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Controlling Hydrogen Evolution during CO₂ Photoreduction to Formic Acid using [Rh(R-bpy)(Cp*)Cl]⁺ Catalysts: A Structure-Activity Study.

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ABSTRACT: The photochemical CO₂ reduction to formic acid catalyzed by a series of [Rh(4,4'-R-bpy)(Cp*)Cl]⁺ and [Rh(5,5'-COOH-bpy)(Cp*)Cl]⁺ complexes (Cp* = pentamethylcyclopentadienyl, bpy = 2,2'-bipyridine, R = OCH₃, CH₃, H, COOC₂H₅, CF₃, NH₂ and COOH) was studied in order to assess how modifications in the electronic structure of the catalyst affect its selectivity, defined as the HCOOH : H₂ product ratio. A direct molecular-level influence of the functional group on the initial reaction rate for CO₂ vs. proton reduction reactions was established. Density functional theory computations elucidated for the first time the respective role of the [RhH] vs [Cp*H] tautomers, recognizing the rhodium hydride as the key player for both reactions. In particular, our calculations explain the observed tendency of electron-donating substituents to favor CO₂ reduction by means of lowering the hydricity of the Rh-H bond, resulting in lower hydride transfer barrier towards formic acid production as compared to substituents with electron-withdrawing nature that favor more strongly the proton reduction to hydrogen.

INTRODUCTION

The reduction of carbon dioxide is one of the most promising approaches to valorize CO₂ into fuels or chemicals.¹⁻⁵ However, the chemical inertness of CO₂ makes its reduction a very challenging task, requiring the use of catalysts in order to increase the rate, efficiency and selectivity of the chemical transformations involved.^{2,6-10} Molecular catalysts have attracted major attention as their well-defined structure can help establish structure-function relationships. Indeed, structural variations of the molecular complex introduced, for instance, through synthetic modification of the ligands can allow fine-tuning of the complex reactivity, as well as understanding of the key steric and electronic effects on operating mechanism, product selectivity, and catalytic efficiency.^{8,11-28} Up to date, very few studies have characterized the effects of ligand substituents on the performances of a given class of molecular CO₂ reduction catalysts, based on a significant set of representatives.^{18-20,25-30} Product selectivity in CO₂ reduction is one of the most important issues to be addressed.³¹⁻³⁶ While in general molecular catalysis is limited to 2-electron reduction leading to formic acid and/or carbon monoxide, a major competing reaction is the reduction of protons into dihydrogen.^{10,37} Optimization of the catalytic systems thus requires a better understanding of the factors which would limit the hydrogen evolution reaction. Knowledge on how it can be controlled is essential for the design and development of more efficient and selective CO₂ reduction catalysts.

Recently we have addressed this specific issue in the case of Co-terpyridine complexes, which catalyze the electroreduction of CO₂ into CO, while simultaneously performing a significant proton reduction into hydrogen.¹⁸ The work demonstrated how simple variations in substituents on the terpyridine (terpy) ligand can have major effects on the CO/H₂ product ratio.¹⁸ Specifically, using 5 differently substituted terpy ligands, we showed that

electronic tuning of the ligand sphere had greater effect on proton reduction rates relative to CO₂ reduction rates. As a consequence, electron-withdrawing groups disfavored H⁺ reduction, thus led to an increased selectivity for CO₂ reduction. These findings validated the concept of “turning off” proton reduction, in order to gain increased selectivity for CO₂-derived products. However, Co-terpy systems suffered from low efficiency (low Faradic yields) and significant instability and could not be studied further.

While the great majority of molecular CO₂ reduction catalysts convert CO₂ into CO, only very few have been reported as catalysts for the reduction of CO₂ to formic acid.^{37,38} Well-known examples are Ru-polypyridyl, Mn(bpy)(CO)₃ and Rh(bpy=2,2'-bipyridine)(Cp*=pentamethylcyclopentadienyl) complexes, followed recently by Co(diphosphine)(Cp) complexes³⁰ and Fe-carbonyl clusters.³²⁻³⁵ These systems most often give a mixture of HCOOH and H₂, but the control of their selectivity has not been addressed in details.

In this context, the [Rh(bpy)(Cp*)X]⁺ catalyst is of particular interest for several reasons. It has been studied extensively for the reduction of a wide range of substrates (protons, ketones, NAD⁺ and flavins) either by a hydride donor (such as formate) or *via* electrochemical or photochemical reduction in the presence of protons.^{39,40} Initially, Kölle and Grätzel have shown that this rhodium-based system could catalyze photochemical hydrogen generation by using weakly reducing electrons of a TiO₂ colloid.⁴¹ Subsequently, Deronzier et al.⁴²⁻⁴⁴ and Gray et al.⁴⁵⁻⁴⁷ have used [Rh(bpy)(Cp*)X]⁺-derived catalysts both in homogeneous solution or immobilized on electrode to study the electrochemical proton reduction to hydrogen. On the other hand, electrocatalytic CO₂ reduction by this catalyst was investigated for the first time by Deronzier and co-workers in 1997, reporting the formation of a mixture of formate and hydrogen.⁴⁸ Then, the system was left aside for almost 20

years until we used it for the first time as a catalyst for CO₂ photochemical reduction, in the presence of a photosensitizer and a sacrificial electron donor, also observing formate as the only carbon-containing product together with H₂.⁴⁸ With TONs above 100, this stable system compares well with Ru- and Mn-based photosystems.³⁸ It thus offers an interesting opportunity to carry out a structure-selectivity study aiming at understanding how to tune the HCOOH : H₂ ratio by varying the electronic nature of substituents on the bpy ligand. In this work, a series of [Rh(R-bpy)(Cp*)Cl]Cl organometallic complexes (R = OCH₃, CH₃, H, COOC₂H₅, CF₃, NH₂ and COOH) have thus been synthesized, characterized by cyclic voltammetry in order to probe the electronic properties of the bpy substituents, and compared in terms of the obtained HCOOH : H₂ ratio using photochemical conditions.

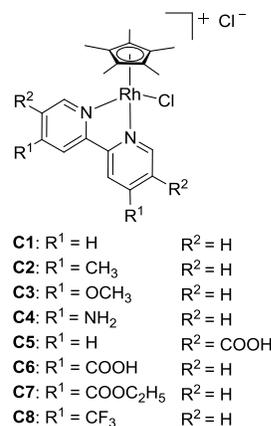
Another reason for studying this class of complexes is the existence of two potential active intermediates which have been studied, however only during proton electroreduction to H₂.^{40,47,51} It was established that the metal center acts as the primary site of proton capture generating a metal hydride, but subsequently the latter tautomerizes by proton transfer to the Cp* ligand, giving rise to the thermodynamically more favorable (Cp*H)Rh(bpy) form.^{40,47,51} The resulting species bearing the uncommon [η^4 -Cp*H] ligand was isolated and structurally characterized by X-ray diffraction and ¹H NMR spectroscopy.^{47,40} In turn, these findings opened a new question regarding the way such a catalyst mediates hydride transfer to an electrophilic substrate: indirectly *via* a Rh-H intermediate or directly from the [Cp*H] moiety of the cyclopentadiene ligand. In the case of H₂ evolution or NAD⁺ reduction, the suggested scenario includes an intramolecular hydride transfer to the Cp* ring, followed by binding of the substrate (H⁺ or NAD⁺) to the metal center.^{40,47}

We here extend these studies to CO₂ reduction. Our work is the first theoretical assessment of the mechanistic pathways for CO₂ reduction catalyzed by this class of complexes. Combining photochemical CO₂ reduction catalytic assays using [Rh(R-bpy)(Cp*)Cl]Cl complexes to assess the effect of the R substituents on the HCOOH : H₂ ratio with density functional theory (DFT) computations, we establish a structure-function relationship which can be used to tune the selectivity of the CO₂ reduction. Our calculations identify the respective roles of the two hydride tautomers in CO₂ *vs.* proton reduction and provide an understanding on how the presence of electron-withdrawing or donating moieties on the bpy ligand can affect the operating mechanism and the product selectivity of the Rh(R-bpy)(Cp*) catalysts.

RESULTS AND DISCUSSION

Preparation and characterization of Rh complexes. Eight [Rh(R-bpy)(Cp*)Cl]Cl complexes, R being a substituent group in the 4,4' positions of bipyridine (H, CH₃, OCH₃, NH₂, COOH, COOC₂H₅ and CF₃) or a 5,5'-COOH group, were prepared according to previously reported methods.⁴¹ Structures of the catalysts investigated in this study are shown in Scheme 1. Bipyridine (complex **C1**) was functionalized with seven electron-donating (complexes **C2–C4**: CH₃, OCH₃ and NH₂, respectively) or electron-withdrawing (complex **C5**: COOH at *meta* positions, complexes **C6–C8**: COOH, COOC₂H₅, and CF₃ groups at *para* positions, respectively) substituents. After purification, they were characterized by

elemental analysis and NMR spectroscopy (see Experimental methods).



Scheme 1. Structure of [Rh(R-bpy)(Cp*)Cl]Cl complexes.

Cyclic Voltammetry in Ar. First, the complexes were studied *via* cyclic voltammetry (CV) under Ar to assess the effect of the electronic nature of the bpy substituents. Figure 1 summarizes the CVs of all **C1–C8** complexes, with the potentials reported *vs.* Fc⁺⁰ (ferrocene was added as an internal standard to the solution after each measurement). The potential values for all complexes are given in Figure S1. As previously reported,^{33,46–48} **C1** displays a single 2-electron reduction wave centered at -1.18 V *vs.* Fc⁺⁰, with a peak-to-peak separation (ΔE_p) of 120 mV, indicating electrochemical quasi-reversibility. This wave has already been assigned,⁴⁸ and here confirmed by DFT orbital analysis to correspond to a metal-based reduction of Rh(III) to Rh(I), accompanied by the loss of the labile chloride ligand. Complexes **C2** and **C3** also display such a single virtually reversible 2-electron reduction feature assigned to Rh(III)/Rh(I) but, owing to the electron-enriched bpy ligands, it occurs at slightly more cathodic potentials of -1.22 and -1.28 V, respectively. Additionally, the charge in these systems results in a smaller ΔE_p value of 80 and 70 mV, respectively. The CV of the most electron-donating complex **C4** that has NH₂ substituents on the bpy ligands is characterized by two separate one-electron reduction features centered at -1.23 and -1.53 V, with ΔE_p values of 240 and 60 mV, respectively, indicating that only the Rh(II)/Rh(I) couple is reversible.

The CV profiles of the electron-withdrawing complexes **C5–C8** are substantially different from the parent complex (**C1**) or the electron-donating **C2–C4**, notably with a significant or complete loss of reversibility. In the case of **C5**, the COOH substituents are at *meta* position and have thus more substantial impact on the electronic properties of bpy ligand compared to **C6** with $-COOH$ groups at *para* position. The CV of **C5** is more complex, showing two reduction features with cathodic potentials at $E_{pc}' = -1.11$ V and $E_{pc}'' = -1.74$ V *vs.* Fc⁺⁰. The 130 mV anodic shift of the first reduction potential with respect to the unsubstituted complex **C1** reflects the strong electron-withdrawing nature of the *meta* COOH group. The second reduction wave is strongly cathodically shifted, which might be due to the involvement of the Cl ligand in the coordination sphere.

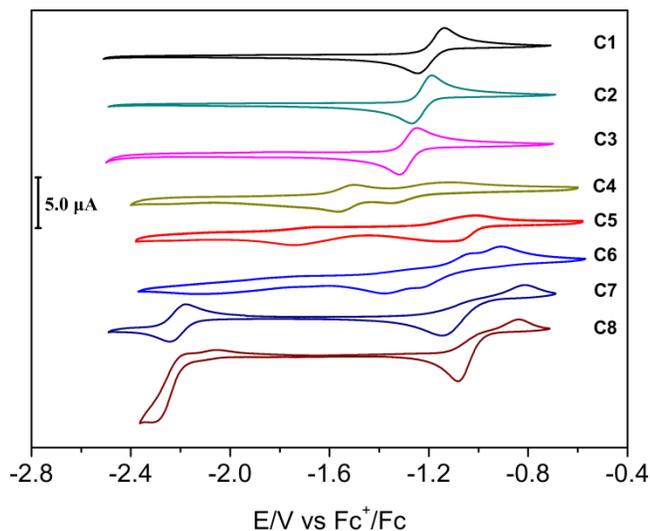


Figure 1. Cyclic voltammetry of **C1–C8** complexes in acetonitrile with 0.1 M TBAPF₆ as an electrolyte under Ar and a scan rate of 100 mV s⁻¹.

In complex **C6**, the two consecutive one-electron metal-based reduction waves are electrochemically irreversible, with $E_{pc} = -1.23$ and -1.36 V vs. $Fc^{+/0}$. The CV of complex **C7** is characterized by one irreversible reduction at $E_{pc} = -1.14$ V vs. $Fc^{+/0}$, while in the anodic scan, the product is reoxidized at $E_{pa} = -0.82$ V. A third one-electron reversible reduction event is observed at $E_{1/2} = -2.23$ V and is associated with the reduction of the bpy-COOC₂H₅ ligand. Very similar electrochemical features are seen for complex **C8**, for which the more electron-withdrawing $-CF_3$ substituent groups on the bpy shift the irreversible reduction more anodically to $E_{pc} = -1.08$ V vs. $Fc^{+/0}$, while the reoxidation occurs at $E_{pa} = -0.84$ V. However, in contrast to **C7**, the third reduction of this complex results in an irreversible wave at $E_{pc} = -2.28$ V. The general trend evident from Figure 1 is that increasing the electron-withdrawing character of the functional group on the bpy ligand in the [Rh(R-bpy)Cp*]⁺ complex, increases the irreversibility of the Rh(III)/Rh(I) reduction. A possible reason could be the strong stabilization of the Rh(I) complex, resulting from the enhanced delocalization of electron density, which makes in turn more difficult to oxidize it to the Rh(III) form. Similar electrochemical behavior for complexes with *para* substituted $-tBu$ and $-CF_3$ on the bpy ligand in [Rh(bpy)Cp*Br]⁺ system was reported recently by Blakemore et. al. in their studies on the role of the ligand substituents on the proton reduction activity.⁵²

The potential of the first cathodic peak was used as a measure of the electronic properties of the substituted bpy ligands. Figure 2 shows that under Ar it spans over a 270 mV range and correlates almost linearly ($R^2 = 0.95$) with the values of the Hammett sigma parameter,⁵⁵ in the following order: $NH_2 > OCH_3 > CH_3 > H > m-COOH > COOC_2H_5 > CF_3$. The *para* substituted COOH complex (**C6**) falls off the line (blue square in Figure 2), as its reduction is more difficult than that of the corresponding ester (**C7**), despite the same Hammett constant values. This is possibly due to surface adsorption of **C6** on the glassy carbon electrode as shown from a rinse test (Figure S2). Similar findings for linear relationship between the first reduction potential and the Hammett parameter were reported for Ru-bis-diimine complexes by Connick and co-

workers⁵⁶ as well as for a series of *fac*-Re(4,4'-R-bpy)(CO)₃X catalysts by Kubiak and co-workers.²⁷ One should note that the range of accessible potentials in this work (over 270 mV) is much lower than that obtained with Co-bisterpyridyl complexes (over 1V),⁵⁷ reflecting the weaker sensitivity of the [Rh(R-bpy)(Cp*)]⁺ systems to the electronic effects introduced *via* electron-withdrawing or donating functional groups on the bpy ligand.

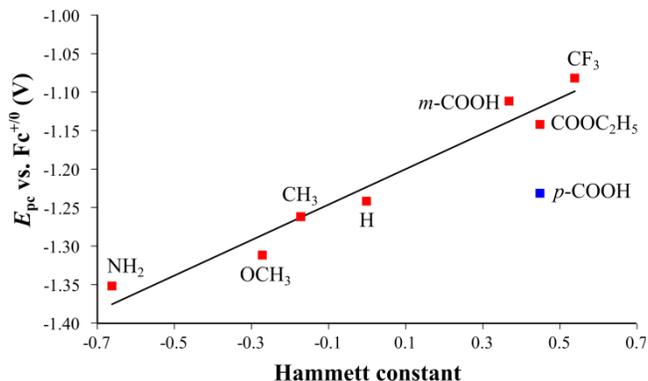


Figure 2. Trend between the electron-donating character of the bpy substituent and the first cathodic peak potential (E_{pc}) of complexes **C1–C8**. Blue square corresponds to **C6**.

Photoreduction of Carbon dioxide. The catalytic performance of the **C1–C8** complexes was studied towards photochemical CO₂ reduction under conditions described in the experimental section. As the complexes are not photocatalysts they need to be sensitized. The [Ru(bpy)₃]²⁺ complex was used as a photosensitizer. Because of the larger extinction coefficient in the visible light region and larger concentration of the Ru complex with respect to the Rh-based catalysts, inefficient light absorption by the photosensitizer was excluded.⁵⁸ Furthermore, triethanolamine (TEOA) was used the electron donor and the proton source, as generally done in photochemical CO₂ reduction of molecular systems.⁵⁹ H₂ and HCOOH were detected as reduction products. Control experiments did not show any significant activity when the reaction was carried out in the dark as well as in the absence of [Rh(R-bpy)(Cp*)Cl]⁺ catalysts or [Ru(bpy)₃]Cl₂ photosensitizer, thus confirming that the Rh complexes are not photocatalysts (Figure S3).

The performance of **C1–C8** complexes was compared in terms of initial turnover frequency (TOF) obtained within 1 h of reaction and turnover numbers (TON) after 16 hours (Table 1). Figure 3 depicts the representative complexes **C3** (a) and **C8** (b) in terms of TON for each product as a function of time. The curves obtained for the other six complexes are summarized in the SI section (Figures S4–S9). The initial linear part of the curve was used to calculate a TOF value for each product. Both products (HCOOH and H₂) form immediately upon illumination, with a reaction rate that does not vary significantly during the first two hours. After 2h, the rate slowly decays with time as a consequence of photosensitizer bleaching. This is supported by the observed recovery of catalytic activity upon addition of fresh sample of [Ru(bpy)₃]Cl₂ during irradiation.⁴⁹

Complexes **C1–C3** that have electron-enriched bpy ligands show similar properties: (i) they produce formic acid

with the highest TON values (above 100) in the order **C3** > **C1** > **C2**, and have the highest initial TOF values (about 30 h⁻¹) and (ii) they are the most selective catalysts for CO₂ reduction among the set of catalysts under study here (highest value of TOF(HCOOH) : TOF(H₂) of 1.36).

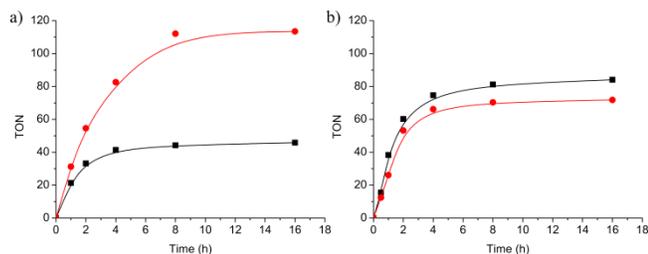


Figure 3. Formate (red) and H₂ (black) evolution catalyzed by a 0.1 mM solution of **C3** (a) and **C8** (b) in the presence of 1 mM of [Ru(bpy)₃]Cl₂ in CO₂-saturated CH₃CN/TEOA (5:1, v/v) mixture upon irradiation with a 300 W Xe arc lamp equipped with a 415 nm filter.

In sharp contrast, complexes **C4–C8** show much weaker catalytic activity for CO₂ reduction. Among them, a sub-class of **C4–C6** emerges as systems with special catalytic properties, which do not follow the general trend (*vide infra*), due to the presence of protic substituents (–COOH and –NH₂). They are characterized by (i) very low catalytic activity for CO₂ reduction, as illustrated by the very low TON and TOF values (Table 1) and (ii) production of H₂ as a major product. On the other hand, complexes **C7** and **C8** that have the most electron-deficient ligands and no protic groups on the bpy ligand produce similar amount of products, with a HCOOH : H₂ ratio of about 1 : 1. Interestingly, substitution of the –COOH group (**C6**) by –COOC₂H₅ (**C7**) leads to a two-fold increase of the formate production rate, while the H₂ evolution rate is only marginally enhanced, resulting in two-fold increase of the HCOOH : H₂ ratio.

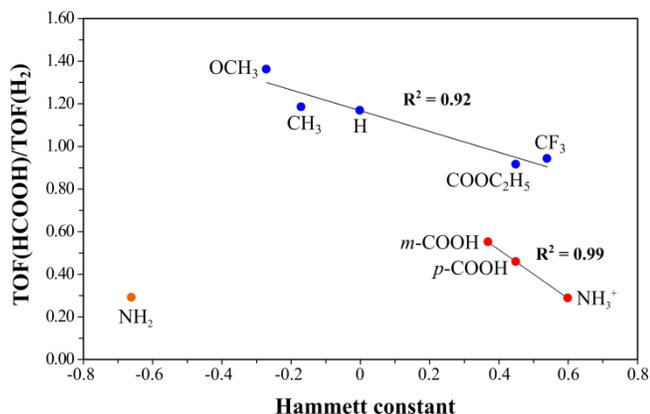


Figure 4. TOF(HCOOH)/TOF(H₂) ratio as a function of the Hammett constant (σ) of the functional groups on the bpy ligand for [Rh(R-bpy)(Cp*)Cl]Cl complexes **C1–C8**.

Our photochemical results demonstrate that electronic modifications on the bpy ligand of [Rh(R-bpy)(Cp*)Cl]Cl catalysts have a significant effect on product selectivity, measured in terms of TOF(formate)/TOF(H₂), and ranging from 1.36 to 0.29. Moreover, selectivity correlates almost linearly ($R^2 = 0.92$) with the Hammett constant (σ), hence with

the cathodic potential for the Rh(III)/Rh(I) couple (Figure 2), used as a descriptor of the electronic effect of the substituents (Figure 4), with the exception of complexes **C4–C6**. **C4**, with the most electron-donating bpy ligand ($\sigma = -0.66$) was expected to show the highest selectivity for formic acid. Instead, the lowest selectivity that it shows likely reflects the fact that the –NH₂ substituents are protonated by the large excess of TEOA. Thus in Figure 4 we also plotted **C4** in the NH₃⁺ state ($\sigma = +0.60$), which greatly improves the correlation ($R^2 = 0.99$) among the **C4–C6** systems. Figure 4 also suggests that there are two classes of catalysts, displaying two different linear trends. Within each class, increasing the electron-donating nature of the bpy ligand increases the selectivity of the catalyst for formic acid production. It should be noted that **C4–C6** complexes differ from the others by the presence of proton-exchange groups. Whether this explains their greater propensity to reduce protons has to be considered even though intramolecular processes seem unlikely due to the large distance between these substituents and the metal center.

Table 1. Results of photolytic CO₂ reduction catalyzed by [Rh(R-bpy)(Cp*)Cl]Cl complexes and the [Ru(bpy)₃]Cl₂ photosensitizer, given in terms of initial TOF and TON after 16 hours reaction.

Catalyst	TON _{16h}		TOF (h ⁻¹)		Selectivity
	formate	H ₂	formate	H ₂	
C1 (R = H)	105.2	63.3	31.4	26.9	1.17
C2 (R = CH ₃)	99.5	51.8	26.4	22.3	1.18
C3 (R = OCH ₃)	113.5	45.8	32.1	23.6	1.36
C4 (R = NH ₂)	21.5	68.3	7.7	26.9	0.29
C5 (R = <i>m</i> -COOH)	38.3	49.2	11.1	20.2	0.55
C6 (R = <i>p</i> -COOH)	31.2	64.6	11.7	25.6	0.46
C7 (R = CO ₂ C ₂ H ₅)	69.8	77.9	25.5	27.9	0.91
C8 (R = CF ₃)	71.8	84.1	28.7	30.5	0.94

We found that **C4–C6** catalysts show very low CO₂ reduction ability and strong tendency to favor H₂ formation. Recently, Monte Carlo simulating annealing coupled with DFT calculations revealed that upon immobilization of complexes **C4** or **C5** into the porous metal-organic framework MIL-101-NH₂(Al), the –COOH groups of the Rh system can establish hydrogen bonding interactions with the MOF host (with an –NH₂ group of the neighboring linker and/or H₂O molecule of an inorganic sub-unit).⁵⁰ Since the immobilized Rh-Ru@MIL-101-NH₂(Al) composite performed photochemical CO₂ reduction to produce exclusively formate, the MOF host was recognized as a key component in altering the selectivity of the catalyst achieved by inhibiting the competing proton reduction.⁵⁰ In contrast, the photochemical reduction of the homogeneous complexes **C4–C6** in this work showed the formation of hydrogen as a main product, with little amount of formic acid (Table 1), which could indicate the involvement of the carboxylic groups (as well as –NH₃⁺ groups) in H₂ formation

via a reaction path that is suppressed when immobilized in the MOF host. Further studies are required to better understand this behavior.

Finally, the relationship depicted in Figure 4 reveals a direct molecular-level influence of the functional group on the initial reaction rate for CO₂ vs. proton reduction reactions. It can be used to predict the product selectivity of other [Rh(R-bpy)(Cp*)] complexes based on the corresponding Hammett constant value of the R group.

Density functional theory calculations. DFT calculations were performed in order to investigate the mechanistic pathways for CO₂ reduction to HCOOH and proton reduction to H₂ by this class of catalysts, as well as to assess the role of substituents on the bipyridine ligand on the product selectivity. To the best of our knowledge, there have been no DFT studies on the CO₂ reduction to formate by [Rh(R-bpy)(Cp*)]⁺ systems reported in the literature. In terms of proton reduction to hydrogen, the only computational work addresses the unsubstituted [Rh(bpy)(Cp*)Cl]Cl complex.⁵¹ Here, we go a step further to investigate the effect of the substituent on the bpy ligand on the H₂ evolution mechanism and on the catalyst selectivity.

As revealed by the CV data and in agreement with previous electrochemical experiments on the unsubstituted [Rh(bpy)(Cp*)X]⁺ catalyst (**C1**)^{43,44,53} and very recently on [Rh(R-bpy)(Cp*)X]⁺ with R = -tBu and -CF₃,⁵² initially, a two-electron metal-centered reduction of Rh^{III} to Rh^I takes place (see Figures S18-S19), accompanied by a release of the halogen ligand. The computations were performed on complexes **C3** and **C8**, chosen as representatives of the [Rh(R-bpy)(Cp*)Cl]Cl catalysts functionalized with electron-donating and withdrawing groups, respectively.

First proton-transfer step. We started by computing the possible reaction pathways for the protonation of the initial two-electron reduced complex **1** (Figure 5). Et₃NH⁺ was used in the calculations as a model of triethanolammonium ion derived from TEOA.^{59,60} Complex **1** is a Rh(I) complex, most favorably protonated at the metal site to form a Rh(III)-H hydride species, complex **2**, with a transition state barrier (TS_{1,2}) of only 3.6 kcal mol⁻¹ for **C3** and 10.3 kcal mol⁻¹ for **C8**. Direct protonation at the Cp* ring forming an η⁴-pentamethylcyclopentadiene ligand with the new C-H bond *endo* with respect to the metal center, requires much higher transition state barriers TS_{1,3} of 21.6 and 27.4 kcal mol⁻¹ for **C3** and **C8**, respectively. Hence, direct protonation of the Cp* ring is unlikely to occur. Formation of complex **2** is exergonic by 7 kcal mol⁻¹ for the electron-donating complex **C3**, and endergonic by 6.9 kcal mol⁻¹ for the electron-withdrawing **C8**. Next, the Rh(III)-hydride **2** has to undergo an intramolecular proton transfer to the Cp* ring, in order to form the thermodynamically stable species **3**. The TS_{2,3} barrier is computed to be 17.2 and 12.8 kcal mol⁻¹ for **C3** and **C8**, respectively, which indicates that the proton transfer from the Rh site to the Cp* ring is significantly easier in the presence of electron-withdrawing substituents. It should be noted that for all **C1**–**C8** systems the [RhH] form is always less stable than the [Cp*H] tautomer by about 2-3 kcal mol⁻¹, which is in agreement with the experimental isolation of (Cp*H)Rh(bpy) complex and subsequent characterization by X-ray crystallography and NMR spectroscopy.^{40,47}

Reaction pathway for CO₂ reduction to formate. Then, we investigated the mechanistic pathways for the reduction of CO₂ to formate via the two key intermediates, i.e., complexes **2** and **3**, and established the role of the [RhH] vs. [Cp*H] moieties. Figure 6 shows that formate production occurs only from the Rh(III)-hydride species via a direct CO₂ attack to form a transition state TS_{2,4} with a free energy of activation of 17.2 and 19.5 kcal mol⁻¹ for **C3** and **C8**, respectively. The direct hydride transfer to form the [Rh⋯HCO₂] complex **4** is followed by further protonation and a release of HCOOH and the [Rh^{III}(R-bpy)(Cp*)]²⁺ complex **5** (ΔG = 4.4 and 23.1 kcal mol⁻¹ for **C3** and **C8**, respectively). Complex **5** most likely binds a CH₃CN solvent molecule (the Gibbs free energies for this reaction are +2.6 (**C3**) and -0.9 (**C8**) kcal mol⁻¹). Further two-electron reduction recovers the catalytic active Rh^I species **1**. In contrast, CO₂ attack at the η⁴-Cp*H complex **3** goes through much higher transition state barriers of 43 (**C3**) and 42 (**C8**) kcal mol⁻¹ (see Figure 6). This clearly indicates the key role of the Rh(III)-hydride intermediate and excludes the [Cp*H] tautomer for the reduction of CO₂ to formate by the [Rh^I(R-bpy)(Cp*)] class of catalysts.

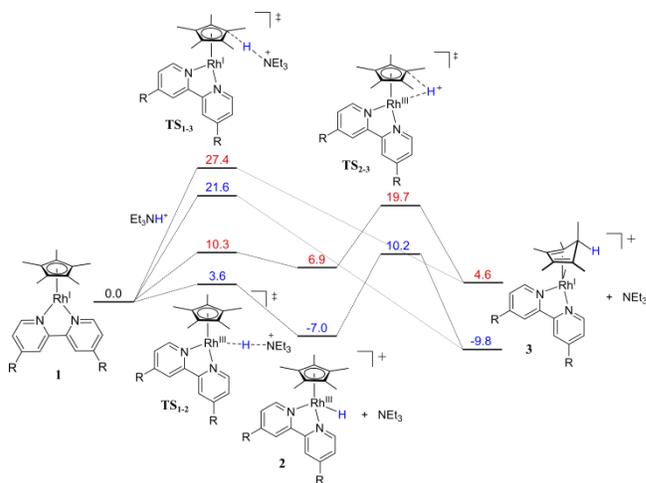


Figure 5. Reaction profile for the protonation of [Rh^I(R-bpy)(Cp*)], with R = -OCH₃ in blue and R = -CF₃ in red. Energies (in kcal mol⁻¹) are given with respect to complex **1**.

The lower TS barrier for the rate-limiting step of direct hydride transfer to CO₂ corroborates the experimental findings that [Rh^I(R-bpy)(Cp*)] complexes containing electron-donating groups at the bpy ligand are better CO₂ reduction catalysts than those with electron-withdrawing substituents in terms of producing more formate.

Reaction pathway towards hydrogen formation. The second main product observed in our photochemical reduction experiments on [Rh(R-bpy)(Cp*)Cl]⁺ catalysts is resulting from the competitive proton reduction reaction leading to the formation of hydrogen. Up to date, most of the research efforts have focused on the hydrogen production by the unsubstituted complex **C1**^{41,47,51,54} and, only very recently, Blakemore et al. have reported electrochemical H₂ formation by complexes with *para* substituted -tBu and -CF₃ on the bpy ligand in [Rh(bpy)Cp*Br]⁺ system.⁵² Electrochemical proton reduction studies revealed that 1 equiv. of acid results in transfer of proton to the Cp* ring, creating the [Cp*H] intermediate **3**, which is suggested to play a key role for hydrogen evolution

upon addition of more acid.^{47,52,54} Furthermore, DFT computations by S.I. Johnson et al. demonstrated the role of the acid strength in assessing different reaction mechanisms, and that H₂ forms only upon direct attack of strong acid on the Rh(III)-H bond.⁵¹ In this work, we computed the H₂ evolution reaction mechanism as a function of the substituent groups on the bpy ligand, in order to assess how their electronic nature affects the competition between HCOOH and H₂.

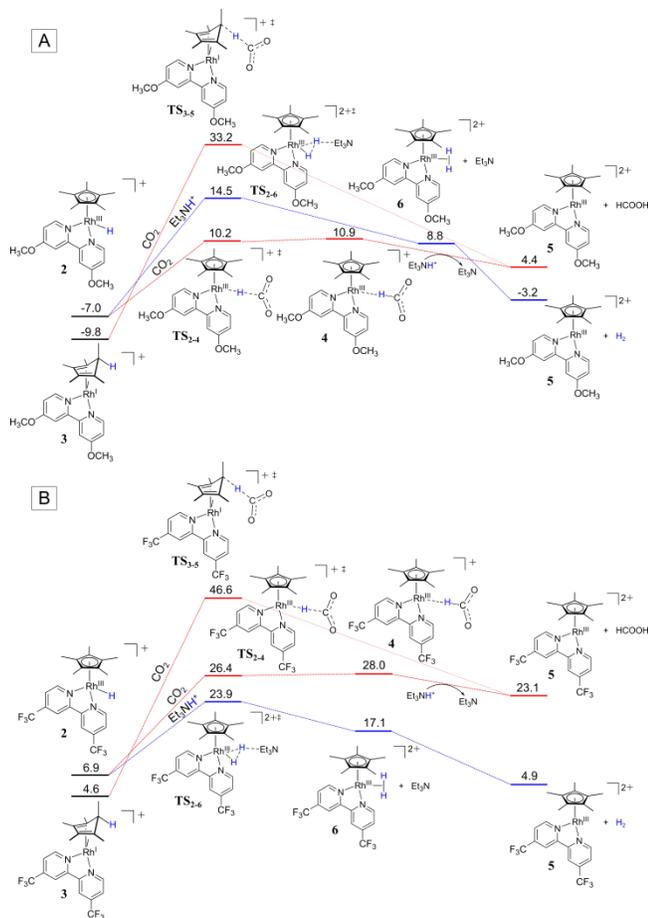


Figure 6. Reaction profile for CO₂ reduction to formate (pathway in red) and H₂ formation (in blue), for complex **C3** (top panel A) and **C8** (bottom panel B). Energies (in kcal mol⁻¹) are given with respect to complex **1**.

As shown in Figure 6, both complexes **C3** and **C8** form hydrogen from a direct attack of the acid on the Rh-H bond, leading to an H-H bond in a RhH₂ adduct **6**, followed by a release of H₂ and the [Rh^{III}(R-bpy)(Cp*)]²⁺ complex **5** ($\Delta G = -3.2$ and 4.9 kcal mol⁻¹ for **C3** and **C8**, respectively). The transition state barriers TS_{2,6} amount to 21.5 (**C3**) and 17 (**C8**) kcal mol⁻¹. Hydrogen evolution pathway *via* the [Cp*H] tautomer involving an acid attack at the Rh(I) center that generates the Rh(III)H(Cp*H) species proceeds through an intramolecular H-H interaction (Figures S20 and S21). While this step has virtually the same TS barrier (21.3 kcal mol⁻¹) as that originating from the direct attack on the Rh-H bond for **C3**, it amounts to 24.8 kcal mol⁻¹ for **C8**. As such, our calculations suggest that this reaction pathway might be operational for complexes with electron-donating substituents, but highly unlikely for the electron-withdrawing ones.

Interestingly, we observe an inversion in the transition state energies: in the case of **C3** the lowest barrier is computed

for the hydride transfer to CO₂ (TS_{2,4} of 17.2 vs 19.5 kcal mol⁻¹), while for **C8** it is for the hydride transfer to protons (TS_{2,6} of 17 vs 21.5 kcal mol⁻¹). Thus decreasing the electron density on bipyridine (here from **C3** to **C8**) results in opposite effects on the computed energies of the transition states of the rate-determining step of the reduction reactions, i.e., TS barrier for proton reduction decreases, while the barrier for the CO₂ reduction increases. This trend is in excellent agreement with the experimental observation that during the photochemical CO₂ reduction, the HCOOH : H₂ ratio decreases from **C3** to **C8**, thus recognizing the complexes with electron-donating functionalized ligands as more selective catalysts for formate production.

Several studies have recognized the importance of hydricity of the intermediate hydride species as a descriptor of the CO₂ vs H⁺ selectivity.^{33–36,61–65} Here, the computed hydricity values for **C3** and **C8** are 70.8 and 74.8 kcal mol⁻¹, respectively (see the Supporting Information for the employed protocol). These values are significantly higher than the hydricity of HCOO⁻ (45.1 kcal mol⁻¹ computed in this work, 43 kcal mol⁻¹ reported experimentally⁶⁶). However, if the Rh complex is further reduced by one electron, the corresponding hydricities become 43.1 (**C3**) and 51 (**C8**) kcal mol⁻¹. Interestingly, the transition state barriers for the hydride transfer from the [Rh^{III}H(R-bpy)(Cp*)]⁰ complex upon CO₂ attack are lowered by only ~ 2 kcal mol⁻¹ to 15.4 and 17.4 kcal mol⁻¹ for **C3** and **C8**, respectively. As such, these hydricity values are consistent with **C3** being a better CO₂ reduction catalyst.

CONCLUSIONS

In this work, we studied the photochemical CO₂ reduction to formic acid catalysed by a series of [Rh(R-bpy)(Cp*)Cl]⁺ complexes, with R being a substituent group in the 4,4' positions of bipyridine (H, CH₃, OCH₃, NH₂, COOH, COOC₂H₅ and CF₃) or a 5,5'-COOH group. This study aimed at using variously substituted ligands in order to fine-tune the selectivity of the catalyst, defined as the HCOOH : H₂ product ratio. The first cathodic peak potential of the complexes was found to correlate linearly with the values of the Hammett parameter of the substituents, in the following order NH₂ > OCH₃ > CH₃ > H > *m*-COOH > COOC₂H₅ > CF₃, spanning 270 mV range from NH₂ to CF₃. While this range is small, the [Rh(R-bpy)(Cp*)]⁺ series of complexes was appropriate for correlating the catalytic activity with the electronic properties of the coordination sphere.

We experimentally demonstrated the general trend that electronic modifications at the bpy ligand have a significant effect on product selectivity and that two classes of catalysts can be identified, which display two different linear trends. More specifically, we showed that increasing the electron-donating nature of the bpy ligand increases the HCOOH : H₂ product ratio. Among the systems investigated in this work, [Rh(OCH₃-bpy)(Cp*)Cl]⁺ was found to be the most selective catalyst for formic acid production. Our DFT calculations rationalized the observed tendency of electron-donating substituents to favor CO₂ reduction by means of lowering the hydride transfer barrier towards formate production as compared to electron-withdrawing substituents that favor more strongly the proton reduction to hydrogen. Similar strategies have been proposed in order to alter the electronics of Mn and Fe catalysts for CO₂ hydrogenation.^{67,68} In addition, we have clarified for the first time the respective role of the [RhH] vs.

[Cp*H] tautomers in CO₂ vs. proton reduction, recognizing the Rh(III)-hydride as the key player in both reactions.

EXPERIMENTAL METHODS

All starting materials and solvents were commercially available and were used without further purification. ¹H NMR spectra were recorded on a Bruker Avance III 300 NMR spectrometer at room temperature. FT-IR spectra were recorded on a IR Prestige-21 spectrometer (Shimadzu, Kyoto, Japan); the spectra are given in Figures S10-S17 in the Supporting Information.

Synthesis of Cp*Rh(bpy)Cl₂·H₂O (C1). A 50 mL reaction flask was charged with 0.506 g (0.820 mmol, 1 equiv) of [Cp*RhCl₂]₂, 0.256 g (1.64 mmol, 2 equiv) of 2,2'-bipyridine, and 25 mL of MeOH. The mixture was allowed to stir at room temperature for 1 hour. The reaction mixture became fully homogeneous over an hour of the experiment and the solution obtained an orange color. The reaction mixture was concentrated *in vacuo*. Excess diethyl ether was added to the reaction flask to yield an orange precipitate complex **C1**, which was further collected on a Buchner funnel and dried under vacuum (92%). ¹H NMR (300 MHz, CD₃CN): δ(ppm) 8.89 (d, *J* = 5.4 Hz, 2H), 8.44 (d, *J* = 8.0 Hz, 2H), 8.29-8.18 (m, 2H), 7.81 (t, *J* = 6.6 Hz, 2H), 1.66 (s, 15H). ¹³C NMR (75 MHz, CD₃CN): δ(ppm) 154.37, 15.00, 140.31, 128.36, 123.92, 97.29 (d, ¹*J*_{C,Rh} = 8.25 Hz, Cp*), 8.18 (CH₃(Cp*)). ESI-MS(+) (CH₃CN): *m/z* calcd for C₂₀H₂₃ClN₂Rh 429.06, found 429.2 (M⁺). FT-IR (CD₃CN): ν_{max} (cm⁻¹) 3634, 3542, 2106, 1632, 1606, 1493, 1473, 1448, 1386, 1381, 1311, 1248. *Anal.* Calcd. for C₂₀H₂₅N₂Cl₂ORh (483.24): C 49.71, H 5.21, N 5.80; Found: C 49.51, H 4.94, N 5.69.

Synthesis of Cp*Rh(4,4'-CH₃-bpy)Cl₂·H₂O (C2). A 50 mL reaction flask was charged with 0.506 g (0.820 mmol, 1 equiv) of [Cp*RhCl₂]₂, 0.302 g (1.64 mmol, 2 equiv) of 4,4'-methyl-2,2'-bipyridine, and 25 mL of MeOH. The mixture was allowed to stir at room temperature for 1 hour. The reaction mixture became fully homogeneous over an hour of the experiment and the solution obtained an orange color. The reaction mixture was concentrated *in vacuo*. Excess diethyl ether was added to the reaction flask to yield an orange precipitate complex **C2**, which was further collected on a Buchner funnel and dried under vacuum (89%). ¹H NMR (300 MHz, CD₃CN): δ(ppm) 8.70 (d, *J* = 5.7 Hz, 2H), 8.28 (s, 2H), 7.61 (d, *J* = 4.8 Hz, 2H), 2.58 (s, 6H), 1.65 (s, 15H). ¹³C NMR (75 MHz, CD₃CN): δ(ppm) 154.06, 152.99, 151.11, 128.95, 124.41, 96.94 (d, ¹*J*_{C,Rh} = 8.25 Hz, Cp*), 20.41 (CH₃(4,4'-CH₃-bpy)), 8.16 (CH₃(Cp*)). ESI-MS(+) (CH₃CN): *m/z* calcd for C₂₂H₂₇ClN₂Rh 457.09, found 457.2 (M⁺). FT-IR (CD₃CN): ν_{max} (cm⁻¹) 3631, 3544, 1622, 1558, 1486, 1455, 1420, 1381, 1321, 1302, 1282, 1244, 1223. *Anal.* Calcd. for C₂₂H₂₉N₂Cl₂ORh (511.29): C 51.68, H 5.72, N 5.48; Found: C 51.69, H 5.48, N 5.38.

Synthesis of Cp*Rh(4,4'-OCH₃-bpy)Cl₂·2H₂O (C3). A 50 mL reaction flask was charged with 0.506 g (0.820 mmol, 1 equiv) of [Cp*RhCl₂]₂, 0.355 g (1.64 mmol, 2 equiv) of 4,4'-methoxy-2,2'-bipyridine, and 25 mL of MeOH. The mixture was allowed to stir at room temperature for 1 hour. The reaction mixture became fully homogeneous over an hour of the experiment and the solution obtained an orange color. The reaction mixture was concentrated *in vacuo*. Excess diethyl ether was added to the reaction flask to yield an orange precipitate complex **C3**, which was further collected on a Buchner

funnel and dried under vacuum (91%). ¹H NMR (300 MHz, CD₃CN): δ(ppm) 8.63 (d, *J* = 6.5 Hz, 2H), 7.96 (d, *J* = 2.7 Hz, 2H), 7.30 (dd, *J* = 6.5, 2.7 Hz, 2H), 4.07 (s, 6H), 1.64 (s, 15H). ¹³C NMR (75 MHz, CD₃CN): δ(ppm) 168.63, 155.86, 152.55, 114.47, 110.33, 96.55 (d, ¹*J*_{C,Rh} = 8.25 Hz, Cp*), 57.09 (CH₃(4,4'-OCH₃-bpy)), 8.16 (CH₃(Cp*)). ESI-MS(+) (CH₃CN): *m/z* calcd for C₂₂H₂₇ClN₂O₂Rh 489.08, found 489.2 (M⁺). FT-IR (CD₃CN): ν_{max} (cm⁻¹) 3629, 3542, 2108, 1617, 1563, 1498, 1473, 1441, 1422, 1339, 1313, 1282, 1270, 1257, 1230. *Anal.* Calcd. for C₂₂H₃₁N₂Cl₂O₄Rh (561.31): C 47.08, H 5.57, N 4.99; Found: C 47.33, H 5.16, N 5.08.

Synthesis of Cp*Rh(4,4'-NH₂-bpy)Cl₂·2H₂O (C4). A 50 mL reaction flask was charged with 0.506 g (0.820 mmol, 1 equiv) of [Cp*RhCl₂]₂, 0.305 g (1.64 mmol, 2 equiv) of 4,4'-amino-2,2'-bipyridine, and 25 mL of MeOH. The mixture was allowed to stir at room temperature for 1 hour. The reaction mixture became fully homogeneous over an hour of the experiment and the solution obtained an orange color. The reaction mixture was concentrated *in vacuo*. Excess diethyl ether was added to the reaction flask to yield an orange precipitate complex **C4**, which was further collected on a Buchner funnel and dried under vacuum (81%). ¹H NMR (300 MHz, DMSO-d₆): δ(ppm) 8.19 (d, *J* = 1.6 Hz, 2H), 7.20-7.04 (m, 6H), 6.81 (dd, *J* = 6.5, 2.4 Hz, 2H), 1.58 (s, 15H). ¹³C NMR (75 MHz, DMSO-d₆): δ(ppm) 157.05, 154.76, 151.22, 112.26, 106.38, 95.56 (d, ¹*J*_{C,Rh} = 7.5 Hz, Cp*), 8.89 (CH₃(Cp*)). ESI-MS(+) (CH₃CN): *m/z* calcd for C₂₀H₂₅ClN₄Rh 459.08, found 459.1 (M⁺). FT-IR (d₆-DMSO): ν_{max} (cm⁻¹) 3499, 3431, 3338, 3187, 1658, 1623, 1558, 1506, 1479, 1464, 1370, 1354, 1270. *Anal.* Calcd. for C₂₀H₂₉N₄Cl₂O₂Rh (531.28): C 45.21, H 5.50, N 10.55; Found: C 45.54, H 5.09, N 10.81.

Synthesis of Cp*Rh(5,5'-COOH-bpy)Cl₂·H₂O (C5). A 50 mL reaction flask was charged with 0.506 g (0.820 mmol, 1 equiv) of [Cp*RhCl₂]₂, 0.400 g (1.64 mmol, 2 equiv) of 5,5'-carboxylic acid-2,2'-bipyridine, and 25 mL of MeOH. The mixture was allowed to stir at room temperature for 1 hour. The reaction mixture became fully homogeneous over an hour of the experiment and the solution obtained an orange color. The reaction mixture was concentrated *in vacuo*. Excess diethyl ether was added to the reaction flask to yield an orange precipitate complex **C5**, which was further collected on a Buchner funnel and dried under vacuum (81%). ¹H NMR (300 MHz, DMSO-d₆): δ(ppm) 9.27 (d, *J* = 1.6 Hz, 2H), 8.93 (d, *J* = 8.4 Hz, 2H), 8.76 (dd, *J* = 8.3, 1.8 Hz, 2H), 1.69 (s, 15H). ¹³C NMR (75 MHz, DMSO-d₆): δ(ppm) 164.53, 156.05, 152.40, 141.21, 131.71, 125.40, 97.78 (d, ¹*J*_{C,Rh} = 8.25 Hz, Cp*), 8.92 (CH₃(Cp*)). ESI-MS(+) (CH₃OH): *m/z* calcd for C₂₂H₂₃ClN₂O₄Rh 517.04, found 517.1 (M⁺), 581.4 ([M]⁺ + 2CH₃OH). ESI-MS(-) (CH₃OH): *m/z* calcd for C₂₂H₂₁ClN₂O₄Rh 515.02, found 515.1 ([M-2H]⁺). FT-IR (d₆-DMSO): ν_{max} (cm⁻¹) 3499, 3442, 2913, 2778, 2602, 2478, 1914, 1710, 1668, 1611, 1593, 1428, 1377, 1278. *Anal.* Calcd. for C₂₂H₂₅N₂Cl₂O₅Rh (571.26): C 46.26, H 4.11, N 4.90; Found: C 46.16, H 4.22, N 4.88.

Synthesis of Cp*Rh(4,4'-COOH-bpy)Cl₂·2H₂O (C6). A 50 mL reaction flask was charged with 0.506 g (0.820 mmol, 1 equiv) of [Cp*RhCl₂]₂, 0.400 g (1.64 mmol, 2 equiv) of 4,4'-carboxylic acid-2,2'-bipyridine, and 25 mL of MeOH. The mixture was allowed to stir at room temperature for 1 hour. The reaction mixture became fully homogeneous over an hour of the experiment and the solution obtained an orange color. The reaction mixture was concentrated *in vacuo*. Excess diethyl ether was added to the reaction flask to yield an orange

precipitate complex **C6**, which was further collected on a Buchner funnel and dried under vacuum (83%). ^1H NMR (300 MHz, DMSO- d_6): δ (ppm) 9.19-9.06 (m, 4H), 8.21 (dd, $J = 5.7$, 1.5 Hz, 2H), 1.68 (s, 15H). $^{13}\text{C}\{^1\text{H}\}$ NMR (75 MHz, DMSO- d_6): δ (ppm) 165.19, 154.79, 153.64, 143.30, 127.87, 123.80, 97.97 (d, $^1J_{\text{C,Rh}} = 7.5$ Hz, Cp*), 8.92 (CH_3 (Cp*)). ESI-MS(+) (CH_3OH): m/Z calcd for $\text{C}_{22}\text{H}_{23}\text{ClN}_2\text{O}_4\text{Rh}$ 517.04, found 517.1 (M^+), 581.3 ($[\text{M}]^+ + 2\text{CH}_3\text{OH}$). ESI-MS(-) (CH_3OH): m/Z calcd for $\text{C}_{22}\text{H}_{21}\text{ClN}_2\text{O}_4\text{Rh}$ 515.02, found 515.1 ($[\text{M}-2\text{H}]^-$). FT-IR (d_6 -DMSO): ν_{max} (cm^{-1}) 3492, 3441, 2916, 2777, 2457, 1908, 1712, 1664, 1558, 1480, 1446, 1401, 1315, 1280, 1257, 1234. *Anal.* Calcd. for $\text{C}_{22}\text{H}_{27}\text{N}_2\text{Cl}_2\text{O}_6\text{Rh}$ (589.27): C 44.24, H 4.25, N 4.65; Found: C 44.84, H 4.62, N 4.75.

Synthesis of Cp*Rh(4,4'-COOC₂H₅-bpy)Cl₂·2H₂O (C7). A 50 mL reaction flask was charged with 0.506 g (0.820 mmol, 1 equiv) of $[\text{Cp}^*\text{RhCl}_2]_2$, 0.492 g (1.64 mmol, 2 equiv) of 4,4'-ethyl carboxylate-2,2'-bipyridine, and 25 mL of MeOH. The mixture was allowed to stir at room temperature for 1 hour. Over an hour the reaction mixture was fully homogeneous and the solution obtained an orange color. The reaction mixture was concentrated on *in vacuo*. Excess diethyl ether was added to the reaction flask to yield an orange precipitate complex **C7**, which was further collected on a Buchner funnel and dried under vacuum (72%). ^1H NMR (300 MHz, DMSO- d_6): δ (ppm) 9.19 (m, 4H), 8.25 (d, $J = 9$ Hz, 2H), 4.49 (q, $J = 6$ Hz, 4H), 1.68 (s, 15H), 1.41 (t, $J = 6$ Hz, 6H). $^{13}\text{C}\{^1\text{H}\}$ NMR (75 MHz, DMSO- d_6): δ (ppm) 163.68, 154.77, 153.90, 141.24, 127.69, 123.84, 99.26 (d, $^1J_{\text{C,Rh}} = 7.5$ Hz, Cp*), 63.02, 14.51, 9.06 (CH_3 (Cp*)). ESI-MS(+) (CH_3OH): m/Z calcd for $\text{C}_{26}\text{H}_{31}\text{ClN}_2\text{O}_4\text{Rh}$ 573.1, found 573.2 (M^+). FT-IR (d_6 -DMSO): ν_{max} (cm^{-1}) 3490, 3451, 2981, 1729, 1655, 1558, 1475, 1458, 1402, 1370, 1319, 1288, 1258, 1233. *Anal.* Calcd. for $\text{C}_{26}\text{H}_{35}\text{N}_2\text{Cl}_2\text{O}_6\text{Rh}$ (645.38): C 48.39, H 5.47, N 4.34; Found: C 48.40, H 5.51, N 4.31.

Synthesis of $[\text{Cp}^*\text{Rh}^{\text{III}}(4,4'\text{-CF}_3\text{-bpy})\text{Cl}]\text{Cl}$ (C8). A 50 mL reaction flask was charged with 0.506 g (0.820 mmol, 1 equiv) of $[\text{Cp}^*\text{RhCl}_2]_2$, 0.479 g (1.64 mmol, 2 equiv) of 4,4'-bis(trifluoromethyl)-2,2'-bipyridine, and 25 mL of MeOH. The mixture was allowed to stir at room temperature for 1 hour. The reaction mixture became fully homogeneous over an hour of the experiment and the solution obtained a yellowish-orange color. The reaction mixture was evaporated *in vacuo* to obtain an oily residue. This residue was dissolved in 2 mL CH_3CN , followed by addition of excess diethyl ether to it to yield a yellow precipitate complex **C8**, which was further collected on a Buchner funnel and dried under vacuum (80%). ^1H NMR (300 MHz, CD_3CN): δ (ppm) 9.15 (d, $J = 5.4$ Hz, 2H), 8.88 (s, 2H), 8.14 (dd, $J = 5.85$, 1.2 Hz, 2H), 1.72 (s, 15H). $^{13}\text{C}\{^1\text{H}\}$ NMR (75 MHz, CD_3CN): δ (ppm) 154.7, 153.6, 140.9 (q, $^1J_{\text{C,F}} = 35.6$ Hz, CF_3), 124.8 (q, $^4J_{\text{C,F}} = 3.75$ Hz), 123.9, 121.1 (q, $^4J_{\text{C,F}} = 3.75$ Hz), 98.2 (d, $^1J_{\text{C,Rh}} = 8.25$ Hz), 8.27. ^{19}F NMR (CD_3CN): δ (ppm) -65.39. ESI-MS(+) (CH_3OH): m/Z calcd for $\text{C}_{22}\text{H}_{21}\text{ClF}_6\text{N}_2\text{Rh}$ 565.04, found 565.1 (M^+). FT-IR (CD_3CN): ν_{max} (cm^{-1}) 3630, 3542, 2104, 1632, 1412, 1344, 1326, 1292, 1275, 1186, 1156. *Anal.* Calcd. for $\text{C}_{22}\text{H}_{21}\text{N}_2\text{Cl}_2\text{F}_6\text{Rh}$ (601.22): C 43.95, H 3.52, N 4.66; Found: C 43.90, H 3.49, N 4.69.

Electrochemistry. All cyclic voltammetry (CVs) experiments were performed in a conventional three-electrode two-compartment cell, using the potentiostat SP 300 Bio-Logic (Bio-Logic Science Instruments SAS). Glassy carbon electrode (GCE, 1mm diameter) was used as working electrode and was polished using a 1 μm diamond suspension and 0.05

μm alumina slurry. A silver wire was used as the reference electrode, and all potential values are reported versus the potential of the $\text{Fc}^{+/0}$ couple that was added as an internal standard to the solution after the measurements. A platinum counter electrode was placed in a separate compartment connected to the main compartment by a glass-frit and filled with the supporting electrolyte solution. Studied complexes were dissolved in acetonitrile containing 0.1 M of tetrabutylammonium hexafluorophosphate (TBAPF₆, Sigma-Aldrich) as the supporting electrolyte and were bubbled with Ar for 30 minutes before measuring CVs.

Photochemical assays. Photochemical reactions were performed using a 300 W, high pressure Xe arc lamp (Oriental Instruments). The beam was passed through an infrared filter, a collimating lens, a filter holder equipped with a 415 nm band pass filter. Samples were prepared in a 1 cm path length quartz cuvette (Starna) which was placed in a temperature controlled cuvette holder (Quantum Northwest) maintained at 20°C with a circulated water bath. The solvent consists of a CO_2 -saturated mixture of acetonitrile (CH_3CN) and triethanolamine (TEOA) in 5:1 volumetric ratio, in which TEOA acts as both a sacrificial electron donor and a source of protons. 1.0 mM of $[\text{Ru}(\text{bpy})_3]\text{Cl}_2$ was used as a photosensitizer, which is in a 10-fold excess with respect to the $[\text{Rh}(\text{R-bpy})(\text{Cp}^*)\text{Cl}]^+$ catalyst. Samples were saturated with CO_2 via directly bubbling CO_2 through the solution mixture for 10 minutes.

Product detection. H_2 measurements were performed by gas chromatography on a Shimadzu GC-2014 equipped with a Quadrex column, a Thermal Conductivity Detector with N_2 as a carrier gas. CO was measured using a Shimadzu GC-2010 Plus gas chromatography, fitted with a S9 Restek Shin Carbon column, Helium carrier gas, a methanizer and a Flame Ionization Detector. The typical volume of gas injected was 50 μL .

Formate concentration was determined using a Metrohm 883 Basic IC plus ionic exchange chromatography instrument, using a Metrosep A Supp 5 column and a conductivity detector. A typical measurement requires the sampling of 200 μL of solution (except in kinetic studies where 15 μL aliquots were sampled), followed by a 100 times dilution in deionised 18 M Ω water and injection of 20 μL into the instrument.

Computational Details. All molecular geometries were fully optimized at the M11-L⁶⁹/def2-TZVP level of density functional theory (DFT) using the Gaussian 09 software package⁷⁰ and the SMD implicit-solvation model ($\epsilon = 35.688$ for acetonitrile).³¹ Quasi-relativistic LANL2TZ(f) pseudopotential was used for Rh.^{32,73} The integral evaluation made use of the grid defined as "ultrafine" in G09. Harmonic vibrational frequencies were computed on the optimized geometries to ensure that all local minima display real frequencies only, whereas the transition states were characterized by a single imaginary frequency. Thermochemical contributions were calculated using the ideal gas, rigid rotor, and harmonic oscillator approximations at a temperature of 298.15 K. The activation barriers were computed using Et_3NH^+ as an explicit proton source.

ASSOCIATED CONTENT

Supporting Information. Supporting electrochemical data (Figures S1-S2), photochemical experiments (Figures S3-S9), FT-IR

spectra (S10-S17), computational details and Cartesian coordinates of all the species involved. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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The manuscript was written through contributions of all authors.

Notes

The authors declare no competing financial interest.

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Table of Contents (TOC)

Synopsys: We report a photochemical CO₂ reduction study on a series of [Rh(R-bpy)(Cp*)Cl]⁺ complexes and show how modifications in the electronic structure of the catalyst affect its selectivity, defined as the HCOOH : H₂ product ratio. DFT computations were used to explain the observed tendency of electron-donating substituents to favor CO₂ reduction by means of lowering the hydride transfer barrier towards formic acid production, as compared to substituents with electron-withdrawing nature that favor more strongly the proton reduction to hydrogen.

