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Porous materials for carbon dioxide separations

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Global investment in counteracting climate change has galvanized increasing interest in carbon capture and sequestration (CCS) as a versatile emissions mitigation technology. As decarbonization efforts accelerate, CCS can target the emissions of large point-source emitters, such as coal- or natural gas-fired power plants, while also supporting the production of renewable or low-carbon fuels. Furthermore, CCS can enable decarbonization of difficult-to-abate industrial processes and can support net CO_2 removal from the atmosphere through bioenergy coupled with CCS or direct air capture. Here we review the development of porous materials as next-generation sorbents for CO_2 capture applications. We focus on stream- and sector-specific challenges while highlighting case studies within the context of the rapidly shifting energy landscape. We conclude with a discussion of key needs from the materials community to expand deployment of carbon capture technologies.

Driven by economic and population growth, global CO_2 emissions from fossil fuel combustion have more than doubled since the 1970s and now exceed 32 Gt of CO_2 per year[1,2]. As a result, human activities have contributed to an estimated increase of 0.8–1.2 °C in global temperature since pre-industrial levels, and the Intergovernmental Panel on Climate Change (IPCC) anticipates that current trends will lead to 1.5 °C of warming by 2030 to 2052[3]. Warming at these levels has been correlated with a number of increased risks for people, economies and ecosystems, including sea-level rise, extreme weather events, species extinction, and threats to human health, security, food and water[3]. Facing these challenges will require political, economic and technological investment at a global scale towards the rapid deployment of decarbonization strategies. The materials community can play a critical role in these efforts through the development of new technologies for efficient management of carbon emissions.

In particular, carbon capture and sequestration (CCS)—in which CO_2 is selectively captured and permanently stored underground—has been recognized as a vital component of strategies to limit warming below 2 °C (refs. [1,4,5]). Industrial development of carbon capture technology dates to the 1930s, when aqueous amine scrubbing was first patented for the selective removal of CO_2 from crude natural gas[6]. Supported largely by economic incentives related to enhanced oil recovery, CO_2 transport and storage have also already achieved commercialization[4]. However, deployment of commercial-scale CCS projects specifically for the purposes of emissions mitigation has been slow. At the time of writing, the Global CCS Institute lists 65 commercial CCS facilities, with 26 in operation[7]. These facilities can currently capture and sequester approximately 40 million tons per annum (Mtpa) of CO_2, with the potential for an ultimate combined capacity of >100 Mtpa (ref. [8]). Although this ultimate capacity addresses a modest 0.3% of global annual emissions, the contributions of these established commercial-scale operations can catalyse broader adoption of CCS during this critical period of accelerated decarbonization. For an excellent broader discussion of the current status of CCS, including remaining commercial and political barriers, we refer readers to a recent comprehensive review[4].

Research efforts towards CCS have largely focused on post-combustion capture from fossil fuel-fired power plants, which are attractive targets due to their emission of large quantities of CO_2 at relatively high concentrations (~4–15%)[9]. Indeed, in 2017, the production of electricity and heat generated 41% of global CO_2 emissions (Fig. 1), and thus decarbonization of the power sector is critical to mitigating emissions[2]. Beyond fossil fuel sources, CCS can additionally be coupled with bioenergy production, potentially enabling the net removal of CO_2 from the atmosphere ('negative emissions') in a process termed bioenergy with carbon capture and sequestration (BECCS). Furthermore, CCS can support the production of renewable or lower-carbon fuels. The industrial sector, which contributes 24% of global CO_2 emissions (Fig. 1)[2], also offers a number of opportunities for decarbonization in cement production, oil refineries, iron and steel mills, and the pulp and paper industry. Finally, direct air capture (DAC) of CO_2 can provide an additional strategy for negative emissions[10]. The role of CCS in the rapidly evolving decarbonization landscape is discussed in greater detail in Box 1, with a particular focus on difficult-to-abate sectors that may be well suited to adsorptive CO_2 capture.

Aqueous amine solutions, which capture CO_2 through the reversible formation of carbamate or bicarbonate species, remain the most technologically advanced capture systems. Despite their proven performance at commercial scale, amine solutions suffer from volatilization and oxidation as well as corrosivity, which necessitates dilute solutions that require energy-intensive regeneration due to the large volume of inert water that must be thermally cycled[11]. As a result, the capture step in an aqueous amine-based CCS process at a coal-fired power plant currently comprises 60–80% of the total cost of CCS, which encompasses capture, compression, pipeline transport and underground storage of CO_2 (ref. [12]). Ongoing research in amine absorption has led to energy savings through the use of new amines or blends of amines, corrosion inhibitors, promoters or catalysts to enhance the absorption rate, and thermal integration within a plant; nonetheless, only incremental improvements in overall process efficiency are anticipated for solvent-based processes moving forward[12]. To overcome these limitations, several new capture technologies have been reported for CCS in recent years. Although at an earlier stage of development, water-lean solvents[13], membranes[14], metal oxides[15] and encapsulated liquid sorbents[16] may offer means to increase the efficiency of CCS. As another alternative, porous materials have received growing attention due to their potential to achieve intrinsically lower energy consumption than amine solutions

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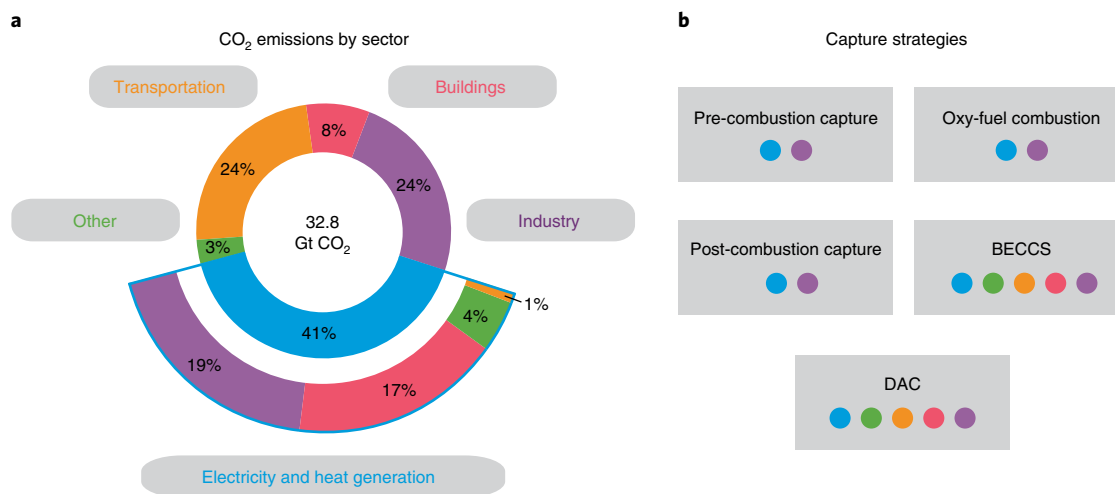
Fig. 1 | Emission sources and capture strategies. a, Global CO_2 emissions by sector in 2017, with emissions due to electricity and heat generation further reallocated by end-use sector (purple, pink, orange and green represent industry, buildings, transportation and other sectors, respectively)[2]. Emissions from the industrial sector also include energy industry own-use emissions resulting from the extraction, refining, mining or manufacture of fuels. The 'other' sector encompasses emissions from commercial and public services, agriculture and forestry, and fishing. **b**, Capture strategies suitable to target emissions from each sector. BECCS and DAC processes can indirectly target emissions from all sectors through net CO_2 removal from the atmosphere. Figure adapted with permission from ref. [2], IEA.

in CO_2 capture processes[17], with a reduction of up to 30–40% in parasitic energy projected for adsorptive versus absorptive carbon capture processes at coal-fired power plants[18]. Adsorbents offer a number of other potential advantages in carbon capture processes: pore size and shape act as additional handles to fine-tune capture chemistry in the solid state; adsorbents and cycling configurations can be varied to target a wide range of thermodynamic conditions; and toxic or corrosive volatiles emitted from amine absorption units can be avoided with dry capture systems[4]. In this Review, we discuss the state of the art in CO_2 capture with porous materials, beginning with an overview of the primary adsorbent classes. We then examine individual target separations with a focus on remaining technological barriers to deployment, such as contaminants that can act as adsorbent poisons. Throughout the latter section, we highlight recent developments in materials design towards overcoming stream-specific CCS challenges. We then conclude with a discussion of critical needs from the materials community to drive continued progress in this area.

Overview of adsorbent classes

A wide array of porous inorganic, organic and inorganic–organic hybrid structures have been proposed for adsorptive CO_2 capture (Fig. 2). Key metrics for evaluating the utility of an adsorbent include; the CO_2 selectivity of the adsorbent in the presence of all mixture components, the CO_2 swing capacity of the adsorbent in adsorption–desorption cycling, the kinetics of adsorption and desorption, the energy required to cycle or regenerate the adsorbent, the stability of the adsorbent to chemical and mechanical stresses during extended cycling, and the economic and environmental viability of the adsorbent in a cradle-to-grave lifecycle assessment. Ultimate evaluation of an adsorbent requires analysis of a structured material (for example, pellets, fibres, monoliths) within a full-scale process, with a number of possible cycling configurations (for example, temperature swing, pressure or vacuum swing, concentration swing) and adsorption unit configurations (for example, fixed bed, fluidized bed, rotating bed). Although these engineering considerations are critical to the overall process efficiency, we focus here on recent developments in the optimization of the fundamental adsorbent design for carbon capture. The primary adsorbent classes evaluated

for carbon capture so far are reviewed below, and adsorbent selection criteria are discussed in greater detail in Box 2.

Activated carbons. Activated carbons (Fig. 2a) are among the most industrially mature adsorbents, with applications in air and water purification, solvent recovery systems, and decolorization of sugar and other products through the removal of trace organic species[19]. Preparation of activated carbon involves pyrolysis of biomass followed by high-temperature activation (typically at 700–1,100 °C) using physical agents including steam, CO_2, O_2 or other gases[19]. Alternatively, chemical activation agents can be used to access higher surface areas or incorporate specific surface functionalities, such as nitrogenous groups to increase basicity[19,20]. Porosity in activated carbons is generated through random stacking of microcrystalline graphite domains and can be controlled through modulation of the pyrolysis and activation conditions[19]. Because they can be prepared from low-cost, environmentally benign feedstocks, such as waste biomass[20], these materials are attractive candidates from an adsorbent lifecycle perspective. Furthermore, given their generally non-polar, hydrophobic surfaces, activated carbons can capture CO_2 in the presence of moisture and minimize regeneration energy costs associated with adsorption–desorption cycling of water[21]. However, the non-polar adsorbent surface also limits the equilibrium CO_2/N_2 selectivity and CO_2 capacity of typical carbons at conditions relevant to CO_2 capture from flue gases ($\leq$15% CO_2)[21]. As a result, cost savings achieved with inexpensive, low-enthalpy carbonaceous adsorbents must be balanced with the potential requirements of increased adsorbent bed size and/or shorter cycle times.

Zeolites. Zeolites (Fig. 2b) have likewise reached a state of maturity for industrial separations[22]. The commercialization of these aluminosilicate materials has been facilitated by their high degree of stability, a result of their strong constituent tetrahedral Al–O and Si–O bonds[23]. This stability has in turn supported the processing of zeolites into industrially viable structured forms, such as pellets. Furthermore, the crystalline nature of zeolites has enabled computational screening of known and predicted structures to identify optimal architectures for specific separations[18,24]. Zeolites for carbon capture often achieve equilibrium selectivity for CO_2 through the interaction of the CO_2

Box 1 | The role of CCS in cross-sector decarbonization

The start of the 2020s has led to a flurry of decarbonization activity as parties within the Paris Agreement execute their nationally determined contributions. China, the world's largest greenhouse gas emitter, has committed to reaching peak emissions before 2030 and carbon neutrality by 2060[140]. The United States, the second-largest emitter, has rejoined the Paris Agreement and committed to decreasing overall greenhouse gas emissions to 50–52% below 2005 levels by 2030, while targeting 100% carbon-free electricity by 2035 and economy-wide net-zero emissions by 2050[141]. Roadmaps to meet these commitments focus heavily on massive mobilization of renewable energy technologies coupled with rapid electrification of transport, buildings and industry. What is the outlook for carbon capture within this fast-moving transition?

The power sector is the crux of the net-zero transition, and recently plunging costs of wind and solar energy have shifted the economics of decarbonized electricity. In the United States, an illustrative recent report outlined a path to 90% carbon-free electricity by 2035 that would reduce wholesale electricity costs by 10% versus 2020 levels while supporting a greater number of jobs versus a business-as-usual case[142]. Such a plan would require strong policy—which the authors advocate for in the form of a staged federal clean electricity standard[143]—as well as a highly aggressive build-out of 1,100 GW (70 GW per year) of new wind and solar capacity[142]. (Comparatively, ~34 GW of wind and solar capacity was installed in the United States in 2020[144]. In China, the record one-year capacities for wind and solar expansion sum to 84 GW; ref. [144]). While US utility companies have begun making net-zero pledges, current resource plans from utility companies are largely not keeping pace with the necessary shift away from fossil energy. A recent study of 79 US operating companies that generate 43% of US electricity found that these companies plan to add over 36 GW of new gas capacity by 2030 while retiring only 25% of their coal generation[145]. This energy system inertia follows from the >100 GW of new gas capacity added in the United States in the past decade[145]. Policy shifts could dramatically alter this trajectory, but even plans with aggressive deployment of wind and solar often lean on existing natural gas assets to smooth periods of high demand or low renewables output, particularly in the near term[142,144]. New technologies, such as long-duration storage, could help bridge the gap to 100% carbon-free electricity while reducing curtailment of intermittent energy sources. However, CCS can provide a tool to address both the inertia of the current energy system and the final gap to a fully carbon-free grid. Given the scale of power plant emissions and the compressed timeline needed for carbon-free electricity, widespread CCS in the power sector would require well understood, inexpensive and imminently scalable materials. (See Box 2 for further discussion.)

Considering decarbonization of transport and buildings, rapid electrification will lead the transition to net-zero emissions: electric vehicles, electric heat and hot water, and electric appliances must replace fossil fuel-consuming counterparts. However, certain subsets of these sectors will prove more difficult to decarbonize, such as aviation, shipping and heavy-duty trucking. Carbon capture could contribute to decarbonization in these sectors through the use of DAC- or biomass-sourced CO_2 for carbon offsets (via sequestration) or carbon-neutral fuel production[146], or through the production of 'blue hydrogen' via steam reforming of natural gas coupled with CCS. ('Green hydrogen', generated by renewable-powered electrolysis of water, is a cleaner alternative when and where it can be produced cost-competitively.) The smaller niche, more limited optionality and longer projected transition timeline for difficult-to-electrify subsectors may support earlier-stage materials development for CCS in these areas.

Several areas of industry will also likely prove difficult to abate with electrification alone. In contrast to the power sector, which operates within controlled regional markets, heavy industry must compete in global commodity markets with extremely thin margins[147]. Industrial facilities require large capital investments with decades-long lifetimes, and profitability hinges on maximizing capacity factors and minimizing downtime. As a result, fossil energy is abundant in heavy industry due to its ability to provide high-temperature and high-flux heat with both a steady supply and low cost. Low-carbon replacement options are limited, particularly for the highest-temperature ($\geq$1,200 °C) processes in the steel and cement industries, and the path to net-zero is not yet clear. In a recent evaluation of decarbonization strategies for heat in heavy industry, CCS was generally found to hold the greatest technical and economic feasibility compared with alternatives such as blue or green hydrogen, electrification via resistive heating, biomass or advanced nuclear processes[147]. In addition, CCS will likely be favoured to address emissions generated as by-product streams within industrial processes[148]. While alternative processes that minimize liberated carbon are under development, producers of structural materials are extremely conservative when considering any changes that could impact the physical properties of their products. Overall, given the large abatement potential, concentrated CO_2 point sources, limited optionality and earlier stage of decarbonization, the industrial sector is a particularly promising area for adsorptive CCS. Growing investment from the materials community is needed in this area.

Beyond these sectors, negative emissions technologies, such as DAC, remain at the forefront of decarbonization discussions. The technological challenges associated with CO_2 capture from ultradilute streams are discussed in the main text, but non-technological factors are also shaping the future of DAC. In recent years, the negative emissions space has seen an outpouring of public and private sector support, including government research and development funding, tax credits, venture capital, and voluntary financial commitments from large multinational corporations. Furthermore, negative emissions approaches are featured prominently in the recent IPCC report outlining pathways to keep warming below 1.5 °C (ref. [3]). In addition to financial and policy incentives, the greater flexibility in deployment timeline and scale for negative emissions technologies makes DAC amenable to exploratory materials research and commercialization of new breakthrough technologies.

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quadrupole moment with exposed metal cation sites within the pores[25,26]. While such equilibrium selectivity is effective for the removal of CO_2 from dry emission or process streams, this selectivity is often lost in the presence of water, which outcompetes CO_2 in coordinating exposed metal sites[21,27,28]. Because gas streams of interest for CCS are often saturated with water, continued development of zeolites for CCS will benefit from new design motifs, such as amine-impregnated organic/inorganic hybrids, that preserve CO_2 capacity and selectivity

in its presence. Alternatively, while pre-drying CCS process streams is likely to be cost prohibitive[29], other innovative process configurations, or separations leveraging differences in mass transport of guest species through the pores, may afford viable engineering solutions for CO_2 capture from humid streams.

Amine-functionalized silicas. As with amine solutions, polyamine-functionalized silicas (Fig. 2c) leverage the selective
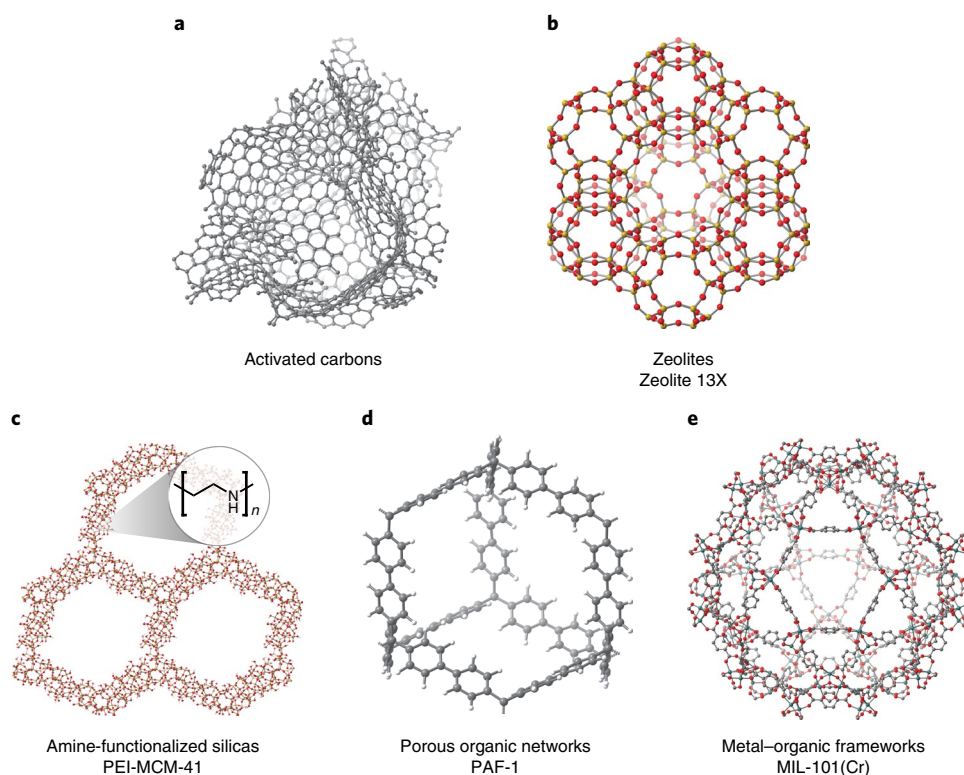
Fig. 2 | Illustrative examples of adsorbent classes discussed in this work. a, Activated carbons[135]. **b**, Zeolites, represented by zeolite 13X (base faujasite cage structure shown; Na^{+} ions omitted for clarity)[136]. **c**, Amine-functionalized silicas, represented by PEI-MCM-41 (PEI, polyethylenimine; MCM, Mobil Composition of Matter)[137]. **d**, Porous organic networks, represented by PAF-1 (also known as PPN-6; PAF, porous aromatic framework; PPN, porous polymer network). The structure depicts one possible local environment within the amorphous material[138]. **e**, Metal–organic frameworks, represented by MIL-101(Cr) (Cr$_3$O(bdc)$_3$F; MIL, Matérial Institut Lavoisier; bdc^{2-}, 1,4-benzenedicarboxylate)[139]. In **a–e**, yellow, red, grey, green and white spheres represent Al/Si, O, C, Cr and H atoms, respectively.

acid–base chemistry of amines, enabling effective CO_2 capture from humid streams[11,30]. Through the use of a solid support in place of an aqueous solvent medium, energetic costs associated with heating the solvent can be avoided, potentially enabling more efficient capture processes. Polyamines can be physically impregnated (class 1) or covalently grafted (class 2) to the silica support[30], and selectivity is achieved through the formation of ammonium carbamate, carbamic acid or bicarbonate species, with the product distribution varying as a function of amine identity, amine proximity to adjacent amine groups and water content[31]. To achieve full-scale CCS processes with amine-functionalized silicas, chemical or engineering solutions are needed to overcome common limitations of amine chemistry, such as leaching of amines from class 1 materials and amine deactivation via oxidation or urea formation[30,32].

Porous organic networks. Purely organic porous networks, such as amorphous porous polymers (Fig. 2d) or crystalline covalent organic frameworks, can be synthesized from multitopic organic monomers[33–35]. Although these materials are at an earlier stage of development, they afford a high degree of chemical tunability, as well as the potential for high gravimetric and volumetric capacities due to the use of light constituent elements. Covalent linkages within these frameworks can further provide a high degree of hydrothermal stability[36], and CO_2-targeting functional groups such as amines can be incorporated directly into the polymer backbone, thereby mitigating volatilization concerns. Advances in the technology readiness of this class of materials will require greater characterization of stability and CO_2 selectivity under simulated process streams, as well as the development of scalable syntheses and structured forms suitable for commercial use.

Metal–organic frameworks. Metal–organic frameworks (Fig. 2e) are a class of crystalline, porous materials constructed from inorganic ions or clusters joined by multitopic organic ligands[37,38]. Through pre- or post-synthetic modification, a high degree of control can be exerted over the pore size, shape and surface chemistry. The development of metal–organic frameworks for CO_2 capture applications has largely focused on the use of charge-dense adsorption sites, such as coordinatively unsaturated metal cations, to select for CO_2. However, as with cationic binding sites in zeolites, these adsorption sites are prone to water passivation in carbon capture applications involving humid process or emission streams[21,39]. Accordingly, frameworks with CO_2-binding functionalities, such as amines, have gained increasing attention in recent years[40,41]. Alternatively, stable and scalable frameworks that maintain partial CO_2 capacity following water adsorption may offer a rapid pathway to commercialization[42]. Functionalization with hydrophobic groups can likewise improve capture performance from humid streams[43]. The success of metal–organic frameworks in commercial carbon capture applications further necessitates a focus on materials with earth-abundant constituent metals and scalable synthetic routes. In addition, candidate materials must have suitable hydrothermal stability of the labile metal–ligand coordination bonds[44], as well as oxidatively robust metal nodes and organic constituents. Ongoing work is needed to evaluate these materials under more realistic process conditions and to develop pellets, monoliths, fibres or other industrially viable structured forms[45,46].

Box 2 | Sorbent selection considerations

The choice of adsorbent strongly influences both capital and operating costs in a carbon capture process. Considering capital costs, adsorption columns and associated equipment will be sized according to gas equilibria and kinetics within the material: adsorbents that bind and release greater quantities of CO_2, and at faster rates, may enable smaller columns. However, for materials with high sorption enthalpies, additional capital investment may be required to ensure that the capture equipment can effectively control thermal excursions. High enthalpies may likewise drive operating costs by requiring time- and resource-intensive heating and/or cooling. The stability of an adsorbent can also influence capital and operating costs by driving investment in pretreatment technologies and dictating adsorbent replacement rates. More expensive materials may be justified if a long sorbent lifetime can be achieved without extensive pretreatment. Nonetheless, given the sorbent quantities needed to achieve impactful emissions mitigation, every effort must be made to minimize the cost, deployment timeline, and environmental footprint of large-scale synthesis, shaping and end-of-life processes for any CCS material. Trade-offs in key sorbent selection criteria are captured in the figure for various sorbent classes.

Examining the strengths and weaknesses of various carbon capture sorbents raises key questions towards resource allocation in deploying emissions mitigation technologies. Given the broad range of capture conditions for different CO_2-containing streams, and even within a single class of emissions or process streams (Table 1), should researchers optimize capture processes around a limited set of materials, or rather optimize individual materials for each process, or even each plant? Greater process efficiency may be possible with sorbents purpose-built for specific CCS separations. However, the high cost to de-risk the production, use and disposal/recycle of new materials at CCS-relevant scales favours a focus on a minimal number of inexpensive, well understood sorbents. In practice, viable solutions will require a degree of versatility in both the materials and process design. Close collaboration between materials scientists and process engineers will accelerate identification of optimal paths forward.

The scale and urgency of each carbon capture opportunity should also drive decision-making in the CCS community. Average annual CO_2 emissions per sector and source are provided in the table below. At present, fossil fuel-fired power plants are the largest point-source emitters of CO_2 and have thus attracted the majority of CCS research attention. The scale of these emissions would need to be met with a proportionate response in materials production. For example, a 2013 study projected that capturing 90% of the CO_2 from all coal-fired power plants in the United States (annual emissions of 1.97 $GtCO_2$) with a metal–organic framework would require production of 1.5 million tons of adsorbent per year[115]. The authors demonstrate the high sensitivity of their estimates to the adsorption/desorption cycle time (taken as 60 min) and the lifespan of the adsorbent (taken as 8,000 cycles), with a projected consumption rate of 0.7 kg adsorbent per tCO_2 captured[115]. (Comparatively, solvent consumption rates for absorptive CCS processes are estimated as 0.2–1.6 kg per tCO_2, with the Mitsubishi Heavy Industries hindered amine KS-1 at the low end, and Fluor's ECONAMINE at the high end[125]). Production and disposal or recycle of materials at this scale would require rapid, massive mobilization if adsorptive CCS efforts are to contribute to keeping warming below 2 °C.

As decarbonization efforts in the power sector accelerate, unavoidable industrial emissions, such as those from cement production, will assume a greater proportion of overall emissions. The adsorption community will therefore benefit from increased investment in these enduring yet understudied CCS challenges. Likewise, CCS opportunities in BECCS and DAC will persist as well.
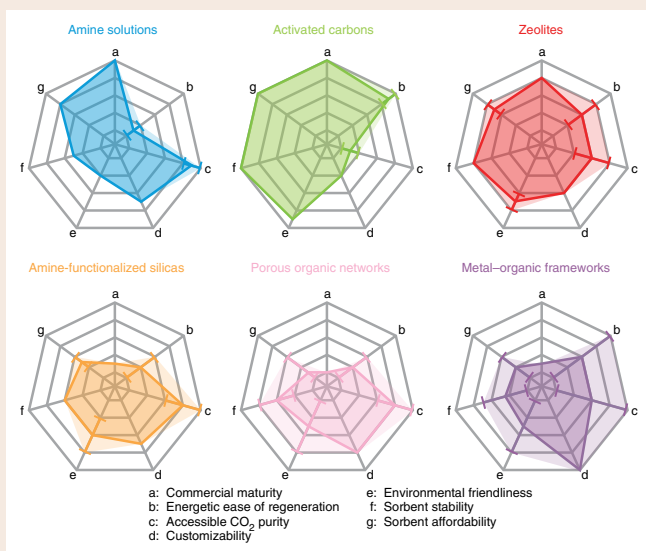
Radar charts for key sorbent selection criteria. Qualitative assessment of key metrics for materials selection in carbon capture applications. Bold lines indicate average values for each property within a materials class, with error bars indicating typical variability for a given property within that class.

Global annual total emissions and average emissions per source for CO_2-containing streams

Process	Global emissions[2,149] ($MtCO_2$ yr^{-1})	Average emissions/source[125] ($MtCO_2$ yr^{-1})
Power sector (as of 2017)		
Coal	9,761	3.94
Natural gas	2,975	0.77–1.01
Industry (as of 2014)		
Cement	2,545	0.79
Refineries[a]	950	1.25
Iron and steel[a]	3,487	3.67

[a]For annual average substream emissions within a representative refinery or 2 Mt integrated steel mill, see ref. [93].

Target separations and case studies

As shown in Table 1, potential target streams for CCS contain CO_2 concentrations spanning several orders of magnitude. Opportunities for adsorptive CCS from individual streams are discussed in greater detail below, along with recent advances in materials design towards overcoming stream-specific challenges.

The power sector. The production of electricity and heat is responsible for 41% of global annual CO_2 emissions (Fig. 1) and is therefore a primary focus of CO_2 emission mitigation efforts[2]. A number of potential separation strategies may be used to reduce or eliminate CO_2 emissions from thermal power plants, such as pre-combustion, oxy-fuel combustion and post-combustion capture, as well as

Pre-combustion capture

Oxy-fuel combustion

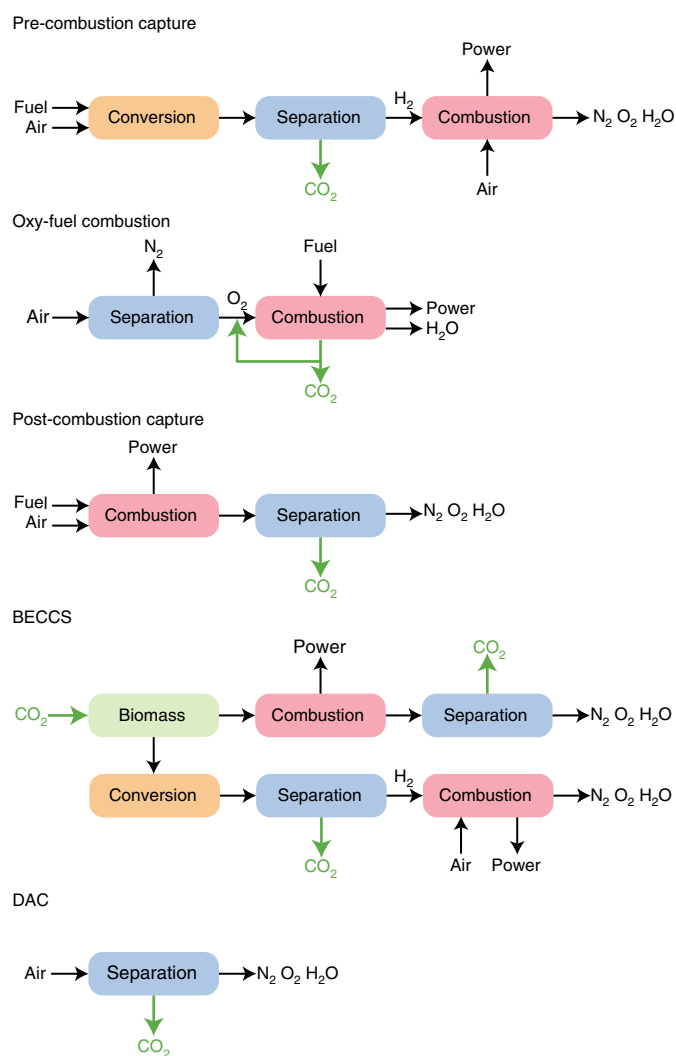Post-combustion capture

BECCS

DAC

Fig. 3 | Carbon capture configurations. Strategies for carbon capture in the power sector include pre-combustion, oxy-fuel combustion and post-combustion capture from fossil fuel-fired power plants, as well as BECCS and DAC. Processes for BECCS are further subdivided into pre- and post-combustion strategies.

BECCS and DAC (Fig. 3)[17]. In pre-combustion capture, synthesis gas (or syngas, consisting of a mixture of H_2 and CO) is produced from gasified fuel and sent to a shift reactor, which oxidizes CO to CO_2 and reduces H_2O to produce additional H_2. The resulting CO_2/H_2 mixture is then separated into H_2 for fuel and CO_2 for subsequent compression and sequestration. In oxy-fuel combustion, pure oxygen is used in place of air during the combustion of a hydrocarbon fuel, resulting in a flue gas containing only CO_2 and easily condensable H_2O. In the latter scenario, the majority of energy is consumed in the initial separation of O_2 from N_2 in air. Here we focus on post-combustion CO_2 capture, in which CO_2 is removed from a flue gas containing primarily N_2, O_2, H_2O and CO_2.

Coal-fired power plants. Although coal is the second-largest fossil fuel energy source after crude oil, it is the largest contributor to global CO_2 emissions as a result of its heavy carbon intensity (87–109 tCO_2 TJ^{-1}, versus 54–58 tCO_2 TJ^{-1} for natural gas)[2,47]. For example, in 2017, coal supplied 27% of global primary energy while generating nearly 50% of global CO_2 emissions[2]. Accordingly, coal-fired power plants have garnered considerable attention in

the CCS community. A typical coal-fired power plant emits a flue gas stream at ambient pressure that can be cooled to ~40–60 °C and contains 70–75% N_2, 10–15% CO_2, 8–10% H_2O, 3–4% O_2, and trace SO_x, NO_x and other impurities[12]. The relatively high concentration of CO_2 in the flue gas stream is favourable for adsorptive CO_2 capture. Importantly, the primary challenge for adsorptive post-combustion carbon capture from coal-fired plants is not typically separation of CO_2 from N_2, but instead the selective capture of CO_2 in the presence of H_2O and other contaminants. As mentioned above, water has long been known to outcompete CO_2 to coordinate at exposed metal cations, which are often the primary adsorption sites in zeolites and metal–organic frameworks with equilibrium selectivity for CO_2 over N_2 (refs. [21,28,39]).

In a recent evaluation of 15 activated carbons, zeolites, mesoporous silicas and metal–organic frameworks, only adsorbents functionalized with alkylamines maintained appreciable CO_2 capacity in ternary ($CO_2/N_2/H_2O$) equilibrium experiments simulating a coal flue gas[21]. Of these adsorbents, the metal–organic framework mmen–Mg_2(dobpdc) (mmen, N,N'-dimethylethylenediamine; dobpdc^{4-}, 4,4′-dioxidobiphenyl-3,3′-dicarboxylate) was identified as particularly promising[48]. This material features step-shaped CO_2 adsorption isotherms resulting from cooperative, reversible insertion of CO_2 into the metal–amine bonds to form chains of ammonium carbamate along the pore axis[49]. Incorporation of the diamine 2,2-dimethyl-1,3-diaminopropane (dmpn) in place of mmen was subsequently found to shift the cooperative adsorption pressure to an optimal range for coal flue gas capture and to improve the stability of the material substantially[50]. In a related approach, the metal–organic frameworks $M^{II}M^{III}$(OH)Cl$_2$(bbta) (M, Mn, Co; H_2bbta, 1H,5H-benzo(1,2-d:4,5-d')bistriazole) were found to capture large quantities of CO_2 under simulated coal flue gas conditions through the reversible formation of metal-bound bicarbonate at surface sites bearing monodentate hydroxide ligands[51]. Likewise, incorporation of amines within the organic linkers of metal–organic frameworks has been demonstrated as an effective strategy to achieve selective CO_2 capture under humid conditions[52]. Furthermore, amine-functionalized silicas have long been valued for their ability to bind CO_2 selectively in the presence of water, and these materials often exhibit improved CO_2 capture performance under humid conditions due to bicarbonate formation[30,53]. Amine-functionalized zeolites have also been demonstrated to enable CO_2 capture from humid streams[54–58]. As a notable recent example, a chemically grafted ethylenediamine-Y zeolite was shown to have high thermal stability to 180 °C, resistance to urea formation and CO_2 selectivity in the presence of water[54]. As water-tolerant adsorbents advance towards commercialization, the most efficient materials must not only maximize the quantity of CO_2 cycled but also minimize the energetic sink of any co-cycled water[59,60].

In tandem with experimental efforts, computational approaches have become increasingly powerful screening tools. A recent survey of 325,000 hypothetical metal–organic framework structures led to the identification of a physisorptive binding pocket for CO_2, consisting of aromatic rings 6.5–7.0 Å apart, that minimizes the binding energy of water by hindering the formation of hydrogen-bonding networks[61]. Indeed, two aluminium-based frameworks synthesized with the computationally identified binding pocket showed modest, stable CO_2 working capacities from humid simulated coal flue gas over ten cycles[61]. Continued partnership between computational and experimental researchers will accelerate sorbent development and can potentially unlock new advantageous CO_2 binding modes[62].

Another key challenge for post-combustion capture from coal-fired power plants is the presence of SO_x, NO_x, Hg and particulate matter in the flue gas stream. In a comprehensive two-part investigation, class 1 and class 2 aminosilica materials were found to be unaffected by NO but irreversibly bound NO_2 at high concentrations (200 ppm, 35 °C) to form nitrates, resulting in a

Table 1 | Representative CO_2 concentrations and stream-specific challenges for various process and emission streams

Crude stream properties	Units	Power plant flue gas				Crude biogas		Industrial process streams			Air
		Coal-fired boiler	Natural gas-fired boiler	NGCC	Biomass-fired boiler (willow wood)	Anaerobic digester biogas	Landfill biogas	Blast furnace gas (integrated steel mill)	Cement kiln off-gas	Oil refineries/petrochemical plant fired heaters[a]	DAC
CO_2	vol%	10–15	7–10	3–4	13.1	30–50	25–47	22	18.9	8–9	0.041
N_2	vol%	70–75	67–72	76–77	51.4	2–6	<1–17	45	60.6	73	78
O_2	vol%	3–4	3	12	15.09	0–5	<1–3	0.2	7.7	3–4	21
H_2O	vol%	8–10	18–20	8	20.4	Saturated	Saturated	4–5	12.8	14–15	Varies with humidity
CH_4	vol%	–	–	–	–	48–68	30–65	–	–	–	–
SO_x[b]	ppmv	300–5,000	Minimal	Minimal	67	–	–	37	5–1,200	<15	–
NO_x[c]	ppmv	500–800	Varies	10–300	100	–	–	–	10–1,500	Not specified	–
H_2S[d]	ppmv	–	–	–	–	0–2000	30–500	26	–	Not specified	–
NH_3	ppmv	–	–	–	–	<100	0–5	–	–	–	–
Siloxanes	mg Nm^{-3}	–	–	–	–	<0.08–0.5	<0.3–36	–	–	–	–
Stream temperature[e]	°C	143 (raw), 56 (after FGD)	150	117	278 (raw), 60 (after FGD)	35–55	35–55	300	118	180 or 350	Ambient
Stream pressure	bar	1	1	1	1	1	1	2–3	1	1	1
Other concerns	–	Hg, HCl, particulates		Kinetics of dilute CO_2 capture	Variation in composition with biomass source; particulates, trace metals	Chlorinated compounds (<0.25 mg Nm^{-3})	H_2 (≤3%); chlorinated compounds (0.3–225 mg Nm^{-3})	CO (23%), H_2 (5%)	HCl (<10 mg Nm^{-3}); dust; lack of low-grade heat sources	Hg, HCl, particulates	Techno-economic challenges with ultradilute feed
References	–	9,12,122,123	124,125	9,122,123	79	126	126	93,125,127	122,125,128–130	93,125,131	99

aAssumes a heater fuel of 60% refinery gas/40% imported natural gas; temperatures correspond to forced (180 °C) or natural (350 °C) draft heaters[131]. bPre-desulfurization concentrations vary with sulfur content of feed. Commercial technologies typically remove 98–99% from coal flue gas, with a representative exit value of 37 ppmv following desulfurization via wet limestone forced oxidation[125]. For SO_x-sensitive sorbents, additional polishing scrubbers may be required to reduce SO_x levels to ~1 ppmv (ref.[b]). cConcentrations vary with burner design, process conditions and NO_x control strategies (for example, flue gas recirculation; selective catalytic or non-catalytic reduction) to satisfy local emissions regulations. In the United States, many states set limits for new gas boilers as <40 ppm NO_x, with some requiring <10 ppm on a dry volume basis (~0.05 lb MMBtu^{-1}, where MMBtu is million British thermal units)[132]. Mass-based units are preferred in industry to enable comparisons across different oxidants, which yield different volumes of dry products[133]. dPurified to 4–16 ppmv for pipeline transport[134]. eFor coal- and biomass-fired boilers, temperatures are provided for both the raw flue gas and the stream after flue gas desulfurization (FGD), the point at which post-combustion CCS technology would most likely be installed. The reported temperature for NGCC power stations reflects the stream condition following the heat recovery steam generator. A minimum viable adsorption temperature of ~40 °C is typically assumed for common cycling configurations with flue and process streams in which the feed is cooled to increase the adsorption capacity of Langmuir-type adsorbents.

dramatic loss of CO_2 capacity[63,64]. Similarly, exposure of amino-silicas to 20 ppm of SO_2 at 35 °C led to a loss in CO_2 uptake from dry 10% CO_2 streams, a result ascribed to the formation of sulfates and/or sulfites on the adsorbent surface[63]. Further research is needed to determine the influence of water on the competitive adsorption of CO_2, SO_x and NO_x in these materials, as well as any degradation resulting from combined exposure to water and SO_x. Critically, deactivation of amine-based binding sites by SO_x and NO_x has also been observed for other amine-based capture materials[65], including amine solutions, which form heat-stable salts[66]. Early evaluation of the stability of metal–organic frameworks to acid gases also suggests that humid SO_2 will compromise the stability and/or CO_2 capacity of many of these adsorbents[67], although the zeolitic imidazolate framework ZIF-71 (Zn(dcim)$_2$; dcim, 4,5-dichloroimidazolate; RHO topology) was found to withstand humid SO_2 exposure[67]. As a result, carbon capture processes may require additional pretreatment, such as the introduction of a sacrificial adsorbent layer or a NaOH-based polishing scrubber, to reduce the SO_2 concentration beyond typical flue gas desulfurization levels (~37 ppmv for wet limestone forced oxidation) to 1–2 ppm (ref. [9]). Alternatively, new CO_2 capture materials with large CO_2 swing capacities in the presence of water, SO_x and NO_x would be highly desirable. Although carbon-based materials have shown strong stability to cycling under real flue gas, their CO_2 working capacities may not be sufficient to allow them to be cost-competitive with aqueous amines[65]. Likewise, TDA Research has developed a 0.5 MW electric pilot-scale process incorporating a low-cost, steam-regenerable alkalized alumina adsorbent with strong SO_x and NO_x tolerance but a low CO_2 swing capacity[68]. Similarly, while zeolites offer attractive stability, SO_2, along with water, will probably outcompete CO_2 to coordinate exposed metal cation sites[69].

Limited experimental data have been reported regarding the effect of other flue gas contaminants, such as particulate matter and Hg, on the performance of CO_2 capture materials. However, the degradative nature of these contaminants on adsorbent structure is likely to be minimal compared with the degradation risks associated with O_2 and acid gases[30]. Nonetheless, characterization of accumulated toxic metals within the adsorbent bed will be necessary in the ultimate safe disposal of spent material. Notably, beyond CO_2 capture, adsorbents may also play a role in Hg emission control efforts in processes such as activated carbon injection, in which vapour-phase Hg is captured by activated carbon dispersed in the flue gas ductwork[70].

Natural gas-fired power plants. Adsorptive, post-combustion CO_2 capture from natural gas-fired power plants is also poised to become a critical strategy to reduce emissions in the power sector[71]. Indeed, due to increasingly available reserves and its lower CO_2 emissions footprint among fossil fuels, natural gas is anticipated to surpass coal in its contribution to global primary energy by 2030 (new policies scenario, IEA)[72] or 2032 (EIA)[73]. The flue gas of natural gas combined cycle (NGCC) power plants contains lower levels of SO_x, particulate matter and Hg compared with coal flue gas and therefore may be more readily treated in an adsorptive post-combustion capture process. However, NGCC flue gas contains lower CO_2 concentrations (~4%) and higher O_2 concentrations (~12%) compared with coal flue gas (~10–15% CO_2, 3–4% O_2), as well as similar water concentrations (~8% H_2O). Consequently, adsorbents for carbon capture from NGCC power stations must have strong oxidative stability as well as binding sites capable of selective CO_2 uptake from more dilute, humid streams. While amine-based capture materials have suitable chemical selectivity to achieve this separation, the high oxygen content of NGCC flue gas is likely to lead to deleterious reaction pathways. For example, solution-phase amines tend to generate soluble iron and copper species through equipment corrosion,

and these trace metals act to catalyse oxidation reactions of the mobile amine species[30,32].

Tethering amines to an adsorbent surface has therefore been proposed as a general strategy for engineering improved oxidation resistance compared with solution-phase amines by reducing the likelihood of equipment corrosion[30,32]. Nonetheless, the reactions of amine-functionalized adsorbents with oxygen to form imines, amides and other carbonyl-containing species remain a challenge for these materials in carbon capture from oxygen-rich streams[32]. Notably, the use of poly(propylenimine) (PPI) in place of polyethylenimine (PEI) in aminopolymer structures afforded enhanced oxidative stability at elevated temperatures[74]. In addition, the incorporation of hydrogen-bonding groups and phosphate or phosphonate sodium salt chelators to capture trace-metal oxidation catalysts was found to enhance the oxidative stability of aminosilica materials[75]. Other amine-functionalized materials, such as porous polymer networks, have been computationally predicted as efficient adsorbents for CCS from dry NGCC flue streams[24], but further experimental evaluation of their oxidative stability is needed. Recently, a cyclic diamine functionalized metal–organic framework, 2-ampd–Mg$_2$(dobpdc) (2-ampd, 2-(aminomethyl)piperidine), was shown to exhibit exceptional thermal and oxidative stability coupled with a high CO_2 capture rate from simulated natural gas flue gas[76]. Continued efforts are needed to build on these results by further optimizing the most promising materials and accelerating their incorporation into pilot- and full-scale capture systems.

Biofuel-fired power plants. BECCS has been proposed as another necessary technology to meet climate targets and is included in several of the IPCC integrated assessment models[1,4,77,78]. In BECCS, biomass is cultivated both to sequester CO_2 and generate energy. If the CO_2 generated during energy production from biomass is subsequently captured and sequestered, net removal of CO_2 from the atmosphere can be achieved. The composition of the target stream in a BECCS process can vary widely based on the fuel composition, but post-combustion streams will typically contain SO_x, NO_x, particulate matter, and trace alkali and transition metals[77]. Considering adsorptive capture from a willow wood-fired BECCS plant (flue gas properties in Table 1), a recent report highlighted the criticality of a long adsorbent lifetime (>2 years) and slow capacity fade (half-life ≥1.3 years), as well as a moderate CO_2 working capacity (≥0.75 mol kg^{-1}) and heat of adsorption (optimally −40 kJ mol^{-1})[79]. Overall, BECCS remains an underexplored area for adsorbents, and additional research is needed to accelerate the deployment of this important technology. With greater BECCS adoption, careful decision-making will be required in designating land for the cultivation of food versus biomass fuel and in management of water resources[4,77,80].

Biomethane. Adsorptive CO_2 capture can also contribute to the production of renewable or low-carbon fuels. Notably, biomethane, a renewable natural gas equivalent, can be produced by removing CO_2 contamination from crude biogas (~25–50% CO_2 in CH_4) generated through the anaerobic digestion of plant or animal waste[81]. Biomethane production offers the dual environmental benefits of harnessing otherwise harmful methane emissions from organic waste for energy production, while also supporting intermittencies of other renewable sources, such as wind and solar power. Further emissions reductions can be achieved if biomethane consumption is coupled with CCS, an example of BECCS, as mentioned above. Considerable precedent exists for industrial removal of CO_2 from CH_4 in the processing of fossil-derived natural gas, although adsorptive CO_2 capture remains at an earlier stage of development compared with well-established amine absorption technologies[82]. Natural gas-processing facilities have provided much of the early support for commercial CCS demonstrations and will probably remain major contributors to long-term CCS efforts[4].

Desirable adsorbents for gas processing will reduce CO_2 concentrations to pipeline-acceptable levels (typically ≤2%), achieve high CH_4 recovery and tolerate—and ideally remove—H_2S present in the stream[82]. For biogas upgrading, adsorbents may also need to tolerate siloxanes present as a waste product from consumer goods, although these species may be removed in pretreatment beds containing activated carbon, molecular sieves or polymer beads[83]. Notably, 'trapdoor' zeolites have been developed that exhibit high selectivity for CO_2 over CH_4 as a result of temporary and reversible displacement of pore-blocking cations to admit CO_2 (ref. [84]). Computational approaches have also proven valuable in identifying zeolites with optimal properties for gas processing[85]. In addition, metal–organic frameworks have received increasing attention for CO_2/CH_4 separations[86]. A recently reported fluorinated framework, $NiAlF_5(H_2O)(pyr)_2$ (KAUST-8, AlFFIVE-1-Ni; pyr, pyrazine), was found to enable simultaneous removal of CO_2 and H_2S from CH_4, a result that the authors attribute to a favourable pore volume and segregated binding sites for CO_2 and H_2S (ref. [87]). Metal–organic frameworks with amine-functionalized linkers[88] and 'molecular basket' aminosilica adsorbents such as TMHDA/SBA-15 (TMHDA, tetramethyl hexanediamine; SBA, Santa Barbara amorphous)[89] have recently been demonstrated as effective materials for selective H_2S removal. To meet pipeline specifications, purified gas must typically contain <4% total inert species, which may further necessitate nitrogen removal[82]. Towards this end, titanosilicate materials with adjustable pore apertures, such as ETS-4 (ETS, Engelhard titanosilicate), remain particularly interesting technologies that operate by a commercialized 'molecular gate' process of size-selective gas sieving[90].

Industrial CO_2 streams. Beyond gas processing, a number of industrial CO_2-containing streams are candidates for CCS[4,91,92]. The iron and steel industry generates the largest fraction of industrial emissions (31%), but deployment of CCS in this sector is complicated by the large number of CO_2-emitting processes within each mill[93]. Removal of CO_2 from the blast furnace, the largest source of CO_2 in an integrated steel mill, is under active investigation[94], and adsorbents could play a role in reducing the costs of capture compared with traditional liquid amine scrubbers. In the refining industry, CCS deployment may be favoured due to the considerable relevant expertise in this sector, as well as the relatively small cost of CCS compared with typical price differentials routinely managed by the industry in the cost of crude oil[4].

The cement industry, a particularly attractive target sector, generates approximately 5% of global CO_2 emissions that result from both fuel consumption to power the kiln (40% of cement industry emissions) and unavoidable emissions associated with production of lime from limestone ($CaCO_3 \rightarrow CaO + CO_2$)[4]. Many process configurations have been proposed for carbon capture from cement plants, including post-combustion capture, with research efforts largely focused on aqueous amine technology thus far[95]. However, a pilot-scale demonstration incorporating PEI-functionalized silica was undertaken in a collaboration between RTI and Norcem at the first cement plant CCS test centre in Brevik, Norway[96]. Additionally, a new cement CCS pilot collaboration was recently announced between the building materials company LafargeHolcim and Svante, developers of a rotating carbon capture system with a laminated adsorbent sheet structure and steam-based desorption[97]. This 'CO2MENT' project will target 2 Mt yr⁻¹ of CO_2 capture from the US Holcim Portland Plant in Florence, Colorado[97]. The Svante unit will incorporate the metal–organic framework CALF-20 (Zn_2Tz_2Ox; Tz, 1,2,4-triazolate, Ox, oxalate), a physisorbent material with strong hydrothermal stability[98]. Approximately 220 t of CALF-20 will be needed (1 $t_{adsorbent}$ per 30 t d⁻¹ of captured CO_2) with a projected cost of US$20–30 per $kg_{adsorbent}$, and the adsorbent laminate lifetime is projected as

3–5 years, with an annualized replacement cost of US$2–3 per tCO_2 (ref. [97]).

Momentum for CCS continues to build across difficult-to-abate industrial sectors, and growing investment from the materials community is needed to accelerate deployment in this area.

Direct CO_2 capture from air. Along with BECCS, DAC has received growing attention in recent years as a potential negative emissions technology[10]. Proponents highlight the necessity of DAC for CO_2 removal if warming overshoots target limits[4]. In the near term, DAC may accelerate the development of CCS by circumventing technical challenges associated with integration of capture systems within power plants or other industrial facilities. To achieve net negative emissions, DAC facilities must be coupled with transport and storage infrastructure, and the energy consumed to power DAC systems must emit less CO_2 than is sequestered. A primary technical challenge in DAC arises from the low concentration of CO_2 in air (414 ppm at the time of writing)[99], which is over 100 times more dilute than the exhaust streams of fossil fuel-fired power plants (4–15%)[9]. As a result, the theoretical minimum work to separate CO_2 from air (19–21 kJ mol⁻¹ CO_2) is two to four times greater than that required for CCS from the emissions of power plants fired by gas (6–9 kJ mol⁻¹) or coal (5–7 kJ mol⁻¹) (Fig. 4)[100]. While cost estimates for DAC vary over orders of magnitude, scaling the average cost of CO_2 captured from a coal-fired power plant (roughly US$100 per tCO_2) by the minimum work suggests a cost of US$300 per tCO_2 for DAC[4]. However, the power and industrial sectors are obligated to focus not on minimizing the cost of captured CO_2 but instead on the cost of decarbonized product (MWh, cement, steel) while maintaining consistent quality and meeting demand[4]. In contrast, DAC researchers can work to minimize capture costs without these additional constraints.

As discussed above, amine-functionalized materials, including porous polymers[101], metal–organic frameworks[102] and silicas[103], often have the requisite CO_2 selectivity at low partial pressures to enable DAC. To increase the efficiency of DAC processes, alternative mechanisms for adsorptive capture and release of CO_2 have also been proposed, such as a 'moisture swing' process, in which CO_2 captured from dry air is released upon an increase in humidity[104]. Similarly, steam has been proposed as a desorption medium, and promising early results have been demonstrated with amine-functionalized silica, γ-alumina and metal–organic framework adsorbents[105–109]. The low concentration of CO_2 in air further requires the processing of large quantities of air with a low pressure drop, which has prompted the development of fibre-based adsorbents, such as a recently reported PEI-functionalized cellulose acetate/SiO_2 composite[110]. Finally, the oxidative stability[103] and kinetics[111] of CO_2 capture are critical to consider for dilute streams.

Outlook and key needs from the materials community

The materials community has advanced substantially towards deploying adsorbents for carbon capture. Nonetheless, continued investment is needed to address several key needs on the path to commercialization. In general, greater attention is needed towards lifecycle considerations, with increasingly rigorous analyses performed as materials advance along the development pipeline[112–114]. Specifically, starting materials must be viable at the target scale (particularly for metal–organic frameworks, given limited extraction rates and reserves of certain metals[115]), and proposed synthetic routes must be safe and scalable, with minimal steps and high space–time yields. Recyclability and management of waste streams must likewise be considered[112]. For materials that meet these criteria, computational efforts will remain essential in supporting adsorbent down-selection by elucidating key adsorbent–adsorbate interactions and by predicting competitive adsorption behaviour for increasingly realistic mixtures[61,116]. From experimentalists, as
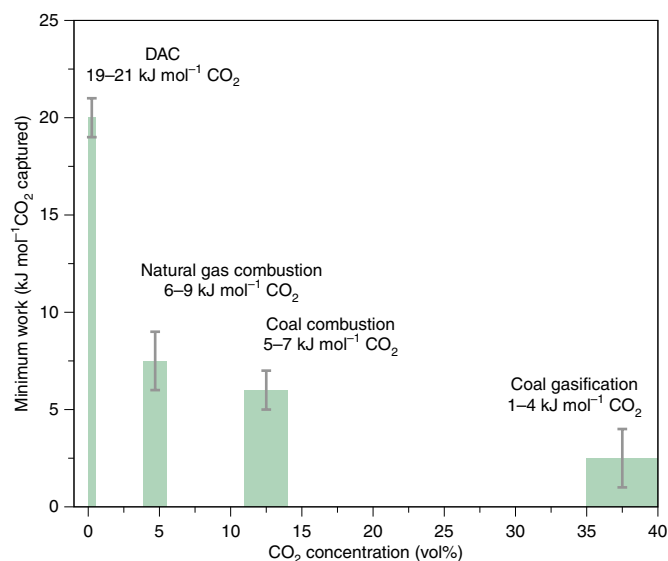
Fig. 4 | Minimum work versus CO₂ concentration. Theoretical minimum work required for CO$_2$ capture in different applications as a function of CO$_2$ concentration. Grey bars and ranges indicate the variation in minimum work anticipated for 50% CO$_2$ capture at 80% purity (lower bound) to 90% CO$_2$ capture at 99% purity (upper bound). Figure adapted with permission from ref. [100], Annual Reviews.

promising materials are identified, additional research is needed to illuminate adsorbent deactivation mechanisms and rates in the presence of humid streams containing O$_2$, SO$_x$, NO$_x$, H$_2$S and other stream-specific contaminants. These data can in turn guide pretreatment options and inform adsorbent replacement rates in techno-economic models, while facilitating the development of next-generation materials with enhanced stability. In addition, continued experimental efforts are needed to quantify the energetic impact of co-adsorbed and co-cycled species, particularly water.

Beyond fundamental adsorbent development, the expertise of the materials community is also needed in the production of adsorbents at large scale and in structured forms such as pellets, monoliths, films or fibres[46]. Industrial-scale formulation is well understood for traditional adsorbents such as zeolites, but continued development is still needed for newer materials, such as porous organic networks and metal–organic frameworks[35,45]. The ultimate structure of a commercial material will strongly influence the pressure and thermal gradients across the adsorption unit, which in turn will dictate factors such as the bed size, cycle times and overall energy demand[46]. Process design efforts therefore require expanded characterization of the thermal properties, mechanical stability and volumetric capacities of both powdered adsorbents and structured forms[59,117].

In addition, the materials community can support process engineering efforts to enhance the efficiency of CCS systems. For example, combining materials within multi-adsorbent systems or hybrid processes, such as adsorption–membrane systems, could facilitate carbon capture by coupling technologies at their peak efficiencies[59]. Aligning materials and engineering solutions may additionally offer opportunities to leverage existing, inexpensive and easily scaled adsorbents across a broader range of process conditions, and with shorter commercialization timelines. As another opportunity area, materials scientists can develop solutions to mitigate sorption enthalpy. Notably, in a recent report, micro-encapsulated phase-change materials were incorporated in fibre sorbents to dampen thermal excursions via adsorption–melting/desorption–freezing cycles[118]. New materials have also enabled

alternative cycling configurations that expand the mechanisms and thermodynamic space under consideration for adsorption–desorption cycling. For example, composites of metal nanoparticles and metal–organic frameworks have been used to demonstrate magnetic induction swing adsorption[119], and large-pore adsorbents have been proposed for use in a subambient pressure swing process to yield ultrahigh CO$_2$ swing capacities[120]. In an even greater deviation from traditional adsorptive approaches, carbon nanotubes have been decorated with quinones as redox-active species capable of electrochemically mediated capture and release of CO$_2$ (ref. [120]). Ongoing innovation at this nexus between materials science and process engineering will continue to improve CCS technologies.

Increased dialogue between materials scientists and power plant or industrial personnel will likewise aid in accelerating CCS deployment[12,121]. Carbon capture test centres, such as the Technology Centre Mongstad (Norway), the National Carbon Capture Center (United States) or the Pilot-Scale Advanced Capture Technology facility (United Kingdom), can serve as a bridge between these groups[7]. While these centres are largely focused on de-risking technologies beyond the laboratory scale, we propose that test centres could also play a key role in early-stage materials development by providing experimentalists with access to real flue or process gas to conduct small-scale stability tests. Led by these facilities, standardization of analysis conditions and reporting metrics will enable the field to converge on the most promising materials more rapidly.

Meeting ambitious decarbonization targets will require political, economic and technological alignment at an unprecedented global scale to deploy a suite of mitigation solutions while balancing allocation of intertwined energy, water, land and food resources. Carbon capture and sequestration is widely recognized as a vital component of the least-cost pathways to limit warming below 2 °C, and porous materials are strong contenders to form the basis of next-generation capture technologies. Continued research by the materials community will accelerate the deployment of CCS within the power and industrial sectors and for negative emissions technologies. Together with strong investment in renewable energy, rapid cross-sector electrification and ongoing efficiency improvements, CCS can help secure a cleaner future for generations to come.

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Competing interests
The authors declare the following competing interests: J.R.L. has a financial interest in Mosaic Materials, Inc., a start-up company working to commercialize metal–organic frameworks for gas separations. J.R.L. and R.L.S. are listed as co-inventors on patents and patent applications encompassing the diamine-appended Mg$_2$(dobpdc) metal–organic frameworks referenced herein (J.R.L., US10137430B2; J.R.L. and R.L.S., US10780388B2 and US20210129071A1). J.R.L., R.L.S. and E.J.K. are listed as co-inventors on a patent pertaining to the tetraamine-appended metal–organic frameworks referenced herein (US11014067B2).

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