

AperTO - Archivio Istituzionale Open Access dell'Università di Torino

Hydrogenation of CO₂ to Methanol by Pt Nanoparticles Encapsulated in UiO-67: Deciphering the Role of the Metal-Organic Framework

This is the author's manuscript

Original Citation:

Availability:

This version is available <http://hdl.handle.net/2318/1739981> since 2020-05-27T18:33:01Z

Published version:

DOI:10.1021/jacs.9b10873

Terms of use:

Open Access

Anyone can freely access the full text of works made available as "Open Access". Works made available under a Creative Commons license can be used according to the terms and conditions of said license. Use of all other works requires consent of the right holder (author or publisher) if not exempted from copyright protection by the applicable law.

(Article begins on next page)

1 Hydrogenation of CO₂ to Methanol by Pt Nanoparticles Encapsulated 2 in UiO-67: Deciphering the Role of the MOF

3 Emil S. Gutterød^a, Andrea Lazzarini^a, Torstein Fjermestad^b, Gurpreet Kaur^a, Maela Manzoli^c, Silvia
4 Bordiga^{a,d}, Stian Svelle^a, Karl P. Lillerud^a, Egill Skúlason^e, Sigurd Øien-Ødegaard^a, Ainara Nova^b,
5 Unni Olsbye^{a,*}

6 ^aCentre for Materials Science and Nanotechnology, Department of Chemistry, University of Oslo, Sem
7 Saelandsvei 26, N-0315 Oslo, Norway

8 ^bHylleraas Centre for Quantum Molecular Sciences, Department of Chemistry, University of Oslo, P.O. Box
9 1033, Blindern, N-0315 Oslo, Norway

10 ^cDepartment of Drug Science and Technology and NIS - Centre for Nanostructured Interfaces and Surfaces,
11 University of Turin, Via P. Giuria 9, Turin 10125, Italy

12 ^dDepartment of Chemistry, NIS Interdepartmental Centre and INSRM reference centre, University of Turin, via
13 Quarello 15A, I-10135 Turin, Italy

14 ^eScience Institute and Faculty of Industrial Engineering, Mechanical Engineering and Computer Science,
15 University of Iceland, VR-III, 107 Reykjavik, Iceland

16 17 **Abstract**

18 Metal-organic frameworks (MOFs) show great prospect as catalysts and catalyst support
19 materials. Yet, studies that address their dynamic, kinetic and mechanistic role in target reactions are
20 scarce. In this study, an exceptionally stable MOF catalyst consisting of Pt nanoparticles (NPs)
21 embedded in a Zr-based UiO-67 MOF was subject to steady-state and transient kinetic studies
22 involving H/D and ¹³C /¹²C exchange, coupled with operando infrared spectroscopy and density
23 functional theory (DFT) modeling, targeting methanol formation from CO₂/H₂ feeds at 170 °C and 1-
24 8 bar pressure. The study revealed that methanol is formed at the interface between the Pt NPs and
25 defect Zr nodes, via formate species attached to the Zr nodes. Methanol formation is mechanistically
26 separated from the formation of co-products CO and methane, except for hydrogen activation on the Pt
27 NPs. Careful analysis of transient data revealed that the number of formate intermediates was higher
28 than the number of open Zr sites in the MOF lattice around each Pt NP. Hence, additional Zr sites
29 must be available to formate formation. DFT modelling revealed that Pt NP growth is sufficiently
30 energetically favored to enable displacement of linkers and creation of open Zr sites during
31 pretreatment. However, linker displacement during formate formation is energetically disfavored, in
32 line with the excellent catalyst stability observed experimentally. Overall, the study provides firm

1 evidence that methanol is formed at the interface of Pt NPs and linker-deficient Zr_6O_8 nodes resting on
2 the Pt NP surface.

3

4 **Keywords:** CO₂ hydrogenation, methanol, formate, transient kinetic analysis, kinetic isotope effect,
5 operando FTIR, DFT, MOF, UiO-67.

6

7 **Introduction**

8 Atmospheric levels of CO₂ have risen at an alarming rate since the first half of the 20th century
9 following our continuous and increasing use of fossil fuels. Large cuts in CO₂ emissions can be made
10 through utilization of greener alternatives of energy production such as solar and wind power;
11 however, these energy sources suffer from lack of continuity in energy output and requires efficient
12 methods for large scale energy storage in order to compete with fossil fuels.¹ One of the solutions to
13 this problem is production of easily stored liquid fuels with high volumetric and gravimetric energy
14 density, such as methanol, from CO₂ and green hydrogen.² This allows for continued use of already
15 existing infrastructure.³ Substantial research efforts have already been dedicated to the topic of
16 valorizing CO₂ through hydrogenation, mainly with focus on the reverse water-gas shift (RWGS)
17 reaction, methanation and methanol production.⁴⁻¹³

18 The product distribution of CO₂ hydrogenation varies significantly with the nature of the
19 catalyst and operating conditions.⁷ Most prior studies show that Pt-based systems are highly selective
20 for the RWGS reaction, with minor selectivity towards methane.^{11, 14-19} In that respect, Kattel et al.¹⁸
21 performed a computational study of CO₂ hydrogenation over Pt nanoparticles supported on SiO₂ and
22 TiO₂. They concluded that a RWGS and CO hydrogenation path, forming CO and small amounts of
23 methane, dominate over those materials. This finding is in agreement with experimental evidence of
24 CO formation mainly via surface carbonates.^{15, 16}

25 Surface formates are also observed in several studies of the RWGS^{15, 16, 20, 21} and of WGS²²⁻²⁴
26 reactions; however, the significance of such a pathway over Pt-based catalysts is debated. In this
27 regard, Burch, Goguet and Meunier²³ conducted a critical analysis of the experimental evidence for
28 and against a formate mechanism over highly active Pt and Au WGS catalysts. They argue that most
29 published results do not provide definite evidence for or against a formate pathway for the WGS
30 reaction, and in the cases where reliable data are available, it is at most a minor and slow reaction
31 pathway.

32 Recent studies show that when supporting Pt on a methane producing Co-oxide catalyst,
33 methanol selectivity is observable under favorable conditions of low temperature and elevated
34 pressure²⁵⁻²⁷. Furthermore, one prior study²⁸ demonstrated selectivity towards methanol over oxide-

1 supported Pt where the supports alone are inactive in CO₂ hydrogenation: out of a set of catalysts
2 producing mainly CO (> 91 %), Pt/ZrO₂ showed the highest CH₃OH selectivity, reaching 6 % at 200
3 °C and 10 atm pressure.

4 Over the Zr-MOFs UiO-66 and -67, functionalized with Cu and Cu/Zn, high methanol
5 selectivity is ascribed to an important role of the Zr-MOF interface in the reaction. Rungtaweivoranit
6 et al.²⁹ found XPS evidence of Zr reduction in the presence of Cu when studying Cu NPs deposited on
7 UiO-66 as a model system for the encapsulated version of the catalyst (i.e. Cu in UiO-66). Similar
8 findings from XPS on CuZn@UiO-67 samples with 100% bipyridine-type linkers treated with
9 reaction gas showed indications of Zr(IV) reduction to Zr(III), argued as caused by H adsorption.³⁰ In
10 combination with H₂- and CO₂-TPD results, the authors suggested participation of the Zr-cluster in the
11 reaction by means of H-spillover from Cu and CO₂ adsorption on unsaturated Zr-sites. When the
12 catalyst was prepared with regular UiO-67 (i.e. biphenyl-type linkers), both the CH₃OH selectivity and
13 catalytic stability decreased. Although the CuZn@UiO-67 material showed substantial activity in
14 methanol formation, notably, both the crystallinity and specific surface area of the MOF were severely
15 reduced already by the deposition of copper. Thus, the material did not exhibit the well-defined MOF
16 structure of UiO-67 during the subsequent experiments.³⁰

17 In a previous contribution, we reported the CO₂ hydrogenation activity and selectivity of an
18 exceptionally stable Pt Zr-MOF catalyst, UiO-67-Pt, at ambient pressure. This catalyst maintains its
19 well-defined MOF structure even after long-term operation and is therefore well suited as a model
20 system for studying the influence of the MOF framework on the reaction. In the current study, the
21 focus is set on elucidating the role of the UiO-67 framework in CO₂ hydrogenation to methanol
22 through a kinetic investigation. In addition to standard steady-state kinetic measurements, we employ
23 H/D- and ¹³C/¹²C SSITKA, and *operando* FT-IR measurements, methods scarcely employed in MOF
24 catalysis literature. In combination with DFT calculations, this work reveals unprecedented insight in
25 the Pt-Zr-MOF interplay that leads to methanol formation during conversion of CO₂/H₂ mixtures at
26 170 °C and 1–8 bar.

27 **Experimental Details**

28 Details of material preparation and standard characterization methods (N₂ adsorption, ¹H-
29 NMR, EDX, TGA, TEM and CO-chemisorption) are provided in the SI.

30 *Operando* FT-IR spectroscopy was performed using a Bruker Vertex70 instrument equipped
31 with a liquid nitrogen-cooled MCT detector. Each spectrum was collected by averaging 64
32 acquisitions with a resolution of 2 cm⁻¹. The sample (pressed in a self-sustained pellet of approx. 4
33 mg) was mounted inside a low free-volume cell from AABSPEC (model #CXX), by which pressure,
34 temperature and gas flow are controllable. Due to the low sample amount, the CO₂ conversion was too

1 low to be determined reliably and parallel experiments under comparable conditions were performed
2 with the focus on gas-phase analysis (vide infra). The sample was activated at 350 °C (5 °C/min ramp)
3 in 10 % H₂/He (10 ml/min) for 4 hours, and then cooled to 170 °C in 10 ml/min He. The sample was
4 kept under CO₂ hydrogenation (CO₂/H₂ = 1/6, 10 ml/min) reaction conditions for two hours, before the
5 H₂ flow was exchanged to D₂.

6 Catalytic testing was performed in a fixed-bed flow setup with a straight stainless steel reactor
7 (7 mm I.D.) operated under 1–8 bar, where effluent species is analyzed with an on-line Q-MS
8 (Pfeiffer) and GC-TCD-FID (Agilent). The MOF samples were reduced for 4 hours at 350°C (5
9 °C/min ramp) in 20 ml/(min·0.1g_{cat}) flow of 10 % H₂/Ar under ambient pressure. Following the
10 activation procedure, the reactor was cooled to 240 °C in inert flow, then operated for 4 hours reaching
11 steady-state under a set of reference conditions (1/6/3 CO₂/H₂/inert, 20 ml/min, 200 mg, $\tau = 0.01$
12 g_{cat}·min/ml and ambient pressure) before changing conditions. The pre-reduced commercial samples
13 Pt/SiO₂ (abcr), Pt/Al₂O₃ (Chimet) and Pt/C (Chimet), were heated directly to 240 °C under reference
14 conditions, which were maintained until steady state was reached. Dependent on the experimental aim,
15 0.05–0.2 g catalyst was tested for CO₂ hydrogenation in range: 5–25 % CO₂, 40–90 % H₂, T = 170 °C,
16 p = 1–8 bar and contact time $\tau = 0.004–0.04$ g_{cat}·min/ml. A given set of operating conditions was fixed
17 until steady state was reached and for at least two hours. During kinetic studies, changes in reaction
18 conditions were performed in a random sequence. Each 3–4 set of conditions were the reference
19 conditions. They showed that the change in catalyst performance was negligible during the kinetic
20 studies. As reported in ref.¹⁷ a minor increase in the catalytic activity and change in selectivity is
21 observed for UiO-67-Pt during long-term operation. The same procedure as described above was
22 followed in the H/D exchange experiments but with D₂ instead of H₂. H/D SSITKA experiments were
23 performed by operating the catalysts at steady state under reference conditions, then switching the feed
24 (1/6/3 CO₂/H₂/inert) rapidly to another feed containing D₂ instead of H₂ (1/6/3 CO₂/D₂/inert) using an
25 electronically controlled 4-port 2-way valve. Switches back and forth between the two feeds were
26 performed in intervals of 8 hours. ¹³CO₂/¹²CO₂ SSTIKA experiments were performed in the same
27 manner. The m/z values traced for each specie in the respective experiments are tabulated in Table S1.

28 Intermediates and catalyst structures were optimized using Density functional theory (DFT)
29 calculations. The calculations were carried out using the mixed Gaussian and plane wave method³¹⁻³³
30 as implemented in CP2K 6.1.^{34, 35} The functional was PBE+D3, the atom-centered basis set was
31 DZVP-MOLOPT-SR-GTH,³⁶ and the plane wave kinetic energy cut-off was 360 Ry. Further details
32 are provided in the SI.

33

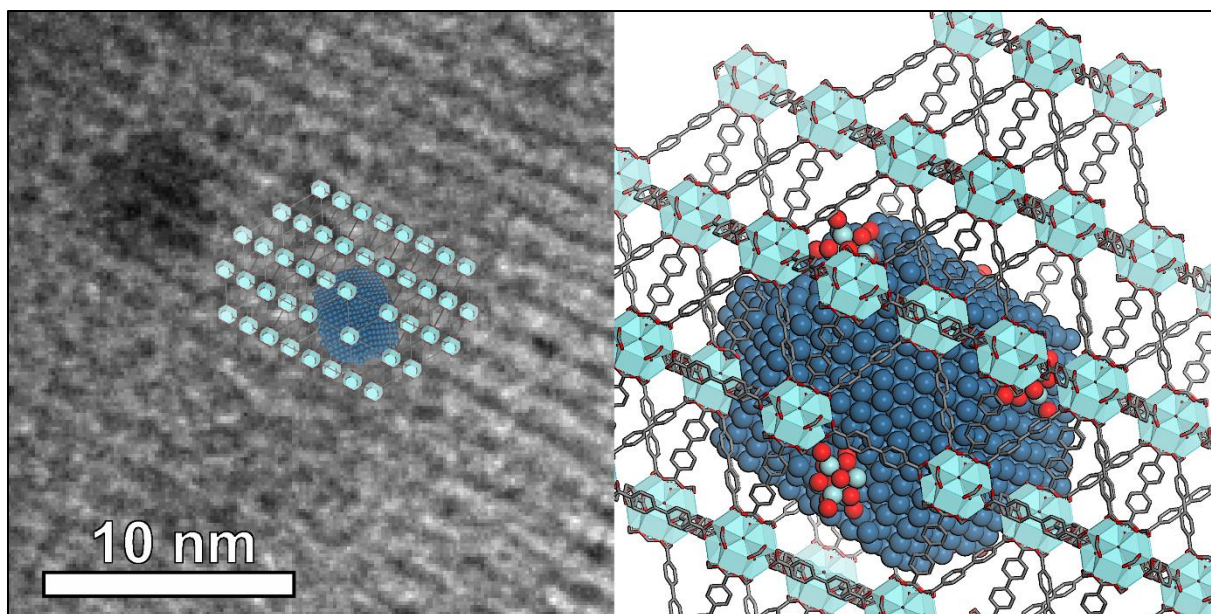
1 **Results and Discussion**

2 The UiO-66 series of Zr-MOFs (UiO-66, -67, -68) consists of Zr_6O_8 nodes connected by
3 dicarboxylate-terminated linkers. The ideal linker-to-node ratio is 6:1, but prior investigations showed
4 that factors like synthesis conditions (type of modulator and concentration, temperature and
5 crystallization time) and activation conditions may strongly affect this ratio, leading to materials that
6 are commonly referred to as having “missing cluster” or “missing linker” defects, respectively³⁷⁻⁴³.
7 Missing linker defects may be capped by modulator, anions of the MOF precursor salts, solvent or
8 OH/H₂O pairs.^{39, 42, 44, 45}

9 The current study was carried out using UiO-67 with 90 % biphenyl-4,4'-dicarboxylic acid
10 (BPDC) linkers and 10 % 2,2'-bipyridine-5,5'-dicarboxylic acid (BPYDC) linkers, hereafter called
11 **UiO-67-Pt**. Prior studies have demonstrated that the bipyridine entity in BPYDC is the preferred
12 anchoring site for Pt salts in this MOF.^{17, 46-48} In the current study, ¹H NMR analysis of digested
13 material showed that the as-synthesized MOF contained 11 BPYDC linkers, 13 benzoic acid and 2
14 formic acid ligands, respectively, per 100 BPDC linkers (Table S3). Furthermore, Thermo-
15 Gravimetric Analysis (TGA) measurements indicated that the as-synthesized MOF had a linker-to-
16 node ratio of 5, suggesting that, in addition to benzoic acid and formic acid, the material contained Cl⁻
17 or OH/H₂O pairs, adding up to an average of 4 out of 24 Zr coordination sites per Zr-node that were
18 not connected to a linker molecule (Table S3).

19 After wet impregnation with the Pt NP precursor, K₂PtCl₄, the BPYDC and benzoic acid
20 contents of UiO-67-Pt decreased slightly, while the formic acid content increased to 4 per 100 BPDC
21 linkers (Table S2). Activation in a reducing atmosphere (10 % H₂/Ar flow at 350 °C, 1 bar, 4 h)
22 transformed the Pt precursor salt into the active catalytic entity for CO₂ hydrogenation, Pt NPs.^{17, 46, 48}
23 In the current case, Transmission Electron Microscopy (TEM) investigations after activation showed
24 the presence of Pt NPs homogeneously dispersed within the MOF framework (Figure S5). The Pt NPs
25 supported on UiO-67 have average diameter of 3.6 ± 0.7 nm (Figure S5), i.e. larger than the diameter
26 of the tetrahedral (1.2 nm) and octahedral (2.3 nm) cavities of the UiO-67 structure. Most of the Pt
27 NPs displayed spherical shape, however, careful inspection revealed the presence of NPs with squared
28 borders and irregular shape, possibly exposing well defined terraces, after activation and after reaction
29 (Figure S5 and Figure S6). Such features can arise from strong Pt-support interaction, and indeed,
30 limited broadening of the Pt NP size distribution was observed after prolonged testing (Figure S6). A
31 schematic illustration of a 3.6 nm Pt particle embedded in an 8 unit cell-enclosed octahedral cavity,
32 mimicking a representative Pt NP observed by TEM, is presented in Scheme 1.

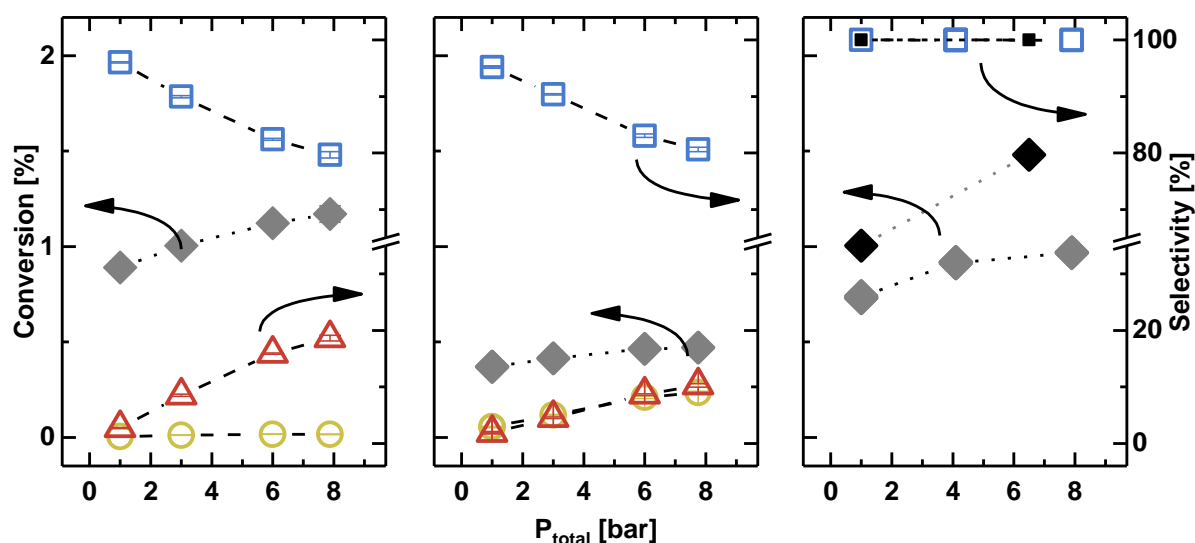
33



1
 2 Scheme 1. Left: TEM micrograph showing the close packed (1 1 1) layers of Zr_6 clusters in UiO-67,
 3 with a spacing of 15.5 Å, overlaid with a 1600 atom Pt NP in the structure of UiO-67 viewed along (1
 4 1 2) which is perpendicular to (1 1 1). Right: A 1600 atom Pt NP in UiO-67 viewed in the same
 5 direction. 6 Zr_6 clusters have been removed to accommodate the NP, and are decorating the NP
 6 surface.

7
 8 CO_2/H_2 conversion and product selectivity obtained over Pt/C, Pt/SiO₂, Pt/Al₂O₃ and UiO-67-
 9 Pt at 170 °C and 1–8 bar is shown in Figure 1. Substantial selectivity differences were observed at
 10 similar conversion levels (0.4–1.5 %): Over UiO-67-Pt, the methanol selectivity increased from
 11 around 3 to 19 %—corresponding to a turn-over-frequency (TOF) of 0.01 s⁻¹—when the pressure
 12 increased from 1 to 8 bar (Figure 1). This is, to the best of our knowledge, the second report of
 13 significant methanol formation from CO₂ over a Pt-based catalyst where the support alone is inactive
 14 in the reaction.²⁸ Under the same conditions, there was only a slight increase in methane selectivity
 15 from 1.2 to 1.6 %. Over Pt/Al₂O₃, both the methane and methanol selectivity reached 10 % under 8 bar
 16 pressure (Figure 1). In contrast to UiO-67-Pt, methane selectivity increased substantially with
 17 increasing pressure. Finally, over Pt/SiO₂ and Pt/C (Figure 1), CO was the only carbon-containing
 18 product observed, in accordance with the theory predictions of Kattel et al. for unsupported Pt NPs.¹⁸
 19 The formation of methanol over UiO-67-Pt points to strong metal-support interactions, as previously
 20 reported for Cu NPs embedded in UiO Zr-MOFs,^{29, 30} and may suggest that the MOF support plays an
 21 active role during reaction, similarly to Al₂O₃ in the Water Gas Shift (WGS) and CO₂ hydrogenation
 22 reactions.^{8, 24, 49}

1

2
3

4 Figure 1. CO₂ conversion (left axes, diamonds) and product selectivity (right axes) during CO₂
 5 hydrogenation under 1–8 bar total reaction pressure and T = 170 °C. Left: UiO-67-Pt. Middle:
 6 Pt/Al₂O₃. Right: Pt/SiO₂ (grey, blue) and Pt/C (black). CO, CH₄ and CH₃OH selectivity is depicted as
 7 squares, circles and triangles, respectively. $\tau = 0.01 \text{ g}_{\text{cat}} \cdot \text{min}/\text{ml}$, CO₂/H₂/inert = 1/6/3. For Pt/Al₂O₃ $\tau =$
 8 $0.02 \text{ g}_{\text{cat}} \cdot \text{min}/\text{ml}$.

9

10 To further assess the role of Pt NPs vs. support in CO₂ hydrogenation, steady-state H₂/D₂
 11 exchange experiments were performed under CO₂ hydrogenation conditions over UiO-67-Pt, Pt/Al₂O₃,
 12 Pt/SiO₂, UiO-67 and SiO₂. The transient evolution of the HD molecule following a feed switch from
 13 CO₂ + H₂ to CO₂ + D₂ is shown in Figure S9. Importantly, formation of HD (and other products) was
 14 observed only over the Pt containing materials but not over the UiO-67 and SiO₂ supports alone,
 15 showing that dissociation of H₂/D₂ only occurs when Pt is present. The amount of HD formed over
 16 UiO-67-Pt and Pt/Al₂O₃ was larger than over Pt/SiO₂, and in all cases 1–2 orders of magnitude higher
 17 than the amount of exposed Pt atoms in Pt nanoparticles (Table 1). This observation, in combination
 18 with the observed HD tailing, strongly suggests H/D exchange with hydroxyl groups on the support
 19 materials, either directly by hydrogen spillover to/from the Pt NPs, or by H/D exchange with the water
 20 molecules formed during reaction.

21 Insights into the origin of HD tailing and formed amount over the UiO-67-Pt sample were
 22 obtained by a parallel *operando* FT-IR experiment under comparable conditions (1 bar, 170 °C,
 23 CO₂/H₂ = 1/6). When exchanging H₂ for D₂, the sharp signal of Zr- μ_3 -OH at 3669 cm⁻¹³⁹ decreased to
 24 zero with time while another equally sharp and intense peak, corresponding to the deuterated species
 25 Zr- μ_3 -OD, increased at 2705 cm⁻¹ (Figure S16). Interestingly, quantification of the molar number of H

1 in HD, $N_{A,HD}$, yields 1200 $\mu\text{mol H}$ per gram catalyst, which corresponds to about 70 % of the
 2 theoretical number of Zr- μ_3 -OH groups in the sample. No other indication of H/D exchange (neither
 3 on Pt nor in linkers) was found from FT-IR experiments. More detailed description of the spectra
 4 obtained during FT-IR experiments over UiO-67-Pt, including the hydroxyl group region and the C-H
 5 bonds present in the aromatic linkers (carboxylates region is omitted as out of scale), is given in the
 6 supporting section (Figure S16).

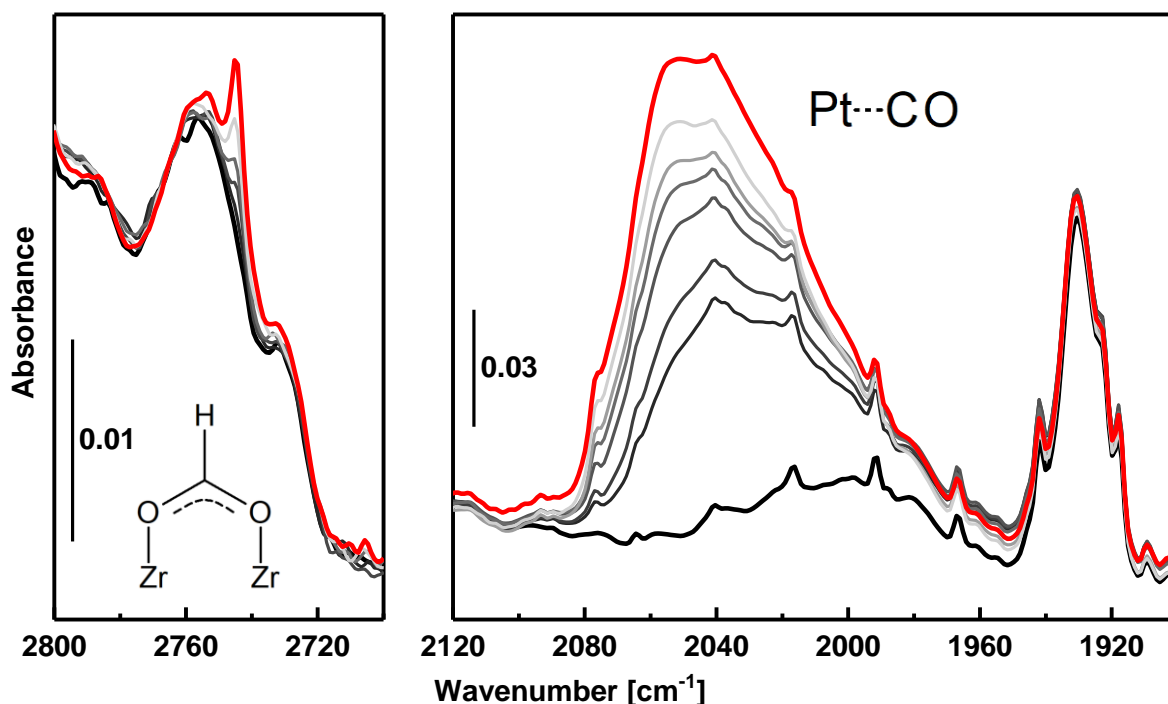
Table 1. Pt amount, NP diameter (d_{NP}), CO-uptake ($N_{A,CO,RT}$), estimated exposed Pt surface ($N_{surf,Pt}$) and the amount of HD formed ($N_{A,HD}$) after switching from H_2+CO_2 to D_2+CO_2 at 170 °C, 1 bar.

Catalyst	Pt amount (wt %)	d_{NP} (nm)	$N_{A,CO,RT}$ ^c ($\mu\text{mol/g}_{cat}$)	$N_{surf,Pt}$ ^d ($\mu\text{mol/g}_{cat}$)	$N_{A,HD}$ ($\mu\text{mol/g}_{cat}$)
UiO-67-Pt	2.7 ^a	3.6 \pm 0.7	1.7 \pm 0.3	55	1200
Pt/Al ₂ O ₃	5 ^b	1.4 ^b	36	200	1100
Pt/SiO ₂	5 ^b	5 \pm 2	13	76	540
Pt/C	5 ^b	2 ^b	-	-	-

^atheoretical amount of impregnation. A Pt amount of 2.4 \pm 0.4 wt % was estimated from EDX analysis (see SI). ^bobtained from the provider. ^cpulse-chemisorption at room temperature. ^destimated from TEM by following the procedure described in the SI.

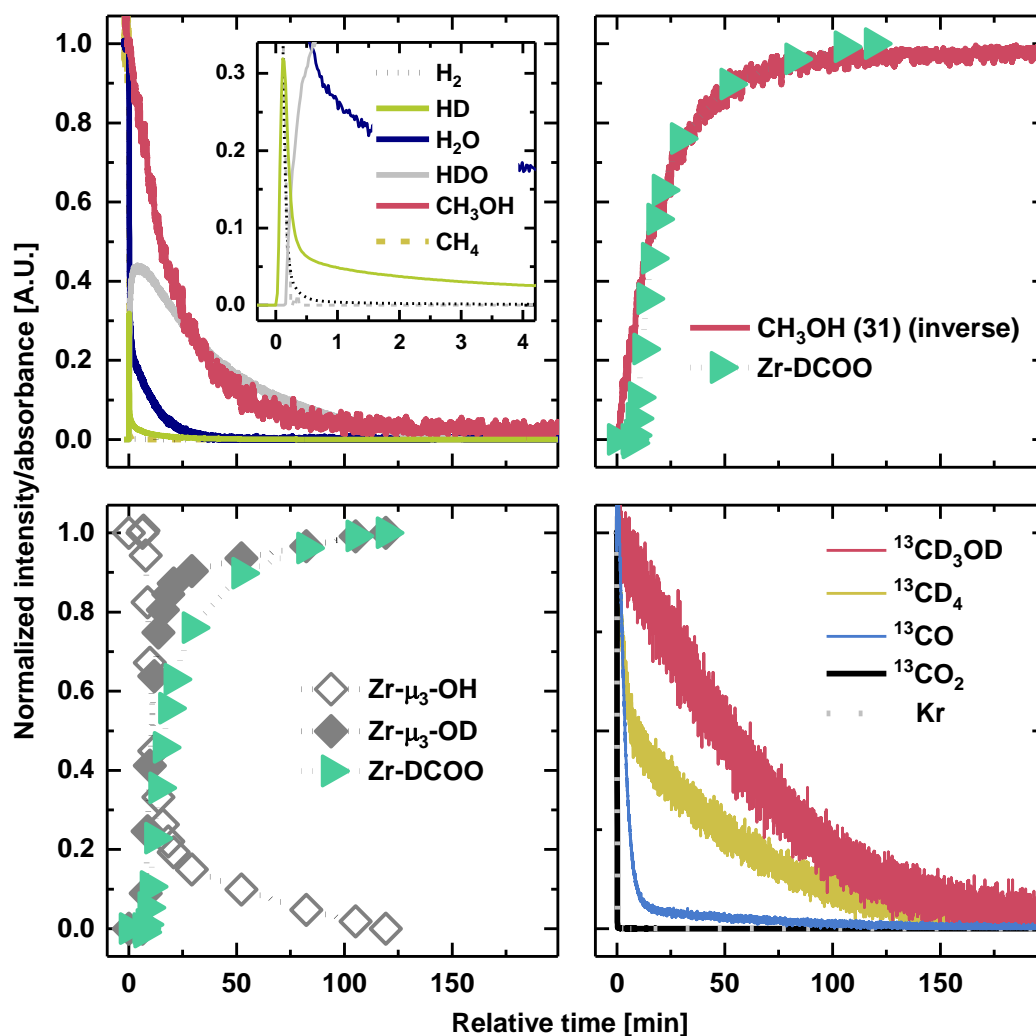
7
 8 It is important to note that the chemical integrity of the catalyst is preserved during reaction
 9 and changes in the spectra are therefore caused by reaction products interacting with the sample. The
 10 most evident change is caused by the progressive increase of CO on the Pt nanoparticles (Figure 2).
 11 The shape and frequency of this signal is compatible with carbonyls linearly adsorbed on Pt atoms at
 12 the surface of NPs, as we already addressed in our previous study on an analogous material.¹⁷ The size
 13 of the particles (3.6 nm) and the temperature (170 °C) justify the absence of bridged carbonyl species
 14 at lower frequencies. Changes in one of the smaller peaks in the IR spectra is the most novel
 15 observation of this study: the peak arising at 2745 cm^{-1} (Figure 2) is due to the appearance of bidentate
 16 formate groups³⁹ (which, notably, are absent after activation, see Figure 2) most likely coming from
 17 the progressive process of CO₂ reduction. The frequency of this weak feature is compatible with
 18 $\nu_s(\text{COO}) + \delta(\text{CH})$ vibration of bidentate formates directly connected to open Zr-sites of the Zr-nodes
 19 in the MOF framework.^{39, 50, 51} Further bands associated to formate are visible in the top part of Figure
 20 S16 in the region 3000-2800 cm^{-1} . The spectrum of the sample collected during CO₂ hydrogenation
 21 after the subtraction of the activated one (Figure S17) highlights the formation of four additional bands
 22 at 2910, 2888, 2868 and 2854 cm^{-1} , ascribable to various formate species at the Zr-node.³⁹ This is to

1 the best of our knowledge, the first report of formate formation at the MOF Zr-node under CO₂
2 hydrogenation reaction conditions.



3
4
5 Figure 2. FT-IR spectra of UiO-67-Pt collected during CO₂ hydrogenation (CO₂/H₂ = 1/6, 10 ml/min,
6 170 °C, 1 bar) at different times (thick black curve for t = 0 min, grey scale from darkest to brightest
7 for 0 < t < 120 min, thick red curve for t = 120 min). The left figure shows the magnified spectral
8 region of the ν(C-H) for formate groups, while the right figure depicts the spectral interval typical for
9 CO linearly adsorbed on metal nanoparticles. Full range spectra are reported in Figure S16.

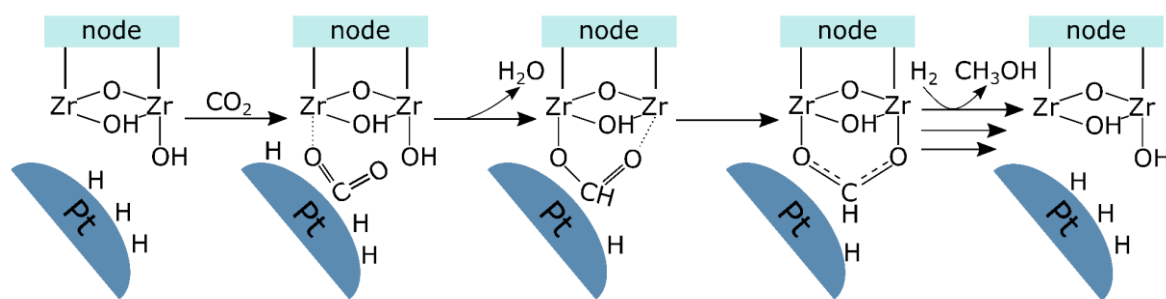
10 The importance of these moieties is even more evident, thanks to the isotopic exchange
11 experiment between H₂ and D₂. When exchanging H₂ for D₂, the signals of the formate groups shifted
12 to lower wavenumbers; the signals in the 2950–2850 cm⁻¹ region shifted to the region of the CO₂ roto-
13 vibrational profile and are therefore not detectable. Conversely, the band at 2745 cm⁻¹ shifted to 2168
14 cm⁻¹ ³⁹ (Figure S16) and the intensity vastly increased as compared to the H-analogue ($I_{\text{HCOO}}/I_{\text{DCOO}} \approx$
15 0.02). The intensity increase indicates an inverse kinetic isotope effect, although possible differences
16 in the extinction coefficient of the two species cannot be excluded. Importantly, a corresponding,
17 gradual increase in methanol production rate was observed upon H₂/D₂ exchange under steady-state
18 CO₂ hydrogenation conditions (Figure S14). At isotope equilibration, this difference in H- and D-
19 methanol production rates corresponds to an inverse Kinetic Isotope Effect (KIE), $r_{\text{H}}/r_{\text{D}} = 0.36$.
20 Moreover, the temporal scale of exchange was very similar for the formate species and for methanol in
21 the parallel H₂/D₂ exchange experiments performed in the FT-IR transmission cell and the test-setup,
22 respectively (Figure 3) (See Experimental section for details). Together, these experiments provide
23 firm evidence that the Zr-formate species is a key intermediate in the methanol formation path.



1
 2 Figure 3. Top left: The normalized intensity of H₂ ($m/z = 2$), HD ($m/z = 3$), H₂O ($m/z = 18$), HDO
 3 ($m/z = 19$), CH₃OH ($m/z = 31$) and CH₄ ($m/z = 15$) when switching from CO₂+H₂ to CO₂+D₂ at $t = 0$.
 4 Top right: Comparison of Zr-DCOO and CH₃OH (inverse) during H/D exchange. Bottom left:
 5 Normalized absorbance of Zr-μ₃-OH (open diamonds), Zr-μ₃-OD (filled diamonds) and deuterated
 6 formate (triangles) during exchange of H₂ to D₂ at steady state CO₂ hydrogenation. CO₂/H₂(D₂) = 1/6,
 7 10 ml/min, 170 °C, 1 bar. Bottom right: The normalized intensity of Kr ($m/z = 84$), ¹³CO₂ ($m/z = 45$),
 8 ¹³CO ($m/z = 29$), ¹³CD₄ ($m/z = 21$) and ¹³CD₃OD ($m/z = 35$) products when switching from ¹³CO₂ + D₂
 9 to ¹²CO₂ + D₂ at $t = 0$. T = 170 °C, 1 bar, $\tau = 0.01 \text{ g}_{\text{cat}} \cdot \text{min}/\text{ml}$.

10 Furthermore, during a complementary (¹³CO₂+D₂)/(¹²CO₂+D₂) exchange experiment (Figure
 11 3), ¹³CD₃OD decreased steadily to zero in about 200 minutes, similarly to what observed for formate
 12 and methanol during the H₂/D₂ switch. The slope of the normalized intensity of methanol in a semi
 13 logarithmic plot (Figure S15) is inversely proportional to the mean surface residence time ($-1/\tau_{\text{res}}$) of
 14 intermediates leading to the formation of methanol (Table 3), and is characteristic of formation from a
 15 single pool of intermediates.⁵²

1 Overall, the transient experiments provide firm evidence that formate species, attached to the
 2 Zr nodes in a bidentate configuration, are formed by H transfer from an adjacent Pt NP. The inverse
 3 KIE observed for methanol formation ($r_{\text{H}}/r_{\text{D}} = 0.36$) is a signature of reactions where the rate limiting
 4 step involves hydrogen addition to an sp - or sp^2 -hybridized carbon, leading to a hybridization change
 5 (sp to sp^2 , or sp^2 to sp^3).^{10, 53} CO_2 hydrogenation to methanol via formate species involves two such
 6 steps, CO_2 hydrogenation to form formate, and formate hydrogenation to (probably) form
 7 dioxymethylene. The observation of abundant formate species by FT-IR and by $^{13}\text{C}/^{12}\text{C}$ transient
 8 integration (Table 3) further suggest that hydrogenation of the formate species is the rate limiting step
 9 of methanol formation in UiO-67-Pt. Previously, an inverse KIE (albeit not as strong as in our case)
 10 was reported for CO_2 to methanol over $\text{Cu}/\text{ZnO}/\text{Al}_2\text{O}_3$, Cu/SiO_2 , Cu/MgO and Pd/SiO_2 .¹⁰ In that case,
 11 DFT calculations predicted an inverse KIE for hydrogenation of the formate species, in line with our
 12 results. A schematic presentation of the postulated reaction mechanism is shown in Scheme 2.



13
 14 Scheme 2. Schematic presentation of the postulated reaction mechanism of CO_2 hydrogenation to the
 15 formate intermediate in CH_3OH formation at the Pt–Zr-node interface.

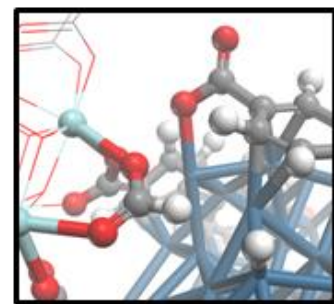
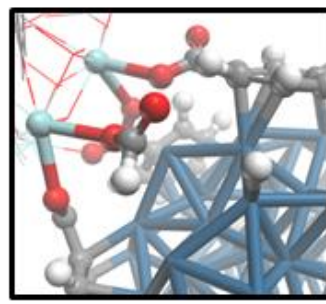
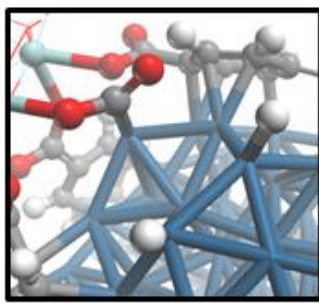
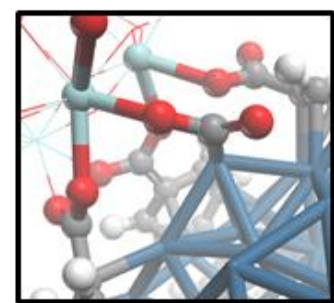
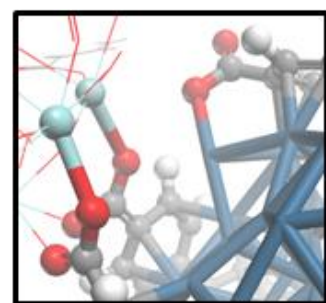
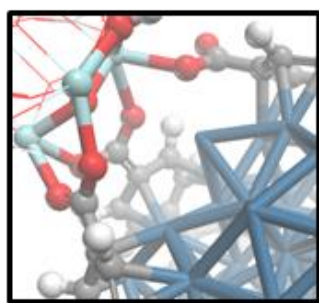
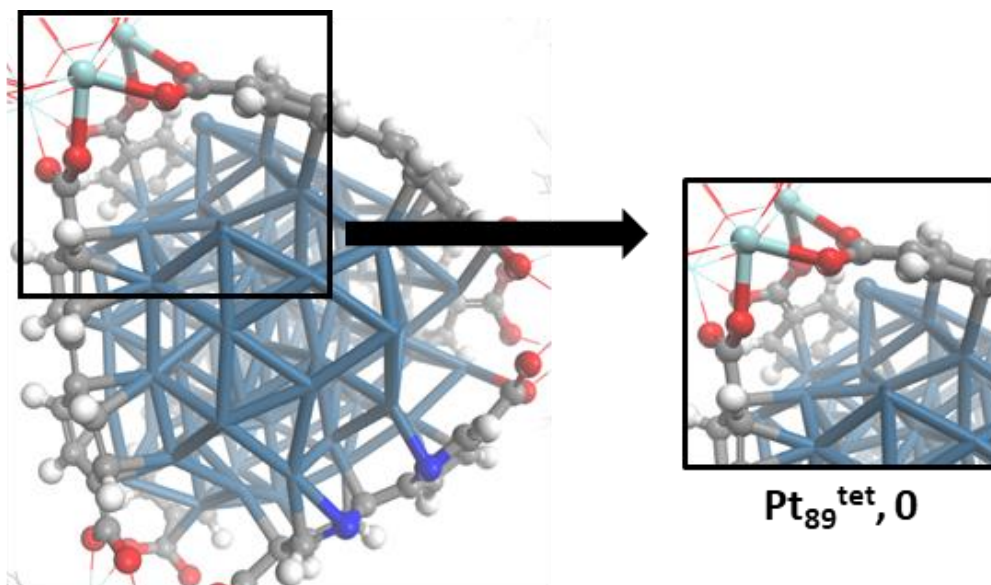
16 Integration of the $^{13}\text{C}/^{12}\text{C}$ transient response of methanol showed an intermediate species
 17 concentration of $23 \mu\text{mol}/\text{g}$ (Table 3), i.e. close to half the amount of Pt surface species estimated for
 18 the ensemble of Pt NPs identified by TEM (3.6 nm average diameter, Table 1). The schematic
 19 illustration of such a particle embedded in the MOF structure suggests that the average Pt NP contains
 20 640 surface Pt sites, and is surrounded by 32 Zr nodes that have a total of 224 Zr-sites accessible for
 21 coordination at the Pt – MOF interface, corresponding to 84112 bidentate formate species (Scheme 1,
 22 Figure 2). These numbers yield a formate:Pt surface site ratio of 112:640 (0.2), substantially lower
 23 than the estimated 24:55 (0.4) ratio from transient experiments.

24 Importantly, the numbers imply that additional Zr-sites are available to formate formation
 25 around each Pt NP. In this respect, we hypothesized that Zr-sites might become accessible by
 26 breaking Zr-linker bonds, either during Pt NP formation, or during the catalytic reaction. The
 27 hypotheses were investigated by periodic Density Functional Theory (DFT) calculations. (See
 28 Experimental Details section for a brief description of the methodology and SI for further
 29 computational details and model construction). A Pt_{39} NP occupying the tetrahedral cavity of UiO-67

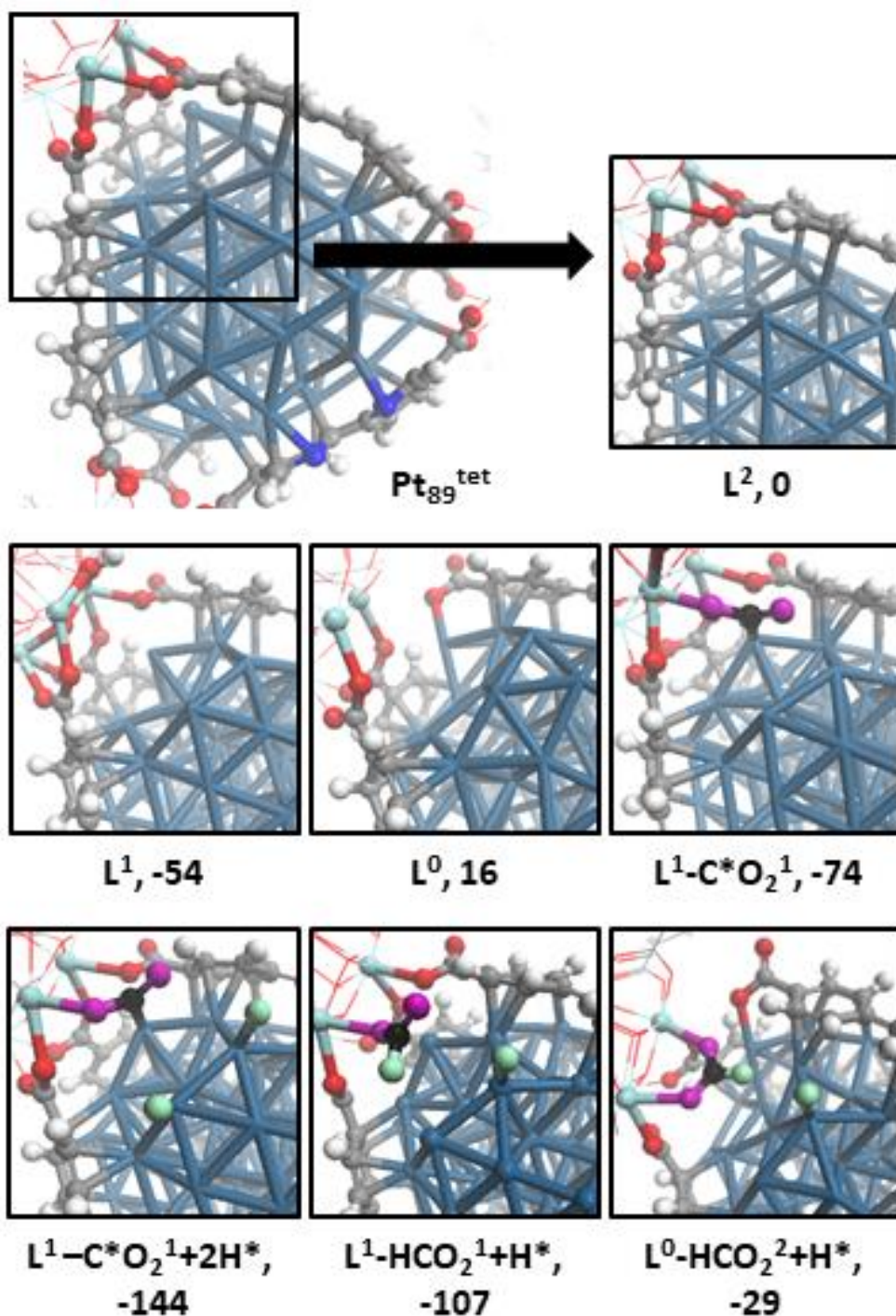
1 (Figure S18), $\text{Pt}_{89}^{\text{tet}}$, was found to be an adequate model, justified by the assumption that the interface
2 between the Pt NP and the linker/Zr node is similar when the NP has a diameter of 3.6 nm or ≈ 1 nm.

3 In the perfect MOF structure, all 24 coordination sites of each Zr-node are occupied by the
4 carboxylate groups of the linker molecules (L). We first investigated the opening of such sites and
5 computed the free energy profile of the system when a linker decoordinates from the node and slides
6 along the Pt NP surface (Figure 4 and Figure S22). Decoordination of the linker presumably occurs via
7 $\sigma(\text{Csp}^2\text{-Csp}^2)$ -bond rotation at the $\text{O}_2\text{C-C(Aryl)}$ fragment, which generally involves low energy
8 barriers. In Figure 4, L^{X} and O_2^{X} indicates the coordination mode of the linker or formate oxygen to
9 the Zr-node (X = number of Zr-O bonds) and * indicates the atom adsorbed to the Pt_{89} NP. These
10 calculations showed that it is unfavorable to open two Zr-sites ($\Delta\text{G}(\text{L}^2 \rightarrow \text{L}^0) = 16$ kJ/mol), while
11 opening one Zr-site is favorable, $\Delta\text{G}(\text{L}^2 \rightarrow \text{L}^1) = -54$ kJ/mol). Considering next the catalytic reaction,
12 the first step of formate formation is the adsorption of a CO_2 molecule which was found to coordinate
13 its C atom to the Pt surface and the O atom to the opened Zr-site ($\Delta\text{G}_{\text{ads}}(\text{L}^1 + \text{CO}_2 \rightarrow \text{C}^*\text{O}_2^1) = -20$
14 kJ/mol) (Figure 4). Continuing on the formate formation pathway from the $\text{L}^1\text{-C}^*\text{O}_2$ intermediate, the
15 two subsequent intermediates, $\text{L}^1\text{-C}^*\text{O}_2^1 + 2\text{H}^*$, $\Delta\text{G} \text{L}^2 + \text{CO}_2 + \text{H}_2 \rightarrow \text{L}^1\text{-C}^*\text{O}_2^1 + 2\text{H}^*) = -144$ kJ/mol
16 and $\text{L}^1\text{-HCO}_2^1 + \text{H}^*$, $\Delta\text{G}(\text{L}^2 + \text{CO}_2 + \text{H}_2 \rightarrow \text{L}^1\text{-HCO}_2^1 + \text{H}^*) = -107$ kJ/mol, correspond to H_2 adsorption
17 on the Pt NP and a formate + hydride species, respectively (Figure 4). The H_2 adsorption is exergonic
18 by -70 kJ/mol, and the subsequent H transfer to the C atom of CO_2 is endergonic by 37 kJ/mol.
19 Interestingly, the transformation from $\text{L}^1\text{-HCO}_2^1 + \text{H}^*$ to $\text{L}^0\text{-HCO}_2^2 + \text{H}^*$, $\Delta\text{G}(\text{L}^2 + \text{CO}_2 + \text{H}_2 \rightarrow \text{L}^0\text{-}$
20 $\text{HCO}_2^2 + \text{H}^*) = -29$ kJ/mol, where the formate species is coordinated to two Zr-sites is highly
21 endergonic, $\Delta\text{G}_r(\text{L}^1\text{-HCO}_2^1 + \text{H}^* \rightarrow \text{L}^0\text{-HCO}_2^2 + \text{H}^*) = 78$ kJ/mol. The transformation from $\text{L}^1\text{-}$
22 $\text{HCO}_2^1 + \text{H}^*$ to $\text{L}^0\text{-HCO}_2^2 + \text{H}^*$ comprises two structural changes: i) The formate moiety goes from
23 being coordinating to one Zr-site to being coordinated to two Zr-sites; ii) the linker decoordinates from
24 one Zr-site, opening two Zr-sites. To estimate the contribution to the free energy change, $\Delta\text{G}(\text{L}^1\text{-}$
25 $\text{HCO}_2^1 + \text{H}^* \rightarrow \text{L}^0\text{-HCO}_2^2 + \text{H}^*)$, of i) and ii), a computational experiment was performed: while
26 keeping the linker in a “completely open position” (L^0), the formate moiety was oriented to its Zr-
27 monodentate configuration HCO_2^1 . This resulted in a potential energy increase of 45 kJ/mol.

28 These results indicate that the coordination of formate by one Zr-O bond (monodentate) is
29 thermodynamically preferred in nodes initially saturated by linkers (L^2), while the coordination of
30 formate by two Zr-O bonds (bidentate) is thermodynamically preferred in nodes initially having lost
31 some linkers (L^0). Therefore, the observation of the latter coordination mode of formate by FT-IR
32 suggests that these species have been generated in Zr nodes with empty coordination sites at the start
33 of the reaction.



1



1

2 Figure 4. 3D representations of intermediates of the reaction pathway towards the formation of the
 3 formate species coordinated to two Zr sites. Values are free energies in kJ/mol. L^X and O_2^X indicates
 4 the coordination number of the linker and formate to the Zr-node, and * the atom adsorbed to Pt. O, C
 5 and H atoms from CO_2 and H_2 are in pink, black and green; and for the linker, in red, grey and white.

6

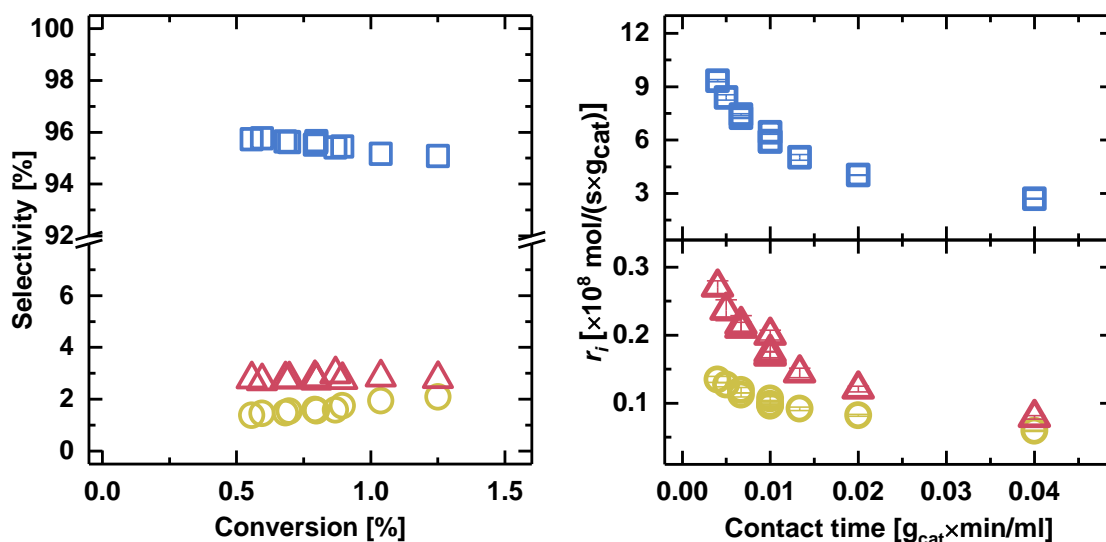
1 It was therefore explored whether the growth of the Pt NP during activation could cause the
2 formation of such Zr nodes with open coordination sites. Insight into this possibility was obtained by
3 computing the free energy of the Pt particle growth from $\text{Pt}_{55}^{\text{tet}}$ to $\text{Pt}_{89}^{\text{tet}}$. These calculations showed
4 that the reaction free energy of the system decreases as the Pt NP grows, and the decrease in energy
5 will eventually exceed the energy loss of linker detachment (Figure S19, Figure S20 and Figure S21).
6 Thus, during the nanoparticle growth, linkers will detach from the Zr nodes, and the Zr nodes will
7 decorate the growing Pt nanoparticle. Returning to Scheme 1, the number of Zr nodes that needs to be
8 removed from a perfect MOF lattice in order to create the 3.6 nm model Pt NP is minimum 6. The
9 corresponding number of additional bidentate formate sites is 54. In combination with the 112 formate
10 sites of the surrounding framework bound nodes, this yields a total number of formate sites of 166 and
11 a formate-to-Pt surface atom ratio of 0.3, in reasonable agreement with the experimentally observed
12 numbers.

13 Support for the computational results were found from on-line Mass Spectrometry (MS)
14 measurements performed during activation in 10% H_2/Ar atmosphere at 350 °C. The MS data revealed
15 traces of phenyl-containing fragments in the effluent gas, suggesting that modulator and/or linker
16 molecules desorbed from the material during Pt NP formation (Figure S8). The crystallographic
17 features of the material were unchanged (Figure S2, Figure S5 and Figure S6) and the BPYDC/BPDC
18 ratio remained constant during subsequent testing (Table S2). Furthermore, no linker fragments were
19 observed during a second activation of UiO-67-Pt after testing, in line with the excellent catalyst
20 stability observed under reaction conditions.

21 Having established the importance of the Zr-nodes and formate intermediates for methanol
22 formation over UiO-67-Pt, the next issue is whether methanol formation could be decoupled from CO
23 and CH_4 formation, hence, optionally leading to higher methanol selectivity. To this end, we first turn
24 to classical kinetic experiments.

25 Contact time variation experiments, under otherwise constant conditions, showed that
26 methanol selectivity is constant when CO_2 conversion increases, suggesting that it is a primary
27 reaction product (Figure 5). Conversely, methane selectivity increases with increasing CO_2
28 conversion, while CO selectivity decreases, suggesting that CH_4 is mainly a secondary product,
29 formed via CO. The latter result is in accordance with our previous studies of an analogous catalyst at
30 higher temperature.¹⁷

31



1
 2 Figure 5. Contact time variation during CO₂ hydrogenation to CO (squares), CH₄ (circles) and
 3 CH₃OH (triangles) at 170 °C, 1 bar, CO₂/H₂/He = 1/6/3 and $\tau = 0.004\text{--}0.04$ g_{cat}·min/ml. Left:
 4 Selectivity versus conversion. Right: Rate of product formation versus contact time.

5 Next, partial pressure variation experiments were performed in order to assess reaction orders
 6 for each product. This assessment was complicated by the decreased formation rate of all products
 7 with increasing contact time (Figure 5), indicating strong adsorption of one or several reaction
 8 products, thereby poisoning the active site(s).^{10, 19} Indeed, when correlating the rate decrease with the
 9 partial pressures of the majority products, CO and H₂O, all products have a reaction order close to
 10 negative 1 in $p(\text{CO}+\text{H}_2\text{O})$, CH₄ slightly less negative (Figure S10 and Table 2). Based on FT-IR
 11 results reported above, showing that CO adsorbed on Pt (2042 cm⁻¹)¹⁷ dominates the Pt surface under
 12 the respective reaction conditions, CO was assessed as the main contributor to the inhibition, likely
 13 suppressing the coverage in H^δ by competitive adsorption. When taking into account the variable
 14 concentration of CO and H₂O, positive reaction orders in $p\text{H}_2$ and $p\text{CO}_2$ were observed for all
 15 products, but with substantial differences (Table 2).

16 Considering first the majority product, CO, its formation rate depends strongly on $p(\text{CO}_2)$, but
 17 less on $p(\text{H}_2)$ (Table 2). Furthermore, no Kinetic Isotope Effect (KIE) was observed for CO during the
 18 (CO₂+H₂)/(CO₂+D₂) transient experiment (Table S5 and Figure S14), showing that breaking or
 19 making of H-H or H-O bonds (which would otherwise lead to a primary KIE)^{10, 54} is not rate-
 20 determining for CO formation under the conditions studied here. Finally, the number of surface
 21 intermediates leading to CO formation and their mean residence time were calculated from the ¹³C/¹²C
 22 transients (Table 3 and Figure 3). The normalized ¹³CO signal rapidly decreased to around 0.05 within
 23 the first 15 minutes then slowly reached zero in the following 150 minutes. It is interesting to note that
 24 the number of surface intermediates leading to CO formation represents half of the Pt surface atoms in
 25 Pt NPs, estimated from TEM measurements (Table 1 vs. Table 3). This observation, in combination

1 with the partial coverage of the Pt NPs by Zr-nodes (and linkers), the inhibiting effect of CO, the high
 2 predicted barrier of CO desorption from Pt,¹⁸ and the observation of a positive correlation between
 3 facile CO desorption and rate of CO formation in our previous study,¹⁷ strongly suggest CO desorption
 4 as rate-limiting step in the RWGS reaction over UiO-67-Pt.

5
 6 Table 2. Reaction orders in total pressure (p_{total}), and in p_{H_2} , p_{CO_2} and $p(\text{CO}+\text{H}_2\text{O})$ (1 bar) for the rate
 7 of conversion (X) and CO, CH₄ and CH₃OH formation at 170 °C over UiO-67-Pt.

p_i	X	CO	CH ₄	CH ₃ OH
P_{total}	0.1	0	0.3	1.1
CO+H ₂ O ^a	-1.1	-1.1	-0.7	-1
H ₂ ^b	0.2	0.2	0.9	1.7
CO ₂ ^b	0.9	0.9	0.1	0.7

^aEstimated from contact time variation experiments (Figure 5 and Figure S10). The reaction orders represent the average of two experiments. ^bReaction orders when taking into account variable p_{CO} and $p_{\text{H}_2\text{O}}$ in the reactor.

8
 9 Turning next to methane formation rate, it depends strongly on $P(\text{H}_2)$ and weakly on $P(\text{CO}_2)$
 10 (Table 2). Considering the high coverage of CO, as well as the presumed indirect formation of
 11 methane via CO, this result is not surprising. In the $(\text{CO}_2+\text{H}_2)/(\text{CO}_2 + \text{D}_2)$ transient experiment, an
 12 inverse KIE of 0.6, i.e. intermediate between CO (KIE = 1) and methanol (KIE = 0.36), was observed
 13 for methane (Table S5 and Figure S14). Intriguingly, the inverse KIE was installed within the 15
 14 minutes resolution of the gas analysis, hence, much more rapid than the transient behavior of methanol
 15 (Figure S14). Thus, the rate-determining step of methane formation involves bonding with
 16 hydrogen,⁵⁴⁻⁵⁷ but the rate-determining step is not the same as for methanol formation. Indeed, the
 17 much more rapid transient behavior of methane compared to formate, disqualifies formate as a
 18 significant intermediate to methane formation. This result implies that, except for hydrogen activation,
 19 methane formation is mechanistically decoupled from methanol formation. The normalized CH₄
 20 formation rate (represented by the $m/z = 15$ signal of CH₃) also decreases rapidly to zero (comparable
 21 to H₂) during the H/D exchange (Figure 3). Due to their mass overlap with the much more abundant
 22 water fragments, the time evolution of partially exchanged methane/methyl species could not be
 23 followed. The transient behavior of methane during the ¹³C/¹²C switch (Figure 3) was markedly
 24 different from that observed in the H/D transient: The normalized ¹³CD₄ formation rate decreased to
 25 0.5 during the first 7 minutes and then slowly to zero in the following 160 minutes. This distinct shape
 26 of the isotope transient indicates methane formation from two pools in parallel,^{52, 58} one rapidly
 27 converted to products and the other more slowly. Integration of the transient curve showed that the
 28 number of surface intermediates leading to methane formation is low (Table 3). Moreover, about 3%

1 of the methane-forming intermediates react fast and is responsible for about 50 % of the steady-state
2 methane formation rate, while the other 97 % react slowly (Table 3 and Figure S15).

3 Returning finally to methanol, its formation depends strongly on both reactant partial
4 pressures, in line with the observation that it is a primary product, formed independently of CO
5 (Figure 5). The $^{13}\text{C}/^{12}\text{C}$ transient experiment shows that methanol is formed from a similar number of
6 surface intermediates as CO, but their turn-over rate is much slower, hence leading to the 9 %
7 methanol selectivity observed under the respective conditions (Table 3).

Table 3. Mean surface residence times τ_{res} and the number N_{ad} of surface intermediates leading to the
formation of ^{13}CO , $^{13}\text{CD}_4$ and $^{13}\text{CD}_3\text{OD}$ at 170 °C (1 bar), calculated from integration of the curves in
Figure 3 and the isotope-independent steady-state reaction rates.

	INT(CO)	INT(CD ₄)	INT(CD ₃ OD)
N_{ads} ($\mu\text{mol}/\text{g}_{\text{cat}}$)	3426 ± 3	323 ± 0.3	2423 ± 2
τ_{res} (s)	540 0.5×10^3	2174 2.1×10^3	3897 3.8×10^3

8
9 Considering finally the non-carbon products HD, H₂O and HDO, they exhibited slow or
10 partially slow transient responses (Figure 3). HD has a sharp initial peak with considerable tailing over
11 the course of the following hour, indicating formation from parallel pools and/or exchange with
12 hydrogen-containing surface species.⁵⁹ H₂O showed transient characteristics suggestive of parallel
13 pools, similar to CO and CH₄, and the HDO signal increased rapidly to a maximum within a few
14 minutes then slowly decreased over the course of 2 hours, closely following the methanol signal. The
15 long surface lifetime of these products is indicative of a long-lived source of H participating in their
16 formation, presumably also in the formation of methanol. Interestingly, quantification of the mol H in
17 HD, H₂O, HDO and CH₃OH yields 1500 μmol H per gram catalyst, which corresponds to about 80 %
18 of the theoretical amount of mol Zr $\mu_3\text{-OH}$ groups in the sample (HD accounts for 70 %, as reported
19 above).

20

21 Conclusion

22 Mechanistic aspects of CO₂ hydrogenation over UiO-67-Pt and the role of the UiO-67
23 framework have been investigated in detail by employment of steady-state and transient kinetic
24 studies, coupled with *operando* infrared spectroscopy and DFT modeling.

25 It was observed that Pt NPs embedded in the MOF structure are responsible for hydrogen
26 activation, and that formate species are formed at the Zr nodes by reaction between adsorbed CO₂ and
27 hydrogen spill-over from an adjacent Pt NP. These results demonstrate that the Pt NPs strongly
28 interact with defect Zr nodes during reaction, and hence, that Zr nodes decorate the surface of the Pt

1 NPs. Formate species are the most abundant intermediates in the reaction path to methanol, and
2 transient results suggest that formate hydrogenation is the rate-limiting step of methanol formation.
3 Importantly, the abundance of formate species is limited by the number of Zr sites made available by
4 linker detachment due to Pt NP growth during catalyst activation.

5 CO and methane formation are mechanistically separated from methanol formation, except for
6 the hydrogen dissociation step. The main route to methane formation is proposed as CO
7 hydrogenation. Moreover, the presented data are consistent with CO desorption being the rate limiting
8 step of the reverse water gas shift reaction over UiO-67-Pt.

9

10 **Acknowledgement**

11 E.S.G, A.L., G.K., S.Ø.-Ø., S.B., S.S., K.P.L. and U.O. acknowledge the Research Council of Norway
12 for financial support (FRINATEK ToppForsk Grant No. 250795 CONFINE). We further acknowledge
13 Chimet for providing Pt/Al₂O₃ and Pt/C catalysts.

14 T.F. acknowledge the Norwegian Metacenter for Computational Science (NOTUR) for computational
15 resources (projects number nn4654k and nn4683k), Michele Cacella for useful advice on the
16 methodology, Sri Harsha Pulumati for fruitful discussions, Jingyun Ye and J. Karl Johnson for help
17 with reproducing their calculations of reference ⁵³.

18 T.F., E.S. and A.N. acknowledge support by the 'Nordic Consortium for CO₂ Conversion' (NordForsk
19 project No. 85378, site.uit.no/nordco2).

20 A. N. acknowledge the support from the Research Council of Norway (FRINATEK Grant No. 250044
21 and Center of Excellence Grant No. 262695).

22 **Author Information**

23 **Corresponding Author**

24 *unni.olsbye@kjemi.uio.no

25 **Associated Content**

26 **Supporting Information**

27 Catalyst preparation, characterization, catalytic testing, operando FTIR and computational details.
28

29 **References**

- 30 1. Bellotti, D.; Rivarolo, M.; Magistri, L.; Massardo, A. F., Feasibility study of methanol
31 production plant from hydrogen and captured carbon dioxide. *J. CO₂ Util.* **2017**, *21*, 132-138.
- 32 2. Chu, S.; Cui, Y.; Liu, N., The path towards sustainable energy. *Nat. Mater.* **2016**, *16*, 16.

- 1 3. Olah, G. A., Beyond Oil and Gas: The Methanol Economy. *Angew. Chem. Int. Ed* **2005**, *44* (18),
2 2636-2639.
- 3 4. Porosoff, M. D.; Yan, B.; Chen, J. G., Catalytic reduction of CO₂ by H₂ for synthesis of CO,
4 methanol and hydrocarbons: challenges and opportunities. *Energy Environ. Sci.* **2016**, *9* (1), 62-73.
- 5 5. Wang, W.; Wang, S.; Ma, X.; Gong, J., Recent advances in catalytic hydrogenation of carbon
6 dioxide. *Chem. Soc. Rev.* **2011**, *40* (7), 3703-3727.
- 7 6. Li, W.; Wang, H.; Jiang, X.; Zhu, J.; Liu, Z.; Guo, X.; Song, C., A short review of recent
8 advances in CO₂ hydrogenation to hydrocarbons over heterogeneous catalysts. *RSC Adv.* **2018**, *8*
9 (14), 7651-7669.
- 10 7. Kattel, S.; Liu, P.; Chen, J. G., Tuning Selectivity of CO₂ Hydrogenation Reactions at the
11 Metal/Oxide Interface. *J. Am. Chem. Soc.* **2017**, *139* (29), 9739-9754.
- 12 8. Wang, X.; Shi, H.; Kwak, J. H.; Szanyi, J., Mechanism of CO₂ Hydrogenation on Pd/Al₂O₃
13 Catalysts: Kinetics and Transient DRIFTS-MS Studies. *ACS Catal.* **2015**, *5* (11), 6337-6349.
- 14 9. Wu, H. C.; Chang, Y. C.; Wu, J. H.; Lin, J. H.; Lin, I. K.; Chen, C. S., Methanation of CO₂ and
15 reverse water gas shift reactions on Ni/SiO₂ catalysts: the influence of particle size on selectivity and
16 reaction pathway. *Catal. Sci. Technol.* **2015**, *5* (8), 4154-4163.
- 17 10. Kunkes, E. L.; Studt, F.; Abild-Pedersen, F.; Schlögl, R.; Behrens, M., Hydrogenation of CO₂
18 to methanol and CO on Cu/ZnO/Al₂O₃: Is there a common intermediate or not? *J. Catal.* **2015**, *328*,
19 43-48.
- 20 11. Chen, X.; Su, X.; Duan, H.; Liang, B.; Huang, Y.; Zhang, T., Catalytic performance of the
21 Pt/TiO₂ catalysts in reverse water gas shift reaction: Controlled product selectivity and a mechanism
22 study. *Catal. Today* **2017**, *281*, 312-318.
- 23 12. Hartadi, Y.; Widmann, D.; Behm, R. J., Methanol formation by CO₂ hydrogenation on Au/ZnO
24 catalysts – Effect of total pressure and influence of CO on the reaction characteristics. *J. Catal.* **2016**,
25 *333*, 238-250.
- 26 13. Gaikwad, R.; Bansode, A.; Urakawa, A., High-pressure advantages in stoichiometric
27 hydrogenation of carbon dioxide to methanol. *J. Catal.* **2016**, *343*, 127-132.
- 28 14. Román-Martínez, M. C.; Cazorla-Amorós, D.; Linares-Solano, A.; Salinas-Martínez de Lecea,
29 C., CO₂ hydrogenation under pressure on catalysts Pt · Ca/C. *Appl. Catal., A* **1996**, *134* (1), 159-167.
- 30 15. Kim, S. S.; Park, K. H.; Hong, S. C., A study of the selectivity of the reverse water-gas-shift
31 reaction over Pt/TiO₂ catalysts. *Fuel Process. Technol.* **2013**, *108*, 47-54.
- 32 16. Goguet, A.; Meunier, F. C.; Tibiletti, D.; Breen, J. P.; Burch, R., Spectrokinetic investigation of
33 reverse water-gas-shift reaction intermediates over a Pt/CeO₂ catalyst. *J. Phys. Chem. B* **2004**, *108*
34 (52), 20240-20246.
- 35 17. Gutterød, E. S.; Øien-Ødegaard, S.; Bossers, K.; Nieuwelink, A.-E.; Manzoli, M.; Braglia, L.;
36 Lazzarini, A.; Borfecchia, E.; Ahmadigoltapeh, S.; Bouchevreau, B.; Lønstad-Bleken, B. T.; Henry, R.;
37 Lamberti, C.; Bordiga, S.; Weckhuysen, B. M.; Lillerud, K. P.; Olsbye, U., CO₂ Hydrogenation over Pt-
38 Containing UiO-67 Zr-MOFs—The Base Case. *Ind. Eng. Chem. Res.* **2017**, *56* (45), 13206-13218.
- 39 18. Kattel, S.; Yan, B.; Chen, J. G.; Liu, P., CO₂ hydrogenation on Pt, Pt/SiO₂ and Pt/TiO₂:
40 Importance of synergy between Pt and oxide support. *J. Catal.* **2016**, *343*, 115-126.
- 41 19. Kim, S. S.; Lee, H. H.; Hong, S. C., A study on the effect of support's reducibility on the
42 reverse water-gas shift reaction over Pt catalysts. *Appl. Catal., A* **2012**, *423*, 100-107.
- 43 20. Tibiletti, D.; Goguet, A.; Meunier, F. C.; Breen, J. P.; Burch, R., On the importance of steady-
44 state isotopic techniques for the investigation of the mechanism of the reverse water-gas-shift
45 reaction. *Chem. Commun.* **2004**, (14), 1636-1637.
- 46 21. Jacobs, G.; Davis, B. H., Reverse water-gas shift reaction: steady state isotope switching study
47 of the reverse water-gas shift reaction using in situ DRIFTS and a Pt/ceria catalyst. *Appl. Catal., A*
48 **2005**, *284* (1), 31-38.
- 49 22. Kalamaras, C. M.; Panagiotopoulou, P.; Kondarides, D. I.; Efstathiou, A. M., Kinetic and
50 mechanistic studies of the water-gas shift reaction on Pt/TiO₂ catalyst. *J. Catal.* **2009**, *264* (2), 117-
51 129.

- 1 23. Burch, R.; Goguet, A.; Meunier, F. C., A critical analysis of the experimental evidence for and
2 against a formate mechanism for high activity water-gas shift catalysts. *Appl. Catal., A* **2011**, *409-410*,
3 3-12.
- 4 24. Kalamaras, C. M.; Olympiou, G. G.; Efstathiou, A. M., The water-gas shift reaction on Pt/ γ -
5 Al₂O₃ catalyst: Operando SSITKA-DRIFTS-mass spectroscopy studies. *Catal. Today* **2008**, *138* (3), 228-
6 234.
- 7 25. Ouyang, B.; Xiong, S.; Zhang, Y.; Liu, B.; Li, J., The study of morphology effect of Pt/Co₃O₄
8 catalysts for higher alcohol synthesis from CO₂ hydrogenation. *Appl. Catal., A* **2017**, *543*, 189-195.
- 9 26. Sápi, A.; Rajkumar, T.; Ábel, M.; Efremova, A.; Grósz, A.; Gyuris, A.; Ábrahámné, K. B.;
10 Szent, I.; Kiss, J.; Varga, T.; Kukovecz, Á.; Kónya, Z., Noble-metal-free and Pt nanoparticles-loaded,
11 mesoporous oxides as efficient catalysts for CO₂ hydrogenation and dry reforming with methane. *J.*
12 *CO₂ Util.* **2019**, *32*, 106-118.
- 13 27. Liu, B.; Ouyang, B.; Zhang, Y.; Lv, K.; Li, Q.; Ding, Y.; Li, J., Effects of mesoporous structure
14 and Pt promoter on the activity of Co-based catalysts in low-temperature CO₂ hydrogenation for
15 higher alcohol synthesis. *J. Catal.* **2018**, *366*, 91-97.
- 16 28. Inoue, T.; Iizuka, T., Hydrogenation of carbon dioxide and carbon monoxide over supported
17 platinum catalysts. *J. Chem. Soc., Faraday Trans. 1* **1986**, *82* (6), 1681-1686.
- 18 29. Rungtaweeworanit, B.; Baek, J.; Araujo, J. R.; Archanjo, B. S.; Choi, K. M.; Yaghi, O. M.;
19 Somorjai, G. A., Copper Nanocrystals Encapsulated in Zr-based Metal–Organic Frameworks for Highly
20 Selective CO₂ Hydrogenation to Methanol. *Nano Lett.* **2016**, *16* (12), 7645-7649.
- 21 30. An, B.; Zhang, J.; Cheng, K.; Ji, P.; Wang, C.; Lin, W., Confinement of Ultrasmall Cu/ZnOx
22 Nanoparticles in Metal–Organic Frameworks for Selective Methanol Synthesis from Catalytic
23 Hydrogenation of CO₂. *J. Am. Chem. Soc.* **2017**, *139* (10), 3834-3840.
- 24 31. Lippert, G.; Hutter, J.; Parrinello, M., The Gaussian and augmented-plane-wave density
25 functional method for ab initio molecular dynamics simulations. *Theor. Chem. Acc.* **1999**, *103*, 124-
26 140.
- 27 32. Lippert, G.; Hutter, J.; Parrinello, M., A hybrid Gaussian and plane wave density functional
28 scheme. *Mol. Phys.* **1997**, *92* (3), 477-487.
- 29 33. VandeVondele, J.; Krack, M.; Mohamed, F., Quickstep: Fast and accurate density functional
30 calculations using a mixed Gaussian and plane waves approach. *Comput. Phys. Commun.* **2005**, *167*,
31 103-128.
- 32 34. Group, C. K. D. *CP2K*, version 6.1; 2018.
- 33 35. Hutter, J.; Iannuzzi, M.; Schiffmann, F.; VandeVondele, J., CP2K: atomistic simulations of
34 condensed matter systems. *WIREs Comput. Mol. Sci.* **2014**, *4*, 15-25.
- 35 36. VandeVondele, J.; Hutter, J., Gaussian basis sets for accurate calculations on molecular
36 systems in gas and condensed phases. **2007**, *127* (11), 114105.
- 37 37. Kaur, G.; Øien-Ødegaard, S.; Lazzarini, A.; Chavan, S. M.; Bordiga, S.; Lillerud, K. P.; Olsbye,
38 U., Controlling the Synthesis of Metal–Organic Framework UiO-67 by Tuning Its Kinetic Driving Force.
39 *Cryst. Growth Des.* **2019**, *19* (8), 4246-4251.
- 40 38. Wu, H.; Chua, Y. S.; Krungleviciute, V.; Tyagi, M.; Chen, P.; Yildirim, T.; Zhou, W., Unusual
41 and Highly Tunable Missing-Linker Defects in Zirconium Metal–Organic Framework UiO-66 and Their
42 Important Effects on Gas Adsorption. *J. Am. Chem. Soc.* **2013**, *135* (28), 10525-10532.
- 43 39. Yang, D.; Ortuño, M. A.; Bernales, V.; Cramer, C. J.; Gagliardi, L.; Gates, B. C., Structure and
44 Dynamics of Zr₆O₈ Metal–Organic Framework Node Surfaces Probed with Ethanol Dehydration as a
45 Catalytic Test Reaction. *J. Am. Chem. Soc.* **2018**, *140* (10), 3751-3759.
- 46 40. Shearer, G. C.; Chavan, S.; Bordiga, S.; Svelle, S.; Olsbye, U.; Lillerud, K. P., Defect
47 Engineering: Tuning the Porosity and Composition of the Metal–Organic Framework UiO-66 via
48 Modulated Synthesis. *Chem. Mater.* **2016**, *28* (11), 3749-3761.
- 49 41. Feng, L.; Yuan, S.; Zhang, L.-L.; Tan, K.; Li, J.-L.; Kirchon, A.; Liu, L.-M.; Zhang, P.; Han, Y.;
50 Chabal, Y. J.; Zhou, H.-C., Creating Hierarchical Pores by Controlled Linker Thermolysis in Multivariate
51 Metal–Organic Frameworks. *J. Am. Chem. Soc.* **2018**, *140* (6), 2363-2372.

- 1 42. Shearer, G. C.; Chavan, S.; Ethiraj, J.; Vitillo, J. G.; Svelle, S.; Olsbye, U.; Lamberti, C.;
2 Bordiga, S.; Lillerud, K. P., Tuned to Perfection: Ironing Out the Defects in Metal–Organic Framework
3 UiO-66. *Chem. Mater.* **2014**, *26* (14), 4068-4071.
- 4 43. Shearer, G. C.; Forselv, S.; Chavan, S.; Bordiga, S.; Mathisen, K.; Bjørgen, M.; Svelle, S.;
5 Lillerud, K. P., In Situ Infrared Spectroscopic and Gravimetric Characterisation of the Solvent Removal
6 and Dehydroxylation of the Metal Organic Frameworks UiO-66 and UiO-67. *Top. Catal.* **2013**, *56* (9),
7 770-782.
- 8 44. Trickett, C. A.; Gagnon, K. J.; Lee, S.; Gándara, F.; Bürgi, H.-B.; Yaghi, O. M., Definitive
9 Molecular Level Characterization of Defects in UiO-66 Crystals. *Angew. Chem. Int. Ed* **2015**, *54* (38),
10 11162-11167.
- 11 45. Øien, S.; Wragg, D.; Reinsch, H.; Svelle, S.; Bordiga, S.; Lamberti, C.; Lillerud, K. P., Detailed
12 Structure Analysis of Atomic Positions and Defects in Zirconium Metal–Organic Frameworks. *Cryst.*
13 *Growth Des.* **2014**, *14* (11), 5370-5372.
- 14 46. Braglia, L.; Borfecchia, E.; Lomachenko, K. A.; Bugaev, A. L.; Guda, A. A.; Soldatov, A. V.;
15 Bleken, B. T. L.; Oien, S.; Olsbye, U.; Lillerud, K. P.; Bordiga, S.; Agostini, G.; Manzoli, M.; Lamberti,
16 C., Tuning Pt and Cu sites population inside functionalized UiO-67 MOF by controlling activation
17 conditions. *Faraday Discuss.* **2017**.
- 18 47. Øien, S.; Agostini, G.; Svelle, S.; Borfecchia, E.; Lomachenko, K. A.; Mino, L.; Gallo, E.;
19 Bordiga, S.; Olsbye, U.; Lillerud, K. P.; Lamberti, C., Probing Reactive Platinum Sites in UiO-67
20 Zirconium Metal–Organic Frameworks. *Chem. Mater.* **2015**, *27* (3), 1042-1056.
- 21 48. Braglia, L.; Borfecchia, E.; Martini, A.; Bugaev, A. L.; Soldatov, A. V.; Øien-Ødegaard, S.;
22 Lønstad-Bleken, B. T.; Olsbye, U.; Lillerud, K. P.; Lomachenko, K. A.; Agostini, G.; Manzoli, M.;
23 Lamberti, C., The duality of UiO-67-Pt MOFs: connecting treatment conditions and encapsulated Pt
24 species by operando XAS. *Phys. Chem. Chem. Phys.* **2017**, *19* (40), 27489-27507.
- 25 49. Wang, X.; Shi, H.; Szanyi, J., Controlling selectivities in CO₂ reduction through mechanistic
26 understanding. *Nat. Commun.* **2017**, *8* (1), 513.
- 27 50. Busca, G.; Lamotte, J.; Lavalley, J. C.; Lorenzelli, V., FT-IR study of the adsorption and
28 transformation of formaldehyde on oxide surfaces. *J. Am. Chem. Soc.* **1987**, *109* (17), 5197-5202.
- 29 51. Tibiletti, D.; Meunier, F. C.; Goguet, A.; Reid, D.; Burch, R.; Boaro, M.; Vicario, M.;
30 Trovarelli, A., An investigation of possible mechanisms for the water–gas shift reaction over a ZrO₂-
31 supported Pt catalyst. *J. Catal.* **2006**, *244* (2), 183-191.
- 32 52. Ledesma, C.; Yang, J.; Chen, D.; Holmen, A., Recent Approaches in Mechanistic and Kinetic
33 Studies of Catalytic Reactions Using SSITKA Technique. *ACS Catal.* **2014**, *4* (12), 4527-4547.
- 34 53. Lowry, T. H.; Richardson, K. S., *Mechanism and Theory in Organic Chemistry*. Harper & Row:
35 1987.
- 36 54. Ojeda, M.; Li, A.; Nabar, R.; Nilekar, A. U.; Mavrikakis, M.; Iglesia, E., Kinetically Relevant
37 Steps and H₂/D₂ Isotope Effects in Fischer–Tropsch Synthesis on Fe and Co Catalysts. *J. Phys. Chem. C*
38 **2010**, *114* (46), 19761-19770.
- 39 55. Watson, D. T. P.; Ge, Q.; King, D. A., Facile H–D exchange in adsorbed methylidyne on
40 Pt{110}–(1×2) and deuteration to gaseous methane. *J. Chem. Phys.* **2001**, *115* (24), 11306-11316.
- 41 56. Polanyi, M., Reaction Rates of the Hydrogen Isotopes. *Nature* **1934**, *133*, 26.
- 42 57. Bawn, C. E. H.; Ogden, G., Wave mechanical effects and the reactivity of the hydrogen
43 isotopes. *Trans. Faraday Soc.* **1934**, *30* (0), 432-443.
- 44 58. Shannon, S. L.; Goodwin, J. G., Characterization of Catalytic Surfaces by Isotopic-Transient
45 Kinetics during Steady-State Reaction. *Chem. Rev.* **1995**, *95* (3), 677-695.
- 46 59. Xie, J.; Yang, J.; Dugulan, A. I.; Holmen, A.; Chen, D.; de Jong, K. P.; Louwse, M. J., Size
47 and Promoter Effects in Supported Iron Fischer–Tropsch Catalysts: Insights from Experiment and
48 Theory. *ACS Catal.* **2016**, *6* (5), 3147-3157.

Supporting Information

Hydrogenation of CO₂ to Methanol by Pt Nanoparticles Encapsulated in UiO-67: Deciphering the Role of the MOF

Emil S. Gutterød^a, Andrea Lazzarini^a, Torstein Fjermestad^b, Gurpreet Kaur^a, Maela Manzoli^c, Silvia Bordiga^{a,d}, Stian Svelle^a, Karl P. Lillerud^a, Egill Skúlason^e, Sigurd Øien-Ødegaard^a, Ainara Nova^b,
Unni Olsbye^{a*}

^aCentre for Materials Science and Nanotechnology, Department of Chemistry, University of Oslo, Sem
Saelandsvei 26, N-0315 Oslo, Norway

^bHylleraas Centre for Quantum Molecular Sciences, Department of Chemistry, University of Oslo, P.O. Box
1033, Blindern, N-0315 Oslo, Norway

^cDepartment of Drug Science and Technology and NIS - Centre for Nanostructured Interfaces and Surfaces,
University of Turin, Via P. Giuria 9, Turin 10125, Italy

^dDepartment of Chemistry, NIS Interdepartmental Centre and INSRM reference centre, University of Turin, via
Quarello 15A, I-10135 Turin, Italy

^eScience Institute and Faculty of Industrial Engineering, Mechanical Engineering and Computer Science,
University of Iceland, VR-III, 107 Reykjavik, Iceland

S1. Catalyst Preparation

UiO-67-Pt

Samples of UiO-67-Pt were prepared by the following procedure: 135 g of ZrCl₄ (1 eq.) was added to a 3 l reactor containing 63 ml distilled water (6 eq.) and 2243 ml dimethylformamide (DMF) (50 eq.) held at room temperature on a stirring plate. The solution was heated to 80 °C and 212 g of benzoic acid (3 eq.) was added. When the benzoic acid was completely dissolved, 14 g 2,2'-bipyridine-5,5'-dicarboxylic acid (BPYDC) was added, followed by 126 g 1,1'-biphenyl-4,4'-dicarboxylic acid (BPDC). The resulting solution was heated overnight at 130 °C in a jacketed glass reactor (with stirring) equipped with a reflux condenser. The resulting product was isolated by filtration, washed with hot DMF (500 ml) and acetone (1 l) on the filter, and then dried at 150 °C in air overnight.

The MOF was then impregnated with K₂PtCl₄ (Sigma-Aldrich) in DMF at 100 °C overnight (with stirring) (details in ref. ¹). This procedure leads to the formation of well-defined BPYDC-PtCl₂

1 sites.¹ The amount K_2PtCl_4 used for the impregnation corresponded to a 2:1 BPYDC:Pt molar ratio
2 and 2.7 wt % Pt in the final material.

3

4 **Pt on Al_2O_3 , SiO_2 and C**

5 Pre-reduced 5 % Pt/ Al_2O_3 and 5 % Pt/C were provided by Chimet.

6 Pre-reduced 5 % Pt/ SiO_2 (Escat 2351) was purchased from abcr.

7

8 **Characterization**

9 The crystallinity and porosity of the prepared material, both before and after Pt-
10 functionalization, was determined by powder X-ray diffraction (XRD) (Bruker D8 Discover, Cu α ,
11 Lynx Eye silicon detector) and N_2 adsorption at 77 K (BELSORP mini-II), respectively.

12

13 The relative amounts of organic species capping the Zr-cluster were determined using solution
14 state proton nuclear magnetic resonance (1H -NMR) after dissolving the sample in NaOD/ D_2O .¹

15 Thermogravimetric analysis was performed on a Netzsch STA 449 F3-Jupiter instrument.
16 Approximately 20 mg of sample was heated (in an Al_2O_3 sample holder) from 30 to 800 °C (5 °C/min)
17 in flow of 5 ml/min O_2 and 20 ml/min of N_2 . The platinum particle size distribution was determined by
18 TEM (Jeol 3010-UHR), counting more than 1000 particles, and the accessible Pt surface was
19 quantified by CO pulse chemisorption.¹

20

21 The Pt/Zr ratio was estimated from energy-dispersive X-ray (EDX) analysis using a Hitachi
22 SU8230 field emission scanning electron microscope (FESEM) with an XFlash 6|10 EDX detector.
23 Powder samples of UiO-67-Pt was sputter coated with gold prior to the analysis. The average Pt/Zr
24 ratio was 0.042 ± 0.002 . Combining this with the results from TGA and 1H -NMR (*vide infra*), the wt
25 % is estimated from the stoichiometric formula $Zr_6O_4(OH)_4BPDC_{4.52}BPYDC_{0.54}BA_{0.6}FA_{0.09}Pt_{0.25}$,
26 where BA and FA is benzoate and formate, respectively.

27

28 Prior to TEM, CO-pulse chemisorption the MOF samples were reduced for 4 hours at 350°C
29 (5 °C/min ramp) in 20 ml/(min·0.1g_{cat}) flow of 10 % H_2 /Ar under ambient pressure, then cooled to
30 room temperature in inert flow (20 ml/min Ar).

31 The turnover frequency (TOF) of a catalyst is defined as the number of reactant molecules
32 converted to products over one active catalyst site per second. The number of exposed (active) Pt
33 surface sites (N_{APt}) for each catalyst was calculated by two methods; the first method was based on
34 CO pulse chemisorption experiments, assuming a CO_{ads} :Pt ratio of 1:1. The second method was based
35 on the average Pt nanoparticle (NP) size determined from TEM measurements. In this case, all
36 exposed Pt atoms on the NP surface were considered active sites, and it was assumed that all Pt was

1 reduced and present in the form of Pt NPs. Furthermore, it was assumed that the Pt NPs were
 2 spherical; in good agreement with the TEM images:

3 $V_{\text{Pt}}(\text{NP}) = 4/3 \cdot \pi \cdot (d/2)^3$ (volume of a Pt NP with diameter $d = D$) (1)

4 $m_{\text{Pt}}(\text{NP}) = \rho_{\text{Pt}} \cdot V_{\text{Pt}}(\text{NP})$ (mass of Pt per NP. ρ_{Pt} is the bulk density of Pt metal) (2)

5 $N_{\text{Pt}}(\text{NP}) = n_{\text{Pt}}(\text{NP}) \cdot N_A$ (nr. of Pt atoms in one NP. $n_{\text{Pt}}(\text{NP})$ is mol Pt in one NP, N_A is Avogadro's number) (3)

6 Calculations 1–3 are repeated for a particle with diameter $d = D - 2 \cdot d_{\text{Pt,atom}}$, where $d_{\text{Pt,atom}}$ is the
 7 diameter of a Pt atom.

8 The number of surface Pt atoms in a Pt NP with diameter $d = D$ is given by

9 $N_{\text{surf,Pt}}(\text{NP}) = N_{\text{Pt}}(\text{NP}, d = D) - N_{\text{Pt}}(\text{NP}, d = D - 2 \cdot d_{\text{Pt,atom}})$ (4)

10 The total mol Pt surface atoms per gram catalyst is given by

11 $N_{\text{surf,Pt}} = N_{\text{surf,Pt}}(\text{NP}) / N_A \cdot m_{\text{Pt}} / (M m_{\text{Pt}} \cdot n_{\text{Pt}}(\text{NP}))$ ($M m_{\text{Pt}}$ is Pt molar mass, m_{Pt} is mass of Pt per g catalyst) (5)

12 The TOF of each catalyst after a given time on stream (TOS) was calculated using the following
 13 formula:

14 $\text{TOF (s}^{-1}\text{)} = (C_{\text{CO}_2}/100\%) \cdot \text{Flow}_{\text{CO}_2} \cdot N_A / N_{\text{surf,Pt}}$ (6)

15 where C_{CO_2} is the CO₂ conversion (in %) and $\text{Flow}_{\text{CO}_2}$ is the CO₂ flow over the catalyst (mol/s).

16 Table S1. List of m/z values traced for reactants and products during H/D and ¹³CO₂/¹²CO₂ exchange
 17 experiments.

Species	m/z values traced	
	H/D	¹³ CO ₂ / ¹² CO ₂
Methanol	<u>31</u> , 33, <u>34</u> , 35, 36	34, 35
Methane	15	21
Water	18, 19	-
CO	28	28,29
Hydrogen	2, 3	4
CO ₂	44	44,45

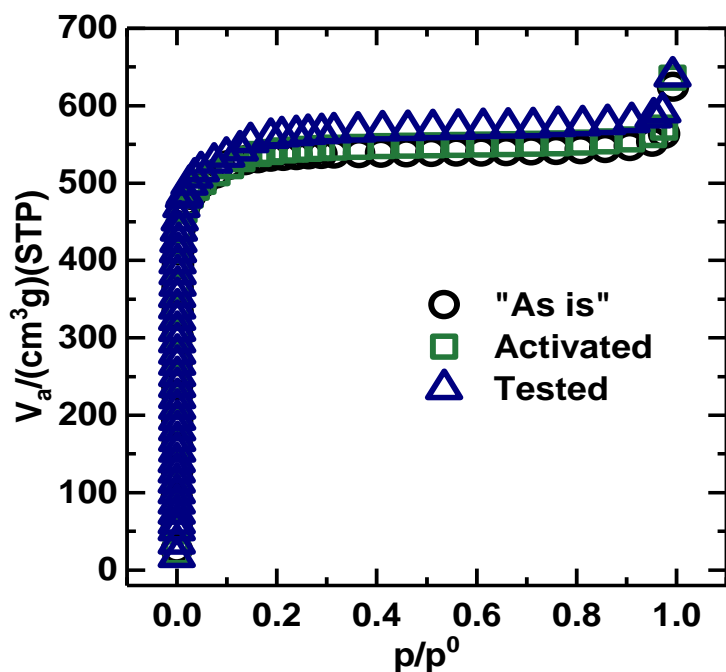
18

19

20

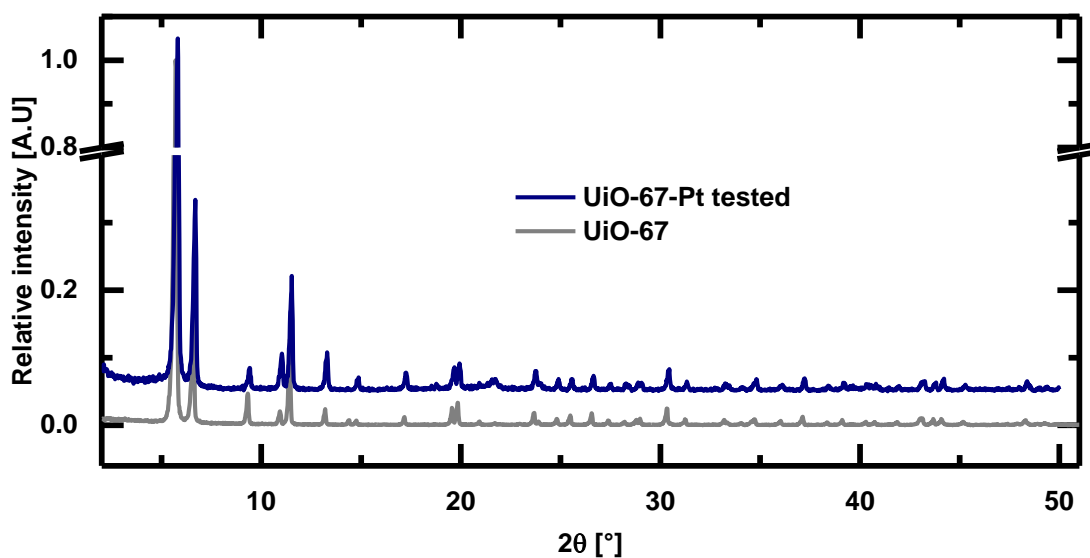
21

1 S2. Characterization
2 N₂ adsorption



3
4 Figure S1. N₂ Adsorption isotherms of UiO-67-Pt after synthesis (black circles), after activation at
5 350°C in 10% H₂ (green squares) and after testing for CO₂ hydrogenation under various conditions for
6 >20 days (mostly at 170°C) (blue triangles). BET specific surface areas are calculated to 2089, 2104
7 and 2161 m²/g, for the three samples, respectively.

8
9 Powder X-ray Diffraction (pXRD)



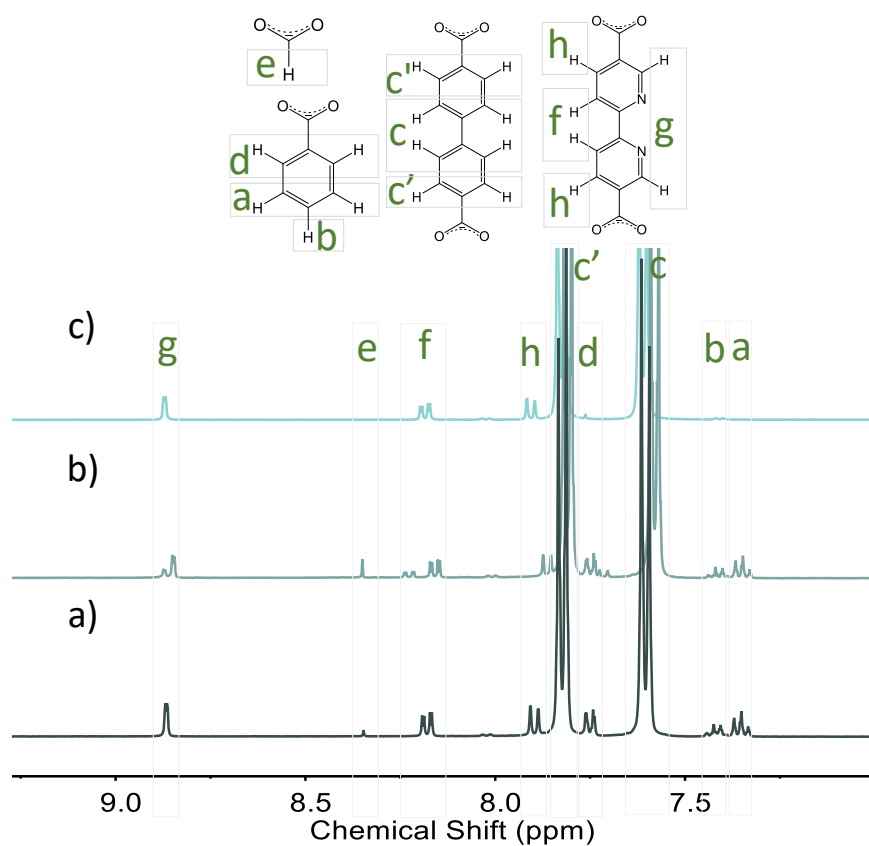
10
11 Figure S2. XRD patterns of UiO-67 (grey, bottom) after synthesis and UiO-67-Pt (blue, top) after
12 testing.

1 **Solution state $^1\text{H-NMR}$**

2 Table S2. Solution state $^1\text{H-NMR}$ data of UiO-67 (a) and UiO-67-Pt before (b) and after testing(c).
 3 The amounts are given as percent with respect to BPDC.

Entry	Sample	BPYDC (w.r.t BPDC)	Benzoic acid (w.r.t BPDC)	Formic acid (w.r.t BPDC)
a	UiO-67	11	12.5	2
b	UiO-67 -Pt	9.7	10.8	3.9
c	UiO-67 -Pt after testing	9.6	3.4	0

4



5

6 Figure S3. $^1\text{H-NMR}$ spectra of a) UiO-67, b) UiO-67-Pt and c) UiO-67-Pt after testing

7

8

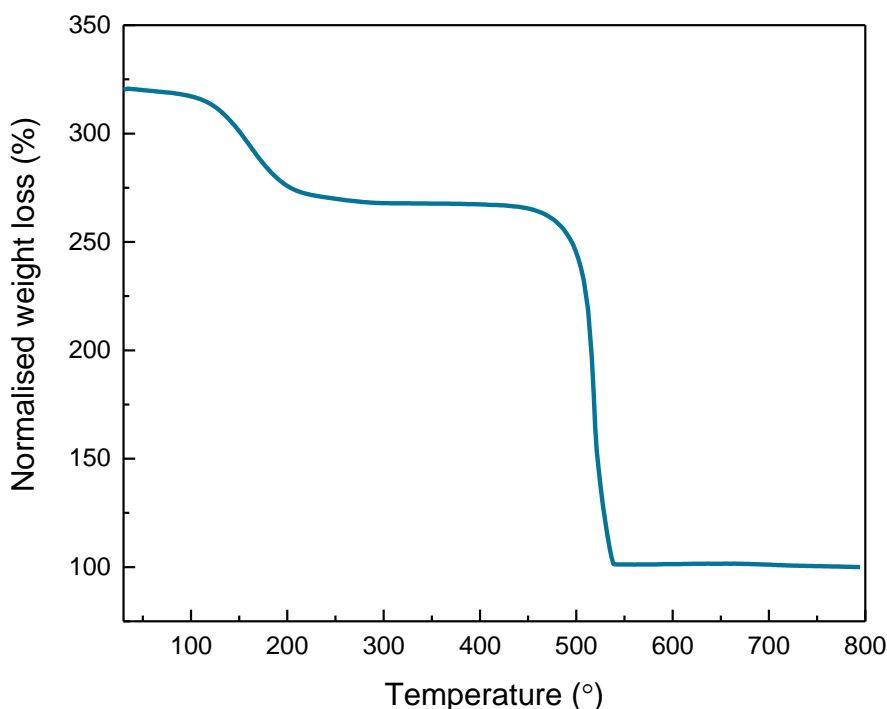
9

10

11

12

1 Thermogravimetric analysis (TGA)



2
3 Figure S4. Thermogravimetric analysis of UiO-67 (30 to 800 °C with the ramp rate of 5 °C/min in a
4 mixture of 5 ml/min O₂ and 20 ml/min of N₂).

5 Table S3. Defectivity of UiO-67-BPYDC estimated from solution state ¹H-NMR and TGA. BPDC:Zr
6 cluster (node) = 6 in the perfect UiO-67 system.

MOF	Wt % _{400 °C}	BPDC: node	BPYDC: node	BA: node	FA: Zr node
UiO-67	267	4.52	0.54	0.60	0.09

10 Transmission electron microscopy (TEM)

11 Transmission electron microscopy (TEM) and high resolution TEM (HR-TEM) measurements
12 were performed using a side entry Jeol JEM 3010 (300 kV) microscope equipped with a LaB₆ filament
13 and fitted with X-ray EDS analysis by a Link ISIS 200 detector. For analyses, the powdered samples
14 were deposited on a copper grid, coated with a porous carbon film. All digital micrographs were
15 acquired using an Ultrascan 1000 camera and the images were processed by Gatan digital micrograph.
16 A statistically representative number of particles was counted in order to obtain the Pt particle size
17 distributions. The mean particle diameter (d_m) was calculated as follows: $d_m = \sum d_i n_i / \sum n_i$, where n_i was
18 the number of particles of diameter d_i . The measurements were carried out on UiO-67-Pt after
19 activation at 4 hours at 350 °C in 20 ml/(min·0.1g_{cat}) 10 % H₂/Ar (Figure S5) and after 6 days of

1 testing at 170 °C and 240 °C (Figure S6). It is worth noting that the UiO-67-Pt samples proved to be
2 stable to prolonged exposition under the electron beam of the instrument, in terms of UiO-67
3 crystallinity as well as Pt NPs size (no metal coalescence).

4

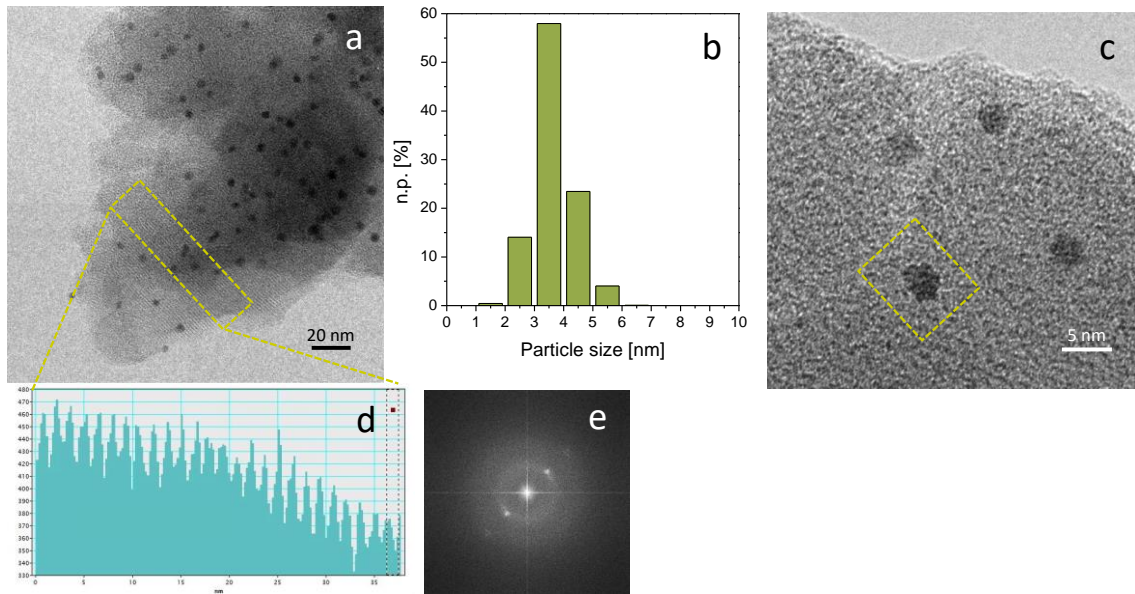
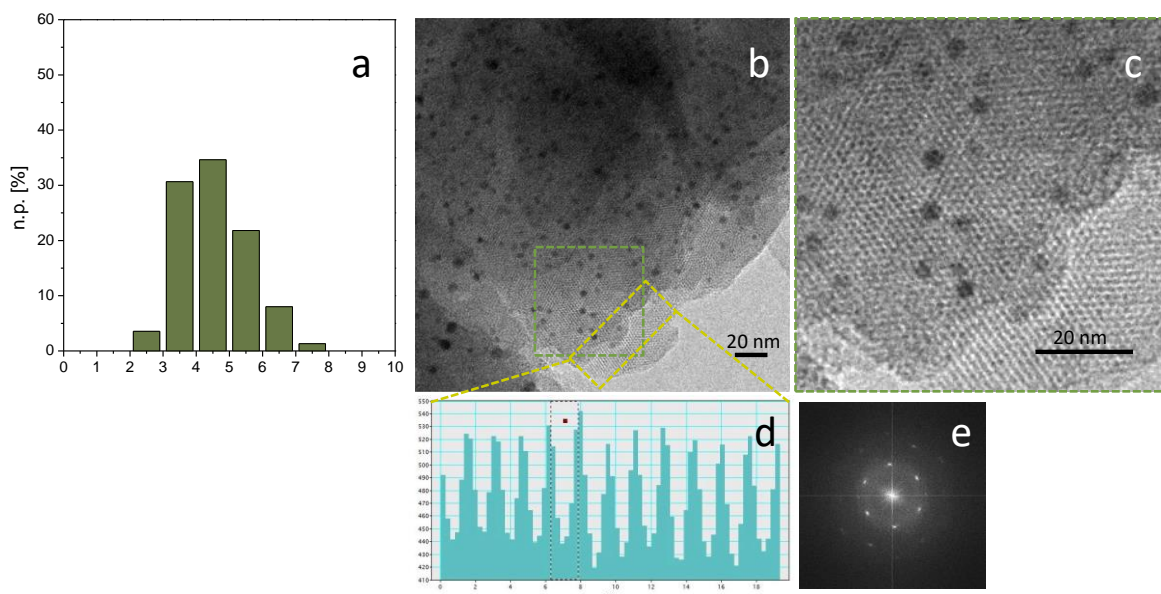


Figure S5. a) HRTEM of UiO-67-Pt after activation for 4 hours at 350°C in 20 ml/(minx0.1g_{cat}) 10% H₂/Ar. b) Pt NP size distribution (more than 1000 NPs were counted) ($d_m = 3.6 \pm 0.7$ nm). c) High magnification HRTEM image of Pt NPs. d) Measure of the spacing between the diffraction fringes observed in the zone highlighted by the green box in a). e) Fourier Transform of the image in a). Instrumental magnification: 100000× and 300000×, respectively.

5

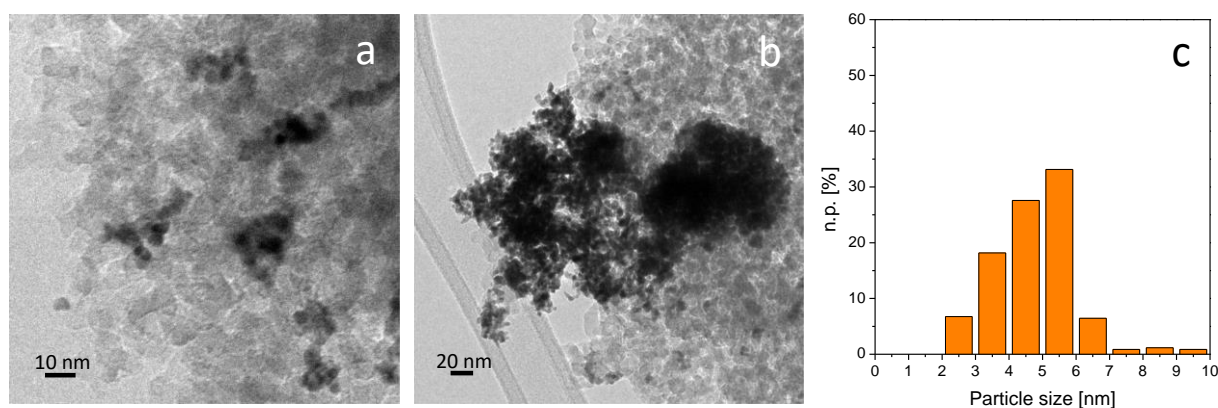
6 Pt NPs were observed mainly as large particle agglomerates on 5% Pt/SiO₂, pointing out poor
7 stabilization of the NPs on the SiO₂ support. Despite this feature, the particle size distribution was
8 built and an average size of 5.0 ± 2.0 nm was estimated (Figure S7) (the images have been taken on
9 several different regions of the grid).

10



1
 2 Figure S6. a) Pt NP size distribution of UiO-67-Pt after activation for 4 hours at 350 °C in 20
 3 ml/(min·0.1g_{cat}) 10% H₂/Ar and 6 days of testing at 170 °C and 240 °C (about 1000 NPs were
 4 counted) ($d_m = 4.5 \pm 1.0$ nm). b) HRTEM image of the catalyst. c) Zoom of the region highlighted
 5 by a green square in the HRTEM image reported in b) in which the Pt NPs are supported on UiO-67
 6 viewed along the [111] direction. d) Measure of the spacing between the diffraction fringes observed
 7 in the zone highlighted by the light green box in b). e) Fourier Transform of the image in b).
 8 Instrumental magnification: 80000×.

9
 10



11
 12 Figure S7. a) TEM image of 5%Pt/SiO₂. b) TEM image of a big agglomerate of Pt NPs. c) Pt NP size
 13 distribution (about 400 NPs were counted). Instrumental magnification: 150000× and 50000×,
 14 respectively.

15
 16
 17

1 Activation of UiO-67-Pt

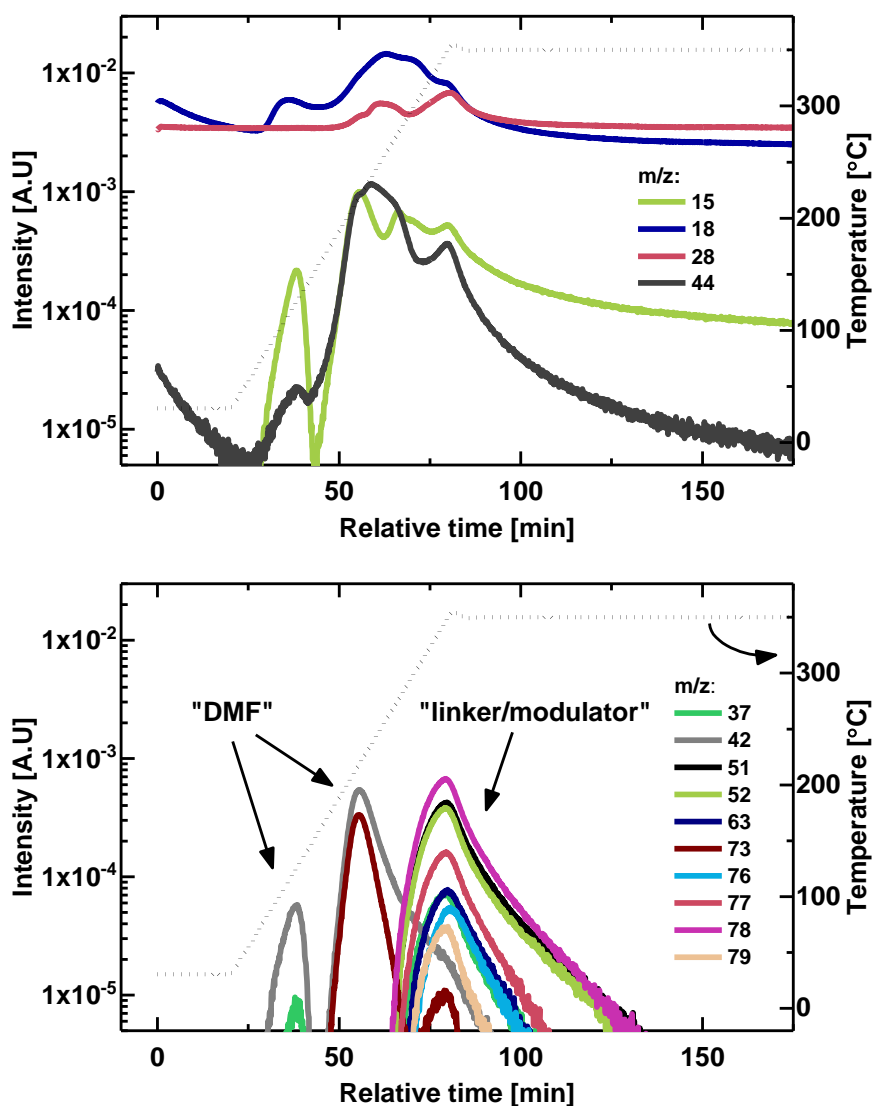


Figure S8. On-line MS signals during activation on UiO-67-Pt. Conditions: 5 °C/min ramp to 350°C (4 h dwell) in 20 ml/(min·0.1g_{cat}) flow of 10 % H₂/Ar. “DMF” indicates the signal-peaks presumably related to DMF and DMF-derived species. “linker/modulator” indicates the signal-peak presumably related to linker and modulator species. During a 2nd activation, no significant signals of “DMF” and “linker/modulator” type were observed.

2

3 S3. Catalytic Testing

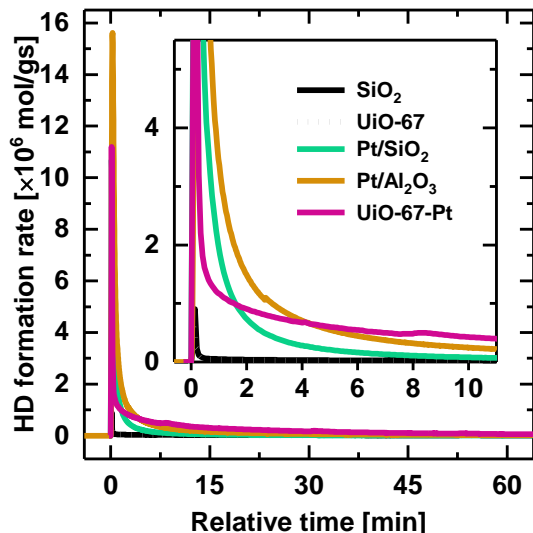
4 Methanol turn-over-frequency (TOF) over UiO-67-Pt and Pt/Al₂O₃

5 **UiO-67-Pt:** The CH₃OH TOF of 0.01 s⁻¹ reported in-text is calculated from the methanol rate
6 of formation (1.62×10⁻⁸ mol/(s·g_{cat})) and the number of exposed Pt surface atoms determined by CO-
7 chemisorption at RT (1.7 μmol/g_{cat}) (Figure 1 and Table 1). Conditions: τ = 0.01 g_{cat}·min/ml, 8 bar,
8 170 °C, CO₂/H₂/inert = 1/6/3.

1 **Pt/Al₂O₃**: CH₃OH TOF = 0.0001 s⁻¹, rate = 3.55×10⁻⁹ mol/(s·g_{cat}), N_{A,CO,RT} = 36 μmol/g_{cat}
 2 (Figure 1 and Table 1). Conditions: τ = 0.02 g_{cat}·min/ml, 8 bar, 170 °C, CO₂/H₂/inert = 1/6/3.

3

4 **H/D exchange during CO₂ hydrogenation over different Pt/support combinations**

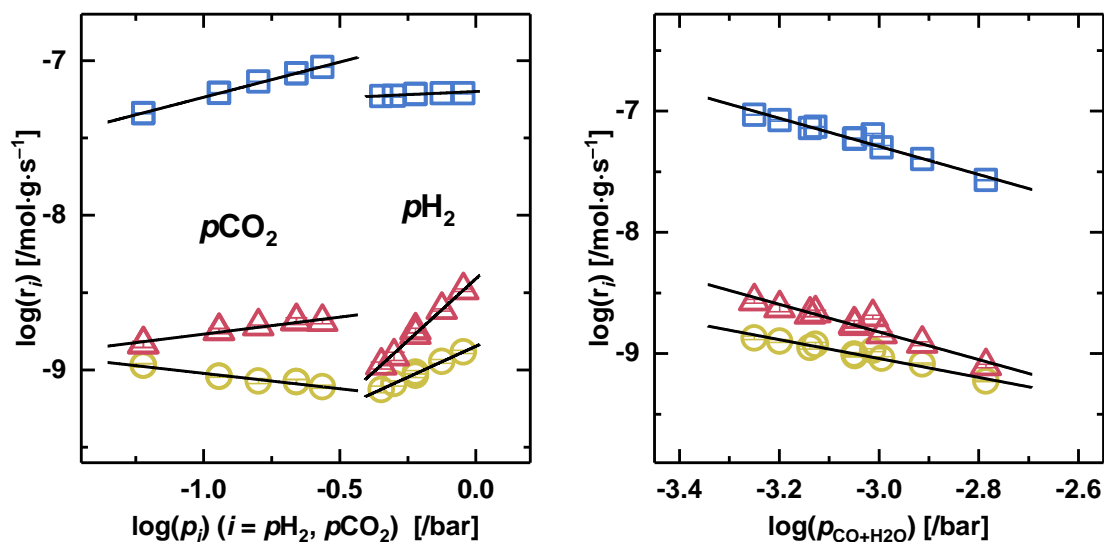


5

6 Figure S9. The HD formation rate after switching from H₂+CO₂ to D₂+CO₂ over UiO-67-Pt, Pt/Al₂O₃,
 7 Pt/SiO₂, UiO-67 and SiO₂. T = 170 °C and P = 1 bar.

8

9 **Kinetic investigation: partial pressure and contact time variation**



10
11

12 Figure S10. **Left**: pCO₂ (left) and pH₂ (right) partial pressure dependency at 170 °C (1 bar) of CO
 13 (squares), CH₄ (circles) and CH₃OH (triangles). pH₂ = 0.6 and pCO₂ = 0.1 when pCO₂ and pH₂ is
 14 varied, respectively. **Right**: CO+H₂O partial pressure dependence of CO, CH₄ and CH₃OH formation

1 rates. The CO+ H₂O partial pressure is as half the measured effluent CO and H₂O outlet concentrations
2 during contact time variation (see Figure 5). The experiment is performed at 170 °C, 1 bar, 1/6/3
3 CO₂/H₂/He and $\tau = 0.004\text{--}0.04 \text{ g}_{\text{cat}} \cdot \text{min}/\text{ml}$.

4

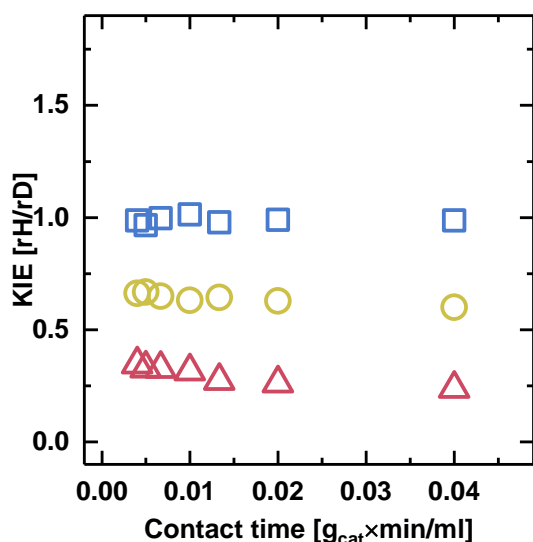
5 Table S4 Reaction orders in pH₂ and pCO₂, prior to p(CO+H₂O) correction, for the rate of conversion
6 (X) and CO, CH₄ and CH₃OH formation at 170 °C (P_{tot} = 1 bar) over UiO-67-Pt. pCO₂ = 0.1 and pH₂

p_i	X	CO	CH₄	CH₃OH
H ₂	0.1	0.1	0.8	1.6
CO ₂	0.5	0.5	-0.2	0.2

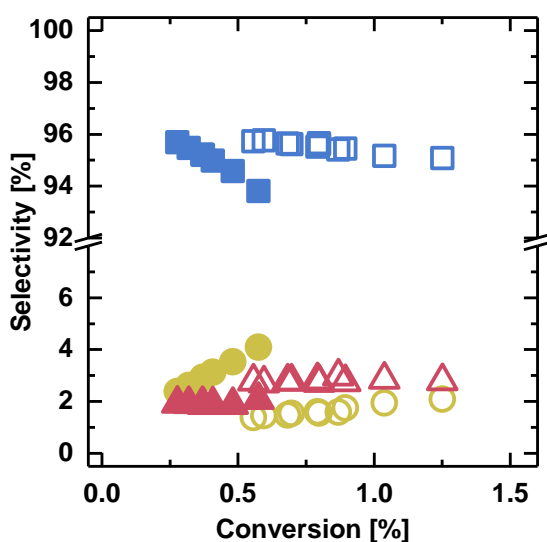
7 = 0.6 when varying pH₂ and pCO₂, respectively.

8

9 The reaction orders in total pressure, pH₂, pCO₂ and p(CO+H₂O) for CO, CH₄ and CH₃OH
10 formation over UiO-67-Pt are listed in Table 2 and Table S4. The influence of total pressure is
11 negligible on the rate of CO formation and minor on the rate CH₄ formation, as evident from the zero
12 and 0.3 order in total pressure, respectively. The reaction order in total pressure is, in contrast,
13 substantially larger (first order) for the rate of methanol formation, suggesting that reactant coverage is
14 a limiting factor in the reaction. In our previous work on UiO-67-Pt,¹ we reported a 0.3 and 0.5 order
15 in pH₂ and pCO₂, respectively, for the rate of CO formation at 240–260 °C. At 170°C, the order in pH₂
16 is even smaller (0.1), while it is unchanged in pCO₂ (Fig. 2). The marginal order in pH₂ suggests that
17 the availability of hydrogen is not critical in the rate-limiting step (RLS) of the RWGS reaction. For
18 the formation of CH₄ and CH₃OH on the other hand, the partial pressure of H₂ is vital compared to
19 CO. The surprisingly large 1.6 order in pH₂ for CH₃OH formation points toward the accessibility of H₂
20 as strongly rate limiting. For CH₄ and CH₃OH formation, a negative and positive 0.2 order in pCO₂ is
21 observed for the two products respectively. A negative order in pCO₂ clearly suggests that the
22 inhibition effect by a species formed with increasing pCO₂ is greater than the positive effect of
23 increase pCO₂ alone.²



1
 2 Figure S11. Isotope effect, r_H/r_D , for CO (squares), CH₄ (circles) and CH₃OH (triangles) during CO₂
 3 hydrogenation at 170 °C, 1 bar, 1/6/3 CO₂/H₂/He and $\tau = 0.004 - 0.04$

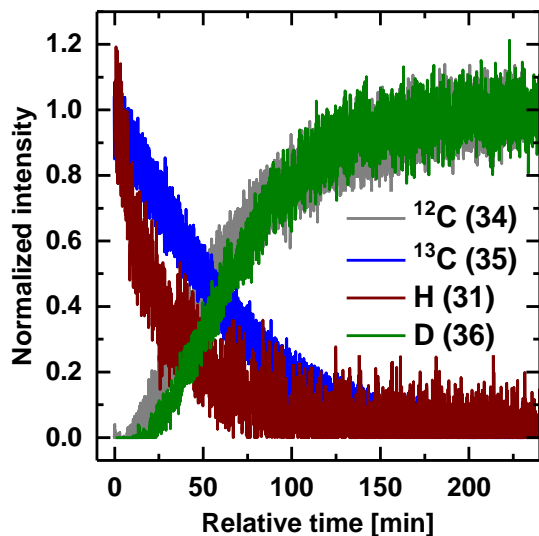


4
 5 Figure S12. Contact time variation experiment during CO₂ hydrogenation at 170 °C, 1 bar, 1/6/3
 6 CO₂/H₂/He and $\tau = 0.004 - 0.04$ g_{cat} · min/ml. CO (squares), CH₄ (circles) and CH₃OH (triangles)
 7 selectivity versus conversion over UiO-67-Pt (open) and Pt/Al₂O₃ (filled).

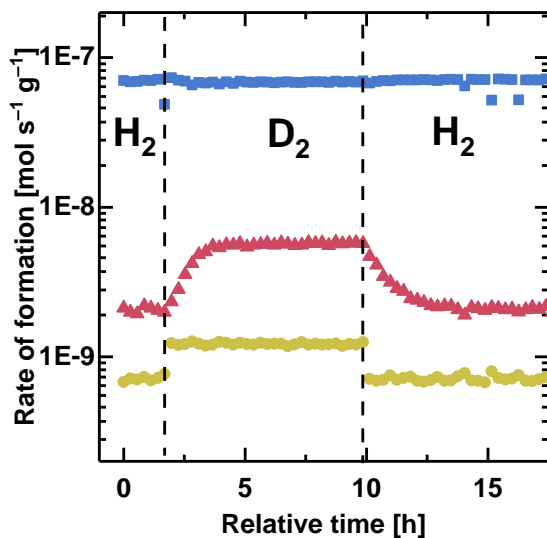
8
 9 **H/D and ¹³CO₂/¹²CO₂ SSITKA and H/D isotope effects**

10 The transient evolution of 13-labeled CO₂, inert Kr and products when switching from ¹³CO₂ +
 11 D₂ to ¹²CO₂ + D₂ at t = 0 is shown in Figure 3. Both Kr and ¹³CO₂ decreased rapidly to zero,
 12 suggesting little gas-holdup in the reactor and a weak interaction between the catalyst and CO₂.³ The

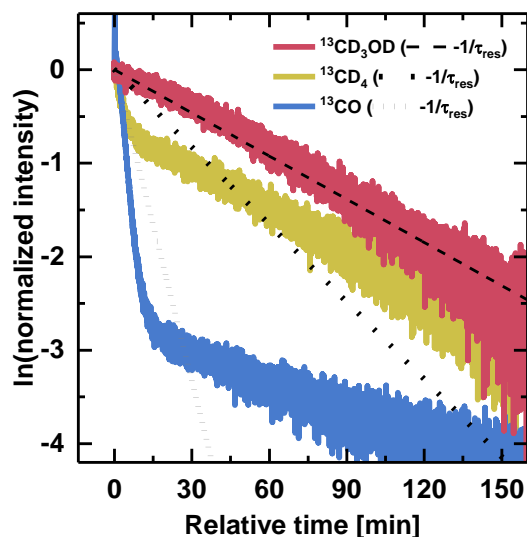
1 normalized intensities of the ^{13}C -labelled products decreased much slower than the inert and CO_2
2 responses.



4 Figure S13. Comparison of methanol during $^{13}\text{CO}_2/^{12}\text{CO}_2$ exchange ($m/z = 35/34$) and during H/D
5 exchange ($m/z = 31/36$).



7 Figure S14. H/D SSITKA during CO_2 hydrogenation at $170\text{ }^\circ\text{C}$, 1bar. Rate of CO (blue squares),
8 methane (yellow circles) and methanol (red triangles) formation over UiO-67-Pt versus time when
9 switching between H_2+CO_2 and D_2+CO_2 in intervals of 8 hours. The rate of methane and methanol is
10 the sum of all isotopologs.



1
 2 Figure S15. Semi-logarithmic plot of the normalized transient responses of ^{13}CO ($m/z = 29$), $^{13}\text{CD}_4$
 3 ($m/z = 21$) and $^{13}\text{CD}_3\text{OD}$ ($m/z = 35$) products when switching from $^{13}\text{CO}_2 + \text{D}_2$ to $^{12}\text{CO}_2 + \text{D}_2$ at $t = 0$. T
 4 $= 170$ °C, 1bar, $\tau = 0.01$ $\text{g}_{\text{cat}} \cdot \text{min}/\text{ml}$. Lines with slopes inversely proportional to the mean surface
 5 residence time ($-1/\tau_{\text{res}}$) of the respective products are included.

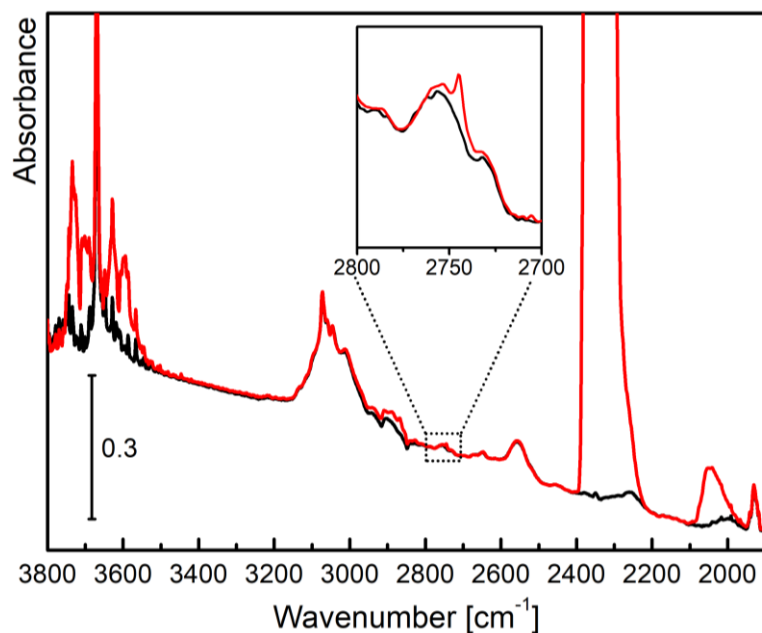
6
 Table S5. Isotope effect ($r_{\text{H}}/r_{\text{D}}$) at full isotope equilibration, on the rate of CO, CH₄ and CH₃OH
 formation at 170 °C (1 bar).

Catalyst	CO	CH ₄	CH ₃ OH
UiO-67-Pt	1.03	0.58	0.36
Pt/Al ₂ O ₃	1.07	0.47	0.40
Cu/ZnO/Al ₂ O ₃ ⁴	0.86 ^a	-	0.57 ^a

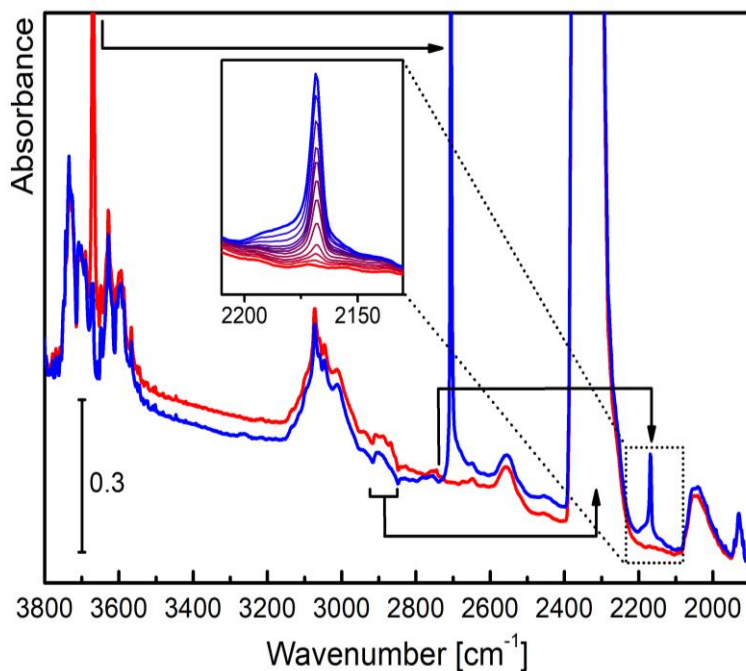
^a230 °C, 30 bar.

1 S4. Operando FTIR

2



3

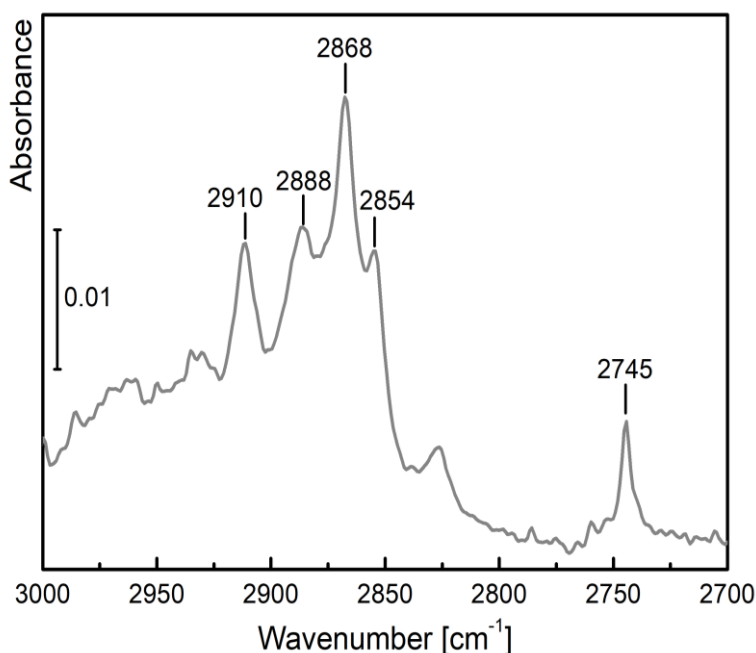


4

5 Figure S16. Top: FT-IR spectra of UiO-67-Pt collected during CO₂ hydrogenation (CO₂/H₂ = 1/6, 10
6 ml/min, 170 °C, 1 bar) at different times (thick black curve for t=0 min, thick red curve for t = 120
7 min). The inset is a reminder of what is shown in Figure 2 in the main text. Bottom: FT-IR spectra of
8 UiO-67-Pt experiencing the effect of H/D isotopic exchange during CO₂ hydrogenation
9 (CO₂/H₂(D₂)=1/6, 10 ml/min, 170 °C, 1 bar). Red line represents the catalyst after 120 min in
10 hydrogenation conditions and the blue represents the catalyst 120 min after the switch to deuteration

1 conditions. The inset shows a magnification of the $\nu(\text{C-D})$ stretching of deuterated formates bound to
2 Zr nodes in the UiO-67 framework (time evolution from red to blue curve).

3 Figure S16 compares the FT-IR spectra of UiO-67-Pt sample right after the activation
4 procedure (black) with the one collected after 120 min in reaction conditions ($\text{CO}_2:\text{H}_2=1:6$, 10 ml/min,
5 $170\text{ }^\circ\text{C}$, 1 bar - red curve). The spectra coincide in most of the intervals, hereafter shortly described: i)
6 $\nu(\text{O-H})$ stretching region, in which both spectra are characterized by the sharp peak at 3670 cm^{-1}
7 related to the $\text{Zr-}\mu_3\text{OH}$ at the cornerstones.^{5,6} In case of the spectrum collected in CO_2 flux, the roto-
8 vibrational overtones of the gaseous phase are very intense and overshadow the spectrum in that
9 region; ii) $\nu(\text{C-H}_{\text{arom}})$ stretching, belonging to the biphenyl and bipyridine type linkers are arising in
10 $3200\text{--}3000\text{ cm}^{-1}$ interval.^{5,6} Only in case of the sample treated in CO_2/H_2 , a very strong signal centred
11 at 2340 cm^{-1} is due to the roto-vibrational profile of gaseous CO_2 . Moreover, a broad signal between
12 2100 and 1950 cm^{-1} can be easily associated to carbon monoxide, linearly chemisorbed on metal
13 nanoparticles (in end-on configuration).¹ Weak bands are observed in the region $2700\text{--}3000\text{ cm}^{-1}$ and
14 have been assigned to various combination modes of C-H from formate groups. A more complete
15 view of the vibrational features of formate is reported in the spectrum reported in Figure S17. Among
16 these signals, 2745 cm^{-1} is assigned to the bidentate coordinated formate groups on the cornerstones of
17 the MOF lacking a connection with a linker or with the modulator (benzoic acid).⁷⁻⁹



18
19 Figure S17. FT-IR spectrum highlighting the formate groups region for UiO-67-Pt. The spectrum
20 represent the sample during CO_2 hydrogenation ($\text{CO}_2/\text{H}_2 = 1/6$, 10 ml/min, $170\text{ }^\circ\text{C}$, 1 bar) after the
21 subtraction of the activated sample (10% H_2 at $350\text{ }^\circ\text{C}$ for 4 h).

1 **S5. Computational Details**

2 **Energy calculations and geometry optimizations**

3 The potential energy of the various structures was computed by periodic DFT calculations.
4 The mixed Gaussian and plane wave method (GPW),¹⁰⁻¹² as implemented in CP2K, version 6.1^{13, 14}
5 was used; the functional being PBE+D3^{15, 16} with the Gaussian basis set DZVP-MOLOPT-SR-GTH.¹⁷
6 The core electrons were represented by norm-conserving, separable dual-space GTH-PBE small core
7 pseudopotentials.^{18, 19} The Gaussian basis functions were mapped onto a multigrid of size 5. The
8 cutoffs of the five grids were determined by the kinetic energy cut-off of the plane wave basis of 360
9 Ry and the grid level progression factor of 3. A relative cut-off of 60 Ry determined onto which of the
10 five grids a given Gaussian function should be mapped. The parameter EPS_DEFAULT was set to
11 $1.0 \cdot 10^{-10}$, and the Brillouin zone was sampled at the gamma point.

12 For systems with band gap, such as the pure UiO-67-BPYDC, the reactant and product
13 molecules, the efficient orbital transformation (OT) method²⁰ was used. The OT minimizer was the
14 direct inversion in the iterative subspace (DIIS), and the preconditioner was FULL_ALL with an
15 energy gap of 0.001 a.u.

16 For metallic systems, i.e. UiO-67-BPYDC with Pt nanoparticle, the orbital transformation is
17 inefficient. For these systems, we resorted to computing the energy through a traditional
18 diagonalization algorithm. The lower efficiency of this algorithm was counteracted by the use of the
19 efficient ELPA library.²¹ The orbital occupation numbers were “smeared” according to the Fermi-
20 Dirac distribution using an electronic temperature of 100 K. A Broyden mixing was employed with the
21 following parameters: alpha = 0.1, beta = 1.5, nbroyden = 8. The default value of the SCF
22 convergence criteria ($1.0 \cdot 10^{-5}$ a.u.) was used. The chosen Gaussian and plane wave basis set were
23 based on values used in previous works²² as well as our own convergence test (see Table S6). The
24 convergence test consisted in checking how the relative energies of three isomers of Pt₅₅@UiO-67-
25 BPYDC, primitive unit cell, changed upon increasing the kinetic energy cutoff. We deemed a kinetic
26 energy cutoff of 360 Ry and a relative cutoff of 60 Ry to correspond to a converged potential energy.

27 Table S6. Convergence test of the kinetic energy cutoff, $E^{\text{kin}}(\text{cutoff})$. Values of $E^{\text{kin}}(\text{cutoff})$ in the range
28 from 360 to 660 Ry and values of 60 and 80 Ry of the relative cutoff, REL_CUTOFF were tested.
29 Energies, ΔE_{rel} , (in kJ/mol) are relative to **IS1**.

IS2	REL_CUTOFF = 60 Ry	REL_CUTOFF = 80
	$\Delta E_{\text{rel}} / \text{kJ/mol}$	Ry $\Delta E_{\text{rel}} / \text{kJ/mol}$
$E_{\text{kin}}(\text{cutoff}) / \text{Ry}$		
360	-98.00	-98.00
420	-97.37	-97.37
480	-97.53	-97.53
500	-97.53	-97.53

540	-97.69	-97.69
600	-97.64	-97.64
660	-97.66	-97.65
IS3		
$E_{\text{kin}}(\text{cutoff}) / \text{Ry}$	$\Delta E_{\text{rel}} / \text{kJ/mol}$	$\Delta E_{\text{rel}} / \text{kJ/mol}$
360	35.06	35.07
420	35.15	35.15
480	35.86	35.86
500	35.86	35.86
540	35.58	35.58
600	35.55	35.55
660	35.57	35.57

1

2 For optimizations of the atomic coordinates, the BFGS optimizer was used. The geometries
3 were considered converged when the maximum and RMS gradients and the maximum and RMS
4 displacements were below $4.5 \cdot 10^{-4}$ and $3.0 \cdot 10^{-4}$ Ha Bohr⁻¹ and $3.0 \cdot 10^{-3}$ and $1.5 \cdot 10^{-3}$ Bohr, respectively.

5 For the combined optimization of atomic coordinates and cell parameters, the kinetic energy
6 cut-off was increased to 720 Ry. The BFGS optimizer was used, and the convergence criteria on the
7 gradients and the displacements were the same as for the geometry optimizations. The external
8 pressure was 1 bar and the pressure tolerance was set to 10 bar.

9 Computation of free energy

10 The free energy was computed to assess the stability of the materials as well as the gas phase
11 species. For the materials, we use two approximations to the free energy. For adsorbed intermediates,
12 we included only the vibrational contribution to the free energy. A numerical partial Hessian was
13 computed involving only the atoms of the adsorbates. A central difference method was used and the
14 atoms were displaced 0.015 Å in positive and negative direction along the x, y, and z coordinates.

15 When computing the reaction free energy of the formation of $\text{Pt}_{55}^{\text{tet}}$ and $\text{Pt}_{89}^{\text{tet}}$, $\Delta G_{\text{r}}(\text{Pt}_{55}^{\text{tet}})$ and
16 $\Delta G_{\text{r}}(\text{Pt}_{89}^{\text{tet}})$, respectively, we included for the materials both the vibrational and configurational
17 contributions. In the computation of the numerical partial Hessian, we included all Pt atoms of the
18 nanoparticle + the linkers defining the tetrahedral cage. For the structures without nanoparticles, the
19 atoms of the linkers defining the tetrahedral cage were included.

20 The change in the configurational contribution to the reaction free energy, ΔG_{config} , was
21 computed from the change in the configurational entropy as

$$1 \quad \Delta G_{\text{config}} = -T \cdot \Delta S_{\text{config}}$$

2 where $T = 623$ K is the temperature of the catalyst activation. ΔS_{config} is the change in configurational
3 entropy from the start to the end of the reaction

$$4 \quad \Delta S_{\text{config}} = S_{\text{config,end}} - S_{\text{config,start}}$$

$$\Delta S_{\text{config}} = kT \ln W$$

5 where W is the number of microstates. In these systems, we count the number of microstates as the
6 product of the number of ways of distributing the nanoparticle (NP) and the number of ways of
7 distributing the BPYDC linker. There are eight tetrahedral cages per unit cell, and the NP can be
8 distributed in $\binom{8 \cdot N_{\text{cells}}}{N_{\text{NP}}}$ ways, where N_{cells} is the number of unit cells involved in the reaction (see
9 Figure S19). Furthermore, there are 24 linkers per unit cell, and the BPYDC linker can be distributed
10 in $\binom{24 \cdot N_{\text{cells}}}{1 \cdot N_{\text{cells}}}$ ways. The number of microstates is therefore

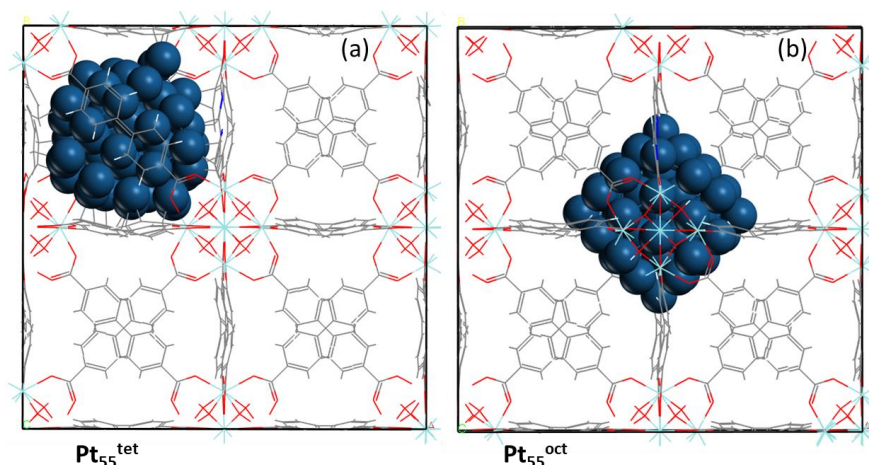
$$W = \binom{8 \cdot N_{\text{cells}}}{N_{\text{NP}}} \cdot \binom{24 \cdot N_{\text{cells}}}{1 \cdot N_{\text{cells}}}$$

11 The configurational contribution to the free energy, ΔG_{config} , is then for $\text{Pt}_{55}^{\text{tet}}$ and $\text{Pt}_{89}^{\text{tet}}$,
12 $\Delta G_{\text{config,Pt}_{55}^{\text{tet}}} = -32$ kJ/mol and $\Delta G_{\text{config,Pt}_{89}^{\text{tet}}} = -34$ kJ/mol

13 For gas phase species, H_2 and CO_2 , all atoms were included in the computation of the
14 numerical Hessian. Their rotation and translations also contribute to the free energies were computed
15 analytically based on the partition functions for an ideal gas. For convenience, Gaussian 16²³ was used
16 to compute these contributions. The ideal gas approximation was employed in the computation of the
17 PV term, $PV = nRT$, where $n = 1$ and $R = 8.31446$ J/(K·mol). The temperature of the free energy
18 calculations was set to $T = 443$ K for the catalytic reactions and to $T = 623$ K for the catalyst
19 activation.

20 Selection of the model system

21 Preliminary computations were carried out to find where in the UiO-67-BPYDC lattice the Pt
22 nanoparticle (NP) preferred to be located. A cuboctahedral Pt_{55} NP was placed in the octahedral,
23 $\text{Pt}_{55}^{\text{oct}}$, and tetrahedral cage, $\text{Pt}_{55}^{\text{tet}}$, respectively (see Figure S18), and the energy of the optimized
24 structures shows a clear preference for the tetrahedral cage. We rationalize this preference by the
25 larger amount of Pt-linker interactions in that structure; and we can generalize this result by noting that
26 the NP in $\text{Pt}_{55}^{\text{tet}}$ fills the tetrahedral cage to a larger degree than the NP in $\text{Pt}_{55}^{\text{oct}}$ fills the octahedral
27 cage. Thus, for a NP of a given size, its preferred location will be in a cage it is able to fill to a larger
28 degree and thus maximize the amount of Pt-linker interactions.

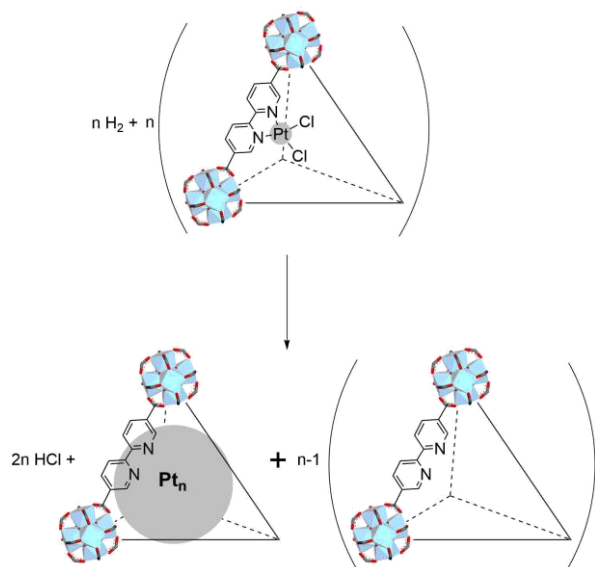


1
 2 Figure S18. Computed structures of embedded Pt₅₅ in UiO-67-BPYDC. (a) Pt₅₅ located in the
 3 tetrahedral cage, **Pt₅₅^{tet}**, $\Delta E = 0$ kJ/mol. (b) Pt₅₅ located in the octahedral cage, **Pt₅₅^{oct}**, $\Delta E = 1111$
 4 kJ/mol.

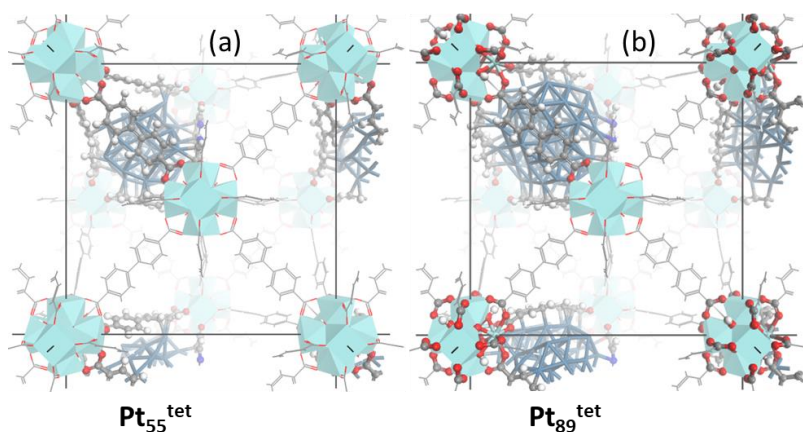
5 We then explore how favorable the growth would be of the Pt-NP in the tetrahedral cage. To
 6 better understand the thermodynamics of the Pt NP growth, the reaction free energy, ΔG_r , of forming
 7 **Pt₅₅^{tet}**, **Pt₆₃^{tet}**, **Pt₇₁^{tet}** and **Pt₈₉^{tet}** from the starting compound PtCl₂ was computed (see Figure S19 for a
 8 schematic illustration). The reaction free energy of the four NPs, $\Delta G_r(\mathbf{Pt}_{55}^{\text{tet}}) = -68$ kJ/mol, $\Delta G_r(\mathbf{Pt}_{63}^{\text{tet}})$
 9 $= -215$ kJ/mol, $\Delta G_r(\mathbf{Pt}_{71}^{\text{tet}}) = -246$ kJ/mol and $\Delta G_r(\mathbf{Pt}_{89}^{\text{tet}}) = -989$ kJ/mol (**Pt₅₅^{tet}** and **Pt₈₉^{tet}** are shown
 10 in Figure S20) shows that the energy decrease as the NP grows. Furthermore, a linear regression ($R^2 =$
 11 0.95) shows that this decrease is linear (coefficient = -30 kJ/(mol · N_{Pt}) with respect to the number of Pt
 12 atoms added. A plot with the data points and the trend line is shown in Figure S21. The addition of
 13 further Pt atoms was not attempted because the linear trend was already apparent from the four data
 14 points. Therefore, we proceed with the study on the formate formation from the **Pt₈₉^{tet}** system because
 15 it was the most stable structure.

16 In addition, we observed that at this size, the decooordination of one of the oxygen of the
 17 linkers became exergonic by 54 kJ/mol, while the complete decooordination is endergonic by 15 kJ/mol
 18 (L^1 and L^0 , in Figure 4). These results indicate that the displacement of the linker could be overcome
 19 by increasing the Pt NP.

20
 21
 22



1
2 Figure S19. Schematic representation of the formation of Pt NP from PtCl₂ linkers under a reducing H₂
3 atmosphere.

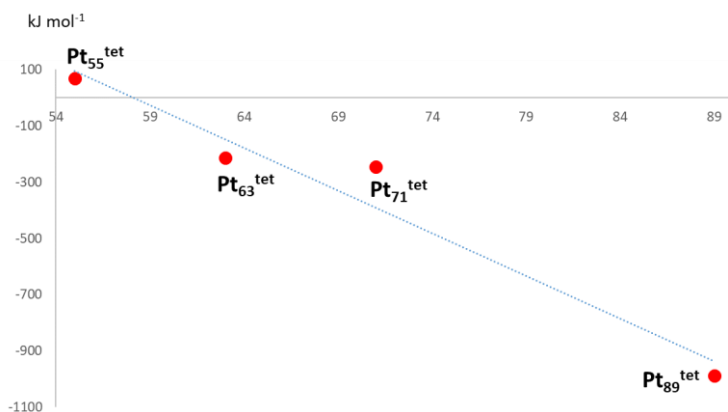


4
5 Figure S20. Optimized structures of (a) Pt₅₅^{tet}, $\Delta G_r(\text{Pt}_{55}^{\text{tet}}) = -68$ kJ/mol and (b) Pt₈₉^{tet}, $\Delta G_r(\text{Pt}_{89}^{\text{tet}}) = -$
6 989 kJ/mol.

7
8
9
10
11
12
13
14

1 Handling of small imaginary frequencies

2



3

4 Figure S21. Reaction free energy, ΔG_r , (in kJ/mol) of Pt_n^{tet} for $n = 55, 63, 71, 89$, as a function of
5 number of Pt atoms, n .

6 For the BPYDC and BPYDC- PtCl_2 structures shown in Figure S21, the initial frequency
7 calculation resulted in small imaginary frequencies. For the BPYDC structure, the initial attempt
8 resulted in an imaginary frequency of $3.2i \text{ cm}^{-1}$. A re-optimization, and a subsequent frequency
9 calculation, with EPS_SCF decreased to $1.0 \cdot 10^{-6}$ a.u. resulted in real frequencies only, with the
10 smallest one being 15.0 cm^{-1} . At 623 K, a frequency of 15.0 cm^{-1} contributes -17 kJ/mol to the free
11 energy. Decreasing EPS_SCF to $1.0 \cdot 10^{-6}$ a.u. increased the total energy by 1 kJ/mol.

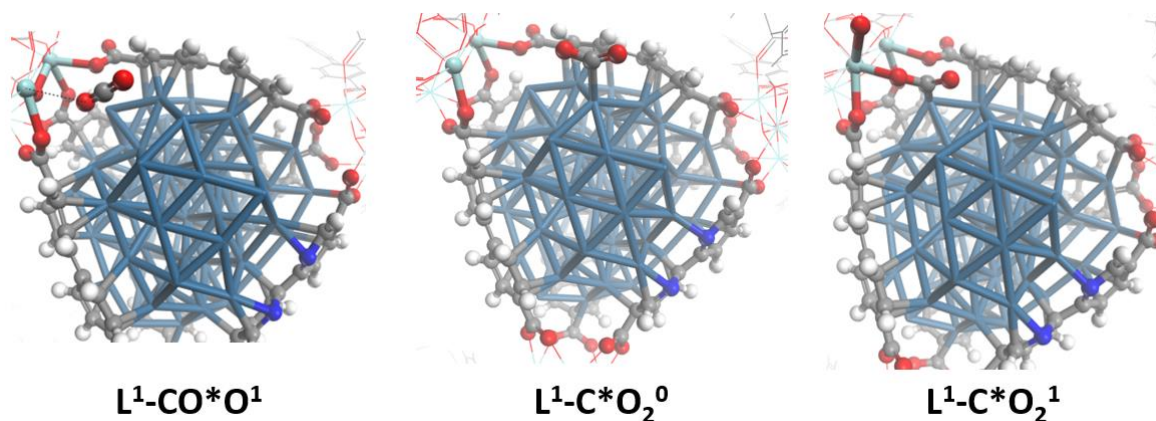
12 For the BPYDC- PtCl_2 structure, the initial frequency calculation resulted in three imaginary
13 frequencies, $14.4i$, $8.6i$, and $3.7i \text{ cm}^{-1}$. A re-optimization, and subsequent frequency calculation, with
14 EPS_SCF decreased to $1.0 \cdot 10^{-6}$ a.u. reduced the number of imaginary frequencies to one, $12.1i \text{ cm}^{-1}$.
15 This imaginary frequency had the same value even after decreasing EPS_SCF to $1.0 \cdot 10^{-9}$ a.u. We
16 therefore deemed $\text{EPS_SCF} = 1.0 \cdot 10^{-6}$ a.u. to give sufficiently accurate frequencies. Continuing from
17 the frequency calculation computed with $\text{EPS_SCF} = 1.0 \cdot 10^{-6}$ a.u., the structure was displaced in the
18 negative direction along the eigenmode corresponding to the imaginary frequency and re-optimized
19 with a subsequent frequency calculation. This re-optimization resulted in real frequencies only, the
20 smallest one being 6.5 cm^{-1} . In the reaction free energies of Pt_n^{tet} , the free energy of BPYDC- PtCl_2 is
21 multiplied by n (See Figure S21). Getting rid of all imaginary frequencies is therefore vital in order to
22 avoid substantial errors in the computation of the reaction free energy.

23

24 Preferred CO_2 coordination in $\text{Pt}_{89}^{\text{tet}}$

25 The formation of formate from L^1 complex (see Figure 4) involves the adsorption of a CO_2
26 molecule. Three modes of adsorption were checked (see Figure S22): i) coordination of the O atom to

1 the opened Zr-site, $L^1\text{-CO}^*\text{O}^1$, $\Delta G(\text{Pt}_{89}^{\text{tet}} + \text{CO}_2 \rightarrow L^1\text{-CO}^*\text{O}^1) = -6$ kJ/mol, ii) coordination of the C
 2 atom to the Pt surface, $L^1\text{-C}^*\text{O}_2^0$, $\Delta G(\text{Pt}_{89}^{\text{tet}} + \text{CO}_2 \rightarrow L^1\text{-C}^*\text{O}_2^0) = -30$ kJ/mol, and iii) coordination of
 3 the C atom to the Pt surface and the O atom to the opened Zr-site, $L^1\text{-C}^*\text{O}_2^1$, $\Delta G(\text{Pt}_{89}^{\text{tet}} + \text{CO}_2 \rightarrow L^1\text{-}$
 4 $\text{C}^*\text{O}_2^1) = -74$ kJ/mol. Of these only $L^1\text{-C}^*\text{O}_2^1$ corresponds to an exergonic free energy of adsorption,
 5 $\Delta G_{\text{ads}}(\text{Pt}_{89}^{\text{tet}}\text{-I} + \text{CO}_2 \rightarrow L^1\text{-C}^*\text{O}_2^1) = -20$ kJ/mol. Because $L^1\text{-C}^*\text{O}_2^1$ corresponds to the most favorable
 6 mode of CO_2 adsorption, the formate formation pathway was continued from that structure (see Figure
 7 4).
 8

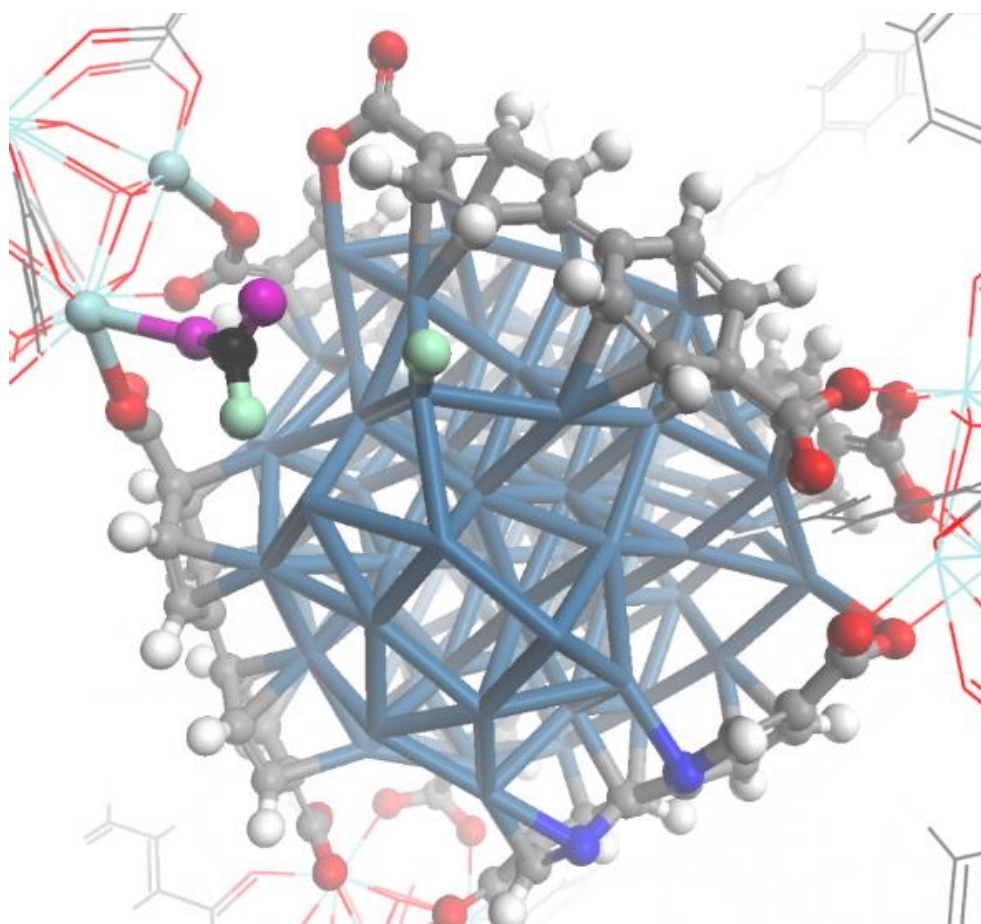


9
 10 Figure S22. Three modes of CO_2 adsorption to $\text{Pt}_{89}^{\text{tet}}\text{-I}$. $L^1\text{-CO}^*\text{O}^1$, $\Delta G(\text{Pt}_{89}^{\text{tet}} + \text{CO}_2 \rightarrow L^1\text{-CO}^*\text{O}^1) =$
 11 -6 kJ/mol, $L^1\text{-C}^*\text{O}_2^0$, $\Delta G(\text{Pt}_{89}^{\text{tet}} + \text{CO}_2 \rightarrow L^1\text{-C}^*\text{O}_2^0) = -30$ kJ/mol, $L^1\text{-C}^*\text{O}_2^1$, $\Delta G(\text{Pt}_{89}^{\text{tet}} + \text{CO}_2 \rightarrow L^1\text{-}$
 12 $\text{C}^*\text{O}_2^1) = -74$ kJ/mol.

13

14 Computational experiment

15 Structure $L^0\text{-HCO}_2^1 + \text{H}^*$ resulting from orienting the formate moiety of $L^0\text{-HCO}_2^2 + \text{H}^*$ to a Zr-
 16 monodentate configuration is shown in Figure S23.



1
 2 Figure S23. Structure $L^0\text{-HCO}_2^1+\text{H}^*$ resulting from orienting the formate moiety of $L^0\text{-HCO}_2^2+\text{H}^*$ to a
 3 Zr-monodentate configuration. Color code: H = white, C = grey, O = red, N = blue, Zr = cyan, Pt =
 4 dark blue. Color code, reacting species: H = light green, C = black O = purple.

5 References

- 6 1. Gutterød, E. S.; Øien-Ødegaard, S.; Bossers, K.; Nieuwelink, A.-E.; Manzoli, M.; Braglia, L.;
 7 Lazzarini, A.; Borfecchia, E.; Ahmadigoltapeh, S.; Bouchevreau, B.; Lønstad-Bleken, B. T.; Henry, R.;
 8 Lamberti, C.; Bordiga, S.; Weckhuysen, B. M.; Lillerud, K. P.; Olsbye, U., CO₂ Hydrogenation over Pt-
 9 Containing UiO-67 Zr-MOFs—The Base Case. *Ind. Eng. Chem. Res.* **2017**, *56* (45), 13206-13218.
- 10 2. Wang, X.; Shi, H.; Kwak, J. H.; Szanyi, J., Mechanism of CO₂ Hydrogenation on Pd/Al₂O₃
 11 Catalysts: Kinetics and Transient DRIFTS-MS Studies. *ACS Catal.* **2015**, *5* (11), 6337-6349.
- 12 3. Wang, X.; Shi, H.; Szanyi, J., Controlling selectivities in CO₂ reduction through mechanistic
 13 understanding. *Nat. Commun.* **2017**, *8* (1), 513.
- 14 4. Kunkes, E. L.; Studt, F.; Abild-Pedersen, F.; Schlögl, R.; Behrens, M., Hydrogenation of CO₂
 15 to methanol and CO on Cu/ZnO/Al₂O₃: Is there a common intermediate or not? *J. Catal.* **2015**, *328*,
 16 43-48.
- 17 5. Chavan, S.; Vitillo, J. G.; Gianolio, D.; Zavorotynska, O.; Civalleri, B.; Jakobsen, S.; Nilsen,
 18 M. H.; Valenzano, L.; Lamberti, C.; Lillerud, K. P.; Bordiga, S., H₂storage in isostructural UiO-67 and
 19 UiO-66 MOFs. *Phys. Chem. Chem. Phys.* **2012**, *14* (5), 1614-1626.
- 20 6. Kandiah, M.; Usseglio, S.; Svelle, S.; Olsbye, U.; Lillerud, K. P.; Tilset, M., Post-synthetic
 21 modification of the metal-organic framework compound UiO-66. *J. Mater. Chem.* **2010**, *20* (44),
 22 9848-9851.
- 23 7. Yang, D.; Ortuño, M. A.; Bernales, V.; Cramer, C. J.; Gagliardi, L.; Gates, B. C., Structure and
 24 Dynamics of Zr₆O₈ Metal-Organic Framework Node Surfaces Probed with Ethanol Dehydration as a
 25 Catalytic Test Reaction. *J. Am. Chem. Soc.* **2018**, *140* (10), 3751-3759.

- 1 8. Tibiletti, D.; Meunier, F. C.; Goguet, A.; Reid, D.; Burch, R.; Boaro, M.; Vicario, M.;
2 Trovarelli, A., An investigation of possible mechanisms for the water–gas shift reaction over a ZrO₂-
3 supported Pt catalyst. *J. Catal.* **2006**, *244* (2), 183-191.
- 4 9. Busca, G.; Lamotte, J.; Lavalley, J. C.; Lorenzelli, V., FT-IR study of the adsorption and
5 transformation of formaldehyde on oxide surfaces. *J. Am. Chem. Soc.* **1987**, *109* (17), 5197-5202.
- 6 10. Lippert, G.; Hutter, J.; Parrinello, M., The Gaussian and augmented-plane-wave density
7 functional method for ab initio molecular dynamics simulations. *Theor. Chem. Acc.* **1999**, *103*, 124-
8 140.
- 9 11. Lippert, G.; Hutter, J.; Parrinello, M., A hybrid Gaussian and plane wave density functional
10 scheme. *Mol. Phys.* **1997**, *92* (3), 477-487.
- 11 12. VandeVondele, J.; Krack, M.; Mohamed, F., Quickstep: Fast and accurate density functional
12 calculations using a mixed Gaussian and plane waves approach. *Comput. Phys. Commun.* **2005**, *167*,
13 103-128.
- 14 13. Group, C. K. D. *CP2K*, version 6.1; 2018.
- 15 14. Hutter, J.; Iannuzzi, M.; Schiffmann, F.; VandeVondele, J., CP2K: atomistic simulations of
16 condensed matter systems. *WIREs Comput. Mol. Sci.* **2014**, *4*, 15-25.
- 17 15. Grimme, S.; Antony, J.; Ehrlich, S.; Krieg, H., A consistent and accurate ab initio
18 parametrization of density functional dispersion correction (DFT-D) for the 94 elements H-Pu. *J.*
19 *Chem. Phys.* **2010**, *132*, 154104.
- 20 16. Grimme, S.; Ehrlich, S.; Goerigk, L., Effect of the damping function in dispersion corrected
21 density functional theory. *J. Comput. Chem.* **2011**, *32*, 1456-1465.
- 22 17. VandeVondele, J.; Hutter, J., Gaussian basis sets for accurate calculations on molecular
23 systems in gas and condensed phases. **2007**, *127* (11), 114105.
- 24 18. Hartwigsen, C.; Goedecker, S.; Hutter, J., Relativistic separable dual-space Gaussian
25 pseudopotentials from H to Rn. *Phys. Rev. B* **1998**, *58* (7), 3641-3662.
- 26 19. Goedecker, S.; Teter, M.; Hutter, J., Separable dual-space Gaussian pseudopotentials. *Phys.*
27 *Rev. B* **1996**, *54*, 1703-1710.
- 28 20. VandeVondele, J.; Hutter, J., An efficient orbital transformation method for electronic
29 structure calculations. *J. Chem. Phys.* **2003**, *118* (10), 4365-4369.
- 30 21. Marek, A.; Blum, V.; Johanni, R.; Havu, V.; Lang, B.; Auckenthaler, T.; Heinecke, A.;
31 Bungartz, H. J.; Lederer, H., The ELPA library: scalable parallel eigenvalue solutions for electronic
32 structure theory and computational science. *J. Phys.: Condens. Matter* **2014**, *26* (21), 213201.
- 33 22. Ye, J.; Johnson, K. J., Design of Lewis Pair-Functionalized Metal Organic Frameworks for CO₂
34 Hydrogenation. *ACS Catal.* **2015**, *5*, 2921-2928.
- 35 23. Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.;
36 Scalmani, G.; Barone, V.; Petersson, G. A.; Nakatsuji, H.; Li, X.; Caricato, M.; Marenich, A. V.;
37 Bloino, J.; Janesko, B. G.; Gomperts, R.; Mennucci, B.; Hratchian, H. P.; Ortiz, J. V.; Izmaylov, A. F.;
38 Sonnenberg, J. L.; Williams; Ding, F.; Lipparini, F.; Egidi, F.; Goings, J.; Peng, B.; Petrone, A.;
39 Henderson, T.; Ranasinghe, D.; Zakrzewski, V. G.; Gao, J.; Rega, N.; Zheng, G.; Liang, W.; Hada, M.;
40 Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.;
41 Nakai, H.; Vreven, T.; Throssell, K.; Montgomery Jr., J. A.; Peralta, J. E.; Ogliaro, F.; Bearpark, M. J.;
42 Heyd, J. J.; Brothers, E. N.; Kudin, K. N.; Staroverov, V. N.; Keith, T. A.; Kobayashi, R.; Normand, J.;
43 Raghavachari, K.; Rendell, A. P.; Burant, J. C.; Iyengar, S. S.; Tomasi, J.; Cossi, M.; Millam, J. M.;
44 Klene, M.; Adamo, C.; Cammi, R.; Ochterski, J. W.; Martin, R. L.; Morokuma, K.; Farkas, O.;
45 Foresman, J. B.; Fox, D. J. *Gaussian 16 Rev. C.01*, Wallingford, CT, 2016.

46