



**HAL**  
open science

## **Photocatalytic CO<sub>2</sub> reduction by Ni-substituted polyoxometalates: Structure-activity relationships and mechanistic insights**

Khadija Talbi, Francesc Penas-Hidalgo, Amanda Robinson, Philipp Gotico, Winfried Leibl, Pierre Mialane, Maria Gomez-Mingot, Marc Fontecave, Albert Solé-Daura, Anne Dolbecq, et al.

### ► To cite this version:

Khadija Talbi, Francesc Penas-Hidalgo, Amanda Robinson, Philipp Gotico, Winfried Leibl, et al.. Photocatalytic CO<sub>2</sub> reduction by Ni-substituted polyoxometalates: Structure-activity relationships and mechanistic insights. *Applied Catalysis B: Environmental*, 2024, 345, pp.123681. <10.1016/j.apcatb.2023.123681>. <hal-04451023>

**HAL Id: hal-04451023**

**<https://hal.science/hal-04451023v1>**

Submitted on 11 Feb 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

# Photocatalytic CO<sub>2</sub> reduction by Ni-substituted polyoxometalates: structure-activity relationships and mechanistic insights

Khadija Talbi<sup>a</sup>, Francesc Penas-Hidalgo<sup>b</sup>, Amanda L. Robinson<sup>b</sup>, Philipp Gotico<sup>c</sup>, Winfried Leibl<sup>c</sup>, Pierre Mialane<sup>a</sup>, Maria Gomez-Mingot<sup>b</sup>, Marc Fontecave<sup>b</sup>, Albert Solé-Daura<sup>d,\*</sup>, Caroline Mellot-Draznieks<sup>b,\*</sup>, Anne Dolbecq<sup>a,\*</sup>

<sup>a</sup>Université Paris-Saclay, UVSQ, CNRS UMR 8180, Institut Lavoisier de Versailles, 78000 Versailles, France

<sup>b</sup>Laboratoire de Chimie des Processus Biologiques, CNRS UMR 8229, Collège de France, Sorbonne Université, PSL Research University, 11 Place Marcelin Berthelot, 75231 Paris Cedex 05, France

<sup>c</sup>Université Paris-Saclay, CEA, CNRS, Institute for Integrative Biology of the Cell (I2BC), 91198 Gif-sur-Yvette, France

<sup>d</sup>Departament de Química Física i Inorgànica, Universitat Rovira i Virgili, Marcel·lí Domingo 1, 43007, Tarragona, Spain

\* Corresponding authors. E-mail addresses: albert.soled@urv.cat (Albert Solé-Daura), caroline.mellot-draznieks@college-de-france.fr (C. Mellot-Draznieks), anne.dolbecq@uvsq.fr (A. Dolbecq)

**Keywords:** Polyoxometalates, Ni substitution, homogeneous photocatalysis, CO<sub>2</sub> reduction, DFT calculations

---

## ABSTRACT

The photocatalytic activity for CO<sub>2</sub> reduction of a series of Ni-substituted polyoxometalates (POMs) differing in nuclearity, shape and size, has been investigated under visible light irradiation, with [Ru(bpy)<sub>3</sub>]<sup>2+</sup> (bpy = 2,2'-bipyridine) as photosensitizer and triethanolamine as sacrificial donor. The tetrabutylammonium salt of the **Ni<sub>4</sub>** tetranuclear species was found to exhibit the highest CO production and its stability under photocatalytic conditions was demonstrated. The catalytic performance was significantly lower for the alkaline salt due to the separation of the POM from its counter-ions occurring only for the tetrabutylammonium salt. Photophysical experiments evidenced a bimolecular electron transfer from the reduced photosensitizer [Ru(bpy)<sub>3</sub>]<sup>+</sup> to the **Ni<sub>4</sub>** POM, the former arising from the reductive quenching of the [Ru(bpy)<sub>3</sub>]<sup>2+</sup> excited state by triethanolamine. This was further supported by DFT calculations, which also showed that the **Ni<sub>4</sub>** POM accumulates at least two electrons and four protons to carry out the CO<sub>2</sub> reduction catalytic process.

---

## 1. Introduction

Polyoxometalates (POMs) are described as molecular oxides based on high-valent metal (M) centers (W<sup>VI</sup>, Mo<sup>VI</sup>, V<sup>IV,V</sup>...) that form MO<sub>x</sub> (x = 5,6) polyhedral building units. They can incorporate heteroelements (P<sup>V</sup>, Si<sup>IV</sup>, Ge<sup>IV</sup>, etc.) and transition metal centers (Fe, Co, Ni, Cu, Zn, etc.) in their structure and they can be further functionalized by organic ligands [1–5]. Besides their high tunability, they exhibit high thermal stability and have the ability to carry out multiple electron and proton transfers, which make them particularly attractive in the field of multi-electron-proton catalysis [6]. Furthermore, these molecular objects may be easily immobilized in various matrices such as metal-organic frameworks [7–9], leading to efficient heterogeneous catalysts.

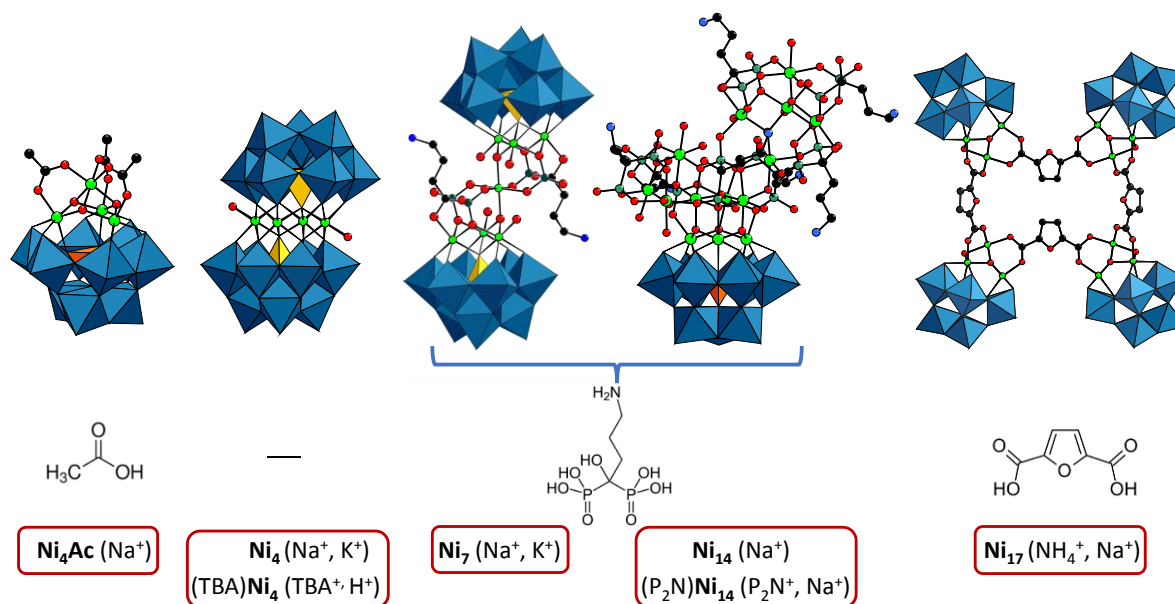
In the field of solar energy conversion, POMs have been widely studied for photocatalytic proton reduction and water oxidation [1–5], while there are notably fewer reports on their use for CO<sub>2</sub>

photoreduction [15,16] and electroreduction [17–19]. Focusing on CO<sub>2</sub> to CO photoconversion, we can observe a few striking examples. In 2010, Neumann and coworkers showed for the first time that a POM substituted by a Ru<sup>III</sup> center can catalyze CO<sub>2</sub> reduction with tertiary amines as sacrificial reducing agents [20]. In 2016, hybrid compounds with Re<sup>I</sup> complexes associated to the Keggin-type PW<sub>12</sub> polyoxotungstate were prepared and a reaction pathway involving the reduced and protonated POM was proposed for the photoreduction of CO<sub>2</sub> [21]. Two years later, a high-nuclear mixed vanadium and cobalt oxo cluster-containing POM showed photocatalytic activity for CO<sub>2</sub> conversion [22]. This study involved for the first time a noble-metal-free POM and was followed by three studies dedicated to the use of homometallic nickel POMs as catalytic species. In 2021, Li, Zheng, Yang and coworkers described the photocatalytic activity of nickel cluster substituted silicotungstates [23]. One year later, Weinstock and coworkers showed that a large molecular assembly of ten hexaniobate POMs encapsulating a {Ni<sub>30</sub>} cluster can act as an efficient

photocatalyst for the reduction of CO<sub>2</sub>, with water serving as electron donor [24]. Finally, Fang and coworkers reported the same year the photocatalytic reduction of CO<sub>2</sub> with catalytic units consisting of self-assembled molecular cages built from {SiW<sub>9</sub>Ni<sub>4</sub>} units connected by rigid dicarboxylate linkers using [Ru(bpy)<sub>3</sub>]<sup>2+</sup> (bpy = 2,2'-bipyridine) complexes as photosensitizers [25]. In addition to these investigations of the catalytic activity of molecular POMs under homogeneous conditions, a few POM-based nanostructures have been studied for heterogeneous photocatalytic CO<sub>2</sub> reduction [26], often based on reduced polyoxomolybdate (*i.e.*, containing Mo<sup>V</sup> ions) structures [27–30]. Composites with Keggin type POMs encapsulated in Cd-based MOFs have also been reported as high-efficient CO<sub>2</sub> reduction catalysts [31]. However, there is still no clear evidence of the structural and compositional parameters that are important for the CO<sub>2</sub> to CO conversion catalytic activity of POMs.

As Ni-substituted compounds are among the most efficient POMs for photocatalytic proton reduction [32–38], and considering the recent reports of their activity for CO<sub>2</sub> reduction [23–25], we decided to investigate the catalytic properties of a series of Ni-based POMs with vacant {SiW<sub>9</sub>} or {PW<sub>9</sub>} units connected to Ni clusters (Fig. 1). The [(SiW<sub>9</sub>O<sub>34</sub>)Ni<sub>4</sub>(CH<sub>3</sub>COO)<sub>3</sub>(OH)<sub>3</sub>]<sup>8-</sup> (**Ni<sub>4</sub>Ac**) [39], [Ni<sub>4</sub>(H<sub>2</sub>O)<sub>2</sub>(PW<sub>9</sub>O<sub>34</sub>)<sub>2</sub>]<sup>10-</sup> (**Ni<sub>4</sub>**) [32],

[[{(PW<sub>9</sub>O<sub>34</sub>)Ni<sub>3</sub>(OH)(H<sub>2</sub>O)<sub>2</sub>(O<sub>3</sub>PC(O)(C<sub>3</sub>H<sub>6</sub>NH<sub>3</sub>)PO<sub>3</sub>)<sub>2</sub>Ni]<sup>14-</sup> (**Ni<sub>7</sub>**) [40], [(SiW<sub>9</sub>O<sub>34</sub>)Ni<sub>14</sub>H<sub>5</sub>(O<sub>3</sub>PC(O)(C<sub>3</sub>H<sub>6</sub>NH<sub>3</sub>)PO<sub>3</sub>)<sub>7</sub>(H<sub>2</sub>O)<sub>11</sub>(OH)<sub>7</sub>]<sup>12-</sup> (**Ni<sub>14</sub>**) [36] and Ni<sub>17</sub>[[{(SiW<sub>9</sub>O<sub>34</sub>)Ni<sub>4</sub>(OH)<sub>3</sub>]<sub>4</sub>(OOC(C<sub>4</sub>H<sub>2</sub>O)COO)<sub>6</sub>]<sup>30-</sup> (**Ni<sub>17</sub>**) [25] POMs were selected for this study. These POMs exhibit various Ni contents, sizes, charges and shapes and possess P or Si as heteroelement. These five POMs crystallize with ammonium and/or alkaline counter-ions (see experimental section). In order to study the influence of the nature of the counter-ions, the tetrabutylammonium (TBA) salt of **Ni<sub>4</sub>** ((TBA)**Ni<sub>4</sub>**) [32] was also studied as well as the bis(triphenylphosphoranylidene)ammonium (P<sub>2</sub>N) salt of **Ni<sub>14</sub>** ((P<sub>2</sub>N)**Ni<sub>14</sub>**) [36]. The photocatalytic proton reduction properties have been previously reported for both ((TBA)**Ni<sub>4</sub>**) [32] and (P<sub>2</sub>N)**Ni<sub>14</sub>** [36] and, as mentioned above, **Ni<sub>17</sub>** has been proven to be a good catalyst for the photocatalytic reduction of CO<sub>2</sub> [25]. Here, it serves as a reference compound. After optimization of the photocatalytic conditions (solvent, nature and concentration of the photosensitizer and the sacrificial donor), the catalytic activities of the seven aforementioned POM salts were investigated. Finally, photophysical measurements and DFT calculations were conducted on the **Ni<sub>4</sub>** catalyst, which exhibits the highest catalytic activity amongst the tested POMs in order to gain insights into the mechanism that governs the catalytic reaction.



**Fig. 1.** Mixed polyhedral and ball-and-stick representation of the Ni-substituted POMs whose photocatalytic activities have been investigated in this study, with the formula of the organic ligand for the hybrid compounds, the abbreviation of the POM salts and the nature of the counter-ions in parentheses. Blue octahedra: WO<sub>6</sub>, orange tetrahedra: SiO<sub>4</sub>, yellow tetrahedra: PO<sub>4</sub>, green spheres: Ni, red spheres: O, black spheres: C, blue spheres: N. Hydrogen atoms have been omitted for clarity.

## 2. Experimental section

### 2.1. Materials and instrumentation

All reagents were purchased from commercial sources and used as received. Infrared (IR) spectra were recorded on a Nicolet 30 ATR 6700 FT spectrometer.

Thermogravimetry analyses (TGA) were performed on a Mettler Toledo TGA/DSC 1, STARe System apparatus under oxygen flow (50 mL min<sup>-1</sup>) at a heating rate of 5°C min<sup>-1</sup> up to 700°C. EDX experiments were performed with a Jeol JSM-5800LV Scanning Microscope. Dynamic Light Scattering (DLS) experiments were performed on a Malvern Zetasizer Nano ZS. Electrospray ionization (ESI) mass spectra were recorded on a Xevo QT of WATERS (quadrupole-time-of-flight) instrument. The temperature of the source block was set to 120 °C, and the desolvation temperature was set to 200 °C. A capillary voltage of 1 kV was used in the negative scan mode, and the cone voltage was set to 10 V to control the extent of fragmentation of the identified species. Mass calibration was performed using a solution of sodium formate in water/acetonitrile (2:8) from m/z = 50 to 3000. Sample solutions were injected via a syringe pump directly connected to the ESI source at a flow rate of 20 µL/min.

## 2.2. Synthesis of POMs

The Ni-substituted polyoxotungstates Na<sub>15</sub>[Na{(SiW<sub>9</sub>O<sub>34</sub>)Ni<sub>4</sub>(CH<sub>3</sub>COO)<sub>3</sub>(OH)<sub>3</sub>}<sub>2</sub>]-4NaCl·36H<sub>2</sub>O (**Ni<sub>4</sub>Ac**) [39], Na<sub>2</sub>K<sub>8</sub>[Ni<sub>4</sub>(H<sub>2</sub>O)<sub>2</sub>(PW<sub>9</sub>O<sub>34</sub>)<sub>2</sub>]-28H<sub>2</sub>O (**Ni<sub>4</sub>**) [32], (TBA)<sub>7</sub>H<sub>3</sub>[Ni<sub>4</sub>(H<sub>2</sub>O)<sub>2</sub>(PW<sub>9</sub>O<sub>34</sub>)<sub>2</sub>]-4H<sub>2</sub>O ((TBA)**Ni<sub>4</sub>**) [32] Na<sub>7</sub>K<sub>7</sub>[{(PW<sub>9</sub>O<sub>34</sub>)Ni<sub>3</sub>(OH)(H<sub>2</sub>O)<sub>2</sub>(O<sub>3</sub>PC(O)(C<sub>3</sub>H<sub>6</sub>NH<sub>3</sub>)PO<sub>3</sub>)<sub>2</sub>Ni}]·34H<sub>2</sub>O (**Ni<sub>7</sub>**) [40], Na<sub>12</sub>[(SiW<sub>9</sub>O<sub>34</sub>)Ni<sub>14</sub>H<sub>5</sub>(O<sub>3</sub>PC(O)(C<sub>3</sub>H<sub>6</sub>NH<sub>3</sub>)PO<sub>3</sub>)<sub>7</sub>(H<sub>2</sub>O)<sub>11</sub>(OH)<sub>7</sub>] · 75H<sub>2</sub>O (**Ni<sub>14</sub>**) [36], (P<sub>2</sub>NC<sub>36</sub>H<sub>30</sub>)<sub>8</sub>Na<sub>4</sub>[(SiW<sub>9</sub>O<sub>34</sub>)Ni<sub>14</sub>(AleOH)<sub>5</sub>(AleO)<sub>2</sub>(H<sub>2</sub>O)<sub>11</sub>(OH)<sub>7</sub>]-60H<sub>2</sub>O ((P<sub>2</sub>N)**Ni<sub>14</sub>**) [36] and (NH<sub>4</sub>)<sub>22</sub>Na<sub>8</sub>Ni<sub>4</sub>[(SiW<sub>9</sub>O<sub>34</sub>)Ni<sub>4</sub>(OH)<sub>3</sub>]<sub>4</sub>(OOC(C<sub>4</sub>H<sub>2</sub>O)COO)<sub>6</sub>]-155H<sub>2</sub>O (**Ni<sub>17</sub>**) [25] were synthesized according to reported procedures. These POMs were characterized in the solid state by IR spectroscopy and EDX measurements and the number of crystallization water molecules was confirmed by TGA measurements (Fig. S1).

## 2.3. Photocatalytic experiments

All photocatalytic experiments, except the kinetic and labelling experiments on **Ni<sub>4</sub>** (*vide infra*), were run in a CH<sub>3</sub>CN:H<sub>2</sub>O:TEOA (1.5 mL:0.33 mL:0.17 mL; TEOA = triethanolamine) solution with 0.06 µmol of POM and 3.9 µmol of [Ru(bpy)<sub>3</sub>]Cl<sub>2</sub>, corresponding to the following concentrations: 30 µM of POM, 0.64 M of TEOA, 1.95 mM of [Ru(bpy)<sub>3</sub>]Cl<sub>2</sub>. Photochemical reactions were performed using a 280 W, high-pressure Xe arc lamp (Newport Instruments). The beam was passed through a water infrared filter, a collimating lens, and a filter holder equipped with a 415 nm band-pass filter (Asahi Spectra). Samples were saturated with CO<sub>2</sub> via directly bubbling CO<sub>2</sub> through the solution mixture for 30 min. During irradiation, the samples were vigorously stirred at a controlled temperature (20

°C) and aliquots of the headspace were analyzed in two gas chromatographs (GCs). H<sub>2</sub> measurements (aliquots of 50 µL of the headspace) were performed by gas chromatography on a Shimadzu GC-2014 equipped with a Quadrex column and a Thermal Conductivity Detector and using N<sub>2</sub> as a carrier gas. CO was measured using a Shimadzu GC-2010 Plus carried by helium and with a S9 Restek ShinCarbon column and a flame ionization (FID) detector with a methanizer. Aliquots of gas were removed with a gas-tight syringe. Formate in the liquid phase was also analyzed using a Metrohm 883 Basic IC plus ionic exchange chromatography instrument, using a Metrosep A Supp 5 column and a conductivity detector. The sample was 100-fold diluted in deionized 18 MΩ water and 20 µL were injected into the IC chromatograph. No significant formate production was detected in all experiments. Calibration curves for H<sub>2</sub> and CO in a CO<sub>2</sub> matrix (0-70000 ppm) and for HCOOH in water (0-30 µM) were performed before analysis.

Kinetic measurements during photocatalysis were performed with blue LED irradiation (SugarCube LED lamp, emission at 463 nm with FWHM of 50 nm, 100 W m<sup>-2</sup> irradiation). Gaseous products were detected by automatic injection into a Micro GC Fusion Gas Analyzer, equipped with PLOT molecular sieve column, Ar carrier gas, and TCD detector. Mass spectrometry coupled to GC (Trace GC Ultra/ISQ, Thermo Scientific) was used for labelling experiments with <sup>13</sup>CO<sub>2</sub>.

## 2.4. Photophysical experiments

Transient absorption and emission experiments were performed on an Edinburgh Instruments LP920 Laser Flash Photolysis Spectrometer. The system incorporated a Continuum Q-switched Nd:YAG laser operating at 355 nm and a Continuum Surelite OPO for sample excitation at 460 nm (5 ns pulse duration, typical energy 7-10 mJ). The LP920 system is equipped with a 450 W Xenon lamp as the probe for the transient absorption measurements. Detection in the LP920 system is performed either via a Czerny-Turner blazed 500 nm monochromator (bandwidth: 1-5 nm) coupled with a Hamamatsu R928 photomultiplier tube (kinetics mode), or via a 500 nm blazed spectrograph (bandwidth: 5 nm) coupled with a water-cooled ICCD camera (Andor DH720; (spectral mode). Samples, having absorbances of 0.6 at the excitation wavelength, were purged with argon prior to each experiment. The turnover number (TON) is defined as :  
TON = Total mole number of product / Total mole number of catalyst.

## 2.5. Computational details

DFT calculations were carried out at the ωB97X-D level using Gaussian16 (rev C.02) quantum chemistry package [41]. The LANL2DZ basis set and associated

pseudopotentials [42] were used to describe Ni and W atoms. These were supplemented by a Frenking's *f*-type polarization function [43]. The remaining atoms were described with the all-electron 6-31g(d,p) basis set [44–46]. As the POM catalyst was experimentally found to remain in the aqueous phase during photocatalytic experiments (*vide infra*), solvent effects of water were included by means of the IEF-PCM implicit solvent model [47] as implemented in Gaussian16. Geometry optimizations were carried out without any symmetry restriction. The nature of all stationary points on the potential energy surface was confirmed by frequency calculations. The standard-state correction of +1.9 kcal mol<sup>-1</sup> (from the 1 atm reference state assumed in Gaussian calculations to the standard state of 1 mol L<sup>-1</sup> in solution at 25 °C) was applied to the free energy of all the species with the exception of water molecules. For the latter, which are part of the solvent, the standard-state correction accounts for +4.3 kcal mol<sup>-1</sup> according to their concentration of 55.3 mol L<sup>-1</sup>. A data set collection of the optimized structures for the most relevant species is available in the ioChem-BD repository [48] and can be accessed via 10.19061/iochem-bd-6-293.

### 3. Results and discussion

#### 3.1. Photocatalytic reduction of CO<sub>2</sub>

Photocatalytic experiments were performed in CH<sub>3</sub>CN:H<sub>2</sub>O:TEOA solutions, with TEOA as sacrificial electron donor (SED), H<sub>2</sub>O as proton source and [Ru(bpy)<sub>3</sub>]<sup>2+</sup> as photosensitizer (PS). The solutions were saturated with CO<sub>2</sub> and irradiated with a 280 W Xe lamp ( $\lambda > 415$  nm) and both gas and liquid phases were analyzed after 2 h. For all the POMs, only negligible amount of formate was detected in the liquid phase while CO and H<sub>2</sub> were present and quantified in the gas phase. The experimental conditions were optimized on (TBA)Ni<sub>4</sub> that proved to be the most efficient catalyst (see below). We considered first the solvent composition ratios. There was an optimum CO production (2.89  $\mu$ mol, Table S1, entry 2) for a CH<sub>3</sub>CN:H<sub>2</sub>O:TEOA ratio equal to 8.8:2:1 which corresponds to a mixture of 1.5 mL of CH<sub>3</sub>CN, 0.33 mL of H<sub>2</sub>O and 0.17 mL of TEOA. When lower or higher TEOA volumes were added, the CO production decreased (Table S1, entries 1 and 3). The presence of water was found to be beneficial for the production of CO, with a significant decrease from 2.89 to 0.74  $\mu$ mol in absence of water (Table S1, entry 4). We then studied the influence of the nature and concentration of the photosensitizer. With 1.95 mM PS concentration, the CO production was higher with [Ru(bpy)<sub>3</sub>]<sup>2+</sup> (2.89  $\mu$ mol) when compared to [Ru(phen)<sub>3</sub>]<sup>2+</sup> (1.61  $\mu$ mol) while only traces were detected with [Ir(dtbbpy)(ppy)<sub>2</sub>]<sup>+</sup> (Table S2, entries 1-3). Furthermore, an optimum condition was

found with [Ru(bpy)<sub>3</sub>]<sup>2+</sup> concentration of 1.95 mM, with lower CO productions observed when higher or lower concentrations were used (Table S2, entries 1, 4-6). Control experiments indicated that (TBA)Ni<sub>4</sub> was inactive with negligible CO production in the absence of CO<sub>2</sub>, light, PS, sacrificial electron donor, or catalyst (Table S3, entries 1-6).

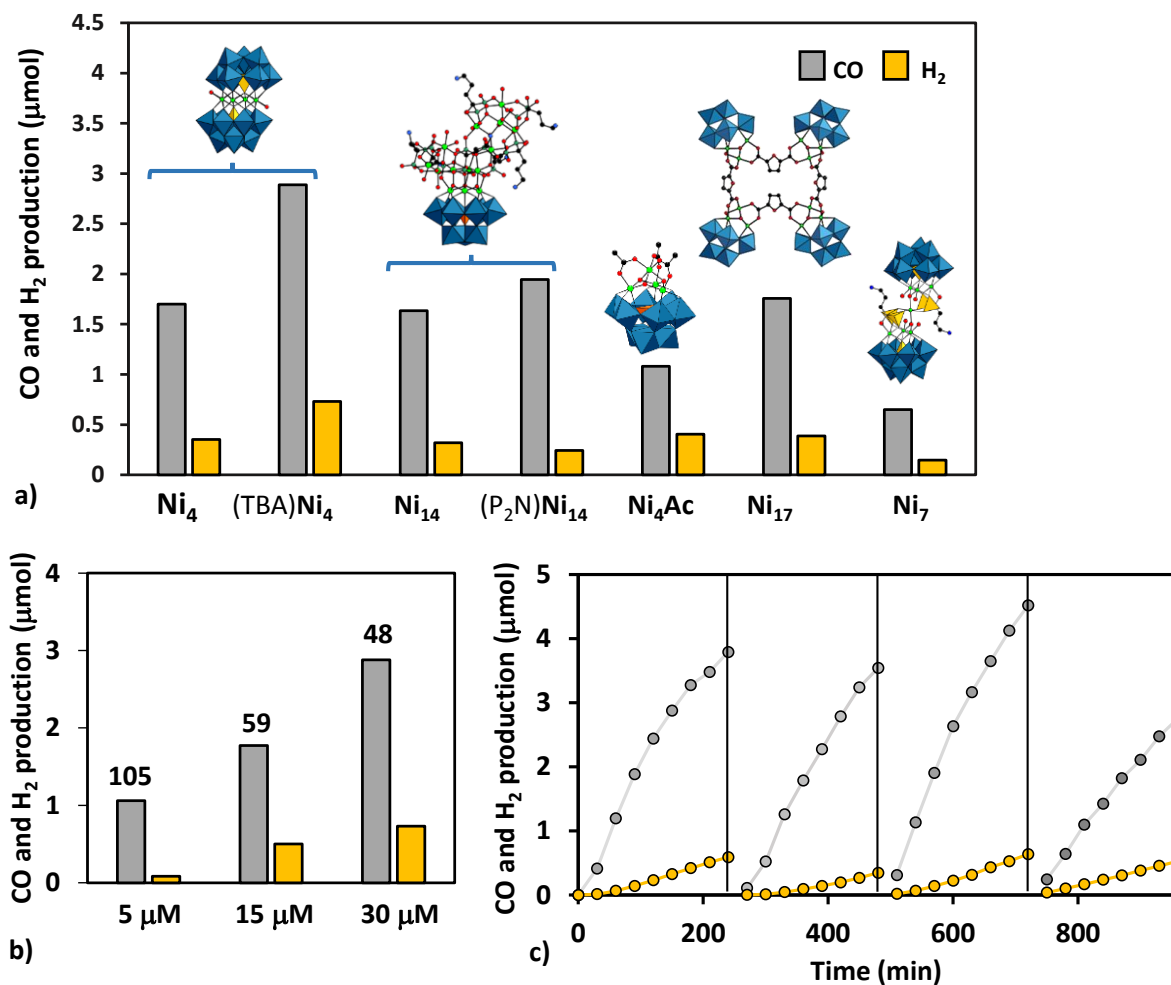
The production of CO and H<sub>2</sub> was measured for the seven salts of Ni-substituted POMs using the optimized conditions (Fig. 2a, Table S4). As shown in Fig. 2a, the lowest CO production was observed for Ni<sub>7</sub> (0.65  $\mu$ mol) and Ni<sub>4</sub>Ac (1.08  $\mu$ mol) while (TBA)Ni<sub>4</sub> exhibited the highest CO production (2.89  $\mu$ mol), showing a higher activity than Ni<sub>17</sub> under similar conditions used in this study. However, the CO production of this Ni<sub>4</sub> POM was far lower (1.70  $\mu$ mol, Fig. 2a, Table S4) when used as a mixed Na<sup>+</sup> and K<sup>+</sup> salt instead of a TBA salt. The same trend, although less pronounced, was observed for Ni<sub>14</sub>, for which the CO production was equal to 1.63  $\mu$ mol as a sodium salt and 1.94  $\mu$ mol as an organic soluble salt (P<sub>2</sub>N salt). For all the POMs, the CO selectivity lies between 73 % (for Ni<sub>4</sub>Ac) and 89 % (for (P<sub>2</sub>N)Ni<sub>14</sub>) (Table S4). Furthermore, the production of CO and H<sub>2</sub> of the Na<sub>8</sub>H[PW<sub>9</sub>O<sub>34</sub>] precursor measured using the same conditions (Table S4) is very low, evidencing that the Ni ions play a crucial role in the catalytic process.

As (TBA)Ni<sub>4</sub> exhibits the best performance, all further studies were performed on it. The CO and H<sub>2</sub> productions were studied for catalyst's concentration ranging from 5 to 30  $\mu$ M (Fig. 2b, Table S1, entries 7, 6 and 2). The CO production increases from 1.06 to 2.89  $\mu$ mol with a selectivity equal to 93% for the lowest concentration. As usually observed, the CO turnover number (TON) is higher at lower catalyst concentrations (105 for 5  $\mu$ M and 48 for 30  $\mu$ M solutions). Finally, kinetic measurements were performed on (TBA)Ni<sub>4</sub> using an automatized set-up with blue LED irradiation (Fig. 2c, Table S5). The CO production increased linearly for the first 2 h but leveled off after 4 h. This plateau was attributed to the deactivation of the [Ru(bpy)<sub>3</sub>]<sup>2+</sup> photosensitizer, following the loss of a bipyridine linker [49–51]. The production restarted after addition of 8.1 mg (10.8  $\mu$ mol) of [Ru(bpy)<sub>3</sub>]Cl<sub>2</sub>. Four consecutive cycles have been done confirming that the plateau is not due to the degradation of the catalyst but to that of the photosensitizer. The CO production amounts to 14.6  $\mu$ mol after 16 h. In addition, an isotope tracer experiment was performed to determine the origin of CO. The peak at *m/z* = 29 observed in the mass spectrum (GC-MS) analysis of the gas generated from the photocatalytic reduction of <sup>13</sup>CO<sub>2</sub> was assigned to <sup>13</sup>CO, providing experimental proof that CO originates from CO<sub>2</sub> reduction (Fig. S2).

Strikingly, for all these photocatalytic experiments, a phase separation was observed (Fig. 3a), with a denser orange-colored phase (S2 solution) and a lighter

colored phase at the top (S1 solution). This phase separation appears only after CO<sub>2</sub> bubbling. Salt-induced liquid-liquid phase separation in water-acetonitrile mixtures is a phenomenon commonly observed [52]. In the photocatalytic medium, ionic species are formed by CO<sub>2</sub> bubbling, such as zwitterionic TEOA-CO<sub>2</sub> adducts [53], carbamate, HTEOA<sup>+</sup> and HCO<sub>3</sub><sup>-</sup> species [44]. The presence of these ions alters the hydrogen-bond interactions between water and acetonitrile molecules, which contribute to the miscibility of these two solvents. Indeed, water

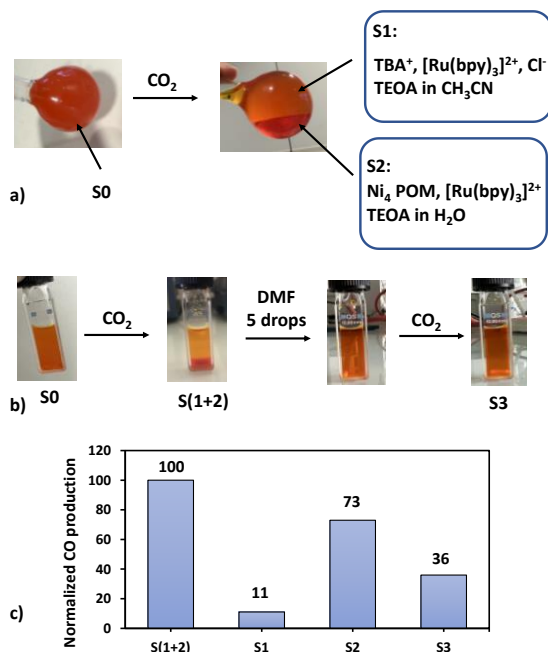
molecules surround the ions, becoming unavailable for the organic solvent that becomes “salted out” from the aqueous phase [54]. The orange color of the S1 and S2 solutions indicates the presence of [Ru(bpy)<sub>3</sub>]<sup>2+</sup> in both phases. Furthermore, after separation of S1 and S2, addition of a large excess of [Ru(bpy)<sub>3</sub>]Cl<sub>2</sub> in S2 leads to the formation of a precipitate for which the vibrational bands of the POM can clearly be identified (Fig. S3). On the contrary, no precipitate was observed after addition of [Ru(bpy)<sub>3</sub>]Cl<sub>2</sub> in S1. It can be deduced that the POM is mainly present in the S2 phase.



**Fig. 2.** CO (gray) and H<sub>2</sub> (yellow) production after 2 h for a CO<sub>2</sub>-saturated solution of CH<sub>3</sub>CN:H<sub>2</sub>O:TEOA (1.5 mL:0.33 mL:0.17 mL) in the presence of 1.95 mM [Ru(bpy)<sub>3</sub>]Cl<sub>2</sub> under visible light irradiation (280 W Xe lamp, λ > 415 nm) with (a) the various salts of Ni-substituted POMs (30 μM) and (b) with various concentrations of the (TBA)Ni<sub>4</sub> POM (number labels indicate TONs); (c) time evolution of CO (gray line) and H<sub>2</sub> (orange line) production of (TBA)Ni<sub>4</sub> (30 μM) under blue LED (463 nm) irradiation; additional 8.1 mg (10.8 μmol) of [Ru(bpy)<sub>3</sub>]Cl<sub>2</sub> were added after 240, 480 and 720 min showing the recovery of activity.

Finally, <sup>1</sup>H NMR measurements performed on both phases of a CD<sub>3</sub>CN:D<sub>2</sub>O:TEOA catalytic medium indicate that TEOA is present in both phases (two peaks at 3.40 and 2.69 ppm in S2 and 3.49 and 2.56 ppm in S1) and that the TBA cations are only present in the S1 phase (Fig. S4). We can further note that while the signals related to the TBA protons of the homogeneous catalytic solution obtained before bubbling CO<sub>2</sub> are broadened, indicating the presence of the paramagnetic POMs, they are well-defined in the <sup>1</sup>H

NMR spectrum of S1, confirming that the POMs are only in the S2 phase. Moreover, we have noticed that the addition of a few drops of DMF to the biphasic mixture also restores a homogeneous phase which is maintained upon further CO<sub>2</sub> bubbling (S3 solution, Fig. 3b). It can be proposed that such addition of DMF regenerates the interactions between solvent molecules, preventing the liquid-liquid separation.



**Fig. 3.** Pictures of a) a 30 mL catalytic solution before and after bubbling CO<sub>2</sub>; b) a 2 mL catalytic solution before and after bubbling CO<sub>2</sub> and after addition of DMF; c) normalized CO production of the various solutions. Catalytic conditions: 2 mL of CO<sub>2</sub>-saturated solution irradiated during 2 h (280 W Xe lamp,  $\lambda > 415$  nm).

All these observations prompted us to further investigate the respective photocatalytic activity of each solution. The photocatalytic activity of 2 mL of the S(1+2) solution vigorously agitated (usual conditions) have been compared to that of 2 mL of S1 and 2 mL of S2 separately and of 2 mL of S3 (Fig. 3c). As expected, the activity of the S1 solution is far lower than that of S(1+2) because the POM is mainly in the S2 solution. Even if all the components of the catalytic reaction are present in the S2 and S3 solutions, the catalytic activity of these two solutions is also lower than that of the S(1+2) solution. This can be expected for S2, knowing that the solubility of CO<sub>2</sub> is lower in H<sub>2</sub>O than in CH<sub>3</sub>CN, but is more surprising for S3. We also carried out two complementary experiments, one with just water and TEOA as the catalytic medium and the other with two drops of DMF added to the CH<sub>3</sub>CN:H<sub>2</sub>O:TEOA mixture, that thus remains biphasic (Fig. S5). The CO production dramatically drops when the catalysis is performed in the H<sub>2</sub>O/TEOA mixture (-71%) whereas it is maintained when only two drops of DMF are added, in the CH<sub>3</sub>CN:H<sub>2</sub>O:TEOA mixture, which is still biphasic. These experiments show that DMF does not inhibit the catalytic reaction and that the formation of a phase separation is essential. It can be proposed that the catalytic reaction takes place in the water phase at its interface with the CH<sub>3</sub>CN phase and that the separation of the POM (in the S2 solution) from its TBA counter-ions (in the S1 solution) has a beneficial impact on the photocatalytic activity. This hypothesis is in line with

the observation that the catalytic activity of the alkaline salt of Ni<sub>4</sub> is lower than that of (TBA)Ni<sub>4</sub> (Fig. 2a). Indeed, with the alkaline salt, the sodium and potassium counter-ions interact strongly with the Ni<sub>4</sub> POM and must remain close to it in the aqueous phase [55] and might hinder the catalytic process. The solutions after photocatalysis were analyzed by electrospray ionization mass spectrometry (ESI-MS). The peak attributed to the oxidized product of TEOA (aldehyde) was clearly visible on the mass spectrum of the aqueous phase S2 (Fig. S6), confirming the oxidation of TEOA during the catalytic process and its role as a sacrificial electron donor. We can note that such oxidation product of TEOA has been previously observed [56,57].

The stability of the catalyst is obviously an important parameter in photocatalytic CO<sub>2</sub> reduction. The IR spectrum of the precipitate obtained by addition of [Ru(bpy)<sub>3</sub>]Cl<sub>2</sub> in S2 after photocatalysis is identical to that of the precipitate obtained before catalysis and also very similar to the IR spectrum of the pristine POM in the W-O, W=O and P-O vibrations regions (Fig. S3). EDX measurements performed on the precipitate obtained by addition of [Ru(bpy)<sub>3</sub>]Cl<sub>2</sub> in S2 after photocatalysis have shown that the Ni/P and P/Ni ratio are the ones expected for a [Ni<sub>4</sub>(H<sub>2</sub>O)<sub>2</sub>(PW<sub>9</sub>O<sub>34</sub>)<sub>2</sub>]<sup>10-</sup> POM (Ni/W ratio calc = 0.22, exp = 0.28; P/Ni ratio calc = 0.50, exp = 0.47). Furthermore, as mentioned above, the addition of [Ru(bpy)<sub>3</sub>]Cl<sub>2</sub> allows to restore the CO production (Fig. 2c). Finally, dynamic light scattering (DLS) experiments indicate the absence of particles having a diameter higher than 1 nm, suggesting that no nickel oxide nanoparticle was formed during the catalytic event. All these observations support that (TBA)Ni<sub>4</sub> is stable under the described catalytic conditions.

### 3.2. Mechanistic study of the (TBA)Ni<sub>4</sub> POM photocatalytic system

#### Photophysical studies

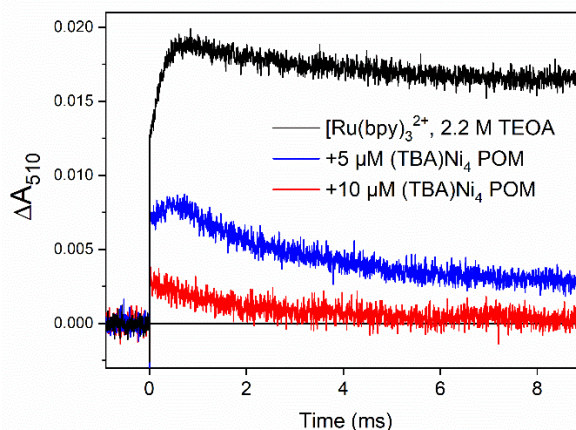
During photocatalysis, photon absorption creates the excited state of the photosensitizer that either interacts with the SED to form the long-lived reduced form [Ru(bpy)<sub>3</sub>]<sup>+</sup> (reductive quenching) which is then activating the catalyst, or reduces the catalyst (oxidative quenching) leading to formation of the strong oxidant [Ru(bpy)<sub>3</sub>]<sup>3+</sup> that is then reduced by the SED. To obtain more insight into the photocatalytic mechanism at work, we performed time-resolved photophysical studies. First, the interaction of the sacrificial electron donor TEOA with the [Ru(bpy)<sub>3</sub>]<sup>2+</sup> photosensitizer was studied. Addition of increasing amounts of TEOA up to 3 M hardly affects the kinetics of the [Ru(bpy)<sub>3</sub>]<sup>2+</sup> excited state (Fig. S7A) although the small bleaching of the MLCT absorption persisting after decay of the excited state indicated formation of the

reduced form of the photosensitizer (Fig. S7B). This was confirmed by the observation of formation of a long-lived ( $\gg$  ms) species with absorption features characteristic of the reduced photosensitizer,  $[\text{Ru}(\text{bpy})_3]^+$  (Fig. S8). Due to the low rate constant for quenching of the excited state by TEOA ( $k_{\text{TEOA}} = 4 \cdot 10^4 \text{ M}^{-1} \text{ s}^{-1}$ ) the quantum yield of formation of  $[\text{Ru}(\text{bpy})_3]^+$  is low and amounts to around 3% for the concentrations of SED (0.64 M) typically used in the photocatalytic reactions (Fig. S9).

We then investigated the interaction between the excited state of the photosensitizer and the catalyst. When 10  $\mu\text{M}$  of  $(\text{TBA})\text{Ni}_4$  POM were added to a solution of 40  $\mu\text{M}$   $[\text{Ru}(\text{bpy})_3]^{2+}$ , the emission of the latter was nearly completely quenched (Fig. S10). This is strong indication for formation of ion-pairing adducts between the highly negatively charged POM and the double positively charged photosensitizer. As the quenching of emission was much weaker in presence of only 3  $\mu\text{M}$  POM it can be concluded that one POM can fix around four photosensitizer complexes. This electrostatic interaction is also detectable as a redshift in the emission and absorption spectra of the photosensitizer (Fig. S11). The most likely pathway for deactivation of the excited state of the photosensitizer is via a fast and reversible electron transfer to the POM. However, this electron transfer does not lead to the formation of a charge-separated state sufficiently stable to be detectable on a nanoseconds time scale. The main reason could be that the  $[\text{Ru}(\text{bpy})_3]^{3+}$  species formed after electron injection into the POM is even more strongly bound to the POM and unable to escape the association complex before charge recombination. This makes a photocatalytic reaction mechanism involving POM reduction from the photosensitizer excited state unlikely. However, it should be noted that with the large excess of photosensitizer over POM employed in the photocatalytic experiments (1.85 mM  $[\text{Ru}(\text{bpy})_3]^{2+}$  for 10  $\mu\text{M}$  POM) only a negligible fraction of photosensitizer activity is lost due to scavenging by the POMs. The grand majority of PS molecules should show a long-lived excited state able to interact with the SED, forming the more reducing  $[\text{Ru}(\text{bpy})_3]^+$  species with an efficiency as described above. This long-lived  $[\text{Ru}(\text{bpy})_3]^+$  species is then the reductant for the catalyst.

Photophysical characterization was also performed on a three-component system comprising the photosensitizer, POM, and TEOA. It appears that the presence of TEOA at high concentration weakens the electrostatic interaction between the photosensitizer and the POM to some extent as in the presence of TEOA less static quenching of the photosensitizer excited state is observed (compare Fig. S12 and Fig. S10). Analysis of the amount of long-lived excited state as a function of concentration of POM (Figs. S12, S13) allows to estimate that the POM can bind up to four

equivalents of  $[\text{Ru}(\text{bpy})_3]^{2+}$  complexes. Fig. 4 shows the kinetics of the reduced state of the (free) photosensitizer, recorded at 510 nm on a long-time scale, for different concentrations of POM. The traces



**Fig. 4.** Kinetics of transient absorption at 510 nm of  $[\text{Ru}(\text{bpy})_3]^{2+}$  (40  $\mu\text{M}$ ) upon excitation with nanosecond laser flashes at 460 nm in Ar-saturated MeCN/H<sub>2</sub>O (9/1), 2.2 M TEOA solution containing increasing concentrations of  $(\text{TBA})\text{Ni}_4$  POM.

show the fast formation of the  $[\text{Ru}(\text{bpy})_3]^+$  state followed by its decay that is accelerated with increasing concentration of POM. This finding is a strong indication for the occurrence of bimolecular electron transfer from the reduced photosensitizer to the POM, with a rate of about  $6 \times 10^7 \text{ M}^{-1} \text{ s}^{-1}$ .

#### DFT calculations

To further investigate the interactions between the  $\text{Ni}_4$  POM catalyst and the other components of the photocatalytic system under light irradiation, we next conducted theoretical DFT calculations. As the redox properties of POMs are strongly dependent on their protonation state [58], we firstly examined the ability of  $\text{Ni}_4$  to associate protons under photocatalytic conditions. To this end, we considered the N-protonated form of TEOA ( $\text{HTEOA}^+$ ) as the source of protons. With a  $\text{p}K_a$  of 7.8 [59], the latter is expected to exist in equilibrium with TEOA in the reaction mixture, but it is also generated through the spontaneous deprotonation of  $\text{TEOA}^{*+}$  radical cations that arise from the reductive quenching of the photoexcited  $[\text{Ru}(\text{bpy})_3]^{2+}$ , by a second TEOA molecule [57,60–62].

Under photocatalytic conditions, the  $\text{Ni}_4$  catalyst was found to spontaneously abstract up to two protons from  $\text{HTEOA}^+$  molecules, the reaction Gibbs free-energies for the first and the second proton transfer events being -6.8 and -5.1 kcal mol<sup>-1</sup>, respectively (Fig. S14). The protons in the doubly-protonated anion, labeled as  $\text{H}_2\text{Ni}_4$ , are accommodated on two  $\mu_2$ -(Ni-O-W) bridging oxygen sites in an antisymmetric

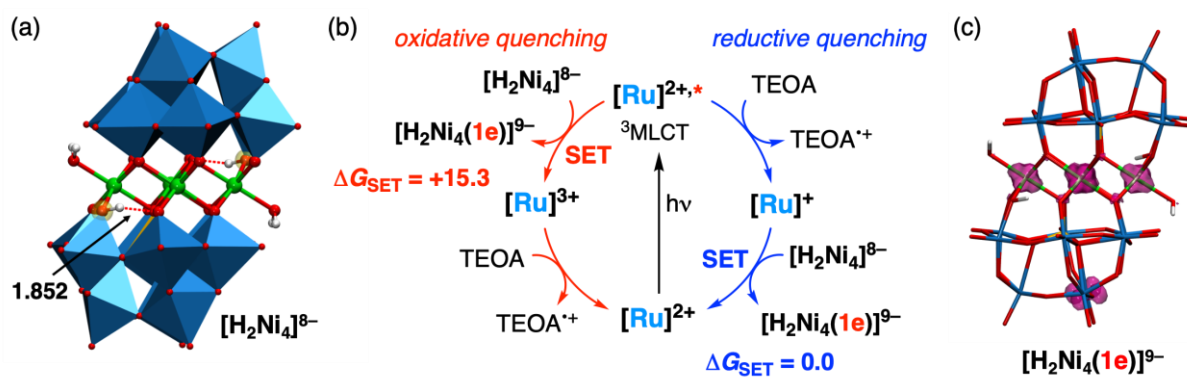
disposition, which grant the formation of stabilizing intramolecular hydrogen bonds with neighboring O sites of the POM framework, as shown in Fig. 5a. Further protonation of  $\text{H}_2\text{Ni}_4$  by  $\text{HTEOA}^+$  was predicted to be thermodynamically unfavorable, by  $4.2 \text{ kcal mol}^{-1}$  (Fig. S14). Thus, we next analyzed the feasibility of electron transfer events from the photosensitizer to  $\text{H}_2\text{Ni}_4$ .

Fig. 5b compares the calculated Gibbs free energies associated to the reduction of the catalyst via single electron transfer (SET) following either oxidative quenching (red arrows) or reductive quenching (blue arrows) mechanisms. As anticipated above, the oxidative quenching pathway involves a SET from the triplet MLCT state of the photoexcited photosensitizer, (labeled as  $[\text{Ru}(\text{bpy})_3]^{2+,*}$ ) to  $\text{H}_2\text{Ni}_4$ , which was calculated to be endergonic by  $15.3 \text{ kcal mol}^{-1}$ . Even though this might be accessible at room temperature, the charge recombination between the reduced POM and the oxidized PS was found to be strongly favorable (by  $64.5 \text{ kcal mol}^{-1}$ ), thus preventing the efficient formation of the reduced POM, as observed experimentally. Conversely, the one-electron reduced form of the photosensitizer,  $[\text{Ru}(\text{bpy})_3]^+$ , formed in the reaction mixture via reductive quenching of  $[\text{Ru}(\text{bpy})_3]^{2+,*}$  by TEOA as evidenced experimentally (see above), can more efficiently reduce  $\text{H}_2\text{Ni}_4$  through a SET process that was estimated to be ergoneutral. Therefore, these results strongly indicate that the  $\text{Ni}_4/[\text{Ru}(\text{bpy})_3]^{2+}/\text{TEOA}$  photocatalytic system operates through a reductive quenching mechanism (Fig. 5b, blue arrows), further supporting the mechanistic picture inferred from photophysical studies. It is worth noting that protonation of the  $\text{Ni}_4$  is essential to allow efficient charge accumulation in the catalyst. As a matter of fact, the SET from  $[\text{Ru}(\text{bpy})_3]^+$  to the non-protonated  $\text{Ni}_4$ , which bears an overall charge of -10, is much less favorable compared to that to the doubly-protonated  $[\text{H}_2\text{Ni}_4]^{8-}$  anion, with a reaction free-energy of  $+16.9 \text{ kcal mol}^{-1}$  (vs.  $0.0 \text{ kcal mol}^{-1}$ ). This can be ascribed to the polyanionic nature of the POM, as reducing its overall negative charge via protonation lowers the energy of its unoccupied Molecular Orbitals (MOs), favoring in turn reduction events [58]. It is also worth noting that possible ion-pairing effects involving the POM, which are not explicitly captured in our models, are expected to ease SET processes due to the same principle, although to a lesser extent than protonation [58]. Hence, it cannot be ruled out that the SET processes from the PS to the POM are actually somewhat more exergonic than what computed values suggest.

As shown in Fig. 5c, reduction of the catalyst by  $[\text{Ru}(\text{bpy})_3]^+$  generates species  $[\text{H}_2\text{Ni}_4(\mathbf{1e})]^{9-}$ , in which the extra electron is accommodated in a d-type MO centered on a W atom of the polyoxotungstate framework, in line with previous studies on the redox

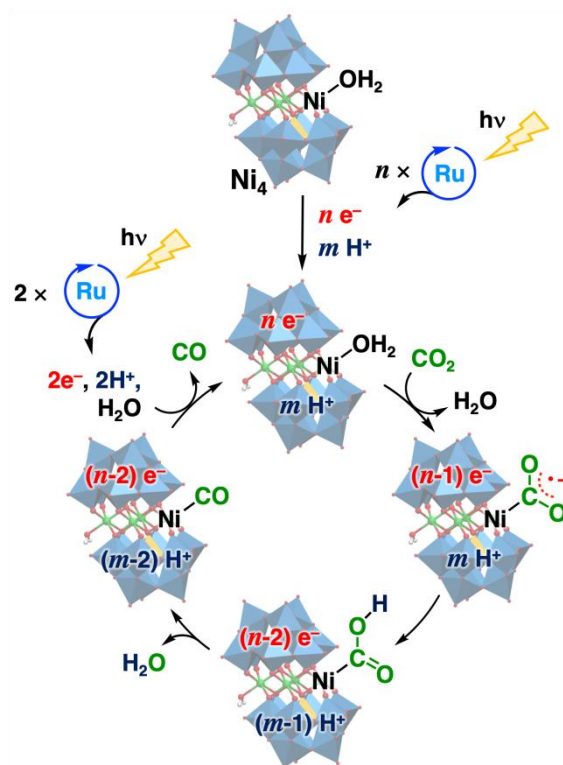
properties of Ni(II)-substituted POMs [33]. Under photocatalytic conditions,  $[\text{H}_2\text{Ni}_4(\mathbf{1e})]^{9-}$  can then accept a second one-electron from a  $[\text{Ru}(\text{bpy})_3]^+$  molecule to yield  $[\text{H}_2\text{Ni}_4(\mathbf{2e})]^{10-}$ . Despite this process was computed to be slightly endergonic ( $\Delta G_{\text{SET}} = +7.2 \text{ kcal mol}^{-1}$ , Fig. S14), the subsequent, spontaneous association of two more protons to  $\mu_2$ -(Ni-O-W) sites ( $\Delta G$  of  $-15.0$  and  $-7.9 \text{ kcal mol}^{-1}$  for the protonation of  $[\text{H}_2\text{Ni}_4(\mathbf{2e})]^{10-}$  and  $[\text{H}_3\text{Ni}_4(\mathbf{2e})]^{9-}$  by  $\text{HTEOA}^+$ , respectively) provides the thermodynamic driving force to the second SET event and prevents undesired back electron transfer from the reduced POM to the PS. This sequence of reduction and protonation processes is highlighted with bold blue arrows in Fig. S14 and leads to species  $[\text{H}_4\text{Ni}_4(\mathbf{2e})]^{8-}$ , for which the optimized structure and spin density distribution are represented in Fig. S15. Overall, our calculations indicate that the photoaccumulation in the  $\text{Ni}_4$  catalyst of the two electrons required for subsequent  $\text{CO}_2$  to  $\text{CO}$  reduction is feasible following a reductive quenching mechanism. Moreover, the fact that the reduction of the catalyst triggers its protonation suggests that the POM might not only play the role of an electron reservoir but also that of a proton reservoir, making protons readily available for the protonation of key reaction intermediates.

From a thermodynamic point of view, the reduction of  $\text{CO}_2$  to  $\text{CO}$  promoted by  $[\text{H}_4\text{Ni}_4(\mathbf{2e})]^{8-}$ , giving a water molecule as a byproduct and regenerating the fully-oxidized  $[\text{H}_2\text{Ni}_4]^{8-}$  anion was computed to be slightly endergonic by  $4.5 \text{ kcal mol}^{-1}$ , although still affordable, while the reduction and protonation of  $[\text{H}_2\text{Ni}_4]^{8-}$  to  $[\text{H}_4\text{Ni}_4(\mathbf{2e})]^{8-}$ , which is strongly exergonic ( $\Delta G = -27.6 \text{ kcal mol}^{-1}$ , Fig. S14), might be expected to provide the thermodynamic driving force to the overall process. However, additional DFT calculations showed that the reduction of  $[\text{H}_4\text{Ni}_4(\mathbf{2e})]^{8-}$  by a third electron is still accessible ( $\Delta G_{\text{SET}} = +3.5 \text{ kcal mol}^{-1}$ , Fig. S15), thus implying that the latter process may be faster than the formation of  $\text{CO}$  catalyzed by  $[\text{H}_4\text{Ni}_4(\mathbf{2e})]^{8-}$ . Therefore, it cannot be ruled out that higher reduction states of the POM are formed during the course of the reaction and that they may also act as active species of the catalyst. In this regard, further computational and experimental efforts would be required to more precisely identify and characterize the active species responsible for the  $\text{CO}_2\text{RR}$  activity of Ni-POMs which is, however, beyond the scope of the present study.



**Fig. 5.** (a) Combined polyhedral and balls-and-sticks representation of the optimized structure of  $\text{H}_2\text{Ni}_4$ . Protonated  $\mu_2$ -(Ni-O-W) bridging oxygens are highlighted with semi-transparent yellow spheres. Red-dashed lines highlight intramolecular hydrogen bonds, for which a selected distance is given in Å. (b) Comparison of the reaction free-energies ( $\text{kcal mol}^{-1}$ ) for the single electron transfer (SET) processes governing the reduction of the catalyst via oxidative quenching (left, red arrows) and reductive quenching (right, blue arrows) mechanisms (see main text for details). (c) Spin density distribution represented on the optimized structure of  $\text{H}_2\text{Ni}_4(1\text{e})$ , showing the reduction of the polyoxotungstate framework.

Still, with the gained knowledge about the  $\text{Ni}_4/[\text{Ru}(\text{bpy})_3]^{2+}/\text{TEOA}$  photocatalytic system and on the basis of previously reported reaction mechanisms for  $\text{CO}_2$  reduction by transition-metal based compounds bearing redox-active ligands [63–71], we propose the following reaction mechanism illustrated in Fig. 6. Upon reduction and protonation of the catalyst by “ $n$ ” electrons and “ $m$ ” protons, respectively, the coordination of  $\text{CO}_2$  through the C atom to a Ni(II) ion replacing an aqua ligand generates a Ni(II)- $\text{COO}^-$  species, in which one electron migrates from the POM to the  $\text{CO}_2$  moiety. Up next, the protonation of a terminal O atom in the latter intermediate triggers the migration of a second electron from the POM to the reactive center leading to a Ni(II)- $\text{COOH}$  species, which then evolves via concomitant C–O(H) bond cleavage and protonation of the leaving group to generate a water molecule. Finally, the replacement of the CO product by a water molecule, along with the reduction and protonation of the catalyst by  $[\text{Ru}(\text{bpy})_3]^+$  and  $\text{HTEOA}^+$ , respectively, which are generated through the light-induced reductive quenching of the PS by TEOA, as detailed in Fig. 5b (and simplified in Fig. 6 with a small blue cycle), regenerates the active species of the catalyst, closing the catalytic cycle.



**Fig. 6.** Proposed reaction mechanism for the photocatalytic reduction of  $\text{CO}_2$  into CO catalyzed by  $\text{Ni}_4$  in the presence of  $[\text{Ru}(\text{bpy})_3]^{2+}$  and TEOA acting as an external photosensitizer and sacrificial donor, respectively (see Fig. 5b for details).

## 4. Conclusions

In this work, the photocatalytic activities for visible-light driven  $\text{CO}_2$  to CO conversion of seven POM salts with vacant  $\{\text{SiW}_9\}$  or  $\{\text{PW}_9\}$  units connected to Ni clusters have been investigated in  $\text{CH}_3\text{CN}:\text{H}_2\text{O}:\text{TEOA}$  solutions. This study confirms that Ni-based POMs are

efficient catalysts and shows that the tetrabutylammonium salt of the POM containing four Ni(II) ions sandwiched between two {PW<sub>9</sub>} units, TBA(Ni<sub>4</sub>), was the most active, with a high selectivity and a good stability. While no clear trend was observed for the impact of the number of Ni ions or the nature and number of vacant POMs bound to these Ni ions, this study highlights the influence of the nature of the counter-ions on the catalytic activity of POMs, the TBA salt of Ni<sub>4</sub> being much more active than the alkaline salt. This observation was correlated with a phase separation that occurs after CO<sub>2</sub> bubbling into the catalytic medium. NMR and IR measurements indeed showed that the POM (in the aqueous phase) is separated from its TBA counter-ions (in the organic phase), which improves the catalytic activity. This opens perspectives for photocatalytic studies of POM compounds, as alkaline salts of POMs can often be easily converted to TBA ones. Focusing on the most active Ni<sub>4</sub> system, both transient absorption spectroscopy and DFT calculations support that the reduction of the catalyst by the [Ru(bpy)<sub>3</sub>]<sup>2+</sup>/TEOA photochemical system proceeds via a reductive quenching pathway, whereby the excited triplet MLCT state of the PS is quenched by TEOA to generate the one-electron reduced [Ru(bpy)<sub>3</sub>]<sup>+</sup> species, which acts as the reducing agent of the Ni<sub>4</sub> catalyst. DFT calculations also indicate that the Ni<sub>4</sub> catalyst is spontaneously protonated by the HTEOA<sup>+</sup> cations that are generated during the reductive quenching of the PS. Such protonation events are essential, enabling the reduction of the catalyst via electron transfer from [Ru(bpy)<sub>3</sub>]<sup>+</sup> by lowering the energy of the unoccupied molecular orbitals of the POM. Moreover, our calculations demonstrate that Ni<sub>4</sub> is capable of undergoing multiple redox processes under photocatalytic conditions, which lead to the accumulation of electrons in the POM for subsequent CO<sub>2</sub> reduction. These results allowed proposing a reaction mechanism in which the Ni(II) centers act as catalytically active sites and the polyoxotungstate framework acts as a reservoir of the electrons and protons needed for the reduction of CO<sub>2</sub> to CO.

### Credit authorship contribution statement

**Khadija Talbi**: Investigation, Formal - analysis, Data curation, Visualization. **Francesc Penas-Hidalgo**: Computational investigation, Formal analysis, Visualization. **Amanda L. Robinson**: Investigation, Validation, Writing - review & editing. **Philipp Gotico**: Investigation, Data Curation, Writing - review & editing. **Winfried Leibl**: Investigation, Data Curation, Writing - original draft. **Pierre Mialane**: Conceptualization, Supervision, Writing - review & editing. **Maria Gomez-Mingot**: Validation, Writing -

review & editing. **Marc Fontecave**: Validation, Resources, Writing - review & editing. **Albert Solé-Daura**: Conceptualization, Methodology, Supervision, Writing-original draft, Writing - review & editing. **Caroline Mellot-Draznieks**: Conceptualization, Methodology, Supervision, Funding acquisition, Writing - review & editing. **Anne Dolbecq**: Conceptualization, Supervision, Project administration, Funding acquisition, Writing - original draft, Writing - review & editing.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Acknowledgements

This work was supported by a grant of the Agence Nationale de la Recherche (ANR-21-CE50-0024). F. P.-H., A.S.-D. and C. M.-D. thank GENCI (CINES/TGCC) for HPC resources through the 2022-2023 grant A0130907343. CMD thanks ANR for funding ANR-21-CE07-0028. A.S.-D. also acknowledges the Spanish Ministry of Universities and the European Union - Next Generation EU for financial support through a Margarita Salas grant. A. D. thanks Julien Bonin for fruitful discussion. Aurélie Damond is gratefully acknowledged for mass spectrometry measurements.

### Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version.

### References

- [1] A. Dolbecq, E. Dumas, C.R. Mayer, P. Mialane, Hybrid organic– inorganic polyoxometalate compounds: from structural diversity to applications, *Chem. Rev.* 110 (2010) 6009–6048.
- [2] H. Zhang, W.-L. Zhao, H. Li, Q. Zhuang, Z. Sun, D. Cui, X. Chen, A. Guo, X. Ji, S. An, W. Chen, Y.-F. Song, Latest progress in covalently modified polyoxometalates-based molecular assemblies and advanced materials, *Polyoxometalates*. 1 (2022) 9140011. <https://doi.org/10.26599/POM.2022.9140011>.
- [3] J.M. Cameron, G. Guillemot, T. Galambos, S.S. Amin, E. Hampson, K. Mall Haidaraly, G.N. Newton, G. Izzet, Supramolecular assemblies of organo-functionalised hybrid polyoxometalates: from functional building blocks to hierarchical nanomaterials, *Chem. Soc. Rev.* 51 (2022) 293–328. <https://doi.org/10.1039/D1CS00832C>.
- [4] P. Ma, F. Hu, J. Wang, J. Niu, Carboxylate covalently modified polyoxometalates: From

- synthesis, structural diversity to applications, *Coord. Chem. Rev.* 378 (2019) 281–309. <https://doi.org/10.1016/j.ccr.2018.02.010>.
- [5] A. Blazevic, A. Rompel, The Anderson–Evans polyoxometalate: From inorganic building blocks via hybrid organic–inorganic structures to tomorrows “Bio-POM,” *Coord. Chem. Rev.* 307 (2016) 42–64. <https://doi.org/10.1016/j.ccr.2015.07.001>.
- [6] S.-S. Wang, G.-Y. Yang, Recent Advances in Polyoxometalate-Catalyzed Reactions, *Chem. Rev.* 115 (2015) 4893–4962. <https://doi.org/10.1021/cr500390v>.
- [7] P. Mialane, C. Mellot-Draznieks, P. Gairola, M. Duguet, Y. Benseghir, O. Oms, A. Dolbecq, Heterogenisation of polyoxometalates and other metal-based complexes in metal–organic frameworks: from synthesis to characterisation and applications in catalysis, *Chem. Soc. Rev.* 50 (2021) 6152–6220. <https://doi.org/10.1039/D0CS00323A>.
- [8] M. Samaniyan, M. Mirzaei, R. Khajavian, H. Eshtiagh-Hosseini, C. Streb, Heterogeneous Catalysis by Polyoxometalates in Metal–Organic Frameworks, *ACS Catal.* 9 (2019) 10174–10191. <https://doi.org/10.1021/acscatal.9b03439>.
- [9] C.T. Buru, O.K. Farha, Strategies for Incorporating Catalytically Active Polyoxometalates in Metal–Organic Frameworks for Organic Transformations, *ACS Appl. Mater. Interfaces.* 12 (2020) 5345–5360. <https://doi.org/10.1021/acscami.9b19785>.
- [10] J.-L. Chen, Z.-W. Wang, P.-Y. Zhang, H. Lv, G.-Y. Yang, 40Ni-Added Poly(polyoxometalate) Assembled by {Ni<sub>6</sub>GeW<sub>9</sub>} and {Ni<sub>8</sub>(GeW<sub>9</sub>)<sub>2</sub>} Units: Structure, Magnetic, and Heterogeneous Catalysis Properties, *Inorg. Chem.* 62 (2023) 10291–10297. <https://doi.org/10.1021/acs.inorgchem.3c01091>.
- [11] X.-B. Han, Z.-M. Zhang, T. Zhang, Y.-G. Li, W. Lin, W. You, Z.-M. Su, E.-B. Wang, Polyoxometalate-Based Cobalt–Phosphate Molecular Catalysts for Visible Light-Driven Water Oxidation, *J. Am. Chem. Soc.* 136 (2014) 5359–5366. <https://doi.org/10.1021/ja412886e>.
- [12] M.A. Fashapoyeh, M. Mirzaei, H. Eshtiagh-Hosseini, A. Rajagopal, M. Lechner, R. Liu, C. Streb, Photochemical and electrochemical hydrogen evolution reactivity of lanthanide-functionalized polyoxotungstates, *Chem. Commun.* 54 (2018) 10427–10430. <https://doi.org/10.1039/C8CC06334F>.
- [13] M. Natali, F. Nastasi, F. Puntoriero, A. Sartorel, Mechanistic Insights into Light-Activated Catalysis for Water Oxidation, *Eur. J. Inorg. Chem.* 2019 (2019) 2027–2039. <https://doi.org/10.1002/ejic.201801236>.
- [14] B. Matt, J. Fize, J. Moussa, H. Amouri, A. Pereira, V. Artero, G. Izzet, A. Proust, Charge photo-accumulation and photocatalytic hydrogen evolution under visible light at an iridium(III)-photosensitized polyoxotungstate, *Energy Environ. Sci.* 6 (2013) 1504–1508. <https://doi.org/10.1039/C3EE40352A>.
- [15] Y. Cao, Q. Chen, C. Shen, L. He, Polyoxometalate-Based Catalysts for CO<sub>2</sub> Conversion, *Molecules.* 24 (2019) 2069. <https://doi.org/10.3390/molecules24112069>.
- [16] J. Gu, W. Chen, G.-G. Shan, G. Li, C. Sun, X.-L. Wang, Z. Su, The roles of polyoxometalates in photocatalytic reduction of carbon dioxide, *Mater. Today Energy.* 21 (2021) 100760. <https://doi.org/10.1016/j.mtener.2021.100760>.
- [17] M. Girardi, S. Blanchard, S. Griveau, P. Simon, M. Fontecave, F. Bedioui, A. Proust, Electro-Assisted Reduction of CO<sub>2</sub> to CO and Formaldehyde by (TOA)<sub>6</sub>[α-SiW<sub>11</sub>O<sub>39</sub>Co( )] Polyoxometalate, *Eur. J. Inorg. Chem.* 2015 (2015) 3642–3648. <https://doi.org/10.1002/ejic.201500389>.
- [18] M. Girardi, D. Platzer, S. Griveau, F. Bedioui, S. Alves, A. Proust, S. Blanchard, Assessing the Electrocatalytic Properties of the Cp\*Rh<sup>III</sup>2+ - Polyoxometalate Derivative [H<sub>2</sub>PW<sub>11</sub>O<sub>39</sub>Rh<sup>III</sup> Cp\*(OH<sub>2</sub>)<sub>3</sub>]<sup>3-</sup> towards CO<sub>2</sub> Reduction, *Eur. J. Inorg. Chem.* 2019 (2019) 387–393. <https://doi.org/10.1002/ejic.201800454>.
- [19] B. Fabre, C. Falaise, E. Cadot, Polyoxometalates-Functionalized Electrodes for (Photo)Electrocatalytic Applications: Recent Advances and Prospects, *ACS Catal.* (2022). <https://doi.org/10.1021/acscatal.2c01847>.
- [20] A.M. Khenkin, I. Efremenko, L. Weiner, J.M.L. Martin, R. Neumann, Photochemical Reduction of Carbon Dioxide Catalyzed by a Ruthenium-Substituted Polyoxometalate, *Chem. – Eur. J.* 16 (2010) 1356–1364. <https://doi.org/10.1002/chem.200901673>.
- [21] C. Ci, J.J. Carbó, R. Neumann, C.D. Graaf, J.M. Poble, Photoreduction Mechanism of CO<sub>2</sub> to CO Catalyzed by a Rhenium(I)-Polyoxometalate Hybrid Compound, *ACS Catal.* 6 (2016) 6422–6428. <https://doi.org/10.1021/acscatal.6b01638>.
- [22] L. Qiao, M. Song, A. Geng, S. Yao, Polyoxometalate-based high-nuclear cobalt–vanadium–oxo cluster as efficient catalyst for visible light-driven CO<sub>2</sub> reduction, *Chin. Chem. Lett.* 30 (2019) 1273–1276. <https://doi.org/10.1016/j.ccllet.2019.01.024>.
- [23] Y. Chen, Z.-W. Guo, Y.-P. Chen, Z.-Y. Zhuang, G.-Q. Wang, X.-X. Li, S.-T. Zheng, G.-Y. Yang, Two

- novel nickel cluster substituted polyoxometalates: syntheses, structures and their photocatalytic activities, magnetic behaviors, and proton conduction properties, *Inorg. Chem. Front.* 8 (2021) 1303–1311. <https://doi.org/10.1039/D0QI01410A>.
- [24] G. Zhang, F. Wang, T. Tubul, M. Baranov, N. Leffler, A. Neyman, J.M. Poblet, I.A. Weinstock, Complexed Semiconductor Cores Activate Hexaniobate Ligands as Nucleophilic Sites for Solar-Light Reduction of CO<sub>2</sub> by Water, *Angew. Chem. Int. Ed.* 61 (2022). <https://doi.org/10.1002/anie.202213162>.
- [25] Q. Chang, X. Meng, W. Ruan, Y. Feng, R. Li, J. Zhu, Y. Ding, H. Lv, W. Wang, G. Chen, X. Fang, Metal–Organic Cages with {SiW<sub>9</sub>Ni<sub>4</sub>} Polyoxotungstate Nodes, *Angew. Chem. Int. Ed.* 61 (2022). <https://doi.org/10.1002/anie.202117637>.
- [26] D. Zang, H. Wang, Polyoxometalate-based nanostructures for electrocatalytic and photocatalytic CO<sub>2</sub> reduction, *Polyoxometalates.* 1 (2022) 9140006. <https://doi.org/10.26599/POM.2022.9140006>.
- [27] X.-X. Li, J. Liu, L. Zhang, L.-Z. Dong, Z.-F. Xin, S.-L. Li, X.-Q. Huang-Fu, K. Huang, Y.-Q. Lan, Hydrophobic Polyoxometalate-Based Metal–Organic Framework for Efficient CO<sub>2</sub> Photoconversion, *ACS Appl Mater Interfaces.* (2019) 6.
- [28] S.-L. Xie, J. Liu, L.-Z. Dong, S.-L. Li, Y.-Q. Lan, Z.-M. Su, Hetero-metallic active sites coupled with strongly reductive polyoxometalate for selective photocatalytic CO<sub>2</sub>-to-CH<sub>4</sub> conversion in water, *Chem. Sci.* 10 (2019) 185–190. <https://doi.org/10.1039/C8SC03471K>.
- [29] H. Xu, S. You, Z. Lang, Y. Sun, C. Sun, J. Zhou, X. Wang, Z. Kang, Z. Su, Highly Efficient Photoreduction of Low-Concentration CO<sub>2</sub> to Syngas by Using a Polyoxometalates/Rull Composite, *Chem. – Eur. J.* 26 (2020) 2735–2740. <https://doi.org/10.1002/chem.201905155>.
- [30] Y. Benseghir, A. Solé-Daura, P. Mialane, J. Marrot, L. Dalecky, S. Béchu, M. Frégnaux, M. Gomez-Mingot, M. Fontecave, C. Mellot-Draznieks, A. Dolbecq, Understanding the Photocatalytic Reduction of CO<sub>2</sub> with Heterometallic Molybdenum(V) Phosphate Polyoxometalates in Aqueous Media, *ACS Catal.* 12 (2022) 453–464. <https://doi.org/10.1021/acscatal.1c04530>.
- [31] J. Du, Y.-Y. Ma, W.-J. Cui, S.-M. Zhang, Z.-G. Han, R.-H. Li, X.-Q. Han, W. Guan, Y.-H. Wang, Y.-Q. Li, Y. Liu, F.-Y. Yu, K.-Q. Wei, H.-Q. Tan, Z.-H. Kang, Y.-G. Li, Unraveling photocatalytic electron transfer mechanism in polyoxometalate-encapsulated metal-organic frameworks for high-efficient CO<sub>2</sub> reduction reaction, *Appl. Catal. B Environ.* 318 (2022) 121812. <https://doi.org/10.1016/j.apcatb.2022.121812>.
- [32] H. Lv, W. Guo, K. Wu, Z. Chen, J. Bacsá, D.G. Musaev, Y.V. Geletii, S.M. Lauinger, T. Lian, C.L. Hill, A Noble-Metal-Free, Tetra-nickel Polyoxotungstate Catalyst for Efficient Photocatalytic Hydrogen Evolution, *J. Am. Chem. Soc.* 136 (2014) 14015–14018. <https://doi.org/10.1021/ja5084078>.
- [33] K. von Allmen, R. Moré, R. Müller, J. Soriano-López, A. Linden, G.R. Patzke, Nickel-Containing Keggin-Type Polyoxometalates as Hydrogen Evolution Catalysts: Photochemical Structure-Activity Relationships, *ChemPlusChem.* 80 (2015) 1389–1398. <https://doi.org/10.1002/cplu.201500074>.
- [34] H. Lv, Y. Chi, J. van Leusen, P. Kögerler, Z. Chen, J. Bacsá, Y.V. Geletii, W. Guo, T. Lian, C.L. Hill, {[Ni<sub>4</sub>(OH)<sub>3</sub>AsO<sub>4</sub>]<sub>4</sub>(B-α-PW<sub>9</sub>O<sub>34</sub>)<sub>4</sub>}<sup>28-</sup>: A New Polyoxometalate Structural Family with Catalytic Hydrogen Evolution Activity, *Chem. – Eur. J.* 21 (2015) 17363–17370. <https://doi.org/10.1002/chem.201503010>.
- [35] X.-B. Han, C. Qin, X.-L. Wang, Y.-Z. Tan, X.-J. Zhao, E.-B. Wang, Bio-inspired assembly of cubane-adjustable polyoxometalate-based high-nuclear nickel clusters for visible light-driven hydrogen evolution, *Appl. Catal. B Environ.* 211 (2017) 349–356. <https://doi.org/10.1016/j.apcatb.2017.04.057>.
- [36] G. Paille, A. Boulmier, A. Bensaid, M.-H. Ha-Thi, T.-T. Tran, T. Pino, J. Marrot, E. Rivière, C.H. Hendon, O. Oms, M. Gomez-Mingot, M. Fontecave, C. Mellot-Draznieks, A. Dolbecq, P. Mialane, An unprecedented {Ni<sub>14</sub>SiW<sub>9</sub>} hybrid polyoxometalate with high photocatalytic hydrogen evolution activity, *Chem. Commun.* 55 (2019) 4166–4169. <https://doi.org/10.1039/C9CC01269A>.
- [37] L. Qin, R. Wang, X. Xin, M. Zhang, T. Liu, H. Lv, G.-Y. Yang, A dual-functional supramolecular assembly for enhanced photocatalytic hydrogen evolution, *Appl. Catal. B Environ.* 312 (2022) 121386. <https://doi.org/10.1016/j.apcatb.2022.121386>.
- [38] E. Tanuhadi, J. Cano, S. Batool, A. Cherevan, D. Eder, A. Rompel, Ni<sub>12</sub> tetracubane cores with slow relaxation of magnetization and efficient charge utilization for photocatalytic hydrogen evolution, *J. Mater. Chem. C.* 10 (2022) 17048–17052. <https://doi.org/10.1039/D2TC03508A>.
- [39] C. Pichon, P. Mialane, A. Dolbecq, J. Marrot, E. Rivière, B.S. Bassil, U. Kortz, B. Keita, L. Nadjo, F. Sécheresse, Octa- and Nonanuclear Nickel(II) Polyoxometalate Clusters: Synthesis and Electrochemical and Magnetic

- Characterizations, *Inorg. Chem.* 47 (2008) 11120–11128.  
<https://doi.org/10.1021/ic801431f>.
- [40] H. El Moll, G. Rousseau, A. Dolbecq, O. Oms, J. Marrot, M. Haouas, F. Taulelle, E. Rivière, W. Wernsdorfer, D. Lachkar, E. Lacôte, B. Keita, P. Mialane, Properties of a Tunable Multinuclear Nickel Polyoxotungstate Platform, *Chem. - Eur. J.* 19 (2013) 6753–6765.  
<https://doi.org/10.1002/chem.201204366>.
- [41] Gaussian 16, Revision C.02, M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, G. A. Petersson, H. Nakatsuji, X. Li, M. Caricato, A. V. Marenich, J. Bloino, B. G. Janesko, R. Gomperts, B. Mennucci, H. P. Hratchian, J. V. Ortiz, A. F. Izmaylov, J. L. Sonnenberg, D. Williams-Young, F. Ding, F. Lipparini, F. Egidi, J. Goings, B. Peng, A. Petrone, T. Henderson, D. Ranasinghe, V. G. Zakrzewski, J. Gao, N. Rega, G. Zheng, W. Liang, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, K. Throssell, J. A. Montgomery, Jr., J. E. Peralta, F. Ogliaro, M. J. Bearpark, J. J. Heyd, E. N. Brothers, K. N. Kudin, V. N. Staroverov, T. A. Keith, R. Kobayashi, J. Normand, K. Raghavachari, A. P. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, J. M. Millam, M. Klene, C. Adamo, R. Cammi, J. W. Ochterski, R. L. Martin, K. Morokuma, O. Farkas, J. B. Foresman, and D. J. Fox, Gaussian, Inc., Wallingford CT, 2016.
- [42] P.J. Hay, W.R. Wadt, Ab initio effective core potentials for molecular calculations. Potentials for the transition metal atoms Sc to Hg, *J. Chem. Phys.* 82 (1985) 270–283.  
<https://doi.org/10.1063/1.448799>.
- [43] A.W. Ehlers, M. Böhme, S. Dapprich, A. Gobbi, A. Höllwarth, V. Jonas, K.F. Köhler, R. Stegmann, A. Veldkamp, G. Frenking, A set of f-polarization functions for pseudo-potential basis sets of the transition metals Sc–Cu, Y–Ag and La–Au, *Chem. Phys. Lett.* 208 (1993) 111–114.  
[https://doi.org/10.1016/0009-2614\(93\)80086-5](https://doi.org/10.1016/0009-2614(93)80086-5).
- [44] M.M. Francl, W.J. Pietro, W.J. Hehre, J.S. Binkley, M.S. Gordon, D.J. DeFrees, J.A. Pople, Self-consistent molecular orbital methods. XXIII. A polarization-type basis set for second-row elements, *J. Chem. Phys.* 77 (1982) 3654–3665.  
<https://doi.org/10.1063/1.444267>.
- [45] P.C. Hariharan, J.A. Pople, The influence of polarization functions on molecular orbital hydrogenation energies, *Theor. Chim. Acta.* 28 (1973) 213–222.  
<https://doi.org/10.1007/BF00533485>.
- [46] W.J. Hehre, R. Ditchfield, J.A. Pople, Self-Consistent Molecular Orbital Methods. XII. Further Extensions of Gaussian-Type Basis Sets for Use in Molecular Orbital Studies of Organic Molecules, *J. Chem. Phys.* 56 (1972) 2257–2261.  
<https://doi.org/10.1063/1.1677527>.
- [47] E. Cancès, B. Mennucci, J. Tomasi, A new integral equation formalism for the polarizable continuum model: Theoretical background and applications to isotropic and anisotropic dielectrics, *J. Chem. Phys.* 107 (1997) 3032–3041.  
<https://doi.org/10.1063/1.474659>.
- [48] M. Álvarez-Moreno, C. de Graaf, N. López, F. Maseras, J.M. Poblet, C. Bo, Managing the Computational Chemistry Big Data Problem: The ioChem-BD Platform, *J. Chem. Inf. Model.* 55 (2015) 95–103.  
<https://doi.org/10.1021/ci500593j>.
- [49] A. Call, M. Cibian, K. Yamauchi, K. Sakai, Visible-light-driven reduction of CO<sub>2</sub> to CO in fully aqueous media using a water-soluble cobalt porphyrin, *Sustain. Energy Fuels.* 6 (2022) 2160–2164.  
<https://doi.org/10.1039/D2SE00291D>.
- [50] X. Chai, H.-H. Huang, H. Liu, Z. Ke, W.-W. Yong, M.-T. Zhang, Y.-S. Cheng, X.-W. Wei, L. Zhang, G. Yuan, Highly efficient and selective photocatalytic CO<sub>2</sub> to CO conversion in aqueous solution, *Chem. Commun.* 56 (2020) 3851–3854.  
<https://doi.org/10.1039/D0CC00879F>.
- [51] R. Gueret, L. Poulard, M. Oshinowo, J. Chauvin, M. Dahmane, G. Dupeyre, P.P. Lainé, J. Fortage, M.-N. Collomb, Challenging the [Ru(bpy)<sub>3</sub>]<sup>2+</sup> Photosensitizer with a Triazatriangulenium Robust Organic Dye for Visible-Light-Driven Hydrogen Production in Water, *ACS Catal.* 8 (2018) 3792–3802.  
<https://doi.org/10.1021/acscatal.7b04000>.
- [52] M. Li, B. Zhuang, Y. Lu, L. An, Z.-G. Wang, Salt-Induced Liquid-Liquid Phase Separation: Combined Experimental and Theoretical Investigation of Water-Acetonitrile-Salt Mixtures, *J. Am. Chem. Soc.* 143 (2021) 773–784.  
<https://doi.org/10.1021/jacs.0c09420>.
- [53] R.N. Sampaio, D.C. Grills, D.E. Polyansky, D.J. Szalda, E. Fujita, Unexpected Roles of Triethanolamine in the Photochemical Reduction of CO<sub>2</sub> to Formate by Ruthenium Complexes, *J Am Chem Soc.* (2020) 16.
- [54] S.A. Jafari, M.H. Entezari, Salting out in ACN/water systems: Hofmeister effects and partition of quercetin, *J. Mol. Liq.* 312 (2020) 113331.  
<https://doi.org/10.1016/j.molliq.2020.113331>.
- [55] A. Misra, K. Kozma, C. Streb, M. Nyman, Beyond Charge Balance: Counter-Cations in Polyoxometalate Chemistry, *Angew. Chem. Int.*

- Ed. 59 (2020) 596–612. <https://doi.org/10.1002/anie.201905600>.
- [56] Y. Benseghir, A. Solé-Daura, D.R. Cairnie, A.L. Robinson, M. Duguet, P. Mialane, P. Gairola, M. Gomez-Mingot, M. Fontecave, D. Iovan, B. Bonnett, A.J. Morris, A. Dolbecq, C. Mellot-Draznieks, Unveiling the mechanism of the photocatalytic reduction of CO<sub>2</sub> to formate promoted by porphyrinic Zr-based metal-organic frameworks, *J. Mater. Chem. A*. 10 (2022) 18103–18115. <https://doi.org/10.1039/D2TA04164B>.
- [57] Y. Pellegrin, F. Odobel, Sacrificial electron donor reagents for solar fuel production, *Comptes Rendus Chim.* 20 (2017) 283–295. <https://doi.org/10.1016/j.crci.2015.11.026>.
- [58] J.-J. Chen, L. Vilà-Nadal, A. Solé-Daura, G. Chisholm, T. Minato, C. Busche, T. Zhao, B. Kandasamy, A.Y. Ganin, R.M. Smith, I. Colliard, J.J. Carbó, J.M. Poblet, M. Nyman, L. Cronin, Effective Storage of Electrons in Water by the Formation of Highly Reduced Polyoxometalate Clusters, *J. Am. Chem. Soc.* 144 (2022) 8951–8960. <https://doi.org/10.1021/jacs.1c10584>.
- [59] W. Song, M.K. Brennaman, J.J. Concepcion, J.W. Jurss, P.G. Hoertz, H. Luo, C. Chen, K. Hanson, T.J. Meyer, Interfacial Electron Transfer Dynamics for [Ru(bpy)<sub>2</sub>((4,4'-PO<sub>3</sub>H<sub>2</sub>)<sub>2</sub>bpy)]<sup>2+</sup> Sensitized TiO<sub>2</sub> in a Dye-Sensitized Photoelectrosynthesis Cell: Factors Influencing Efficiency and Dynamics, *J. Phys. Chem. C*. 115 (2011) 7081–7091. <https://doi.org/10.1021/jp200124k>.
- [60] S.G. Cohen, A. Parola, G.H. Parsons, Photoreduction by amines, *Chem. Rev.* 73 (1973) 141–161. <https://doi.org/10.1021/cr60282a004>.
- [61] S.G. Cohen, R.J. Baumgarten, Photoreduction of Benzophenone by Amines. Photochemical Oxidative Deamination1, *J. Am. Chem. Soc.* 87 (1965) 2996–2997. <https://doi.org/10.1021/ja01091a032>.
- [62] P.J. DeLaive, T.K. Foreman, C. Giannotti, D.G. Whitten, Photoinduced electron transfer reactions of transition-metal complexes with amines. Mechanistic studies of alternate pathways to back electron transfer, *J. Am. Chem. Soc.* 102 (1980) 5627–5631. <https://doi.org/10.1021/ja00537a037>.
- [63] M. Stanbury, J.-D. Compain, S. Chardon-Noblat, Electro and photoreduction of CO<sub>2</sub> driven by manganese-carbonyl molecular catalysts, *Coord. Chem. Rev.* 361 (2018) 120–137. <https://doi.org/10.1016/j.ccr.2018.01.014>.
- [64] P.A. Davethu, S.P. de Visser, CO<sub>2</sub> Reduction on an Iron-Porphyrin Center: A Computational Study, *J. Phys. Chem. A*. 123 (2019) 6527–6535. <https://doi.org/10.1021/acs.jpca.9b05102>.
- [65] J. Shakeri, H. Farrokhpour, H. Hadadzadeh, M. Joshaghani, Photoreduction of CO<sub>2</sub> to CO by a mononuclear Re(I) complex and DFT evaluation of the photocatalytic mechanism, *RSC Adv.* 5 (2015) 41125–41134. <https://doi.org/10.1039/C5RA02002F>.
- [66] F. Wang, B. Cao, W.-P. To, C.-W. Tse, K. Li, X.-Y. Chang, C. Zang, S.L.-F. Chan, C.-M. Che, The effects of chelating N4 ligand coordination on Co(II)-catalysed photochemical conversion of CO<sub>2</sub> to CO: reaction mechanism and DFT calculations, *Catal. Sci. Technol.* 6 (2016) 7408–7420. <https://doi.org/10.1039/C6CY01265E>.
- [67] F. Wang, R. Neumann, C. de Graaf, J.M. Poblet, Photoreduction Mechanism of CO<sub>2</sub> to CO Catalyzed by a Three-Component Hybrid Construct with a Bimetallic Rhenium Catalyst, *ACS Catal.* (2021) 1495–1504. <https://doi.org/10.1021/acscatal.0c04366>.
- [68] Z.-H. Yan, B. Ma, S.-R. Li, J. Liu, R. Chen, M.-H. Du, S. Jin, G.-L. Zhuang, L.-S. Long, X.-J. Kong, L.-S. Zheng, Encapsulating a Ni(II) molecular catalyst in photoactive metal-organic framework for highly efficient photoreduction of CO<sub>2</sub>, *Sci. Bull.* 64 (2019) 976–985. <https://doi.org/10.1016/j.scib.2019.05.014>.
- [69] C.-Y. Zhu, Y.-Q. Zhang, R.-Z. Liao, W. Xia, J.-C. Hu, J. Wu, H. Liu, F. Wang, Photocatalytic reduction of CO<sub>2</sub> to CO and formate by a novel Co(II) catalyst containing a cis -oxygen atom: photocatalysis and DFT calculations, *Dalton Trans.* 47 (2018) 13142–13150. <https://doi.org/10.1039/C8DT02148A>.
- [70] J. Shen, M.J. Kolb, A.J. Göttle, M.T.M. Koper, DFT Study on the Mechanism of the Electrochemical Reduction of CO<sub>2</sub> Catalyzed by Cobalt Porphyrins, *J. Phys. Chem. C*. 120 (2016) 15714–15721. <https://doi.org/10.1021/acs.jpcc.5b10763>.
- [71] M. Isegawa, A.K. Sharma, CO<sub>2</sub> reduction by a Mn electrocatalyst in the presence of a Lewis acid: a DFT study on the reaction mechanism, *Sustain. Energy Fuels.* 3 (2019) 1730–1738. <https://doi.org/10.1039/C9SE00213H>.