectively formed HCO<sub>2</sub>H with a TON value of 428 from CO<sub>2</sub> reduction, and they proposed a catalytic cycle similar to that of ruthenium catalyst [Ru(bpy)<sub>2</sub>(CO)<sub>2</sub>]<sup>2+</sup>.<sup>28</sup> Doyle and coworkers have reported a photocatalyst, Re(CO)<sub>3</sub>(1-(1,10)phenanthroline-5-(4-nitro-naphthalimide))Cl, which is selective for HCO<sub>2</sub>H generation with a TON value of 533.<sup>41</sup> We propose that the catalysts reported here also utilize the same catalytic cycle as that reported by Richeson and coworkers, which features a Re-H intermediate that undergoes CO<sub>2</sub> insertion to give a Re-formate intermediate.<sup>28</sup> Each of the imidazole-pyridine based catalysts reported here generate a mixture of HCO<sub>2</sub>H, CO, and H<sub>2</sub> with HCO<sub>2</sub>H being the dominant product overall; likewise, TON values for H<sub>2</sub> are greater than those of CO. The highest TON values for HCO<sub>2</sub>H production were obtained with catalysts bearing electron withdrawing substituents (RC3 and RC4) on the imidazole donor with HCO<sub>2</sub>H : H<sub>2</sub> ratios of 5.7 (RC4) and 1.6 (RC3). The catalysts with more electron donating substituents (RC2 and RC5) slightly favor HCO<sub>2</sub>H, but with lower TON values and HCO<sub>2</sub>H : H<sub>2</sub> ratios closer to 1. A rhenium-hydride species<sup>28</sup> is expected to be a common intermediate responsible for the production of HCO<sub>2</sub>H and H<sub>2</sub> during catalysis, both of which are formed in higher quantities than CO. The competition between HCO<sub>2</sub>H and H<sub>2</sub> suggests that the hydricity of the putative Re-H is near 44 kcal mol<sup>-1</sup> (i.e. the hydricity of formate in acetonitrile)<sup>42</sup> and sensitive to the ligand substitutions. To the best of our knowledge, Re complex RC4 sets a new benchmark with the highest TON value for HCO<sub>2</sub>H production of 844 reported for rhenium-based CO<sub>2</sub> reduction catalysts.

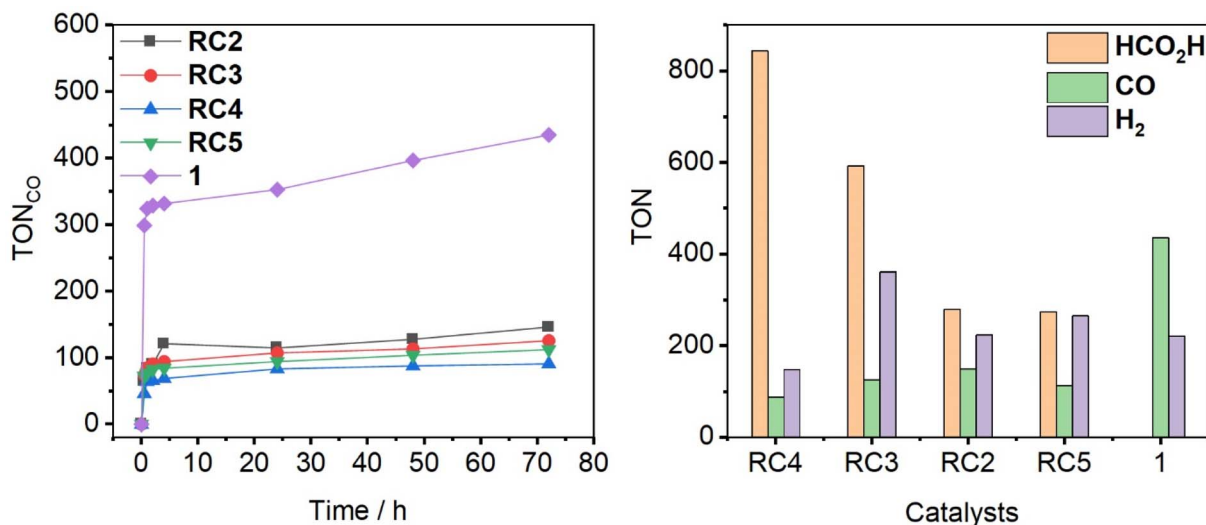


Fig. 6 CO formation over 72 h period (left) and the production of HCO<sub>2</sub>H, CO, and H<sub>2</sub> after 72 h (right) in photocatalytic CO<sub>2</sub> reduction reaction with catalysts RC2, RC3, RC4, RC5, and 1. All experiments were performed with 1 μM catalyst, 50 mM BIH, 0.1 mM [Ru(bpy)<sub>3</sub>]<sup>2+</sup>, and 5% (v/v) TEOA in anhydrous MeCN solution. The data points given are the average of two sample runs.



Under the same conditions, complex **1** outperformed catalyst **RC2–5** regarding CO production (Fig. 6 and Table 4, entry 5). Comparing catalysts **RC2–5**, catalyst **RC2** with a  $\pi$ -bridge on the imidazole ring showed comparatively better catalytic activity with a TON value of 150 for CO generation. In contrast, **RC4** exhibited a relatively low TON value of 88 for CO evolution, strongly favoring HCO<sub>2</sub>H production. Toward H<sub>2</sub> production, the highest activity (TON<sub>H<sub>2</sub></sub> = 362) was observed for complex **RC3**, followed by **RC2** and **RC5**, with complex **RC4** giving the lowest TON value for H<sub>2</sub> (Table 4).

Catalytic performance of **RC2–5** was also evaluated without using an external PS (Table S1†). Although the parent complex **1** is known to exhibit self-sensitized catalytic activity (TON<sub>CO</sub> = 55), only one of the Re complexes (**RC5**) absorbed visible light. Each of the catalysts exhibited very poor self-sensitized photocatalytic activity. Therefore, we conclude that catalysts **RC2–RC5** required a PS for significant catalysis to occur.

The influence of catalyst concentration on TON values was also investigated using complexes **RC4** and **RC2** (Table 5). The TON values decreased dramatically when the catalyst concentration was changed from 1  $\mu$ M to 10 and 100  $\mu$ M. This is a typical result, as lowering the catalyst concentration has been shown to result in higher TON values owing to the catalytic sites being isolated from one another, therefore reducing deleterious side reactions.<sup>43,44</sup>

The control experiments were performed using complex **RC2** to determine the necessity of each component used in the photocatalytic CO<sub>2</sub> reduction. The outcomes of these experiments are summarized in Table 6, where entry 1 is the result of our standard condition (all components present). Photocatalysis under N<sub>2</sub> in the absence of CO<sub>2</sub>, or without the rhenium catalyst, or without irradiation (entries 5–7), resulted in negligible product formation, indicating the necessity of the substrate, the Re catalyst, and light, respectively. The impact of removing the PS (TON<sub>HCO<sub>2</sub>H</sub> with PS = 280 and without PS = 0, entries 1 and 2) and removing the electron donor BIH (TON<sub>HCO<sub>2</sub>H</sub> with BIH = 280 and without BIH = 10, entries 1 and 3) is significant. BIH is a better electron donor (more driving force for electron transfer) than TEOA, and thus, better catalytic activity is observed in the presence of BIH compared to using TEOA alone as the sacrificial electron donor. Interestingly, in

**Table 5** Results of photocatalytic CO<sub>2</sub> reduction with **RC2** and **RC4** at different catalyst concentrations<sup>a</sup>

[Catalyst] ( $\mu$ M)	Catalyst	HCO <sub>2</sub> H (TON)	CO (TON)	H <sub>2</sub> (TON)	CS <sup>b</sup> (%)
1	<b>RC4</b>	844	88	148	86
	<b>RC2</b>	280	150	224	66
10	<b>RC4</b>	53	16	18	79
	<b>RC2</b>	20	69	29	75
100	<b>RC4</b>	17	8	3	89
	<b>RC2</b>	8	6	5	74

<sup>a</sup> Maintained a constant irradiation time of 72 h and the same reaction conditions provided in Table 1. <sup>b</sup> CS% = [(CO TON + CH<sub>4</sub> TON + HCO<sub>2</sub>H TON)/total observed product TON  $\times$  100].

**Table 6** Summary of the photocatalytic control experiments with catalyst **RC2**<sup>a</sup>

Entry	Catalyst	PS <sup>b</sup>	e <sup>-</sup> donor <sup>c</sup>	CO (TON)	H <sub>2</sub> (TON)	HCO <sub>2</sub> H (TON)
1	2	Yes	BIH, TEOA	150	224	280
2	2	No	BIH, TEOA	2	9	0
3	2	Yes	TEOA	16	14	10
4	2	Yes	BIH	45	388	228
5 <sup>d</sup>	2	Yes	BIH, TEOA	2	1	0
6	None	Yes	BIH, TEOA	1	1	0
7 <sup>e</sup>	2	Yes	BIH, TEOA	0	0	0

<sup>a</sup> Irradiation time was constant at 72 h. The activity under standard conditions is provided in entry 1. <sup>b</sup> PS = [Ru(bpy)<sub>3</sub>]<sup>2+</sup>. <sup>c</sup> When both components are listed both are present. <sup>d</sup> Under nitrogen atmosphere. <sup>e</sup> No irradiation.

the absence of TEOA, catalyst **RC2** showed similar TON values for HCO<sub>2</sub>H compared to the experiment with TEOA (Table 6, entries 1 and 4). However, lower TON values for CO and higher values for H<sub>2</sub> production are also observed without TEOA, indicating that the presence of TEOA strongly influences product selectivity.

In Table 7, catalysts **RC2–5** are compared to recent Re(I) catalysts applied to light-driven CO<sub>2</sub> reduction in the presence of a sacrificial electron donor. Müller *et al.*<sup>45</sup> recently synthesized three rhenium tricarbonyl catalysts that produce TON values for CO as high as 125 without the presence of an external PS and using TEOA as the sacrificial electron donor. These excellent TON<sub>CO</sub> values were achieved by relatively simple modification to a 1,10-phenanthroline core by adding different heterocyclic substitutions at the 4 and 7 positions. Rotundo *et al.*<sup>46</sup> also achieved similar TON<sub>CO</sub> values of 120 with Re<sup>I</sup>(CO)<sub>3</sub> catalysts using BIH instead of TEOA while studying the effects of substituted 2,2'-bipyridine based ligands containing various functional groups in the second-coordination sphere. Liang and coworkers<sup>24</sup> reported a self-sensitized rhenium catalyst utilizing pendant dipyrromethene-BF<sub>2</sub> chromophores linked to a 2,2'-bipyridine core to achieve TON<sub>CO</sub> values as high as 1376 with BIH as the sacrificial electron donor. Although catalyst **RC2** possesses similar TON<sub>CO</sub> values to Müller's and Rotundo's catalysts, their compounds function as effective self-sensitized photocatalysts while **RC2** does not. With respect to formic acid production, **RC4** in particular performs remarkably well compared to most Re catalysts that are generally known for their high selectivity for CO<sub>2</sub>-to-CO conversion. However, there are two recent rhenium catalysts that preferentially produce HCO<sub>2</sub>H. Spear *et al.*<sup>27</sup> recently synthesized a rhenium catalyst supported by a phenanthroline nitro-naphthalimide ligand which selectively produced HCO<sub>2</sub>H in the absence of an external PS with a TON value as high as 533. Hameed *et al.*<sup>28</sup> also achieve high selectivity and a HCO<sub>2</sub>H TON value of 428 utilizing the triflate salt of a bis(bipyridine) dicarbonyl rhenium complex which becomes less selective for HCO<sub>2</sub>H over the course of the reaction. Catalyst **RC4** in comparison yields greater TON values for HCO<sub>2</sub>H, but



Table 7 Summary of the catalytic performance of selected rhenium catalysts applied to light-driven CO<sub>2</sub> reduction

Catalyst	PS	e <sup>-</sup> donor	CO (TON)	H <sub>2</sub> (TON)	HCO <sub>2</sub> H (TON)	CS <sup>d</sup> (%)
<b>RC4</b>	[Ru(bpy) <sub>3</sub> ] <sup>2+</sup>	BIH, TEOA	88	148	844	86
<b>RC4</b>	No	BIH, TEOA	5	1	0	85
<i>fac</i> -[Re(NN) <sup>a</sup> (CO) <sub>3</sub> Cl] <sup>45</sup>	No	TEOA	125	nd	nd	100
<i>fac</i> -[ReCl(L) <sup>b</sup> (CO) <sub>3</sub> ] <sup>46</sup>	No	BIH	120	nd	nd	100
[Re(BDP) <sub>2</sub> ] <sup>c</sup> <sup>24</sup>	[Ru(bpy) <sub>3</sub> ] <sup>2+</sup>	BIH	1376	nd	nd	100
[Re(CO) <sub>3</sub> (1-(NN) <sup>a</sup> -5-(4-nitro-naphthalimide))Cl] <sup>27</sup>	No	BIH	0.04	nd	533	100
<i>cis</i> -[Re(bpy) <sub>2</sub> (CO <sub>2</sub> )] <sup>+</sup> OTf <sup>-</sup> (1 <sup>+</sup> OTf <sup>-</sup> ) <sup>28</sup>	[Ru(bpy) <sub>3</sub> ] <sup>2+</sup>	BIH, TEOA	nd	38	428	92

<sup>a</sup> NN = 1,10-phenanthroline having pyrrole. <sup>b</sup> L = Ph-NH<sub>2</sub> substituted 2,2'-bipyridine. <sup>c</sup> BDP = 2,2'-bipyridine having dipyrromethene-BF<sub>2</sub> chromophores. <sup>d</sup> CS% = [(CO TON + HCO<sub>2</sub>H TON)/total observed product TON × 100].

with lower selectivity due to the formation of CO and H<sub>2</sub>, products that are not generated in large quantities or at all with the other two catalysts.

## Conclusions

Carbon dioxide valorization to fuels or fuel precursors is an attractive strategy to reduce the overall use of non-renewable carbon fuel sources. Here, we synthesized four novel imidazolyl-pyridine Re complexes that were applied to the photocatalytic reduction of CO<sub>2</sub> and compared to benchmark catalyst Re(bpy)(CO)<sub>3</sub>Br, **1**. By replacing one of the pyridyl rings for a substituted imidazole group containing electron donating or accepting moieties, we were able to tune the electronic properties and light absorption of the complexes. Of note is that each of the imidazolyl complexes favored HCO<sub>2</sub>H production, which is unusual for Re(CO)<sub>3</sub> based catalysts which overwhelmingly mediate the conversion of CO<sub>2</sub>-to-CO with high selectivity. Catalysts **RC3** and **RC4** strongly favored HCO<sub>2</sub>H generation, with **RC4** being the most active and selective catalyst overall with an overall carbon selectivity (CS) of 86%. The CS percentage of **RC3** is 67% due to a relatively large TON value for H<sub>2</sub> evolution. Catalysts **RC2** and **RC5** also favor HCO<sub>2</sub>H as the dominant CO<sub>2</sub> reduction product but make comparably higher amounts of CO and H<sub>2</sub> and thus have lower carbon selectivity of 66 and 59%, respectively. In sharp contrast, benchmark catalyst **1** does not produce HCO<sub>2</sub>H under the same conditions. The production of HCO<sub>2</sub>H is rare for rhenium-based catalysts for CO<sub>2</sub> reduction with only a few examples known in the literature. Catalyst **RC4** gave a TON value for HCO<sub>2</sub>H as high as 844 at 1 μM catalyst concentration, further demonstrating the high stability of this catalyst under photochemical conditions.

## Data availability

The data supporting this article have been included as part of the ESI.† CCDC 2428908 and 2428909 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via [http://www.ccdc.cam.ac.uk/data\\_request/cif](http://www.ccdc.cam.ac.uk/data_request/cif), or by emailing [data\\_request@ccdc.cam.ac.uk](mailto:data_request@ccdc.cam.ac.uk), or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

## Conflicts of interest

There are no conflicts to declare.

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