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# Carbon dioxide–sulphur hexafluoride adsorption and separation with zirconium metal–organic frameworks bearing basic and fluorinated linkers

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This study describes the synthesis and characterization of two novel zirconium-based mixed-linker metal–organic frameworks (MIXMOFs) of the UiO-6x family (**fcu** topology) containing basic and fluorinated linkers together in the same lattice: **Zr\_TFA\_NH<sub>2</sub>**, built with 2-aminoterephthalic acid (H<sub>2</sub>BDC-NH<sub>2</sub>) and trifluoroacetic acid (HTFA) with minimal formula [Zr<sub>6</sub>O<sub>4</sub>(OH)<sub>4</sub>(TFA)<sub>4.2</sub>(BDC-NH<sub>2</sub>)<sub>3.9</sub>] and **Zr\_TFA\_PyPy**, containing 2,2'-bipyridyl-4,4'-dicarboxylic acid (H<sub>2</sub>PyPy) and HTFA with minimal formula [Zr<sub>6</sub>O<sub>4</sub>(OH)<sub>4</sub>(TFA)<sub>1.8</sub>(PyPy)<sub>5.1</sub>]. The linkers are cheap and commercially available; they were selected to control pore size and functional group distribution: H<sub>2</sub>BDC-NH<sub>2</sub> is a short linker and provides UiO-66-like smaller pores, while H<sub>2</sub>PyPy is a longer linker and generates larger UiO-67-like pores. TFA<sup>−</sup> acts both as modulator and fluorinated functional group source. The two MIXMOFs have been exploited for the adsorption and separation of carbon dioxide (CO<sub>2</sub>) and sulfur hexafluoride (SF<sub>6</sub>), two potent greenhouse gases. Isothermic heats of CO<sub>2</sub> adsorption (Q<sub>st</sub>) are higher than those found in their non-fluorinated analogues, proving the synergistic adsorption enhancement from combining basic and fluorinated linkers in the same solid. SF<sub>6</sub>/CO<sub>2</sub> selectivity values derived from competitive adsorption experiments of equimolar mixtures at ambient temperature and pressure indicated that **Zr\_TFA\_NH<sub>2</sub>** is more efficient than **Zr\_TFA\_PyPy** in separating the two gases. Density functional theory (DFT) calculations were performed to identify primary adsorption sites and estimate binding energies; the calculated adsorption energies agree well with the experimental Q<sub>st</sub> values.

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## 1. Introduction

Air pollution is a critical environmental challenge, with greenhouse gases playing a major role in climate change. The last 30th United Nations Climate Change Conference (COP30) held in Belém (Brazil) in November 2025<sup>1</sup> addressed various climate-related issues, including those pertaining to greenhouse gases. Addressing air pollution necessitates a multifaceted approach, combining technological innovation, robust policy frameworks

and international collaboration. The outcomes of COP30 underscore the global commitment against climate change and the reduction of greenhouse gas emissions. Among these gases, carbon dioxide (CO<sub>2</sub>) and sulfur hexafluoride (SF<sub>6</sub>) are of particular concern due to their significant global warming potential. CO<sub>2</sub> is the primary greenhouse gas emitted by human activities, mainly from the combustion of fossil fuels such as coal, oil and natural gas. It is a key driver of global warming, as it traps heat in the Earth's atmosphere, leading to rising temperatures, extreme weather events and ecosystem disruptions. Efforts to mitigate CO<sub>2</sub> emissions focus on transitioning to renewable energy sources, improving energy efficiency, and developing carbon capture and storage technologies.<sup>2</sup> SF<sub>6</sub> is a synthetic gas widely used in the electrical industry for its excellent insulating properties in high-voltage equipment. However, SF<sub>6</sub> has an extremely high global warming potential (approximately 23 500 times that of CO<sub>2</sub> over a 100-year period) and can persist in the atmosphere for thousands of years. Despite its relatively low emission levels compared to CO<sub>2</sub>, its

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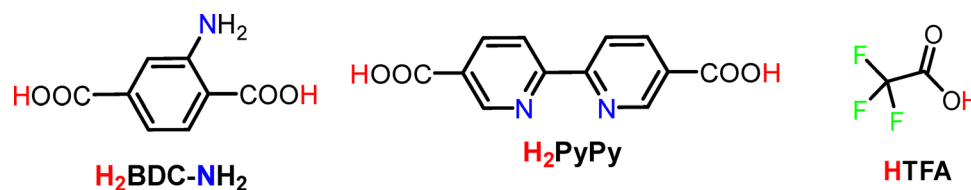
long atmospheric lifetime and potent greenhouse effect make it a major concern. Efforts to reduce SF<sub>6</sub> emissions involve finding alternative insulating gases, improving gas recovery techniques and enhancing equipment maintenance to minimize leaks.<sup>3</sup> An efficient approach to address the pollution caused by CO<sub>2</sub> and SF<sub>6</sub> and reduce their atmospheric concentrations (limiting their environmental impact) is their selective adsorption using porous solids. In particular, Metal–Organic Frameworks (MOFs) are a class of porous crystalline materials that have gained increasing attention in the last years in this context. MOFs are organic–inorganic compounds made by the combination of assorted metal nodes and polytopic organic linkers whose relevance in contemporary chemistry has been brought to the attention of the worldwide news after the assignment of the Nobel Prize in Chemistry 2025 to Omar Yaghi, Susumu Kitagawa and Richard Robson for their pioneering work in this area.<sup>4</sup> Their highly tunable structures, exceptional surface areas and adjustable pore sizes make them ideal candidates for gas adsorption and separation applications.<sup>5–8</sup> In gas adsorption, MOFs exhibit superior capacity due to their well-defined porosity and high affinity toward specific gas molecules, often with remarkable gas uptake and release under mild conditions.<sup>6</sup> More specifically, MOFs offer a highly efficient platform for post-combustion (acidic) CO<sub>2</sub> capture when they contain amine-functionalized (or, more generally, basic groups) on their polar organic linkers that are able to engage with strong chemisorption interactions with CO<sub>2</sub>.<sup>9–13</sup> Another class of MOFs that is being studied for the same application is that of fluorinated MOFs (F-MOFs). Fluorination enhances CO<sub>2</sub> adsorption because of the presence of the electronegative fluorine atoms that enhances dipole–quadrupole interactions with CO<sub>2</sub> molecules, increasing adsorption capacity. In addition, fluorination also reduces water interference in CO<sub>2</sub> adsorption, making F-MOFs highly effective in humid conditions.<sup>14–21</sup> MOFs have also shown excellent performance in SF<sub>6</sub> capture due to their hydrophobicity (SF<sub>6</sub>, being a large, nonpolar molecule, interacts well with hydrophobic MOFs with large pore openings), high binding energy (the strong van der Waals interactions between SF<sub>6</sub> and MOFs enhance adsorption selectivity) and low-pressure capture efficiency (MOFs exhibit high SF<sub>6</sub> uptake even at low pressures).<sup>22</sup> Analogously to what has been described for CO<sub>2</sub>, MOFs bearing basic groups on their linkers and/or fluorinated substituents are also very efficient in SF<sub>6</sub> adsorption. Since SF<sub>6</sub> is a weak Lewis acid, it can interact with basic groups present in the MOF structure, improving capture efficiency. At the same time, fluorine

electronegativity increases SF<sub>6</sub> binding affinity through dispersion forces and quadrupole interactions. For gas mixture separation, MOFs leverage their selective adsorption capabilities to differentiate between gas molecules based on size, shape, and chemical interactions. This makes them highly effective in challenging separations. Separating CO<sub>2</sub> from SF<sub>6</sub> is particularly important in industrial processes where SF<sub>6</sub> is used, such as gas insulation systems, high-voltage equipment and semiconductor manufacturing. It often appears mixed with inert gases such as N<sub>2</sub> or CO<sub>2</sub> during use or waste streams. SF<sub>6</sub>/CO<sub>2</sub> mixtures commonly used in electrical insulation applications have a composition around 20 mol% of SF<sub>6</sub> and 80 mol% of CO<sub>2</sub>.<sup>23</sup> Recovery and separation of SF<sub>6</sub> from such mixtures is both an economic and environmental imperative (reuse of expensive SF<sub>6</sub> and reduction of emissions).<sup>24</sup> Conventional separation techniques, such as cryogenic distillation, are energy-intensive. Again, MOFs offer a promising alternative due to their ability to selectively adsorb one gas over the other. Recent research highlights that F-MOFs enhance SF<sub>6</sub> uptake *via* van der Waals and dispersion interactions making them highly selective for this gas,<sup>25,26</sup> while basic MOFs exploit Lewis base–acid interactions to adsorb SF<sub>6</sub>, but often prefer CO<sub>2</sub> due to its higher quadrupole moment.<sup>27,28</sup> With this in mind and with the target of designing new MOFs for CO<sub>2</sub> and SF<sub>6</sub> adsorption/separation, in our labs we have adopted a “hybrid” strategy combining fluorination and basic functionalization within the same MOF that may optimize SF<sub>6</sub> or CO<sub>2</sub> capture performance while allowing tunable CO<sub>2</sub>/SF<sub>6</sub> separation. Accordingly, two novel zirconium mixed-linker MOFs of UiO-6x (**fcu**) topology<sup>29</sup> built with the basic linkers 2-aminoterephthalic acid (H<sub>2</sub>BDC-NH<sub>2</sub>), [2,2′-bipyridine]-5,5′-dicarboxylic acid (H<sub>2</sub>PyPy) and the fluorinated linker trifluoroacetic acid (HTFA, Scheme 1) have been synthesized and fully characterized: [Zr<sub>6</sub>O<sub>4</sub>(OH)<sub>4</sub>(TFA)<sub>4.2</sub>(BDC-NH<sub>2</sub>)<sub>3.9</sub>] (**Zr\_TFA\_NH<sub>2</sub>**) and [Zr<sub>6</sub>O<sub>4</sub>(OH)<sub>4</sub>(TFA)<sub>1.8</sub>(PyPy)<sub>5.1</sub>] (**Zr\_TFA\_PyPy**). Their performance in CO<sub>2</sub> and SF<sub>6</sub> adsorption/separation has been analyzed.

## 2. Experimental section

### 2.1. Materials and methods

Zirconium chloride (ZrCl<sub>4</sub>), trifluoroacetic acid (HTFA), *N,N*-dimethylformamide (DMF), 2-aminoterephthalic acid (H<sub>2</sub>BDC-NH<sub>2</sub>) and [2,2′-bipyridine]-5,5′-dicarboxylic acid (H<sub>2</sub>PyPy) were purchased from Sigma Aldrich and used as received. NMR experiments were performed using a Bruker 400 Avance III HD 400 instrument equipped with a smart probe (400.13 MHz



**Scheme 1** The linkers used in this study for the construction of the Zr<sup>IV</sup> MIXMOFs **Zr\_TFA\_NH<sub>2</sub>** and **Zr\_TFA\_PyPy**: 2-aminoterephthalic acid (H<sub>2</sub>BDC-NH<sub>2</sub>), [2,2′-bipyridine]-5,5′-dicarboxylic acid (H<sub>2</sub>PyPy) and trifluoroacetic acid (HTFA).



for  $^1\text{H}$ ) at  $T = 298\text{ K}$ .  $^1\text{H}$  and  $^{19}\text{F}$  NMR spectra were recorded using standard pulse sequences available on the Bruker library. Each sample was allowed to equilibrate inside the NMR probe for 10 min before spectral acquisition and each NMR spectrum was acquired using a single scan.  $^1\text{H}$  and  $^{19}\text{F}$  NMR chemical shifts were referenced to external HDO in  $\text{D}_2\text{O}$  by taking into account the  $\gamma_{\text{F}}/\gamma_{\text{H}}$  ratio for  $^{19}\text{F}$ . As for the linker quantification in the solids, solutions of **Zr\_TFA\_NH<sub>2</sub>** and **Zr\_TFA\_PyPy** were prepared by holding 5 mg of each MOF in an oven at  $T = 393\text{ K}$  for 2 h before being digested in 1.5 mL of  $\text{D}_2\text{SO}_4/\text{D}_2\text{O}$  (96 w/w%)/DMSO- $d_6$  solution kept at  $T = 298\text{ K}$  for 36 h and 24 h, respectively. For the calculation details, see SI and Fig. S1. FT-IR spectra (KBr pellets) were recorded on a PerkinElmer spectrum BX series FTIR spectrometer, in the 4000–400  $\text{cm}^{-1}$  range, with a 2  $\text{cm}^{-1}$  resolution. Thermogravimetric analyses (TG-DTG) were performed under a  $\text{N}_2$  flow (100  $\text{mL min}^{-1}$ ) at a heating rate of 5  $\text{K min}^{-1}$  with an EXSTAR Thermo Gravimetric Analyzer Seiko 6200. The latter was coupled with a ThermoStar™ GSD 301T mass spectrometer for mass analysis of the volatile species. The elemental analyses were performed using a Thermo FlashEA 1112 Series CHNS-O elemental analyzer with an accepted tolerance of  $\pm 2\%$  on carbon (C), hydrogen (H) and nitrogen (N). Scanning electron microscopy and energy dispersive X-ray analysis (SEM-EDX) measurements were performed on a field emission-SEM TESCAN S9000G equipped with a Schottky-type EGF source. The voltage used for electron acceleration is 15 kV, and the probe current is 300 pA. An OXFORD model Ultim Max AZTEC software was used for the microanalysis. The nature and purity of all the batches employed for the functional characterization were assessed through powder X-ray diffraction (PXRD). PXRD qualitative measurements were carried out in the 2.0–50.0°  $2\theta$  region with a Panalytical X'PERT PRO diffractometer equipped with a Ni filter in the diffracted beam, a PIXcel<sup>®</sup> solid state detector and a sealed X-ray tube (Cu  $K\alpha$ ,  $\lambda = 1.5418\text{ \AA}$ ). Slits were used on both the incident (soller slits aperture: 0.25°; divergence slit aperture: 0.5°) and the diffracted (anti-scatter slit aperture: 7.5 mm) beam. The generator was operated at 40 kV and 40 mA. PXRD patterns for structural analysis were collected with the same setup but in the 4°–90°  $2\theta$  region with a 50 sec per step. The samples were previously evacuated from solvent molecules at  $T = 393\text{ K}$  for 2 h. The breakthrough (BT) adsorption and desorption curves were measured with a BreakThrough Analyzer (BTA) instrument from Micromeritics<sup>®</sup>. BTA is equipped with one mass flow controller (MFC, Bronkhorst) for each gas; after the mixing of the desired flow, 1/32' inch pipeline leads to a quartz reactor (37.0 cm length and 9.33  $\text{cm}^3$  of internal volume), axially inserted in a ceramic furnace. The reactor is equipped with two K type thermocouples (TC): one in contact with the sample (inlet TC, placed in the middle isothermal region of the furnace) and the other at the outlet of the reactor. The outlet flow was analysed through a GSD 350 OmniStar mass spectrometer from Pfeiffer Vacuum. The pipeline connecting BTA and mass spectrometer was heated to  $T = 423\text{ K}$  to avoid condensation.

## 2.2. Synthesis of Zr\_TFA\_NH<sub>2</sub>

Zirconium chloride [ $\text{ZrCl}_4$ , FW = 233.02  $\text{g mol}^{-1}$ , 0.121 g, 0.52 mmol] and trifluoroacetic acid (1 mL) were mixed together and diluted with *N,N*-dimethylformamide (DMF, 25 mL). The resulting suspension was sonicated in an ultrasonic bath at ambient temperature for 15 minutes, this yielding a clear colorless solution. After that time,  $\text{H}_2\text{BDC-NH}_2$  (FW = 181.15  $\text{g mol}^{-1}$ , 0.050 g, 0.26 mmol, 0.5 equiv.) was added to the solution; the mixture was further diluted with fresh DMF (25 mL), sonicated for additional 15 minutes and finally transferred to a Teflon-lined stainless-steel autoclave (inner Teflon beaker volume *ca.* 100 mL). The autoclave was sealed and heated at  $T = 393\text{ K}$  for 72 h under autogenous pressure. After slow overnight cooling, the microcrystalline light yellow powder of **Zr\_TFA\_NH<sub>2</sub>-DMF** was collected, washed with ethanol ( $3 \times 10\text{ mL}$ ) and petroleum ether ( $3 \times 10\text{ mL}$ ) and finally dried under a nitrogen stream at room temperature. Yield: 0.13 g {67%, based on the minimal formula  $[\text{Zr}_6\text{O}_4(\text{OH})_4(\text{TFA})_{4.2}(\text{BDC-NH}_2)_{3.9}] \cdot 4(\text{DMF})$ }. Elemental analysis calcd. (%) for **Zr\_TFA\_NH<sub>2</sub>-DMF**,  $\text{C}_{51.6}\text{H}_{59.3}\text{F}_{12.6}\text{N}_{7.9}\text{O}_{35.5}\text{Zr}_6$  (MW = 2144.9  $\text{g mol}^{-1}$ ): C 28.9, H 2.8, N 5.2. Elemental analysis found (%): C, 29.0; H, 2.9; N, 5.1. IR bands (KBr pellet,  $\text{cm}^{-1}$ , Fig. S2): 1680(vs, sh) [ $\nu(\text{COO})_{\text{BDC-NH}_2}$ ], 1657(vs) [ $\nu(\text{COO})_{\text{TFA}}$ ], 1573(s) [ $\nu(\text{C}=\text{C})$ ], 1507(w), 1437(vs), 1387(vs) [ $\delta(\text{C-H})$ ], 1260(s) [ $\nu(\text{C-F})$ ], 1204(s), 1145(m), 1101(m), 1024(w), 803(m), 770(m), 721(w) [ $\gamma(\text{C-H})$ ], 664(s), 567(w, br), 489(m, br).

## 2.3. Synthesis of Zr\_TFA\_PyPy

Zirconium chloride [ $\text{ZrCl}_4$ , FW = 233.02  $\text{g mol}^{-1}$ , 0.124 g, 0.52 mmol] and trifluoroacetic acid (1 mL) were mixed together and diluted with *N,N*-dimethylformamide (DMF, 25 mL). The resulting suspension was sonicated in an ultrasonic bath at ambient temperature for 15 minutes, this yielding a clear colorless solution. After that time,  $\text{H}_2\text{PyPy}$  (FW = 244.20  $\text{g mol}^{-1}$ , 0.063 g, 0.26 mmol, 0.5 equiv.) was added to the solution; the mixture was further diluted with fresh DMF (25 mL), sonicated for additional 15 minutes and finally transferred to a Teflon-lined stainless-steel autoclave (inner Teflon beaker volume *ca.* 100 mL). The autoclave was sealed and heated at  $T = 393\text{ K}$  for 72 h under autogenous pressure. After slow overnight cooling, the microcrystalline off-white powder of **Zr\_TFA\_PyPy-DMF** was collected, washed with ethanol ( $3 \times 10\text{ mL}$ ) and petroleum ether ( $3 \times 10\text{ mL}$ ) and finally dried under a nitrogen stream at room temperature. Yield: 0.11 g {58%, based on the minimal formula  $[\text{Zr}_6\text{O}_4(\text{OH})_4(\text{TFA})_{1.8}(\text{PyPy})_{5.1}] \cdot (\text{DMF})$ }. Elemental analysis calcd (%) for **Zr\_TFA\_PyPy-DMF**,  $\text{C}_{67.8}\text{H}_{41.6}\text{O}_{33}\text{N}_{11.2}\text{F}_{5.4}\text{Zr}_6$  (MW = 2191.1  $\text{g mol}^{-1}$ ): C 37.2, H 1.9, N 7.2. Elemental analysis found (%): C, 37.4; H, 2.1; N, 7.3. IR bands (KBr pellet,  $\text{cm}^{-1}$ , Fig. S3): 1650(s, sh) [ $\nu(\text{COO})_{\text{PyPy}}$ ], 1596(vs) [ $\nu(\text{COO})_{\text{TFA}}$ ], 1555(m, sh) [ $\nu(\text{C}=\text{C})$ ], 1419(vs) [ $\delta(\text{C-H})$ ], 1248(w), 1206(w) [ $\nu(\text{C-F})$ ], 1161(w), 1056(vw), 1028(w), 847(w, br), 779(m) [ $\gamma(\text{C-H})$ ], 654(m), 458(w).



#### 2.4. Crystal structure analysis from PXRD data and DFT calculations

The PXRD patterns of **Zr\_TFA\_NH<sub>2</sub>** and **Zr\_TFA\_PyPy** were indexed *ab initio* by using *N-TREOR* implemented in the *EXPO2014* program.<sup>30</sup> The best unit cell solutions found were  $a = b = c = 20.7988 \text{ \AA}$  and  $\alpha = \beta = \gamma = 90^\circ$  for **Zr\_TFA\_NH<sub>2</sub>** and  $a = b = c = 26.3361 \text{ \AA}$  and  $\alpha = \beta = \gamma = 90^\circ$  for **Zr\_TFA\_PyPy**. The systematic extinction analysis suggested *Fm* $\bar{3}$ *m* as most probable space group for both MOFs, thus confirming the structural similarities with the already reported UiO-66-NH<sub>2</sub><sup>31</sup> and UiO-67-PyPy.<sup>32</sup> However, the presence of both HTFA/H<sub>2</sub>BDC-NH<sub>2</sub> linkers for **Zr\_TFA\_NH<sub>2</sub>** and HTFA/H<sub>2</sub>PyPy linkers for **Zr\_TFA\_PyPy** (as assessed by <sup>1</sup>H NMR analysis of the digested sample) suggested a complete disordered linkers configuration into the MOF framework as required by the highly symmetric space group. An ordered linkers disposition would result in a less symmetric space group due to the symmetry lowering of the [Zr<sub>6</sub>] nodes. A structural model was obtained starting from the crystal structures of UiO-66-NH<sub>2</sub> and UiO-67-PyPy. In **Zr\_TFA\_NH<sub>2</sub>**, the crystal symmetry was reduced from *Fm* $\bar{3}$ *m* to *P* $\bar{4}$ *3**m* in order to work with two independent linkers in the asymmetric unit; half of the BDC-NH<sub>2</sub><sup>2-</sup> molecule was replaced by one TFA<sup>-</sup>, thus obtaining the minimal formula [Zr<sub>6</sub>O<sub>4</sub>(OH)<sub>4</sub>(TFA)<sub>6</sub>(BDC-NH<sub>2</sub>)<sub>3</sub>] which displays a higher TFA/BDC-NH<sub>2</sub> ratio than that of the experimental formula [Zr<sub>6</sub>O<sub>4</sub>(OH)<sub>4</sub>(TFA)<sub>4.2</sub>(BDC-NH<sub>2</sub>)<sub>3.9</sub>] (see SI). The same symmetry reduction was also carried out for **Zr\_TFA\_PyPy**. In this case, in order to reproduce to the experimental formula [Zr<sub>6</sub>O<sub>4</sub>(OH)<sub>4</sub>(TFA)<sub>1.8</sub>(PyPy)<sub>5.1</sub>] only one third of the carboxylic PyPy<sup>2-</sup> linkers were replaced by TFA<sup>-</sup> anions providing the minimal formula [Zr<sub>6</sub>O<sub>4</sub>(OH)<sub>4</sub>(TFA)<sub>3</sub>(PyPy)<sub>4.5</sub>]. Due to the equivalent positions of the space group used, this was the only possibility to simulate as much as possible the real MOF composition as derived from the sample digestion followed by <sup>1</sup>H NMR analysis. The two structural models were then optimized by DFT.

#### 2.5. Textural properties assessment through N<sub>2</sub> adsorption. CO<sub>2</sub> and SF<sub>6</sub> adsorption isotherms

The powdered samples (*ca.* 40 mg) of **Zr\_TFA\_NH<sub>2</sub>** and **Zr\_TFA\_PyPy** were activated at  $T = 423 \text{ K}$  under high vacuum ( $10^{-6}$  torr) for 24 h before the measurement. The Brunauer-Emmett-Teller (BET) specific surface area, pore size distribution and pore volume ( $V_{\text{tot}}$ ,  $V_{\text{micro}}$ ) were estimated by volumetric adsorption with an ASAP 2020 Micromeritics instrument, using N<sub>2</sub> as adsorbate at  $T = 77 \text{ K}$ . For the BET specific surface area calculation, the  $0.01\text{--}0.1p/p_0$  pressure range of the isotherm was used to fit the data. Within this range, all the Rouquerol consistency criteria<sup>33,34</sup> are satisfied (Fig. S4 and S5). The material (micro)porosity was determined from the N<sub>2</sub> adsorption isotherm using a NLDFT method (Tarazona approximation) and assuming a cylindrical pore shape (typical of metal oxides). CO<sub>2</sub> and SF<sub>6</sub> adsorption isotherms were recorded at  $T = 273 \text{ K}$ ,  $298 \text{ K}$  and  $323 \text{ K}$  at a maximum pressure of 1.2 bar. The isosteric heat of adsorption ( $Q_{\text{st}}$ ) values of both gases were calculated from the three isotherms according to the

differential form of the Clausius-Clapeyron equation:<sup>35,36</sup>

$$\left[ \frac{\partial(\ln p)}{\partial\left(\frac{1}{T}\right)} \right]_{\theta} = -\frac{Q_{\text{st}}}{R} \quad (1)$$

where  $R$  is the gas constant ( $8.314 \text{ J K}^{-1} \text{ mol}^{-1}$ ). The lowest comparable coverage of the two gases for the two MOFs is 0.4/0.2 wt% (CO<sub>2</sub>) and 2.4/0.9 wt% (SF<sub>6</sub>) for **Zr\_TFA\_NH<sub>2</sub>**/**Zr\_TFA\_PyPy**, respectively. The IAST A/B adsorption selectivity (A, B = SF<sub>6</sub>, CO<sub>2</sub>, N<sub>2</sub>) of binary mixtures at a total pressure of 0.5 bar (for the sake of comparison with the experimental data) and at  $T = 298 \text{ K}$  was determined as the ratio of the adsorbed molar fractions of the two gases divided by the ratio of the gas phase initial molar fractions:<sup>37</sup>

$$S_{\text{A/B}} = \frac{\left(\frac{\chi_{\text{A}}}{\chi_{\text{B}}}\right)_{\text{ads}}}{\left(\frac{\chi_{\text{A}}}{\chi_{\text{B}}}\right)_{\text{gas}}} \quad (2)$$

The  $(\chi_{\text{A}})_{\text{ads}}$  and  $(\chi_{\text{B}})_{\text{ads}}$  values were derived from the application of the free software IAST++<sup>38</sup> to the experimental single-component isotherms collected at the chosen temperature. The initial composition (%) selected for the calculation was [50 : 50] for the [SF<sub>6</sub> : CO<sub>2</sub>] pair and [1 : 99] for the [G : N<sub>2</sub>] pairs (G = SF<sub>6</sub>, CO<sub>2</sub>). Various models (Langmuir, Freundlich, BET, Henry, Dual-Site Langmuir-Freundlich) were employed for the SF<sub>6</sub>, N<sub>2</sub> and CO<sub>2</sub> isotherms fitting, choosing the option that gives the lowest  $R^2$  on the experimental points.

#### 2.6. Breakthrough measurements

BT measurements were performed at a partial pressure of 0.25 of CO<sub>2</sub> and/or SF<sub>6</sub> in a carrier, at ambient temperature and pressure, under a constant flow of  $10 \text{ mL min}^{-1}$ . The samples were prepared by pelletizing the MOF powders at  $p = 1 \text{ ton}$  and the pellets were sieved selecting the 250–500  $\mu\text{m}$  size fraction. The bed packing density was  $0.3 \text{ g mL}^{-1}$ , with a resulting total porosity ( $\epsilon_{\text{t}}$ ) of 0.85. The bed porosity ( $\epsilon_{\text{b}}$ ) was instead estimated at 0.4 based on literature data.<sup>39</sup> For each sample, the sorption of CO<sub>2</sub> alone, SF<sub>6</sub> alone and the competitive sorption of CO<sub>2</sub> and SF<sub>6</sub> were performed. The partial pressure of 0.25 for each sorptive was chosen as the best compromise between the use of the carrier and the enhancement of BT times. The resulting 50 : 50 gas composition in the competitive BT measurements was chosen as a model to study the separation process. The total flow was set as low as possible to measure equilibrium data. The samples were pre-treated by heating at  $T = 423 \text{ K}$  with a  $5 \text{ K min}^{-1}$  ramp under  $25 \text{ mL min}^{-1}$  He (99.9995%) flow for 24 h before the first experiment to allow full removal of DMF solvent. The same pre-treatment was performed before each subsequent experiment, but it was performed for 10 h, to allow full regeneration. The samples were then cooled down to room temperature under a  $25 \text{ mL min}^{-1}$  He flow. The procedure for each adsorption experiment foresees: (i) 10 min under  $9.975 \text{ mL min}^{-1}$  He and  $0.025 \text{ mL min}^{-1}$  of Ar (used as tracer), to equilibrate the mass baseline; in



the meantime, 2.500 mL min<sup>-1</sup> CO<sub>2</sub> (99.998%) and/or 2.500 mL min<sup>-1</sup> SF<sub>6</sub> (99.97%) were flowed to the by-pass to stabilize the flow; (ii) CO<sub>2</sub> and/or SF<sub>6</sub> gases are switched to reactor and contemporary He flow was reduced to keep the total volumetric flow constant at 10 mL min<sup>-1</sup>. The adsorption was conducted until stabilization of the mass signal. Each adsorption experiment was followed by the desorption. The desorption was conducted by switching off CO<sub>2</sub> and/or SF<sub>6</sub> flows and contemporary increasing the He flow to keep the total volumetric flow constant at 10 mL min<sup>-1</sup>. Blank experiments were performed on the empty reactor. For details of the calculations and for the schematic of the inlet flows please refer to the SI and Fig. S6.

### 2.7. Computational details

Periodic density functional theory (DFT) calculations were carried out at the PBEsol0-3c level of theory, as implemented in the CRYSTAL23<sup>40</sup> *ab initio* code. In the PBEsol0-3c method,<sup>41,42</sup> the total energy computed with the PBEsol0 hybrid functional combined with a double- $\zeta$  quality Gaussian basis set is augmented with two semi-empirical corrections to remove the basis set superposition error (BSSE) through the geometrical CounterPoise (gCP)<sup>43</sup> approach and to properly describe weak interactions *via* the D3 scheme<sup>44</sup> in its Becke-Johnson rational damping variant. A (75, 974) pruned grid was employed for the numerical evaluation of the exchange-correlation term, corresponding to the XLGRID keyword as used by the CRYSTAL code. Default convergence criteria for geometry optimization were employed, while the tolerances for one- and two-electron integrals calculation were set to 10<sup>-7</sup>, 10<sup>-7</sup> for the Coulomb and to 10<sup>-7</sup>, 10<sup>-7</sup>, 10<sup>-25</sup> for the exchange series, respectively. The shrinking factors for the diagonalization of the Kohn-Sham matrix in the reciprocal space were set to 2 for the Monkhorst-Pack net and to 2 for the Gilat net. A full relaxation of both unit cell parameters and atomic positions was performed.

## 3. Results and discussion

### 3.1. Synthesis and characterization of Zr\_TFA\_NH<sub>2</sub> and Zr\_TFA\_PyPy

With the aim of preparing robust mixed-linker MOFs with both basic and fluorinated groups, we decided to focus on the zirconium MOFs of the UiO-6x family with cubic *fcu* topology as the best candidates because of their intrinsic chemical and thermal stability.<sup>29</sup> In particular, a “short” basic linker (to get an “UiO-66-like” MOF) and a “long” basic linker (to get an “UiO-67-like” MOF) were selected to build the MOFs to study the effect of the related different pore size on their adsorption/separation capability. Accordingly, the linkers of choice were the two commercially available 2-aminoterephthalic acid and [2,2'-bipyridine]-5,5'-dicarboxylic acid. On the other hand, the fluorinated part comes from the trifluoroacetic acid modulator added to the reaction mixture to improve the material crystallinity. Given the initial (defective) [Zr:linker] stoichiometric ratio (2:1 instead of 1:1 as normally required for the synthesis of defect-free UiO-6x MOFs),<sup>29</sup> the vacant coordination sites on the [Zr<sub>6</sub>] octahedral node are filled by the modulator, thus giving a mixed-linker MOF with dual basic/fluorinated nature. A solvothermal synthesis carried out in DMF for three days and using dilute solutions directly provided the pure products. Zr\_TFA\_NH<sub>2</sub> and Zr\_TFA\_PyPy have been thoroughly characterized in the solid state. The IR spectroscopic analysis confirms the presence of both linkers (Fig. S2 and S3), highlighting some typical bands of H<sub>2</sub>BDC-NH<sub>2</sub>/H<sub>2</sub>PyPy at 1680/1651 cm<sup>-1</sup> [ $\nu$ (COO)], 1573/1555 cm<sup>-1</sup> [ $\nu$ (C=C)], 1387/1419 cm<sup>-1</sup> [ $\delta$ (C-H)], and 721/779 [ $\gamma$ (C-H)] respectively, besides those of TFA<sup>-</sup> at 1657/1596 cm<sup>-1</sup> [ $\nu$ (COO)] and at 1260/1206 cm<sup>-1</sup> [ $\nu$ (C-F)].<sup>45,46</sup> In order to investigate the main elements present in the samples and their morphological homogeneity, SEM-EDX analysis was performed (Fig. S7 and S8). Both MOFs are in the form of uniform polyhedral microcrystals typical of a unique phase, organized in dense aggregates. Besides carbon and oxygen, EDX analysis confirmed the presence of zirconium, fluorine and nitrogen. Powder X-ray diffraction (PXRD, Fig. 1a) confirms that

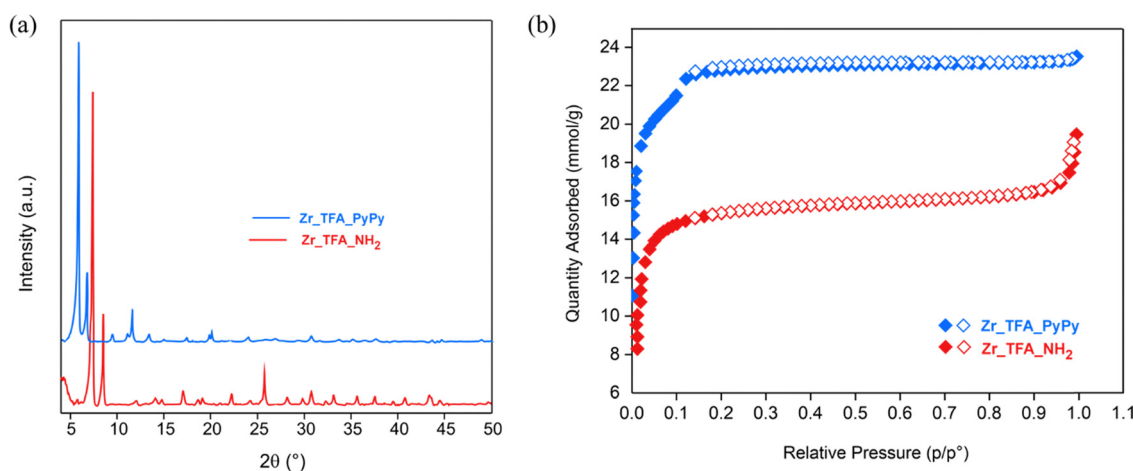


Fig. 1 (a) PXRD patterns (4–50° 2 $\theta$  region) of Zr\_TFA\_NH<sub>2</sub> and Zr\_TFA\_PyPy at comparison. (b) N<sub>2</sub> isotherms measured at T = 77 K on thermally activated Zr\_TFA\_NH<sub>2</sub> and Zr\_TFA\_PyPy at comparison. Empty symbols denote the desorption branch.



the products have the same crystallographic symmetry (cubic, space group  $Fm\bar{3}$  or  $Fm\bar{3}m$ ) as those of UiO-66-NH<sub>2</sub><sup>31</sup> and UiO-67-PyPy.<sup>32,47</sup> The relative amount of fluorinated and non-fluorinated linkers in each MOF was quantified through <sup>1</sup>H and <sup>19</sup>F NMR spectroscopy *via* relative integration of selected <sup>1</sup>H and <sup>19</sup>F NMR signals in **Zr\_TFA\_NH<sub>2</sub>** and **Zr\_TFA\_PyPy** solutions with respect to those of the standard solution (see Experimental section and SI). Consequently, based on the ligands relative stoichiometric ratio the MOFs minimal formulae can be written as [Zr<sub>6</sub>O<sub>4</sub>(OH)<sub>4</sub>(TFA)<sub>4.2</sub>(BDC-NH<sub>2</sub>)<sub>3.9</sub>] and [Zr<sub>6</sub>O<sub>4</sub>(OH)<sub>4</sub>(TFA)<sub>1.8</sub>(PyPy)<sub>5.1</sub>]. Thermogravimetric analysis (TGA, Fig. S9a and S10a) showed that the thermal stability of both MIXMOFs is lower than that of their non-defective parent materials UiO-66-NH<sub>2</sub> ( $T_{dec} = 823$  K)<sup>31</sup> or Zr\_PyPy

( $T_{dec} = 800$  K)<sup>32</sup> ( $T_{dec} = 800/783$  K for **Zr\_TFA\_NH<sub>2</sub>**/**Zr\_TFA\_PyPy**, respectively). This is caused by the lower node connectivity (presence of defects) in our samples. In **Zr\_TFA\_NH<sub>2</sub>**, an initial weight loss of *ca.* 14 wt% can be reasonably ascribed to loss of clathrated DMF coming from the synthesis (theoretical mass loss = 13.6 wt%). The DTG peak found in this range falls at  $T = 470$  K. Further proof of evidence is provided by the MS analysis of the volatiles (Fig. S9b), where the peak at  $m/z = 73$  a.m.u. typical of DMF appears in the same temperature range. Subsequently, another loss of *ca.* 20 wt% centered at  $T = 615$  K is ascribed to TFA ( $m/z = 45$  a.m.u. on the MS spectrum; theoretical mass loss = 21 wt%) before undergoing final decomposition at  $T_{dec}$ . In **Zr\_TFA\_PyPy**, the visible thermal events are a first clathrated DMF solvent loss (*ca.* 4 wt%; theoretical mass

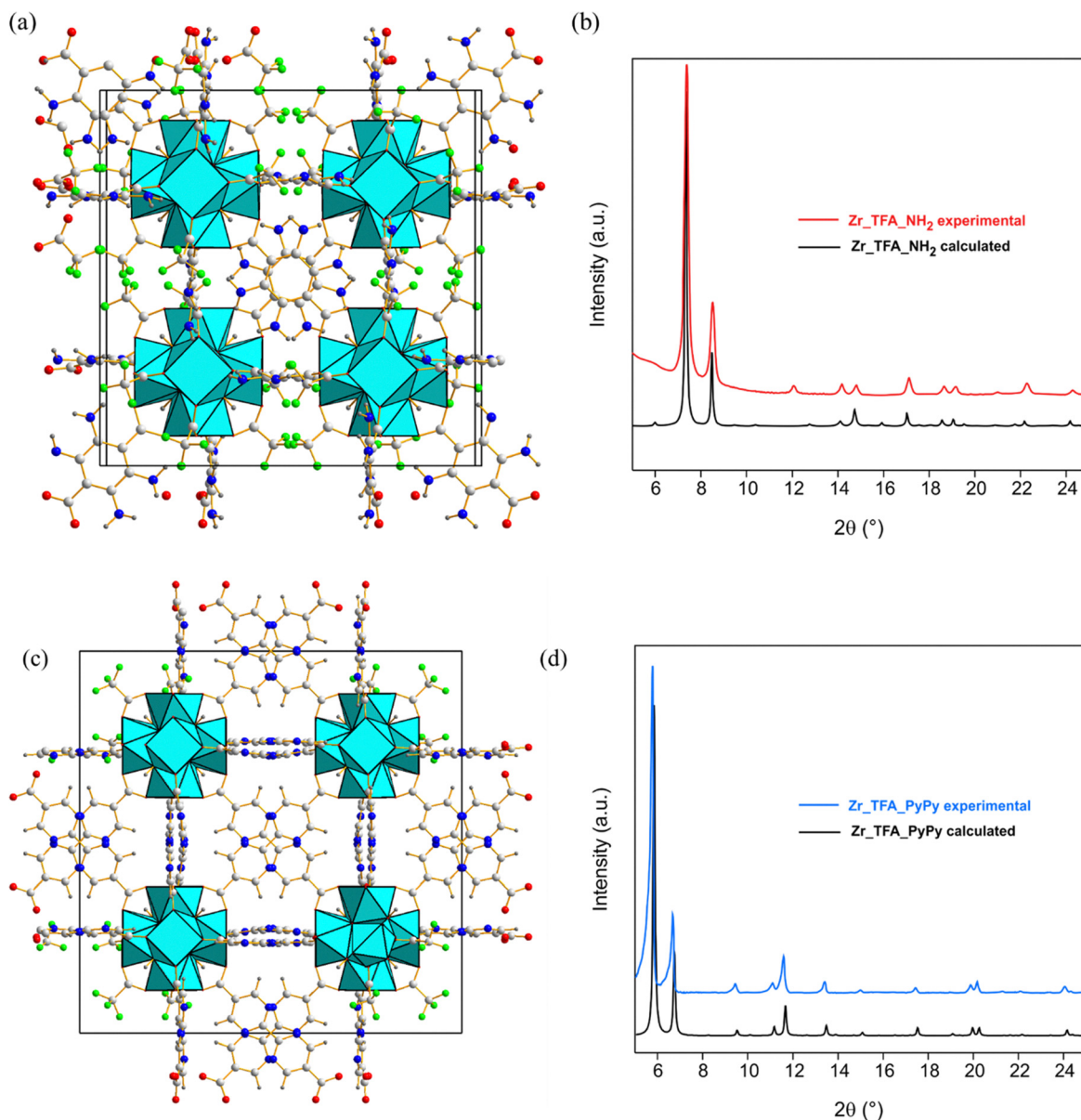


Fig. 2 Polyhedral representation of **Zr\_TFA\_NH<sub>2</sub>** (a) and **Zr\_TFA\_PyPy** (c) viewed along the *c*-axis. Comparison between the calculated and experimental patterns (b) and (d). atom color code: Zr turquoise, O red, C grey, H white, F green and N blue.



loss = 3.3 wt%) centered at  $T = 473$  K ( $m/z = 73$  a.m.u. in the mass spectrum of the volatiles, Fig. S10b) and the final MOF decomposition at  $T_{\text{dec}}$  witnessed by the presence in the MS spectrum of the peak at  $m/z = 79$  a.m.u. related to pyridine (coming from  $\text{H}_2\text{PyPy}$  degradation).

### 3.2. Crystal structure description

The structure of the two MIXMOFs as obtained by DFT calculations are shown in Fig. 2a–c, whereas comparison between the calculated and experimental patterns are shown in Fig. 2b–d.

The two DFT models provide a good agreement between the calculated and observed patterns. The generated CIF files are available as SI. However, they were not validated through Rietveld refinement because of the high number of free parameters to refine against the low number of reflections that imposed strong restraints and caused instability in the convergence procedure. As already mentioned in the Experimental section, to describe the presence of the two linkers in the right stoichiometry a symmetry reduction from the F-centred high symmetry  $Fm\bar{3}m$  cubic space group to the less symmetric primitive  $P\bar{4}3m$  group has been made. This allowed to handle the two linkers in the asymmetric unit independently, building a reliable structural model for both MOFs. However, the systematic extinction analysis of the diffraction patterns suggested the conventional **fcu** structure with  $Fm\bar{3}m$  as space group. This means that for a mixed-linker system their real disposition around the  $[\text{Zr}_6]$  clusters is completely disordered,

giving rise to statistically equivalent reticular nodes. Obviously, our models generated instead *ordered* SBUs made of  $[\text{Zr}_6]$  clusters with different chemical environments. The hexanuclear clusters for the two MOFs are reported in Fig. 3.

The  $[\text{Zr}_6\text{O}_4(\text{OH})_4]^{12+}$  hexanuclear cluster for **Zr\_TFA\_NH<sub>2</sub>** is charge-compensated by six apical bridging BDC-NH<sub>2</sub><sup>2-</sup> linkers and six TFA<sup>-</sup> anions all placed in the equatorial region. Given the monovalent nature of TFA<sup>-</sup>, in the proposed crystal structure there is an excess of this linker with respect to the equimolar composition found by NMR experiments. As for **Zr\_TFA\_PyPy**, the charges are compensated by nine bridging PyPy<sup>2-</sup> linkers and three adjacent TFA<sup>-</sup> anions thus giving the overall minimal formula (taking into account the bivalent nature of PyPy<sup>2-</sup> and monovalent nature of TFA<sup>-</sup>)  $[\text{Zr}_6\text{O}_4(\text{OH})_4(\text{TFA})_3(\text{PyPy})_{4.5}]$  as best match with the experimentally found  $[\text{Zr}_6\text{O}_4(\text{OH})_4(\text{TFA})_{1.8}(\text{PyPy})_{5.1}]$ . Overall, the calculated patterns of both MOFs here modelled display good agreement with the experimental ones. We believe that our models represent the best compromise to describe a mixed-linker fully disordered structure in a highly symmetric space group maintaining the right stoichiometry.

### 3.3. Textural properties assessment. CO<sub>2</sub> and SF<sub>6</sub> adsorption isotherms

The porosity of **Zr\_TFA\_NH<sub>2</sub>** and **Zr\_TFA\_PyPy** was evaluated through volumetric N<sub>2</sub> adsorption at  $T = 77$  K on pre-activated samples (Fig. 1b). The isotherm shape is of Type I, typical of

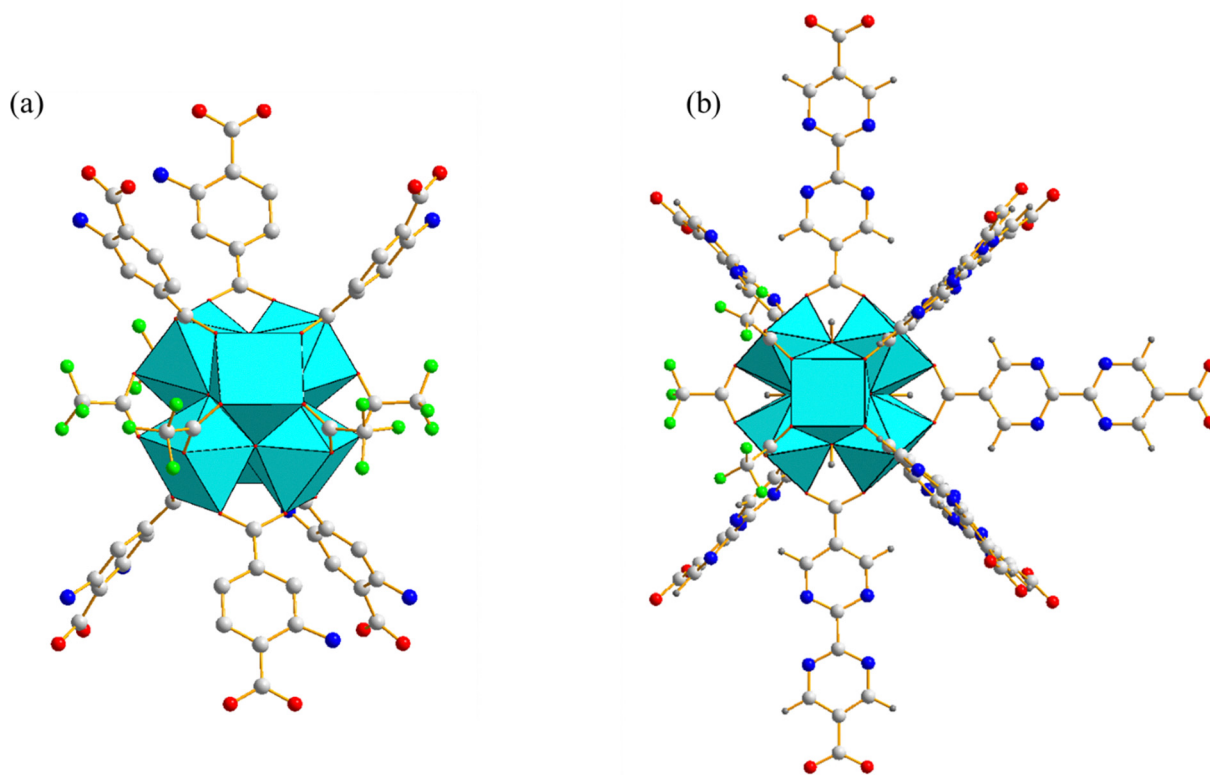


Fig. 3 Details of the connectivity of the  $[\text{Zr}_6]$  clusters in **Zr\_TFA\_NH<sub>2</sub>** (a) and **Zr\_TFA\_PyPy** (b). The PyPy<sup>2-</sup> moiety is represented as disordered in two equivalent 180° tilted positions. Atom color code: Zr turquoise, O red, C grey, H white, F green and N blue.



microporous materials. The measured BET surface areas are 1380 and 1922  $\text{m}^2 \text{g}^{-1}$  for **Zr\_TFA\_NH<sub>2</sub>** and **Zr\_TFA\_PyPy**, respectively. The accessible surface areas were also estimated through the Mercury crystallographic software<sup>48</sup> starting from the CIF files generated after DFT optimization and using N<sub>2</sub> as probe. The calculated values are 1100 and 2200  $\text{m}^2 \text{g}^{-1}$ , respectively. While in **Zr\_TFA\_NH<sub>2</sub>** the accessible surface area is higher than that of its parent MOF UiO-66-NH<sub>2</sub> (BET area = 1112  $\text{m}^2 \text{g}^{-1}$ ),<sup>31</sup> in **Zr\_TFA\_PyPy** the opposite trend is observed in comparison with the non-defective analogue **Zr\_PyPy** (BET area = 2730  $\text{m}^2 \text{g}^{-1}$ ).<sup>32</sup> The total pore volume equals 0.54 and 0.81  $\text{cm}^3 \text{g}^{-1}$  for **Zr\_TFA\_NH<sub>2</sub>** and **Zr\_TFA\_PyPy**, respectively. The DFT micropore size distribution (Fig. S11) shows a comparable pore size at  $15 \leq w \leq 19 \text{ \AA}$ , with an additional contribution at  $w \approx 23 \text{ \AA}$  for **Zr\_TFA\_PyPy** that is absent in **Zr\_TFA\_NH<sub>2</sub>**. The activated materials have been tested in CO<sub>2</sub> and SF<sub>6</sub> adsorption at  $p_{\text{max}} = 1.2 \text{ bar}$  and at variable temperatures:  $T = 273, 298 \text{ and } 323 \text{ K}$ . Fig. 4a and b report the ambient temperature CO<sub>2</sub> and SF<sub>6</sub> isotherms for both MOFs, respectively. The CO<sub>2</sub> uptake at  $p_{\text{CO}_2} = 1 \text{ bar}$  and  $T = 298 \text{ K}$  is 7.6 wt% (1.7  $\text{mmol g}^{-1}$ ) and 7.2 wt% (1.6  $\text{mmol g}^{-1}$ ) for **Zr\_TFA\_NH<sub>2</sub>** and **Zr\_TFA\_PyPy**, respectively. The efficiency of the amino group in capturing CO<sub>2</sub> is higher than that of pyridine, given the higher amount adsorbed by the former despite its lower surface area. This may be due to the ability of the -NH<sub>2</sub> group at reacting with CO<sub>2</sub> (reversibly) to form carbamates.<sup>12,13</sup> In line with this statement, the amount of CO<sub>2</sub> adsorbed at ambient temperature and pressure by **Zr\_TFA\_NH<sub>2</sub>** is lower than that adsorbed by the non-defective analogue UiO-66-NH<sub>2</sub> (3.04  $\text{mmol g}^{-1}$ )<sup>49</sup> and similar to that of UiO-66 (2.0  $\text{mmol g}^{-1}$ ).<sup>49</sup> The amount of CO<sub>2</sub> adsorbed by **Zr\_TFA\_PyPy** is comparable to that of its defect-free analogue **Zr\_PyPy** (1.5  $\text{mmol g}^{-1}$ )<sup>50</sup> and higher than that of UiO-67 (1.2  $\text{mmol g}^{-1}$ ).<sup>51</sup> A much better improvement of the materials CO<sub>2</sub> thermodynamic affinity is observed for both mixed-linker MOFs in comparison with their homo-linker analogues in the CO<sub>2</sub> isosteric heat of adsorption at zero coverage ( $Q_{\text{st}}$ ) values.  $Q_{\text{st}}$  has been calculated from the isotherms collected at three different temperatures applying the Clausius–Clapeyron equation. The values of 29 and 28  $\text{kJ mol}^{-1}$  for **Zr\_TFA\_NH<sub>2</sub>** and **Zr\_TFA\_PyPy** respectively outperform those reported for UiO-66-NH<sub>2</sub>

(25  $\text{kJ mol}^{-1}$ )<sup>49</sup> and **Zr\_PyPy** (21  $\text{kJ mol}^{-1}$ ),<sup>50</sup> proving the beneficial effect of the simultaneous presence of the basic and fluorine-containing linkers on carbon dioxide adsorption. As for SF<sub>6</sub>, the uptake at  $p_{\text{SF}_6} = 1 \text{ bar}$  and  $T = 298 \text{ K}$  is 21.6 wt% (1.5  $\text{mmol g}^{-1}$ ) and 34.5 wt% (2.4  $\text{mmol g}^{-1}$ ) for **Zr\_TFA\_NH<sub>2</sub>** and **Zr\_TFA\_PyPy**, respectively. The absolute gas uptake at ambient temperature is proportional to the material surface area and it is much higher than that found for other Zr-based MOFs from the literature with smaller pore size like UiO-66-Br<sub>2</sub> (0.9  $\text{mmol g}^{-1}$ ),<sup>52</sup> but it is lower than that of UiO-67 (4.0  $\text{mmol g}^{-1}$ ).<sup>53</sup> In terms of SF<sub>6</sub> isosteric heat of adsorption at zero coverage ( $Q_{\text{st}}$ ), the mixed-linker MOFs are featured by a comparable  $Q_{\text{st}}$  value than those found for their homo-linker parent analogues: 31 vs. 32 or 33  $\text{kJ mol}^{-1}$  for **Zr\_TFA\_NH<sub>2</sub>** vs. UiO-66-NH<sub>2</sub><sup>52</sup> or UiO-66,<sup>54</sup> respectively; 23 vs. 20  $\text{kJ mol}^{-1}$  for **Zr\_TFA\_PyPy** vs. UiO-67,<sup>53</sup> respectively (Table 1 and Table S1). This indicates that the simultaneous presence of a basic and a fluorinated linker in the material does not increase its SF<sub>6</sub> thermodynamic affinity significantly, while it has a more important effect for CO<sub>2</sub>. Interestingly, the variation of the MOFs pore size when passing from a “short” aminoterephthalate to a “long” bipyridyl linker induces a switch in the thermodynamic affinity for the two gases: while in **Zr\_TFA\_NH<sub>2</sub>**  $Q_{\text{st}}(\text{SF}_6) > Q_{\text{st}}(\text{CO}_2)$ , the opposite holds for **Zr\_TFA\_PyPy**, where  $Q_{\text{st}}(\text{CO}_2) > Q_{\text{st}}(\text{SF}_6)$ . Therefore, these MOFs may represent useful materials for the discrimination of these polluting gases, opening new horizons in the field of air treatment and cleaning. To shed further light on the MOFs adsorption behavior, IAST selectivity ( $S_{\text{SF}_6/\text{CO}_2}$ ) data for [SF<sub>6</sub>/CO<sub>2</sub>] binary equimolar mixtures at  $T = 298 \text{ K}$  were estimated; the results are summarized in Table 2. Both MOFs are selective towards SF<sub>6</sub>, but **Zr\_TFA\_NH<sub>2</sub>** is a better-performing material than **Zr\_TFA\_PyPy**. The presence of N<sub>2</sub> in the real atmospheric composition does not interfere with the separation process, since both MOFs are selective for SF<sub>6</sub> or CO<sub>2</sub> over N<sub>2</sub> even at very diluted greenhouse gas concentration, as inferred from the N<sub>2</sub> isotherms recorded at  $T = 298 \text{ K}$  (Fig. S12) and related  $S_{\text{SF}_6/\text{N}_2}$  and  $S_{\text{CO}_2/\text{N}_2}$  IAST selectivity values estimated on a binary [G : N<sub>2</sub>] [1 : 99] mixture (G = SF<sub>6</sub>, CO<sub>2</sub>).

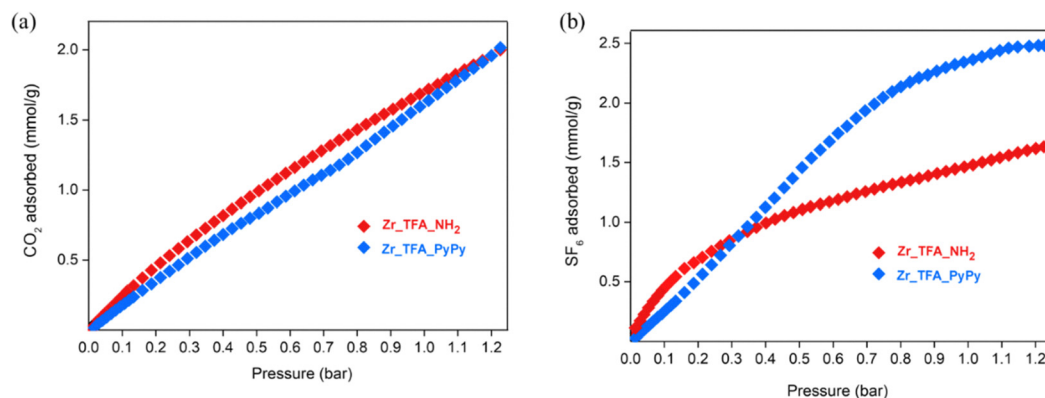


Fig. 4 Collective (a) CO<sub>2</sub> and (b) SF<sub>6</sub> adsorption isotherms at  $T = 298 \text{ K}$  for **Zr\_TFA\_NH<sub>2</sub>** and **Zr\_TFA\_PyPy** at comparison.



Table 1 Main adsorption data for the MOFs in this study

Sample	BET area [m <sup>2</sup> g <sup>-1</sup> ]	Q <sub>st</sub> (CO <sub>2</sub> ) [kJ mol <sup>-1</sup> ]	CO <sub>2</sub> quantity adsorbed at T = 298 K, p = 1 bar [mmol g <sup>-1</sup> ]	Q <sub>st</sub> (SF <sub>6</sub> ) [kJ mol <sup>-1</sup> ]	SF <sub>6</sub> quantity adsorbed at T = 298 K, p = 1 bar [mmol g <sup>-1</sup> ]
Zr_TFA_NH <sub>2</sub>	1380	29	1.7 (7.6 wt%)	31	1.5 (21.6 wt%)
Zr_TFA_PyPy	1922	28	1.6 (7.2 wt%)	23	2.4 (34.5 wt%)

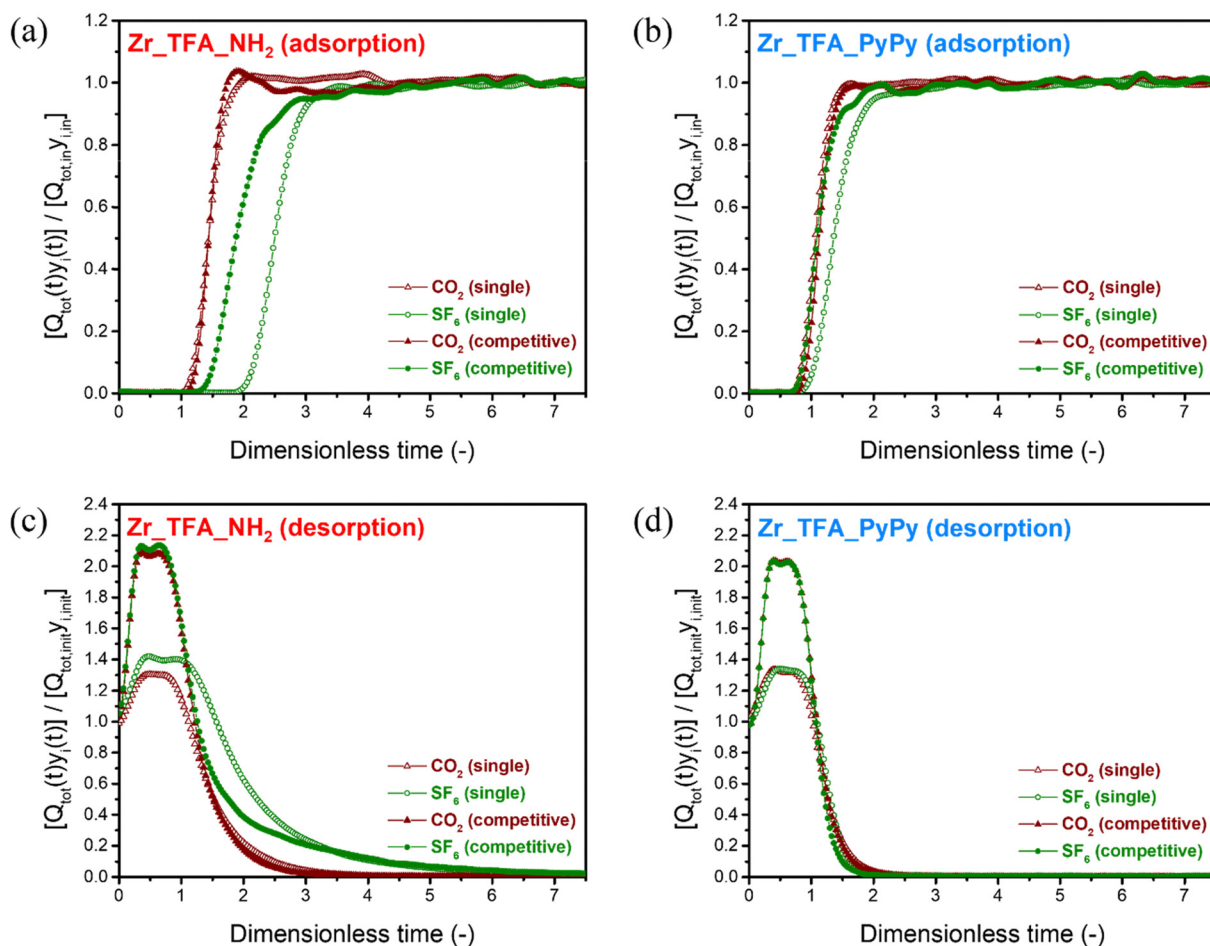
Table 2 IAST SF<sub>6</sub>/CO<sub>2</sub>, SF<sub>6</sub>/N<sub>2</sub> and CO<sub>2</sub>/N<sub>2</sub> adsorption selectivity data of binary gas mixtures [50 : 50] or [1 : 99] at p<sub>tot</sub> = 0.5 bar and T = 298 K for Zr\_TFA\_NH<sub>2</sub> and Zr\_TFA\_PyPy

MOF	S <sub>SF<sub>6</sub>/CO<sub>2</sub></sub> [50 : 50]	S <sub>SF<sub>6</sub>/N<sub>2</sub></sub> [1 : 99]	S <sub>CO<sub>2</sub>/N<sub>2</sub></sub> [1 : 99]
Zr_TFA_NH <sub>2</sub>	1.8	5.4	2.4
Zr_TFA_PyPy	1.5	3.2	2.4

### 3.3. Breakthrough experiments with SF<sub>6</sub>/CO<sub>2</sub> mixtures

To go deeper in studying the performances of Zr\_TFA\_NH<sub>2</sub> and Zr\_TFA\_PyPy in the CO<sub>2</sub>/SF<sub>6</sub> competitive sorption, the breakthrough (BT) curves were recorded and the amount adsorbed in dynamic measurements was calculated. The BT adsorption curves of the single pure gases recorded on Zr\_TFA\_NH<sub>2</sub>

(Fig. 5a, empty symbols) show that the retention time of SF<sub>6</sub> is longer than that of CO<sub>2</sub> (≈2 and ≈1 dimensionless time, respectively). The dimensionless time was calculated by normalization of experimental time by the retention time of an inert gas). The BT curves were recorded under the closest conditions to equilibrium as possible. This was achieved through the adoption of a very low total flow rate and the use of He as inert carrier, that favors molecular diffusivity.<sup>55</sup> Knudsen diffusion was favored by adequate sample preparation (pelletizing and sieving the pellets in the fraction 250–500 μm). This excludes major effects of external mass transfer resistance on the BT measurements.<sup>55</sup> Upon competitive adsorption (Fig. 5a, full symbols), the retention time of CO<sub>2</sub> is not affected at all, while that of SF<sub>6</sub> is substantially reduced to ≈1.3. This is reflected in the amount of adsorbed gas (Table 3): the amount of adsorbed

Fig. 5 Breakthrough curves of adsorption (a) and (b) and desorption (c) and (d) experiments on Zr\_TFA\_NH<sub>2</sub> and Zr\_TFA\_PyPy.

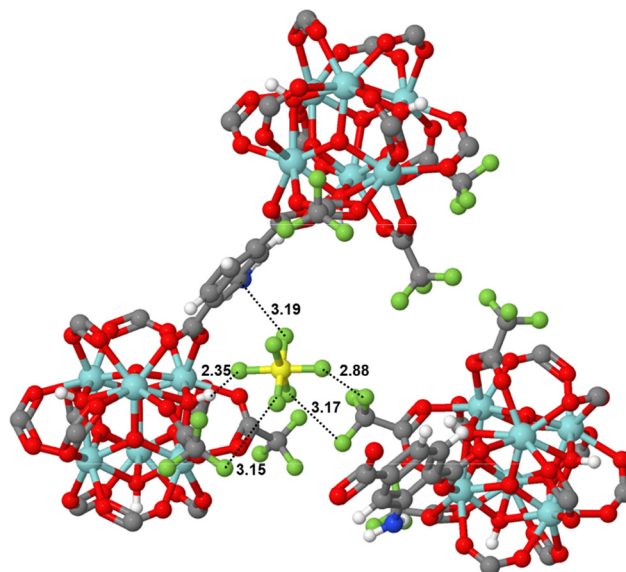
**Table 3** Amount of CO<sub>2</sub> and SF<sub>6</sub> adsorbed in breakthrough experiments (namely under dynamic conditions) on **Zr\_TFA\_NH<sub>2</sub>** and **Zr\_TFA\_PyPy**. In brackets the equilibrium data at 0.24p/p<sub>0</sub> (from the adsorption isotherms of CO<sub>2</sub> and SF<sub>6</sub>) are reported. The selectivity data are calculated at 0.5 of absolute pressure in a 1 : 1 : 2 mixture of CO<sub>2</sub> : SF<sub>6</sub> : inert

	CO <sub>2</sub> adsorbed, single [mmol g <sup>-1</sup> ]	SF <sub>6</sub> adsorbed, single [mmol g <sup>-1</sup> ]	CO <sub>2</sub> adsorbed, competitive [mmol g <sup>-1</sup> ]	SF <sub>6</sub> adsorbed, competitive [mmol g <sup>-1</sup> ]	S <sub>SF<sub>6</sub>/CO<sub>2</sub></sub>
<b>Zr_TFA_NH<sub>2</sub></b>	0.30 (0.53)	0.75 (0.76)	0.35	0.63	1.8
<b>Zr_TFA_PyPy</b>	0.36 (0.42)	0.45 (0.64)	0.41	0.36	0.9

CO<sub>2</sub> slightly changes, in a range within the experimental error (0.30 and 0.35 mmol g<sup>-1</sup> upon single and competitive adsorption, respectively), while that of SF<sub>6</sub> is significantly reduced (0.75 and 0.63 mmol g<sup>-1</sup> upon single and competitive adsorption, respectively). This behavior gives some information about the adsorption sites for the two molecules. The amount of SF<sub>6</sub> adsorbed in single component experiment under dynamic conditions nicely fits with the value recorded in static conditions (SF<sub>6</sub> adsorption isotherm). On the contrary, the amount of adsorbed CO<sub>2</sub> is lower in dynamic than in static conditions. Moreover, the fact that the CO<sub>2</sub> adsorbed amount in dynamic single and competitive adsorption does not significantly change suggests that SF<sub>6</sub> does not compete with CO<sub>2</sub>, but CO<sub>2</sub> partially competes with SF<sub>6</sub>. A slight overshoot is present in the CO<sub>2</sub> BT adsorption curve, suggesting that, even if CO<sub>2</sub> could compete, upon arrival of the slowest SF<sub>6</sub> some CO<sub>2</sub> molecules are replaced by SF<sub>6</sub>. This is also coherent with the Q<sub>st</sub>(SF<sub>6</sub>) value higher than Q<sub>st</sub>(CO<sub>2</sub>). Likewise, upon desorption (Fig. 5c) the effect of the higher Q<sub>st</sub>(SF<sub>6</sub>) is visible in its broad desorption curve. The BT curves of the single gases on **Zr\_TFA\_PyPy** (Fig. 5b and d) show that the CO<sub>2</sub> retention time is not affected by the single-component or double-component adsorption, as observed in **Zr\_TFA\_NH<sub>2</sub>**. On the other hand, SF<sub>6</sub> retention time is slightly reduced by the competition. Hence, the amount of CO<sub>2</sub> adsorbed does not significantly change going from single to competitive adsorption (0.36 and 0.41 mmol g<sup>-1</sup> respectively) while the amount of SF<sub>6</sub> adsorbed is decreased from 0.45 to 0.36 mmol g<sup>-1</sup>. Upon desorption, the SF<sub>6</sub> curve is slightly sharper than that of CO<sub>2</sub>. To find an explanation for this behavior, the enlargement of the adsorption isotherms in the 0–0.26 bar range is reported in Fig. S13. Here, the straight lines highlight that at low relative pressure the SF<sub>6</sub> isotherm on **Zr\_TFA\_PyPy** is of type III, based on IUPAC classification (the isotherm turns to a Langmuir-like type I shape at higher pressures). This implies that the adsorption branch in the dynamic experiment is broader than the desorption branch. The SF<sub>6</sub> type III behavior on **Zr\_TFA\_PyPy** is also coherent with the low Q<sub>st</sub>(SF<sub>6</sub>) of 23 kJ mol<sup>-1</sup>. The opposite occurs for SF<sub>6</sub> on **Zr\_TFA\_NH<sub>2</sub>**, where the Langmuir behavior of the isotherm at low relative pressure is strong: the adsorption branch is very sharp and the desorption branch is broad in dynamic experiments. The SF<sub>6</sub>/CO<sub>2</sub> selectivity measured at 0.5 of partial pressure for the two samples shows an analogous trend as the calculated IAST selectivity at p<sub>tot</sub> = 0.5 bar. In comparative terms, both experimental and calculated evidence highlight that **Zr\_TFA\_NH<sub>2</sub>** is better than **Zr\_TFA\_PyPy** to achieve an efficient SF<sub>6</sub>/CO<sub>2</sub> separation.

#### 3.4. DFT analysis of the interaction of **Zr\_TFA\_NH<sub>2</sub>** and **Zr\_TFA\_PyPy** with CO<sub>2</sub> and SF<sub>6</sub>

To cast light on the **Zr\_TFA\_NH<sub>2</sub>** and **Zr\_TFA\_PyPy** adsorption sites, we modelled the interaction of CO<sub>2</sub> and SF<sub>6</sub> in the pores of the microporous materials using the complementarity of the electrostatic potential map (EPM), shown in Fig. S14 for both hosts and guests. A closer look at the MOFs highlights electrophilic (blue, positive) regions located around the [Zr<sub>6</sub>O<sub>4</sub>(OH)<sub>4</sub>]<sup>12+</sup> moiety of the Inorganic Building Unit (IBU) and nucleophilic (red, negative) spots represented by the nitrogen atoms of the functionalised BDC-NH<sub>2</sub><sup>2-</sup> and PyPy<sup>2-</sup> organic linkers and carboxylate/TFA<sup>-</sup> groups on the octahedral metallic nodes. The PBEsol0-3c results for the adsorption of SF<sub>6</sub> and CO<sub>2</sub> on **Zr\_TFA\_NH<sub>2</sub>** and **Zr\_TFA\_PyPy** are listed in Table S2 and S3 in the SI. For **Zr\_TFA\_NH<sub>2</sub>**, the predicted adsorption energies are in good agreement with the experimental heats of adsorption (Q<sub>st</sub>). For SF<sub>6</sub>, the strongest binding site is located at the μ<sub>3</sub>-OH groups of the MOF IBU (Fig. 6) through an O–H···F–S hydrogen bond with a ΔE of –37.05 kJ mol<sup>-1</sup> (vs. experimental Q<sub>st</sub> = 31 kJ mol<sup>-1</sup>); additional weak π···F–S short contacts between the aromatic π cloud of BDC-NH<sub>2</sub><sup>2-</sup> and SF<sub>6</sub> are present, together with S–F···F–C interactions between SF<sub>6</sub> and the CF<sub>3</sub> group of TFA<sup>-</sup>. For CO<sub>2</sub>, the primary adsorption



**Fig. 6** Portion of the optimized PBEsol-03c geometry for [SF<sub>6</sub>@**Zr\_TFA\_NH<sub>2</sub>**] in the preferential adsorption site. The main gas-framework distances (Å) are reported. Atom color code: Zr turquoise, O red, C grey, H white, N blue, S yellow and F green.



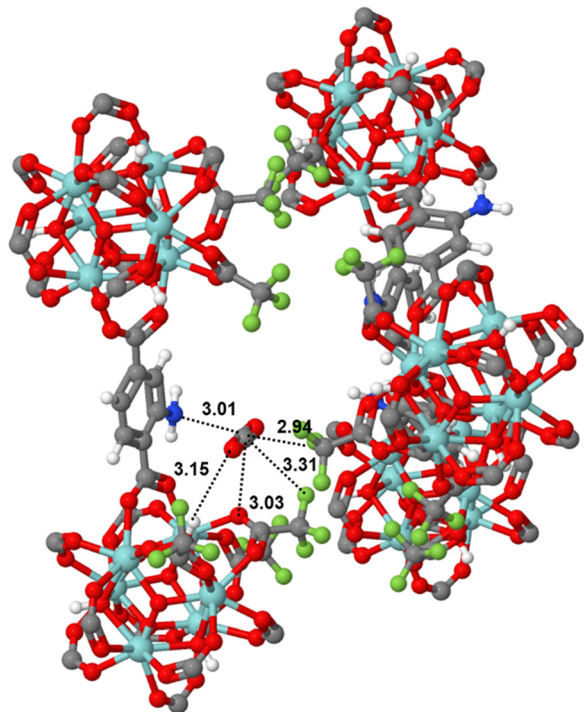


Fig. 7 Portion of the optimized PBEsol0-3c geometry for  $[\text{CO}_2@Zr\text{-TFA-NH}_2]$ . The main gas-framework distances (Å) are reported. Atom color code: Zr turquoise, O red, C grey, H white and N blue.

site is represented by the functionalized  $\text{BDC-NH}_2^{2-}$  linker (Fig. 7) where the basic  $-\text{NH}_2$  tag interacts with the acidic carbon atom of carbon dioxide providing a binding energy of  $-33.22 \text{ kJ mol}^{-1}$  (vs. the experimental  $Q_{\text{st}}$  of  $29 \text{ kJ mol}^{-1}$ ). Additional multiple weak interactions of both  $\text{O}=\text{C}=\text{O} \cdots \text{H}-\text{O}$  and  $\text{O}_2\text{C} \cdots \text{F}-\text{C}(\text{TFA}^-)$  type are also at work. In  $Zr\text{-TFA-PyPy}$ ,  $\text{SF}_6$  has the same binding sites as those observed in  $Zr\text{-TFA-NH}_2$ , the main being again the  $\mu_3\text{-OH}$  groups of the MOF IBU (Fig. 8).  $\text{CO}_2$  interacts *via* its quadrupole with  $\text{PyPy}^{2-}$

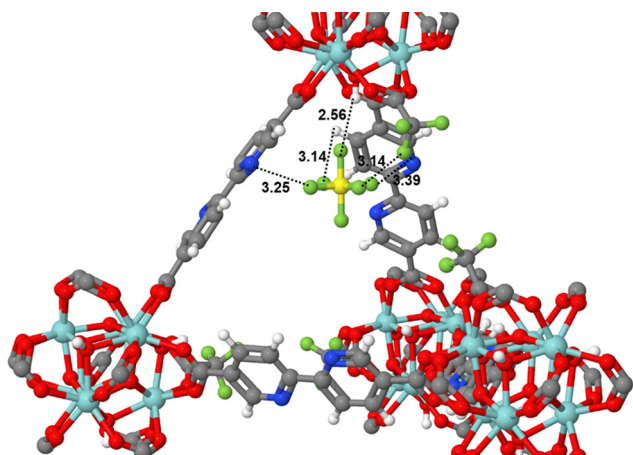


Fig. 8 Portion of the optimized PBEsol0-3c geometry for  $[\text{SF}_6@Zr\text{-TFA-PyPy}]$ . The main gas-framework distances (Å) are reported. Atom color code: Zr turquoise, O red, C grey, H white, N blue, S yellow and F green.

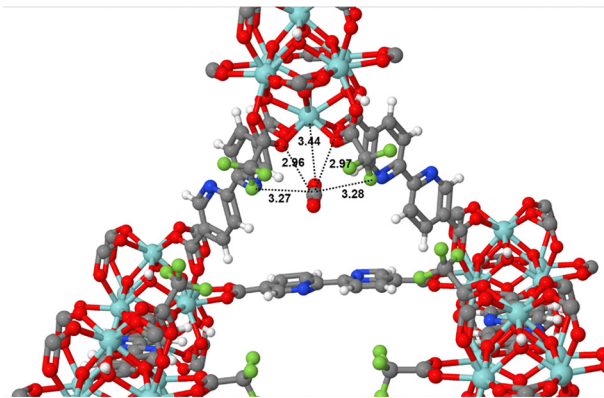


Fig. 9 Portion of the optimized PBEsol0-3c geometry for  $[\text{CO}_2@Zr\text{-TFA-PyPy}]$ . The main gas-framework distances (Å) are reported. Atom color code: Zr turquoise, O red, C grey, H white and N blue.

carboxylates, polarized by the presence of the strongly electron-withdrawing  $\text{CF}_3$  groups on  $\text{TFA}^-$ . Additional  $\text{O}=\text{C}=\text{O} \cdots \text{H}-\text{O}$  and  $\text{O}_2\text{C} \cdots \text{F}-\text{C}(\text{TFA}^-)$  contacts are found (Fig. 9). The calculated adsorption energies are  $-25.64 \text{ kJ mol}^{-1}$  for  $\text{SF}_6$  (vs. an experimental  $Q_{\text{st}}$  equal to  $23 \text{ kJ mol}^{-1}$ ) and  $-26.98 \text{ kJ mol}^{-1}$  for  $\text{CO}_2$  (vs. an experimental  $Q_{\text{st}}$  of  $28 \text{ kJ mol}^{-1}$ ). The interaction with the inorganic unit and the Zr atom is not site-specific; rather, it is averaged out by the surrounding atoms.  $\text{CO}_2$  occupies a more favourable location within a pocket where quadrupolar interactions occur, as shown in Fig. 9. Although the specific role of the  $\text{TFA}^-$  groups cannot be identified, they do contribute overall to the binding of the molecules due to the formation of short contacts with the fluorine atoms.

## Conclusions

This work demonstrates that combining basic and fluorinated linkers in the mixed-linker zirconium MOFs  $Zr\text{-TFA-NH}_2$  and  $Zr\text{-TFA-PyPy}$  effectively tunes their gas adsorption and separation behaviour towards  $\text{CO}_2$  and  $\text{SF}_6$ . The dual functionalization strategy yields materials that display enhanced thermodynamic affinity for  $\text{CO}_2$  compared to single-linker analogues. In addition, selective adsorption of  $\text{SF}_6$  over  $\text{CO}_2$  can be achieved in the smaller-pore  $Zr\text{-TFA-NH}_2$ , as confirmed by the dynamic breakthrough experiments. DFT analysis provided a molecular-level understanding of how pore size and functional group distribution govern adsorption energetics and selectivity. The results highlight the potential of these materials as scalable (given the commercial availability of their constituting linkers) adsorbents for discriminating between gases of different polarity and size, relevant to environmental applications such as capture of greenhouse gases from flue gases or industrial processes or separation of gas mixtures in energy-efficient processes. Future development currently undergoing in our labs will include further tuning of MIXMOFs pore environment to target specific gas pairs of environmental concern.



## Author contributions

G. P., G. B., C. Z., F. C., F. R., F. B.: investigation, formal analysis; B. C., G. G., G. T.: validation; L. D.: investigation, formal analysis, methodology, software, writing – original draft; A. R.: conceptualization, funding acquisition, project administration, supervision, writing – original draft.

## Conflicts of interest

The authors have no conflicts of interest to declare.

## Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information: quantitative  $^1\text{H}$ - and  $^{19}\text{F}$ -NMR spectroscopy on the digested samples, additional characterization data (IR spectra, details of the BT calculations, FE-SEM images and related EDX analysis, TG-DTG-MS traces, micropore size distribution) and computational details (electrostatic potential maps). Comparative tables of  $\text{SF}_6$  and  $\text{CO}_2$  adsorption performance and of calculated interaction energies vs. experimental isosteric heats of adsorption. See DOI: <https://doi.org/10.1039/d6ma00018e>.

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