

## REVIEW

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Cite this: *Energy Environ. Sci.*, 2021,  
**14**, 781

## Electrochemical carbon dioxide capture to close the carbon cycle†

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Electrochemical CO<sub>2</sub> capture technologies are gaining attention due to their flexibility, their ability to address decentralized emissions (e.g., ocean and atmosphere) and their fit in an electrified industry. In the present work, recent progress made in electrochemical CO<sub>2</sub> capture is reviewed. The majority of these methods rely on the concept of "pH-swing" and the effect it has on the CO<sub>2</sub> hydration/dehydration equilibrium. Through a pH-swing, CO<sub>2</sub> can be captured and recovered by shifting the pH of a working fluid between acidic and basic pH. Such swing can be applied electrochemically through electrolysis, bipolar membrane electrodialysis, reversible redox reactions and capacitive deionization. In this review, we summarize main parameters governing these electrochemical pH-swing processes and put the concept in the framework of available worldwide capture technologies. We analyse the energy efficiency and consumption of such systems, and provide recommendations for further improvements. Although electrochemical CO<sub>2</sub> capture technologies are rather costly compared to the amine based capture, they can be particularly interesting if more affordable renewable electricity and materials (e.g., electrode and membranes) become widely available. Furthermore, electrochemical methods have the ability to (directly) convert the captured CO<sub>2</sub> to value added chemicals and fuels, and hence prepare for a fully electrified circular carbon economy.

Received 24th October 2020,  
Accepted 18th December 2020

DOI: 10.1039/d0ee03382k

rsc.li/ees

### Broader context

The necessity of taking actions to achieve a net zero CO<sub>2</sub> emission has brought up the question "*how to achieve a circular carbon economy?*". To close the carbon cycle, sustainable CO<sub>2</sub> capture and utilization are indispensable. Current technologies for CO<sub>2</sub> capture rely dominantly on absorption of CO<sub>2</sub> from flue gas, regenerated via energy-intensive temperature swings, which imply a huge energy consumption when expanding capture towards a net zero CO<sub>2</sub> emission. When also realizing that approximately 40% of the CO<sub>2</sub> emission is decentralized, which may even increase when power plants and industry are transitioning to renewable energy, we are facing a massive challenge for closing the carbon cycle. In that framework, electrochemical technologies for CO<sub>2</sub> capture, from the atmosphere, ocean, and flue gas, can play an important role. The installed renewable electricity generation capacity is increasing each year, with more than 2300 GW in 2018. However, currently, most electrochemical methods are at early stages of development and are still energy intensive. In this contribution, we evaluate each of these technologies while focusing on the pH-swing approach. We establish the current state of the art, describe the major technical barriers and R&D needs, and discuss opportunities for improving electrochemical CO<sub>2</sub> capture.

## 1 Introduction

To honour the Paris Agreement, a global net zero greenhouse gasses (GHG) emission needs to be realized by the end of this century.<sup>1–3</sup> Among all GHG's, CO<sub>2</sub>(g) is accepted to be the main

anthropogenic control knob on the climate and has been the focus of many studies.<sup>4,5</sup> To achieve a net zero emission,<sup>6</sup> reducing the total CO<sub>2</sub> emission obtains most impact in the short term.<sup>7</sup> The largest CO<sub>2</sub> emission is due to combustion of fossil fuels and thus can be reduced through fossil fuels phase out. However, although ultimately fossil fuels phase out might be possible for the power industry and transportation sector (through substitution with renewable energy), many sectors (e.g., steel/cement production, intercontinental air transport or non electrical trains) do not have a suitable alternative for carbon based fuels. In addition, due to the current agriculture techniques, the net global deforestation and the growing demand for carbon as a resource, CO<sub>2</sub> will be emitted due to

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† Electronic supplementary information (ESI) available. See DOI: 10.1039/d0ee03382k



many anthropogenic activities. Therefore, to achieve a net zero GHG's emission, in addition to emission reduction, CO<sub>2</sub> capture and utilization is required in the long term. Also, as the long term CO<sub>2</sub> emitters include decentralized emitters, direct capture from CO<sub>2</sub> sinks (*e.g.*, atmosphere and ocean, see Fig. 1) is necessary for effectively addressing the anthropogenic CO<sub>2</sub> emissions.<sup>8,9</sup>

The main challenge that currently available CO<sub>2</sub> capture methods face is a high energy consumption.<sup>13–15</sup> A few mature, non-electrochemical CO<sub>2</sub> capture technologies *e.g.*, absorption, adsorption, membrane separation and cryogenic capture are already available in industrial scales.<sup>16–25</sup> Section 4. These methods often depend on the availability of thermal energy, which makes them less well suited for CO<sub>2</sub> capture from dilute sources *e.g.*, air and ocean. Furthermore, the cost of direct air capture *via* traditional technologies has been

estimated in the literature from \$100 to \$1000 per tonne of captured CO<sub>2</sub>.<sup>3,26–28</sup>

Electrochemical processes have the potential to be rather energy efficient as they can target molecules directly (instead of the medium surrounding them).<sup>29,30</sup> Using electrochemistry for CO<sub>2</sub> capture dates back to the late 1960s, when molten carbonates as electrolyte were used for CO<sub>2</sub> control in a manned spacecraft.<sup>31–34</sup> Nowadays, electrochemical CO<sub>2</sub> capture methods can be applied to all CO<sub>2</sub> containing streams with any concentration. Direct capture from air,<sup>35</sup> ocean<sup>8,36</sup> and flue gas<sup>37–39</sup> have been reported. Such capture units can be retrofitted as plug-and-play processes, allow small footprints and are geometrically flexible.<sup>39,40</sup> They do not require external sources of heat or high pressures/vacuum for operation, nor degradation of sorbent material is expected.<sup>40</sup> Although heat integration can be beneficial for power plants in reducing the need for energy, other



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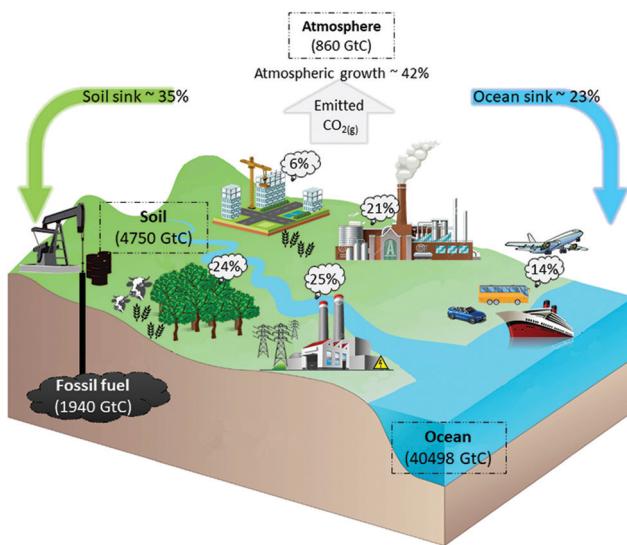


Fig. 1 Schematic of the carbon cycle. The total carbon reserve is shown in gigatonnes of carbon (GtC). The global GHG emissions in CO<sub>2</sub>(eq) by economic sectors: 25% electricity and heat production, 24% agriculture, forestry and land use, 6% buildings, 14% transportation, 21% industry and 10% other energy usages. Data extracted from ref. 10–12.

industries (*e.g.*, food and water sector) cannot integrate high heat, rising the need for technologies that can perform under low heat conditions from centralized emitters as well.<sup>14</sup> In electrochemical systems, the electric potential gradient is the main driving force which can be controlled precisely to drive chemical reactions isothermally.<sup>29,30,41</sup> A number of bench-scale capture demonstrations *via* electrochemical pH-swing have obtained CO<sub>2</sub> capture and release at the promising value of  $\sim 100 \text{ kJ mol}^{-1} \text{ CO}_2$ .<sup>42,43</sup>

The added advantage of the electrochemical methods is their ability to integrate CO<sub>2</sub> capture and utilization<sup>44</sup> (Section 5). An example is the modular, sequential CO<sub>2</sub> capture and conversion system that uses the pH-swing concept to produce CO



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innovate renewable energy technologies. Current projects include (*bipolar*) membranes for electrolysis, electrochemical CO<sub>2</sub> capture, H<sub>2</sub>-Br<sub>2</sub> redox flow batteries, and local transport near gas bubbles and membrane electrode assemblies.

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electrochemically.<sup>45,46</sup> In addition, reactive CO<sub>2</sub> capture, in which the CO<sub>2</sub> capturing medium pre-concentrates the dilute feed and produces favorable local micro-environments, has become an emerging field for integrated CO<sub>2</sub> capture and conversion using electrochemical techniques.<sup>47,48</sup>

A wide variety of efforts to electrochemically capture CO<sub>2</sub> has been demonstrated in the past 50 years, with an intensification of research activities in the last two decades. In this work we give an overview of such advances. The center of our scope are the electrochemical methods that use a pH-swing concept, as shown in Fig. 2a and b. The swing refers to (electrochemically) shifting the pH of a working fluid (continuously) between basic and acidic pH to influence the CO<sub>2</sub> equilibrium to capture and recover CO<sub>2</sub>.

The pH-swing allows absorption and desorption at ambient temperature and does not require use of any special chemicals. Widely available, inexpensive, non toxic/non corrosive/non volatile salt solutions, such as NaCl, KCl, KHCO<sub>3</sub> or even seawater can be used for the process. The pH-swing can be applied electrochemically using electrolysis, bipolar membrane electrodialysis (BPMED), capacitive deionization and reversible PCET agents as demonstrated in Fig. 3. In this work, after providing the required theoretical background in Section 2, each pH-swing route is explained and the research of this route is comprehensive reviewed in Section 3. In addition to a pH-swing approach, other electrochemical technologies involve using redox-active carriers<sup>49</sup> (Section 3.3), molten carbonate cells and hybrid methods (Section 3.4) such as electrochemically enhanced absorption/adsorption.<sup>29,30</sup> To enable comparison, we also briefly describe the main conventional capture methods, their drawbacks and advantages, and opportunities to improve these technologies with electrochemical methods, in Section 4. Finally, CO<sub>2</sub> utilization and storage is discussed briefly in section to close the carbon cycle (Section 5).

## 2 Theory: pH-swing concept and involved reactions

The concept of CO<sub>2</sub> capture *via* pH-swing leverages the responsiveness of the thermodynamic equilibrium of CO<sub>2</sub> to pH changes. A pH-swing is also used for other resource recovery applications than CO<sub>2</sub> capture, but the method is not always explicitly referred to as “pH-swing”. For instance, pH-swing is employed to recover ammonia electrochemically from urine<sup>50,51</sup> and to remove phosphate from waste water streams.<sup>52</sup>

### 2.1 Carbonate equilibrium

The carbonate equilibrium can be described as open or closed based on the contact with an overlying gas and is explained in detail in ref. 53–56. In an open system, the total concentration of the dissolved inorganic carbon varies by changing in the pH; acidification results in CO<sub>2</sub>(g) out-gassing, while basification lead to more CO<sub>2</sub>(g) absorption, increasing the DIC. In a closed system (*e.g.*, inside of an electrochemical cell), the total DIC

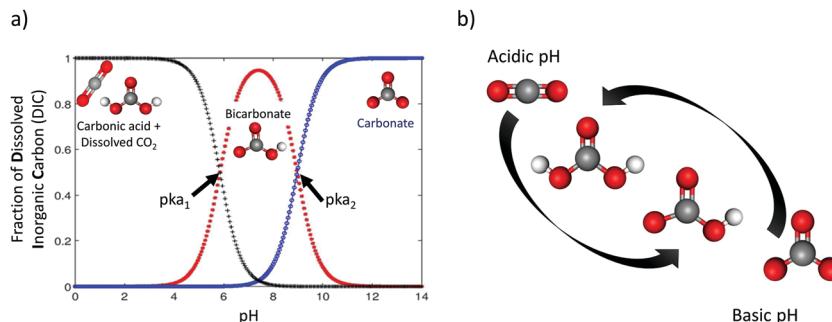


Fig. 2 (a) Effect of pH on the  $\text{CO}_2$  equilibrium (for a closed system at temperature of  $25^\circ\text{C}$  and salinity of 35 ppt). The solution is buffered around two  $pK_a$  values. (b) Schematic of the pH-swing concept.

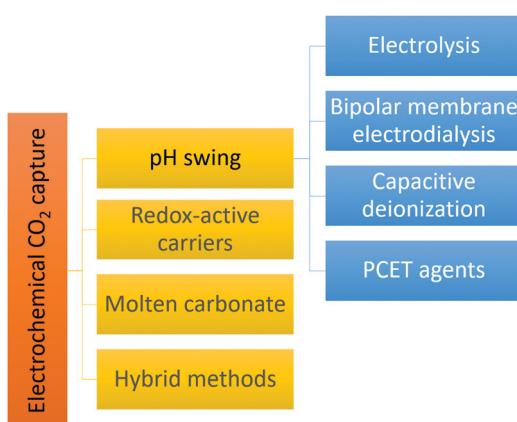
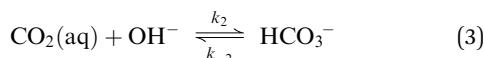
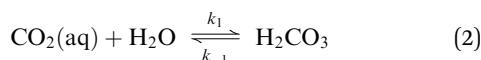
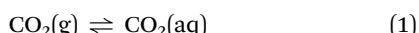


Fig. 3 Summary of electrochemical  $\text{CO}_2$  capture methods.

remains constant regardless of any pH changes. If so, the dominant carbonic species alter by changing the pH as demonstrated in Fig. 2a. The equilibrium can be shown through reactions (1)–(4):



Reaction (1) is dependent on the fugacity of  $\text{CO}_2(\text{g})$  and often described through Henry's law (see Section 2.3). It is often assumed to be really fast (*i.e.*,  $10^{10}\text{ s}^{-1}$  in both directions) in a well-mixed scenario (*i.e.*, only mass-transport limited).<sup>55,57,58</sup> For experimental values of  $k_1$ ,  $k_{-1}$ ,  $k_2$ ,  $k_{-2}$  see ref. 57, 59 and 60. As the pH increases, reaction (3) pushes the equilibrium towards  $\text{HCO}_3^-$ , and it predominates reaction (2) above pH 8.5.<sup>59</sup> See Section 2.2 for more discussion on the kinetics of the reactions. The total dissolved inorganic carbon, DIC, can be described as the summation of the concentration of all present carbonic species:

$$\text{DIC} = [\text{H}_2\text{CO}_3^*] + [\text{HCO}_3^-] + [\text{CO}_3^{2-}] \quad (5)$$

where  $\text{H}_2\text{CO}_3^* = \text{H}_2\text{CO}_3 + \text{CO}_2(\text{aq})$ . In multi-ionic systems, additional carbonate species or complexes (*e.g.*,  $\text{NaCO}_3^-$  and  $\text{NaHCO}_3(\text{aq})$ ) are present in the definition of DIC, as well.<sup>61,62</sup>

## 2.2 Reactions kinetics and how to improve it

To capture and release  $\text{CO}_2(\text{g})$  through a pH-swing, both thermodynamics and kinetics play a role.<sup>57,59</sup> Assuming thermodynamic equilibrium, the equilibrium ratio of  $\frac{[\text{H}_2\text{CO}_3^*]}{[\text{HCO}_3^-]}$  changes

by a factor of more than 100 over when using a small pH-swing of only 2 pH-units, see Fig. 2a. However, although such a narrow pH-swing is thermodynamically favourable and enables lower energy consumption, it suffers from slow kinetics. At near neutral pH, the  $\text{CO}_2$  hydration rate is  $\sim 2.9 \times 10^{-2}\text{ s}^{-1}$  and the  $(\text{HCO}_3^-)$  dehydration rate is  $\sim 2 \times 10^{-4}\text{ s}^{-1}$ .<sup>42,60</sup> These reaction rates are a function of *e.g.* temperature and ionic strength of the system.<sup>63–65</sup> To overcome the slow kinetics, (1) a wider range of pH-swing or (2) a reaction catalyst need to be applied. As for a wider pH-swing range, the base promoted hydration rate of the  $\text{CO}_2/\text{HCO}_3^-$  system is reported to be  $\sim 6 \times 10^3\text{ M}^{-1}\text{ s}^{-1}$  and the acid-promoted dehydration rate is increased to  $\sim 4.1 \times 10^4\text{ M}^{-1}\text{ s}^{-1}$ .<sup>42,59,60,65</sup> Alternatively, the use of a catalyst such as the carbonic anhydrase (CA) enzyme<sup>66</sup> is suggested for improving the kinetics.<sup>42,67,68</sup> CA is reported to enhance both the  $\text{CO}_2$  hydration and dehydration reaction kinetics; hydration rate constant  $\sim 10^5\text{ s}^{-1}$  and dehydration rate constant  $\sim 10^6\text{ s}^{-1}$  near a neutral pH of 7 are reported.<sup>66</sup> However, although initially effective, such enzyme is not stable, and is prone to enzyme loss, deactivation, or degradation. Investigation on improved catalysts is recommended, but until such catalysts are developed, to effectively capture and recover  $\text{CO}_2$ , a wider range of pH-swing ( $\text{pH} < \text{p}K_a_1$  and  $\text{p}K_a_2 < \text{pH}$ ) is needed for capture application.

## 2.3 Inorganic carbon solubility

In equilibrium, the concentration of free  $\text{CO}_2$  in water (*i.e.*,  $[\text{CO}_2(\text{aq})]$ ) is proportional to its partial pressure in the gas phase; according to the Henrys law,  $[\text{CO}_2(\text{aq})] = K_0 \times f_{\text{CO}_2(\text{g})}$  where  $K_0$  (in  $\text{mol L}^{-1}\text{ atm}^{-1}$ ) is the solubility coefficient of  $\text{CO}_2(\text{g})$  and  $f_{\text{CO}_2(\text{g})}$  stands for the gas fugacity (in atm), which is close to the partial pressure of  $\text{CO}_2(\text{g})$  (within 1%). Fig. 4a



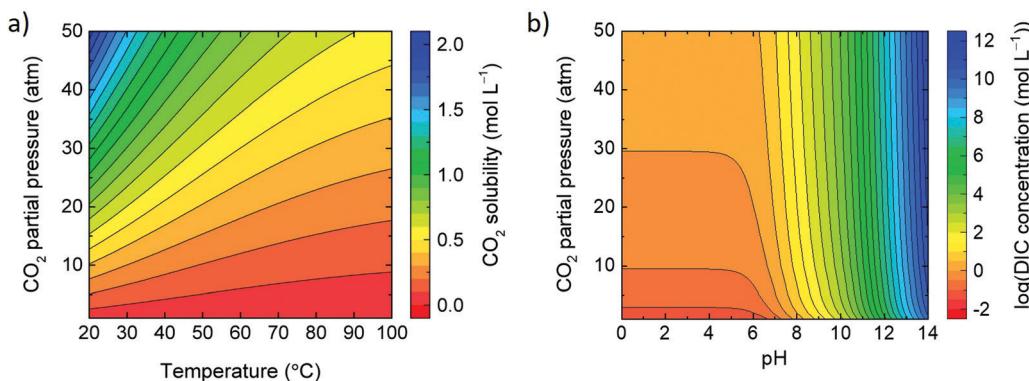


Fig. 4 (a) CO<sub>2</sub> solubility in water as a function of the temperature and CO<sub>2</sub> partial pressure. (b) Logarithmic solubility of dissolved inorganic carbon (DIC) in water at 25 °C as a function of the water pH and CO<sub>2</sub> partial pressure.

shows the solubility of CO<sub>2</sub> as a function of temperature and CO<sub>2</sub> partial pressure. At elevated alkalinity, the total solubility of CO<sub>2</sub>(g), and hence DIC (in eqn (5)) increases due to reaction (3) route. Fig. 4b shows the solubility of DIC as a function of the water pH and the partial pressure of CO<sub>2</sub>. See the ESI† for the used equations and references.

#### 2.4 Inputs and metrics

Fig. 5 demonstrates input parameters and the metrics of electrochemical CO<sub>2</sub> capture based on a pH-swing. The feed, cell, process and kinetics can be leveraged for the product/output. The main challenge such capture technologies are facing is their (estimated) high Capex, resulted from a high energy consumption and the immaturity of the technology.<sup>3</sup> Data on Capex of electrochemical methods is still scarce, making the energy consumption (at high current density and capture efficiency) the most practical metric of comparison. Thankfully, despite the currently high energy consumption, optimization of the process and cell parameters can significantly decrease the energy loss involved in such processes as explained in Sections 3.2.1 and 3.5.

### 3 Electrochemical pH-swing concepts

Electrochemically induced pH-swings for CO<sub>2</sub> capture have been demonstrated through (membrane) electrolysis, bipolar membrane electrodialysis, reversible redox couples, capacitive deionization and hybrid processes that combine two or more methods as shown previously in Fig. 3. In this section we introduce each method separately and compare them in terms of feasibility, energy consumption, energy efficiency and technology readiness level (TRL).

#### 3.1 Electrolysis

Electrolysis can enable the pH-swing in the vicinity of (two) electrodes as shown in Fig. 6. (Membrane) electrolysis for CO<sub>2</sub> capture is used for alkali absorbent (re)generation<sup>38,69–73</sup> or simultaneous H<sub>2</sub> production.<sup>36,74–76</sup> H<sub>2</sub> production can (partially) offset the cost of CO<sub>2</sub> capture and is possible when water electrolysis takes place. In the earliest work done by Stucki *et al.*, CO<sub>2</sub> is absorbed from a flue gas in an KOH absorbent, the resulted (bi)carbonate solution is fed into the electrolyser (for alkaline regeneration), where CO<sub>2</sub> is recovered and H<sub>2</sub> is produced *via* the following reaction:

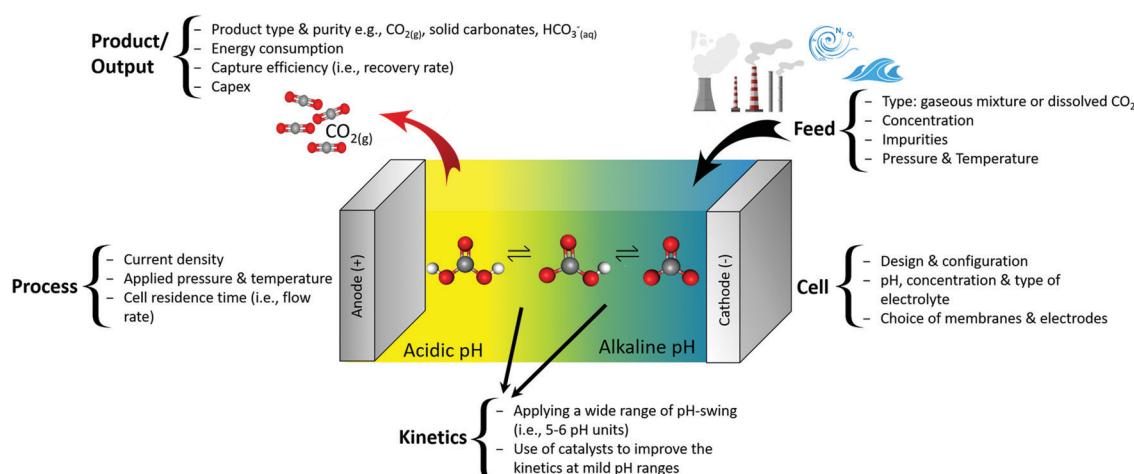


Fig. 5 Input and metrics of electrochemical pH-swing based CO<sub>2</sub> capture and the overall process concept.

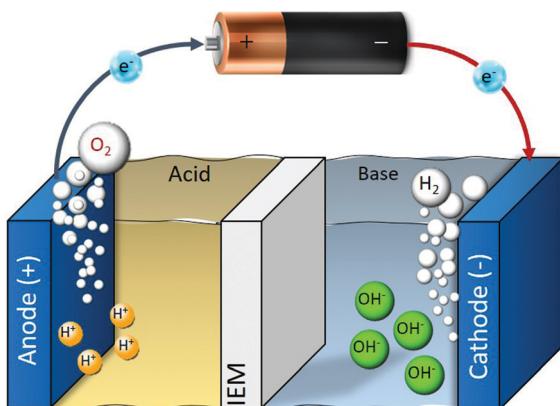
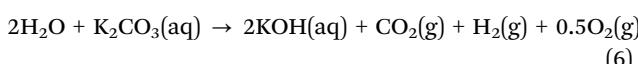


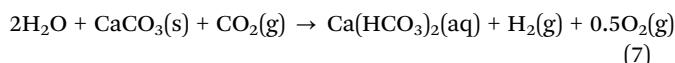
Fig. 6 Schematic of water electrolysis. Depending on the catholyte/anolyte (air, water, etc.), applied voltage and the pH of the medium, different half-reactions take place.



The KOH can be used as absorbent for capturing CO<sub>2</sub>, turning into K<sub>2</sub>CO<sub>3</sub>(aq), which can be fed again to the electrolysis system.

One downside in such systems is that the cell voltage has, in addition to 1.23 V for water splitting, a contribution from the pH difference between the anolyte and the catholyte, represented by Nernstian potential of  $\Phi = 0.059\Delta\text{pH}$  (in volts) at 25 °C, as shown in the Pourbaix diagram (Fig. 7).<sup>74</sup> When using an extreme pH gradient (pH 0 at anode, pH 14 at cathode), this would imply a 2.06 V for balancing the free enthalpy of the reaction.

Using the pH-swing in electrolysis, the CO<sub>2</sub> can be either released as (purified) gas (*e.g.*, *via* reaction (6)), or as (bi)carbonate products in the work of Rau and Park *et al.*<sup>70,71,75,78</sup> The latter has been demonstrated for Ca(HCO<sub>3</sub>)<sub>2</sub>(aq) (Fig. 8a) and<sup>71,75</sup> solid carbonate mineral as shown in Fig. 8b.<sup>70</sup> Natural (mined and crushed) carbonate minerals are used to provide Ca<sup>2+</sup> in Fig. 8a. Through reaction (7), CO<sub>2</sub> can be removed from an overlying gas mixture (*e.g.*, air or flue gas). The produced Ca(HCO<sub>3</sub>)<sub>2</sub>(aq) can be diluted and stored in the ocean, water reservoirs or underground:



Capture of 1 mole of CO<sub>2</sub>(g) for each mole of CaCO<sub>3</sub> *via* reaction (7) is possible, while 22 tonnes of CO<sub>2</sub> can be captured per tonne H<sub>2</sub> generated (assuming a 1:1 molar ratio).<sup>71</sup> This implies that, depending on CO<sub>2</sub> emission involved in the operation (*e.g.*, for supplying electricity and for limestone/carbonate mining, crushing and transport), the system has the potential of producing carbon-negative hydrogen.<sup>79</sup>

The process efficiency in Fig. 8a can be enhanced *e.g.*, by:

- Improving the mass transfer between the overlying gas and the absorbent (to improve CO<sub>2</sub>(g) dissolution).

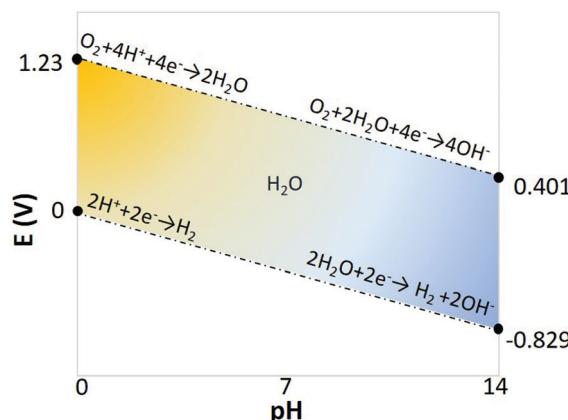
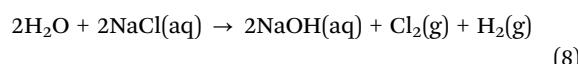


Fig. 7 Pourbaix diagram of water electrolysis.<sup>77</sup>

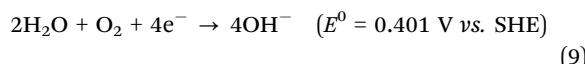
- Introducing an ion selective membrane between the electrodes (to avoid unwanted secondary reactions).

Alternative to water electrolysis, salt electrolysis, such as NaCl<sup>69</sup> and KCl<sup>38</sup> can also be used for CO<sub>2</sub> capture. If so, only an alkaline pH (at the cathode) is enabled, because at the anode *e.g.*, the reaction 2Cl<sup>-</sup> → Cl<sub>2</sub>(g) + 2e<sup>-</sup> takes place instead of the oxygen evolution reaction (OER).<sup>70</sup> The produced alkalinity at the cathode can then be utilized to sequester CO<sub>2</sub> in the form of carbonate salts. When the capture product is CaCO<sub>3</sub>(s), no CO<sub>2</sub>(g) desorption step is required. Furthermore, CaCO<sub>3</sub> is easier to transport and store compared to CO<sub>2</sub>(g). NaCl electrolysis for alkaline absorbent (re)generation follows reaction (8).<sup>69</sup>



Using salt electrolysis for CO<sub>2</sub> capture is especially interesting due to salt availability in the seawater, leveraging possible substitution of the electrolyte with abundant seawater.<sup>69</sup> The produced (toxic) Cl<sub>2</sub>(g) at the anode can be treated by the produced NaOH solution using a scrubber, or can alternatively be utilized as a feedstock for the synthesis of HCl, Cl containing polymers and bleaching agents.<sup>69</sup> Alternatively, using water electrolysis and by inserting two ion exchange membranes (IEMs) between the electrodes (Fig. 9), produces H<sub>2</sub> simultaneous acidifies seawater to recover CO<sub>2</sub>(g).<sup>36,80,81</sup> The use of two IEMs avoids the production of Cl<sub>2</sub>(g) and electrode contamination.

When applying electrolysis using a reversible redox reaction – thus no net gas production – saves energy. For example, the production of O<sub>2</sub>(g) (or Cl<sub>2</sub>(g)) can be avoided by recirculating the produced H<sub>2</sub>(g) from the cathode to the anode compartment.<sup>72,73</sup> Alternatively, H<sub>2</sub> production can be avoided if O<sub>2</sub> reduction takes place on the cathode, instead of the H<sub>2</sub>O reduction.<sup>82</sup> At the cathode, depending on availability of O<sub>2</sub> or H<sub>2</sub>, two possible reactions may exist for OH<sup>-</sup> production:



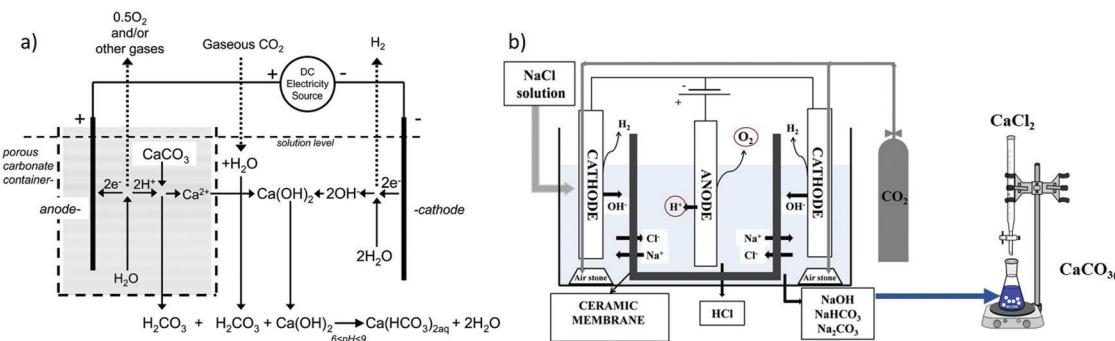


Fig. 8 (a)  $\text{H}^+$  ions at the anode dissolve  $\text{CaCO}_3(\text{s})$ , the resulted  $\text{Ca}^{2+}$  ions move towards the cathode, forming  $\text{Ca}(\text{HCO}_3)_2(\text{aq})$ . Reprinted (adapted) with permission from ref. 71; Copyright (2008) American Chemical Society. (b)  $\text{NaCl}$  electrolysis, where  $\text{NaOH}$  is used as the  $\text{CO}_2(\text{g})$  absorbent and  $\text{CaCO}_3(\text{s})$  is the final capture product, figure from ref. 70. Both approaches use the concept of placing the anode inside of a porous container.

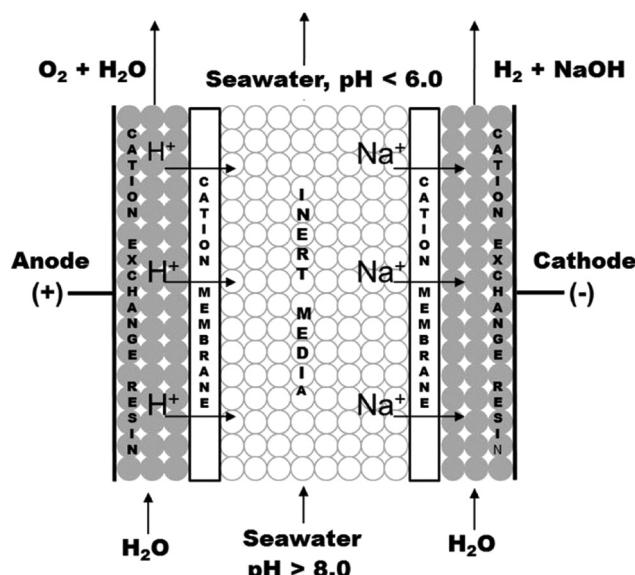


Fig. 9  $\text{CO}_2$  capture and  $\text{H}_2$  production via sea water acidification and water electrolysis. In the middle compartment, cation exchange resins are used. Reprinted (adapted) with permission from ref. 81; Copyright (2014) American Chemical Society.

When sufficient  $\text{O}_2$  is available at the cathode, or sufficient  $\text{H}_2$  at the anode, the  $\text{H}^+/\text{OH}^-$  generation can take place in a practical cell voltage range of 1.3 V to 2.2 V through reaction (9). The supply of sufficient gas to the opposing electrode can be assisted by using gas diffusion electrodes.<sup>83</sup> Without recirculating the gaseous products, the cell voltage is typically  $> 2.2$  V.<sup>82</sup>

From a thermodynamic point of view, the use of (net) water electrolysis requires a significant thermodynamic minimum energy (1.23 V for water splitting), in addition to the potential required for generating a pH difference (see Fig. 7).<sup>77,84</sup> Considering the necessity of a wide pH-swing to enhance the carbon equilibrium kinetics, and using pH 0 and 14 to favour electrolyte conductivity, a minimum of 2.06 V is required, corresponding to  $199 \text{ kJ mol}^{-1} \text{ CO}_2$ . Furthermore, in almost all demonstrated devices/systems, the rate of  $\text{CO}_2$  capture is locked with the rate of  $\text{H}_2$  or  $\text{O}_2$  generation, which sometimes

may not be desirable and present additional challenges for multi-stack development of the system. These drawbacks can be addressed using bipolar membrane electrodialysis as explained in the following section.

### 3.2 Bipolar membrane electrodialysis (BPMED)

A bipolar membrane (BPM) consists of an anion (AEL) and a cation (CEL) exchange layers, laminated together. When a sufficient electric field is applied, the BPM dissociates water into  $\text{OH}^-$  and  $\text{H}^+$ , producing a controllable  $\Delta\text{pH}$  over the membrane as shown in Fig. 10a and b.<sup>85–90</sup> Using a bipolar membrane, the thermodynamic minimum voltage required for this water dissociation is 0.829 volts for a produced  $\Delta\text{pH} = 14$ . That is 2.5 times lower than that of water electrolysis at the same  $\Delta\text{pH} = 14$  ( $1.23 + 0.829$  at minimum), as no gas evolution takes place using a bipolar membrane.<sup>85</sup> The thermodynamic voltages over the BPM are even lower for smaller  $\Delta\text{pH}$  over the membrane.<sup>84,88</sup> The feasibility of using bipolar membrane electrodialysis for pH-swing based  $\text{CO}_2$  capture is shown in early studies in 1995;<sup>91</sup> alkaline  $\text{KOH}$  and acidic  $\text{H}_2\text{SO}_4$  were regenerated in a two compartment BPMED cell, containing a BPM and a cation exchange membrane. After  $\text{CO}_2$  from air is captured in  $\text{KOH}$  absorbent, it can be recovered through acidification. The produced  $\text{K}_2\text{SO}_4$  is treated in the BPMED cell to regenerate the desired acid and base again.  $\text{CO}_2$  capture via BPMED has been further explored by others, and these works are addressed in more details in next sections.

**3.2.1 Energy consumption and capture efficiency.** In BPMED, a trade off between the energy consumption and the process rate, determined by the applied current density, exists. Operating at very low current densities is not effective due to the higher salt ion leakage through the BPM and hence the lower water dissociation rate.<sup>92</sup> On the other hand, at high current densities, the ohmic voltage losses increase, leading to an undesirable higher energy consumption (see ESI†). As an example, Fig. 11a shows the minimum energy consumption for  $\text{CO}_2(\text{g})$  recovery from 0.125 M  $\text{K}_2\text{CO}_3$ -rich solution via BPMED at a current density around  $10 \text{ mA cm}^{-2}$ .<sup>3</sup> However, although the energy consumption is the lowest at that current density, production rate favours higher current densities as shown in

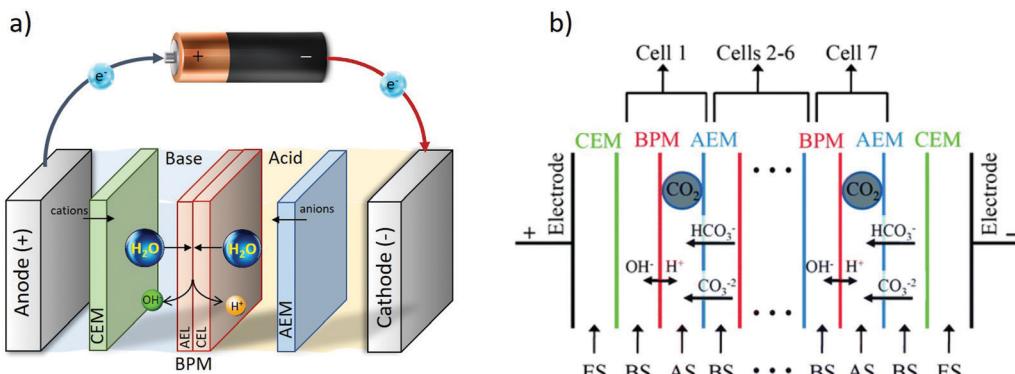


Fig. 10 (a) BPMED schematic. (b) BPMED for  $\text{CO}_2$  recovery in ref. 92. (ES) electrode solution = KOH, (AS) acid solution of  $\text{KH}_2\text{PO}_4 + \text{H}_3\text{PO}_4$ , (BS) base solution of six different mixtures of  $\text{KHCO}_3$ ,  $\text{K}_2\text{CO}_3$  and KOH. Figure adapted from ref. 92.

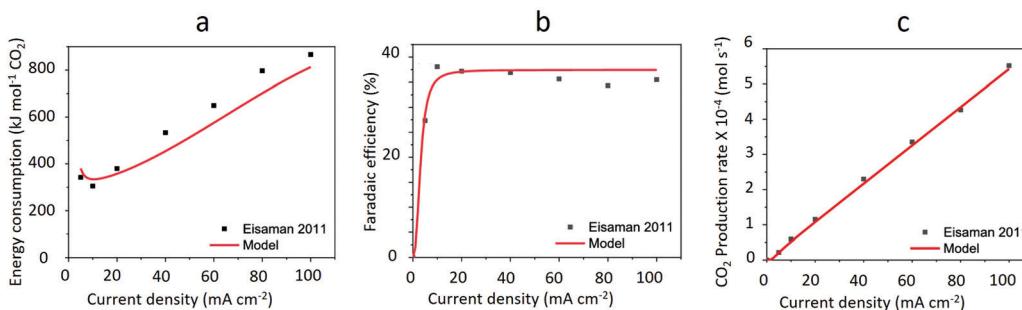


Fig. 11 Trend of energy consumption, faradaic efficiency and  $\text{CO}_2$  production rate vs. current density in  $\text{CO}_2(\text{g})$  recovery from 0.125 M  $\text{K}_2\text{CO}_3$ -rich solution via BPMED. The black squares are experimentally measured data by ref. 92 while the red lines show the calculated values performed by ref. 3. Reprinted (adapted) with permission from ref. 3; Copyright (2020) American Chemical Society.

Fig. 11c. The experimentally measured current efficiency (*i.e.*, faradaic efficiency) in Fig. 11b shows – in addition to its low values at  $i < 10 \text{ mA cm}^{-2}$  due to salt cross-over – a slight decrease at  $i > 20 \text{ mA cm}^{-2}$ . It is hypothesized that current densities above the optimum value, reduce the BPM's permselectivity<sup>93</sup> or enhance the water splitting reaction in the AEM's,<sup>94,95</sup> leading to a lower efficiency.<sup>92</sup> The current efficiency also decreases if the current is carried by an undesired ion through the membranes. For example, in Fig. 10b, the (bi)carbonate ions are the desired current carriers. However, if (as a result of high pH)  $\text{OH}^-$  ions become the main charge carrier through the AEM, the current efficiency decreases. On the other hand, when capturing  $\text{CO}_2(\text{g})$  from flue gas or in DAC, a high pH (*i.e.*, high  $[\text{OH}^-]$ ) is favoured in the outlet of the same compartment, because  $\text{CO}_2(\text{g})$  absorption capacity and rate increase in a solution with high pH. Adopting monovalent-ion-selective AEM's that favour the transport of  $\text{HCO}_3^-$  ions over  $\text{OH}^-$  ions then could improve the efficiency when such process is intended.<sup>3,96</sup>

As opposed to what is shown in Fig. 11b, the current efficiency of BPMED can reach as high as 95% if *e.g.*, a 0.5 M  $\text{KHCO}_3$  is used instead of the 0.125 M  $\text{K}_2\text{CO}_3$  for  $\text{CO}_2(\text{g})$  recovery through acidification. In fact, both in BPMED and (membrane) electrolysis, in addition to the current density, the anolyte and catholyte concentrations and the operation temperature affect

the current efficiency, as demonstrated in Fig. 12<sup>38</sup> and summarized in Table 1.

The (slightly) positive effect of temperature on improving the faradaic efficiency of electrochemical methods has been reported.<sup>38,69</sup> Higher temperatures improve the electrochemical reaction rates. In the case of BPMED, the kinetics of water dissociation in BPM is also enhanced at elevated temperatures.<sup>97,98</sup> However, in addition to the extra energy needed for heating up the electrolytes, the thermal stability of the ion exchange membranes poses a limitation on high temperature processes. For instance, the commercial bipolar membranes are cannot withstand temperatures higher than 40–60 °C for a long duration.<sup>99</sup> Moreover,  $\text{CO}_2$  solubility decrease at higher temperatures (up to 100 °C).<sup>100–102</sup> This means that operating at high temperature is not yet practical.

A breakdown of energy consumption and comparison for (membrane) electrolysis and BPMED is provided in Section 3.5 and the ESI.†

**3.2.2 Cell configuration.** The cell configuration defines the number of membranes, membrane cell pair arrangement, electrolyte flow path and the thickness of the compartment/membrane. The design of the cell is the most important factor to minimize the cell resistance.<sup>74</sup> As opposed to the BPMED for traditional acid and base production (*i.e.*, BPM–CEM–AEM–BPM), the pH-swing process for  $\text{CO}_2$  capture allows a simplified



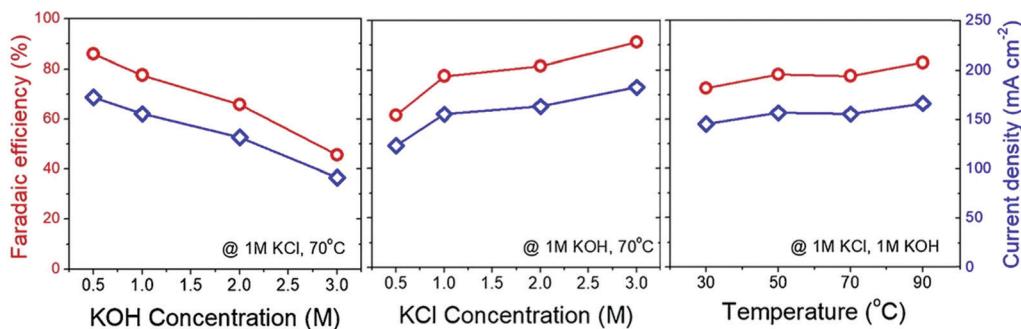


Fig. 12 Change of the measured current density (blue diamond line) and faradaic efficiency (red circle line) with regards to the change in catholyte concentration, anolyte concentration and the applied temperature in an electrochemical KOH (absorbent) production via KCl electrolyser. Reprinted from ref. 38, Copyright (2019), with permission from Elsevier.

Table 1 Electrochemical CO<sub>2</sub> capture

Capture method	Feed	Energy-consumption <sup>a</sup> (kJ mol <sup>-1</sup> CO <sub>2</sub> )	Current-efficiency	Product	Current-density (mA cm <sup>-2</sup> )	Remarks
Fuel-cell <sup>35</sup>	Air + H <sub>2</sub>	350	23%	CO <sub>2</sub> (g)	0.5	Upscaling unfeasible (low current-density)
Electrolysis <sup>74</sup>	Air	290–350 (kJ mol <sup>-1</sup> KOH)	>95% <sup>b</sup>	CO <sub>2</sub> (g) + H <sub>2</sub> (g)	100	KOH/K <sub>2</sub> CO <sub>3</sub> electrolysis at 70 °C
Electrolysis <sup>71</sup>	Air + mined CaCO <sub>3</sub> (s)	1 267 200 <sup>c</sup>	Not reported	H <sub>2</sub> (g) + CO <sub>2</sub> (g)	Not reported	Water electrolysis. Fig. 8a
Electrolysis <sup>38</sup>	Synthetic flue gas + cement kiln dust	>634–1276 (kJ mol <sup>-1</sup> CaCO <sub>3</sub> ) <sup>d</sup>	60–90% <sup>b</sup>	CaCO <sub>3</sub> (s)	100–200	KCl electrolysis. Fig. 12
BPMED <sup>91</sup>	K <sub>2</sub> SO <sub>4</sub>	~308	Not reported	CO <sub>2</sub> (g)	50	Produces KOH + H <sub>2</sub> SO <sub>4</sub>
BPMED <sup>106</sup>	NaHCO <sub>3</sub> /NaOH	160–500	65–80%	CO <sub>2</sub> (g)	5–20	
BPMED <sup>92</sup>	KHCO <sub>3</sub> /K <sub>2</sub> CO <sub>3</sub>	100–450 <sup>e</sup>	95% (KHCO <sub>3</sub> ), 50% (K <sub>2</sub> CO <sub>3</sub> )	CO <sub>2</sub> (g)	5–100	
BPMED <sup>43</sup>	KHCO <sub>3</sub>	200–500	70–90%	CO <sub>2</sub> (g)	22–139	
BPMED <sup>113</sup>	Artificial seawater	250–400	<70%	CO <sub>2</sub> (g)	1–3	Fig. 10b for cell design & Fig. 11 for cell performance High pressure BPMED enables 30% energy win. See Section 3.2.3 59% of DIC from seawater was removed using ca. 242 kJ mol <sup>-1</sup> CO <sub>2</sub>
BPMED <sup>8</sup>	Artificial seawater + NaCl	390–640	60–95% <sup>f</sup>	CO <sub>2</sub> (g) or CaCO <sub>3</sub> (s)	100	Cost of membrane contactors is avoided via the base route
BPMED <sup>107</sup>	Artificial seawater + CO <sub>2</sub> (g)	1080–2880 (kJ mol <sup>-1</sup> CaCO <sub>3</sub> )	Not reported	CaCO <sub>3</sub> (s)	Not reported	CO <sub>2</sub> (g) absorption in basified seawater followed by crystallization
EDI + BPMED <sup>42</sup>	Synthetic flue gas	Not reported	Not reported	CO <sub>2</sub> (g)	2–16	At near neutral pH, the slow kinetics can be enhanced using CA enzyme Fig. 9
EDI + electrolysis <sup>36,76,81,194</sup>	Natural seawater	2775–6940 <sup>g</sup>	Not reported	CO <sub>2</sub> (g)/H <sub>2</sub> (g)	20–61	
MCDI <sup>156</sup>	Synthetic flue gas	40–50	60–80%	CO <sub>2</sub> (g)	0.02–0.06	Using IEM's improve efficiency <sup>37</sup>
Redox-active carriers + pH-swing <sup>140</sup>	Synthetic flue gas	106 <sup>h</sup>	90%	CO <sub>2</sub> (g)	18	Aqueous tiron (Na <sub>2</sub> Q) is used as pH mediator/active carrier to capture CO <sub>2</sub>
Redox-active carriers <sup>147</sup>	Synthetic flue gas	56	>75%	CO <sub>2</sub> (g)	0.5	

<sup>a</sup> Only for the electrochemical step, defined as in eqn (11). <sup>b</sup> For KOH electrochemical regeneration. <sup>c</sup> Although the theoretical work requirement for the reaction is only 266 kJ mol<sup>-1</sup> CO<sub>2</sub>. <sup>d</sup> Calculated from data on energy consumption for KOH production, assuming 2 moles KOH delivers 1 mole CaCO<sub>3</sub>. <sup>e</sup> Plus 200 for CO<sub>2</sub>(g) capture into hydroxide solutions.<sup>193</sup> <sup>f</sup> Only for the production of HCl and NaOH, not for CO<sub>2</sub> capture and recovery. <sup>g</sup> Calculated based on data from ref. 76:  $R = 0.5\text{--}1.8 \Omega$ ,  $i = 20.4\text{--}61.2 \text{ mA cm}^{-2}$  and recovered CO<sub>2</sub> rate of 0.004 mol min<sup>-1</sup>. <sup>h</sup> Only for the CO<sub>2</sub> desorption step.

membrane sequence due to the limited pH-range (*i.e.*, pH 3–9 instead of 0–14).

In choosing the optimised configuration, the (co-)ionic leakage of the membranes is crucial. When using multi-ionic

CO<sub>2</sub> feed, such as seawater, carbonic species should be rejected to obtain a maximum capture efficiency. Carbonic species are neutral (*e.g.*, CO<sub>2</sub>(aq) and H<sub>2</sub>CO<sub>3</sub>) or negatively charged and hence are rejected better by a CEM than by an AEM. In addition

to higher selectivity, the use of CEM's instead of AEM's have proven to increase conductivity and mechanical stability in a BPMED cell for CO<sub>2</sub> capture<sup>72</sup>).<sup>103</sup>

For further reducing co-ionic cross-over, a trade off between the permselectivity of IEM's and their resistance should be considered, which is controlled by the membrane thickness. In general, thicker membranes have higher resistivity but show a better selectivity.<sup>72</sup> Applying a reinforced structure to a thinner membrane can improve its selectivity while maintaining its resistivity to a certain extent.<sup>72,104</sup>

Depending on the charge carriers in the cell, the flow mode (*i.e.*, one-way pass *vs.* batch mode) and feed concentration, each BPMED process asks for a different cell configuration. While BPM-CEM might be the choice of some researchers for CO<sub>2</sub> recovery from carbonate solutions,<sup>105,106</sup> others chose a BPM-AEM<sup>43,92</sup> for the same purpose. That is while novel configurations as BPM-AEM-AEM are also emerging for minimizing BPM fouling when extracting CaCO<sub>3</sub> from seawater,<sup>107</sup> see Section 3.2.4.

**3.2.3 High pressure BPMED.** In a closed system (such as the one created inside of an electrochemical cell), acidification increases the concentration of dissolved CO<sub>2</sub>. This concentration can lead to the formation of CO<sub>2</sub>(g) bubbles inside of the cell. Theoretical models, suggest the trapped CO<sub>2</sub> in the acid solution dominate the cell resistance and increase the energy consumption.<sup>108</sup> Trapped gas bubbles lower the effective membrane surface area, cause high voltages and shorten the membrane lifetime (due to localized "hot spots" of high current density). To avoid gas production inside of the cell, Eisaman *et al.*<sup>43</sup> proposed a high pressure BPMED process using a similar cell as shown in Fig. 10b where the entire stack is kept at high pressure, *i.e.*, there is no pressure difference across the membranes in the stack. The authors observed that by increasing the pressure, the total cell voltage decreases due to the avoided CO<sub>2</sub> gas bubbles production in the cell; the electrochemical energy required at 6 atm (333 kJ mol<sup>-1</sup> CO<sub>2</sub>) was seen to be 29% less than that of 1.5 atm (471 kJ mol<sup>-1</sup> CO<sub>2</sub>) at a current density of 139 mA cm<sup>-2</sup>.

**3.2.4 BPMED for CO<sub>2</sub> extraction from seawater.** The ocean is a massive sink for CO<sub>2</sub>.<sup>11,109,110</sup> The higher carbon content of the oceans compared to that of the atmosphere<sup>8,54,111</sup> makes the ocean an interesting source for CO<sub>2</sub> capture.<sup>109</sup> Moreover, as opposed to the separation of CO<sub>2</sub> from a gas mixture that involves two steps (*i.e.*, capture and release), in CO<sub>2</sub> capture from seawater, a separate CO<sub>2</sub>(g) adsorption/absorption step is not required, because the ocean already acts as CO<sub>2</sub> absorbent leveraging its gigantic surface. The ocean contain DIC of ~2.3–2.5 mM, mainly in the form of HCO<sub>3</sub><sup>-</sup> ions, in normal seawater of pH ~ 8.1.

The product of seawater CO<sub>2</sub> capture can be (1) gaseous CO<sub>2</sub>,<sup>8</sup> (2) solid carbonates,<sup>107</sup> or (3) dissolved bicarbonates and carbonates ions (to be subsequently stored in the ocean).<sup>71,75,78,112</sup> To extract the CO<sub>2</sub> as gas, the bi/carbonate ions present in the seawater can be converted into H<sub>2</sub>CO<sub>3</sub>\* in the acidic compartments adjacent to the BPM.<sup>113</sup> Subsequently, through vacuum stripping of the acidified stream using

membrane contactors, CO<sub>2</sub>(g) can then be produced.<sup>8,113</sup> Alternatively, at alkaline pH > pK<sub>a<sub>2</sub></sub>, HCO<sub>3</sub><sup>-</sup> converts to CO<sub>3</sub><sup>2-</sup> and can subsequently precipitate through reaction with dissolved Mg<sup>2+</sup> or Ca<sup>2+</sup>.<sup>8,107</sup> When the partial pressure of CO<sub>2</sub> remains unchanged, the pH determines which mineral is obtained *e.g.*, the precipitation of CaCO<sub>3</sub> (in synthetic seawater) is favoured in 9.3 < pH < 9.6.<sup>8,114</sup> Considering that the Ca<sup>2+</sup> and Mg<sup>2+</sup> concentrations in seawater are respectively ×4 and ×25 higher than that of DIC, mineralization has the potential to remove all DIC, theoretically.<sup>115</sup> In addition, mineralization eliminates the expenses of using a membrane contactor.<sup>116,117</sup> In the third option, converting CO<sub>2</sub> to dissolved alkaline bicarbonates and carbonates enables carbon sequestration. This is a long-term carbon storage which also helps against ocean acidification by increasing the ocean alkalinity.<sup>71,75,78,112</sup> However, further research is required for understanding the full range and capacity of such approach.

The main bottlenecks in using *in situ* BPMED for this mineral crystallization are the risk of membrane contamination (*i.e.*, fouling) in the stack and the slow kinetics of the carbonate precipitation. To avoid the fouling, pure NaCl (instead of seawater) can be used in the BPMED for NaOH and HCl production.<sup>8</sup> The produced NaOH is then added to the seawater stream in a controlled crystallizer to initiate the precipitation. In order to improve the kinetics of the precipitation, use of a seeded crystallizer unit is suggested.<sup>107,118</sup> Although seawater CO<sub>2</sub> capture through mineralization is shown feasible, debates on the environmental impacts of reducing Ca<sup>2+</sup>/Mg<sup>2+</sup> concentration of the ocean are in progress.<sup>115,119</sup>

**3.2.5 Electrodeionization (EDI).** Electrodeionization (EDI) combines ion exchange membranes technology with ion exchange resins.<sup>120–125</sup> Ion exchange resins are solid cross-linked polymers that contain fixed charged groups typically based on acrylic or styrene monomers. When filling the flow compartments with beads or 3D structures of ion exchange resins, the polymer-electrolyte interface area is increased.<sup>126</sup> The combination can help overcome the concentration polarization losses associated with electrodialysis and electrolysis. The major application of electrodeionization (EDI) includes the removal/recovery of heavy metals and organic acids for pure water production.<sup>127–131</sup> The combination of BPMED with resin wafer electrodeionization (RW-EDI) is demonstrated in the lab-scale, where porous, solid matrix of ion-exchange resin beads are incorporated in between of the CEM's and BPM's in the cell.<sup>42</sup> However, unfortunately, data on the energy consumption and current efficiency of the system is not reported. The combination of electrodeionization (EDI) with electrolysis is shown feasible as demonstrated in Fig. 9.<sup>76,81</sup> However, as shown in Table 1, the process still requires further optimization (in terms of production of H<sub>2</sub>(g) and cost/stability of resins) to decrease its significant energy consumption. Furthermore, the (bio)fouling of the resin beads due to the contact with seawater decreases the overall efficiency of the method and needs yet to be addressed.

The pH-swing based EDI application for CO<sub>2</sub> capture has only been explored at a basic level.<sup>127</sup> More work has been done



on the use of amine based ion exchange resins as adsorbent for CO<sub>2</sub> capture, through thermal swing. Such resins are reported to show good stability after repetitive adsorption–desorption cycles with only a small reduction in capture capacity, and require relatively mild desorption conditions.<sup>126,132,133</sup> Recently, wafer enhanced electrodeionization for conversion of CO<sub>2</sub> into HCO<sub>3</sub><sup>−</sup> feed for algae cultured photobioreactors is reported.<sup>134</sup> Suggestions for further research on EDI technology are producing inexpensive ion exchange resins, reducing possibility of resin fouling (e.g., for the case of seawater feed<sup>76</sup>), and maintaining long-term resin stability.<sup>127</sup>

### 3.3 Redox-active carriers and electrode reactions

An alternative to BPMED and electrolysis for CO<sub>2</sub> capture, is the more classical electrochemically-mediated separation strategies that perform absorber/desorber cycles using specific redox-active sorbent carriers.<sup>39,49</sup> These redox-active carriers can be used for separation of CO<sub>2</sub>(g) from a gas mixture through (1) binding route Fig. 13a and (2) pH-swing route Fig. 13b. Both routes have been demonstrated feasible in the lab-scale.<sup>135,136</sup>

As for the “binding route”, the suitable carrier is activated at the cathode and can bind with the target species at its reduced state. The target species in this case is the CO<sub>2</sub> molecule. Subsequently, the captured CO<sub>2</sub> can be released at the anode through oxidation of the carrier while the carrier is regenerated. This process is also referred to as “electrochemical CO<sub>2</sub> pumping”,<sup>135,137</sup> see Fig. 13a. The cycle can be broken down into four steps:<sup>41</sup>

- Sorbent activation through oxidation or reduction.
- CO<sub>2</sub>(g) capture on the activated sorbent.
- Sorbent deactivation through the reverse electrochemical process.
- CO<sub>2</sub>(g) release.

Alternatively, in order to decrease the required electrical energy, these steps could be integrated in a two or three-stage

process<sup>40,41</sup> by e.g., enabling CO<sub>2</sub> capture or release to be performed simultaneously with electrochemical reduction or oxidation of the carrier.

In order to improve the kinetics of CO<sub>2</sub> capture and release, the “pH-swing route” can be integrated, where the chemistry of redox-active carriers are designed to undergo proton coupled electron transfer (PCET) reactions,<sup>135,136,138,139</sup> as shown in Fig. 13b.<sup>135,136,140</sup> If so, an “electrochemical H<sup>+</sup> pumping” takes place that enables an acidic and a basic pH on the anode and the cathode, respectively.

Although redox-active systems have yet to achieve industrial utility, they have the potential of producing a pure CO<sub>2</sub> stream even from dilute gas mixtures, such as air.<sup>141</sup> Among different classes of redox-active compounds that have been explored, such as bipyridines,<sup>142,143</sup> disulfides<sup>49</sup> and copper/amine systems,<sup>29,30</sup> the quinone species<sup>141,144–146</sup> are of particular interest,<sup>40</sup> owing their strong binding affinity for CO<sub>2</sub> in their reduced form compared to that of their neutral state.<sup>39,147</sup> Quinones are organic compounds derived from aromatics, through conversion of an even number of –CH= groups into –C(=O)– groups.<sup>148</sup> Quinones have also gained great interest as potential ideal candidates for PCET mechanism<sup>138,139,149–153</sup> inspired by their role in biological systems.<sup>154</sup> These redox reactions are (ideally) reversible, and can operate within the water splitting window.<sup>135</sup>

The choice of catalysts on the surface of the electrodes to facilitate the electron transfer together with the type and concentration of the electrolyte are important in determining the process efficiency in terms of capture, transport and release of CO<sub>2</sub>, and kinetics.<sup>136</sup> Furthermore, the local pH shown in Fig. 13b is not the same as the bulk pH.<sup>155</sup> While the high pH at the cathode determines the CO<sub>2</sub> absorption and the lower pH at the anode drives CO<sub>2</sub> desorption, only the bulk pH can be controlled in a practical process. That makes the choice of an appropriate average pH that enhances both reactions, challenging. Alternatively, the local pH can be maintained by inserting (1) an

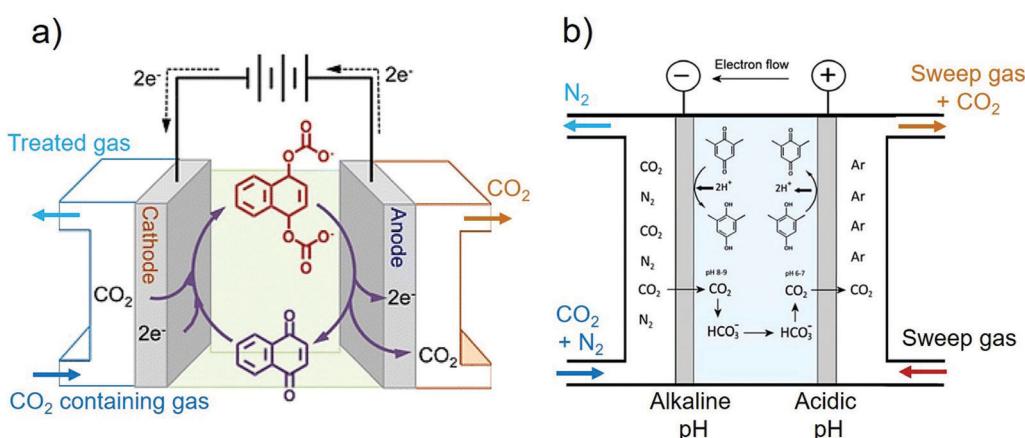


Fig. 13 (a) Electrochemical CO<sub>2</sub> separation using gas diffusion electrodes (GDE) through binding with quinone redox-active carrier (i.e., no pH-swing is created). Reprinted (adapted) with permission from ref. 144; Copyright (2015) American Chemical Society. (b) Combination of pH-swing with the chemistry of redox active carriers through (PCET) reaction using mixture of hydroquinone, quinone, and sodium bicarbonate. Reprinted (adapted) with permission from ref. 136; Copyright (2015) American Chemical Society.

anion-exchange membrane (AEM) or (2) an extra salt compartment sandwiched between an AEM and a cation-exchange membrane (CEM) between the electrodes.<sup>147</sup>

Despite its progress in the lab-scale, CO<sub>2</sub> separation using redox active carriers is not yet practically implemented because of the limitation it faces in terms of both solvents and carriers. It is difficult to find a solvent that is inexpensive, safe, electrochemically stable and allows high solubility of the redox species.<sup>49,147</sup> Possible improvements in terms of solvents can be achieved by using ionic liquids as electrolytes<sup>39,144</sup> or using salt-concentrated aqueous electrolytes.<sup>147</sup> As for the carriers, the solubility, chemical stability and kinetics of the redox molecule can pose limitations on the process.<sup>49</sup> To address these drawbacks, electrochemically mediated amine regeneration can be employed, using a similar concept, but by employing amines rather than quinones as described in Section 4.1.3. Alternative to using dissolved carriers in an electrolyte – where the transport of both the electrolyte and the carrier molecules between the two electrodes is required, the active carriers can be immobilized between the opposite electrodes.<sup>39</sup> The latter is explained further in Section 4.2.1. Recently, solid polymerized quinone (formed into a composite with carbon nanotubes to confer electronic conductivity) is employed.<sup>39</sup> This so called “electro-swing” process exhibits a high faradaic efficiency and a low energy consumption (40–90 kJ mol<sup>-1</sup> CO<sub>2</sub> captured) compared to the thermal or pressure swings for sorbent regeneration. However, it needs to be improved in terms of capacity and kinetics.

**3.3.1 Electrode induced pH-swing.** Another electrochemical based CO<sub>2</sub> capture concept utilizing local pH near electrodes is the (membrane) capacitive deionization (MCDI) method.<sup>37,156</sup> Capacitive deionization is mainly used for water treatment, but its application has recently expanded to energy harvesting and CO<sub>2</sub> capture.<sup>157–165</sup> The motivation to capture CO<sub>2</sub> via such system is that deionized water can be used without the need of any other chemicals, using inexpensive carbon based electrodes.<sup>37,156</sup>

MCDI cells consist of activated carbon electrodes and ion-exchange membranes. When a current is applied in the charging step of MCDI, HCO<sub>3</sub><sup>-</sup> and H<sup>+</sup> ions are adsorbed into the porous electrodes inside of the cell (causing a local low pH at the cathode and increasing pH in the bulk). As the electrolyte is being depleted from ions, more CO<sub>2</sub>(g) can be absorbed in the deionized water due to the shift in the CO<sub>2</sub> equilibrium, to make up for the depletion. It has been proposed to use a gas-liquid contactor spiral glass tube outside of the cell for *in situ* absorption. When the current direction is reversed (*i.e.*, discharging step), the subsequent desorption of H<sup>+</sup> and HCO<sub>3</sub><sup>-</sup> (plus a small amount of CO<sub>3</sub><sup>2-</sup>) ions from the carbon electrodes drives the chemical equilibrium in the opposite direction. As the concentration of H<sub>2</sub>CO<sub>3</sub>\* will exceed the solubility, CO<sub>2</sub>(g) is formed from the electrolyte. CO<sub>2</sub>(g) absorption and desorption can be controlled through shifting the current direction. CDI can also be used in combination with NH<sub>3</sub>-based CO<sub>2</sub> capture.<sup>166</sup>

In addition to the carbon based capacitive electrodes, other metals can also be used. For example, CO<sub>2</sub> can be captured through intercalation/deintercalation of protons on the manganese

dioxide (MnO<sub>2</sub>) based electrodes. The electrodes can host protons (*i.e.*, intercalation) during reduction and release them (*i.e.*, deintercalation) during oxidation, creating the required pH-swing for CO<sub>2</sub> absorption and desorption, respectively.<sup>167</sup> In such methods, periodic electrode polarity and the switching fluid flows ensure a continuous process.

### 3.4 Molten carbonate cells and hybrid electrochemical capture methods

Electrochemical methods can benefit from a pH-swing approach but are not limited to it. Examples are using (high temperature) molten carbonate cells or the hybrid methods that integrate CO<sub>2</sub> capture and conversion.

High-temperature molten carbonate cells are early electrochemical CO<sub>2</sub> capture examples.<sup>32,168</sup> In such process, a CO<sub>2</sub> containing (flue) gas is fed to the cathode side of an electrochemical cell, where electricity is used to drive CO<sub>2</sub> and O<sub>2</sub> (in form of CO<sub>3</sub><sup>2-</sup>) across a molten carbonate salts electrolyte (sandwiched between ceramic membranes in contact with the electrodes). At the anode, carbonate ion will be reduced to CO<sub>2</sub> and O<sub>2</sub> again. An alternative design enables a molten carbonate fuel cell, where CO<sub>2</sub> is captured while H<sub>2</sub> is produced.<sup>169–171</sup> Involved challenges are difficult operating conditions due to the high temperatures, corrosion and sensitivity to the presence of SO<sub>x</sub> in the gaseous mixture.<sup>20,24,172</sup> Research for developing dense molten carbonate CO<sub>2</sub> selective membranes at high temperatures (> 723 K) is still in progress.<sup>173–175</sup>

Examples of electrochemical hybrid capture and utilization is the electrochemical seawater battery system,<sup>176</sup> the alkali metal-based CO<sub>2</sub> batteries (*e.g.*, lithium–CO<sub>2</sub> batteries<sup>177,178</sup>) and electrochemical CO<sub>2</sub> capture and conversion combinations.<sup>25,179–183</sup> The absence of pH-swings, and the lack of further development of these proposed electrochemical capture routes, categorizes these concepts beyond the scope of this review. The broader context in terms of CO<sub>2</sub> utilization is discussed in Section 5.

### 3.5 Which electrochemical method to use?

A comparison of the metrics of electrochemical pH-swing based CO<sub>2</sub> capture methods is given in Table 1. These capture methods have often energy consumption > 300 kJ mol<sup>-1</sup> CO<sub>2</sub>. As a comparison with conventional methods, the energy consumption of CO<sub>2</sub> capture (from flue gas) *via* aqueous monoethanolamine (MEA) using a thermal swing, currently the most mature capture method, is between ~170–300 kJ mol<sup>-1</sup> CO<sub>2</sub>.<sup>184–190</sup> Approximately ~80% of this energy is the contribution of the thermal regeneration,<sup>13</sup> included in the reboiler heat duty.<sup>191</sup> Most conventional and electrochemical captures are energy intensive, when compared to the combustion energy of various fuels and the emitted CO<sub>2</sub> per mole of the fuel. From an economic point of view, CO<sub>2</sub> capture is only interesting if the energy consumption of the capture is < 66 kJ mol<sup>-1</sup> CO<sub>2</sub>.<sup>42,192</sup>

Renewable sources would be preferred over fossil fuels for driving electrochemical CO<sub>2</sub> capture to (1) maximize the reduction in net carbon emission and (2) leverage the advantage of electrifying the CO<sub>2</sub> capture process. At the same time,



the absence of flue gas from power plants in renewable sources would make diffused CO<sub>2</sub> sources (*e.g.*, atmosphere and seawater) the most logical feed for electrochemical CO<sub>2</sub> capture technologies. This is also reflected in Table 1, where most research has focused on capture from air, seawater or (low concentrated) bi(carbonate) solutions.

At present, (membrane) electrolysis and BPMED are the most studied electrochemical capture approaches. Fig. 14a shows the estimated energy consumption of both methods (see ESI† for calculations). This electrical energy consumption,  $E$  (in kJ mol<sup>-1</sup> CO<sub>2</sub>), is calculated *via*:

$$E = \frac{i \cdot A \cdot V}{r_{\text{CO}_2(\text{g})}} \quad (11)$$

where  $i$  is the current density (A m<sup>-2</sup>),  $A$  is effective area of the electrodes (m<sup>2</sup>),  $V$  is the total cell voltage (volts) and  $r_{\text{CO}_2}$  is the recovery rate of the captured CO<sub>2(g)</sub> in mol s<sup>-1</sup>. To put the energy consumption of Fig. 14a in perspective, the energy produced per mole of fuel (through combustion) and the associated emitted CO<sub>2</sub> are shown in Fig. 14b. This emphasizes the energy-intensive nature of the capture process: capturing 1 mole of CO<sub>2</sub> *via* BPMED consumes 25–60% of the energy obtained from combustion of hydrocarbon fuel per mole of CO<sub>2</sub>, dependent on the fuel type. For conventional methods and electrochemical capture *via* electrolysis, this figure is even larger.

Fig. 14a shows that the ohmic losses cover a significant part of the energy losses,<sup>77</sup> and bring in a lever to reduce  $E$ . In electrochemical cells, such losses can appear as *e.g.*, heat and/or unwanted chemical byproducts. For example, losses caused by product recombination, such as recombination of produced H<sup>+</sup> and OH<sup>-</sup> in BPMED or the recombination of O<sub>2(g)</sub> and H<sub>2(g)</sub> in water electrolysis to form water again. Membrane co-ion leakage is another common loss often involved in membrane based electrochemical processes.<sup>93</sup> The limitations and areas of improvements of each electrochemical CO<sub>2</sub> capture method can be summarized as:

(1) It is obvious from Fig. 14a that the energy consumption for BPMED is lower than that of electrolysis when targeting CO<sub>2</sub>

capture. In case hydrogen is an aimed product as well, the energy difference between these two methods (which is equivalent to 1.23 V) can be justified, and can be lower than the energy for two separate systems making acid/base and hydrogen. However, in more detail, the combination of these two products in electrolysis complicates the optimal current density, which is not necessarily the same for hydrogen and acid/base production. Moreover, most hydrogen catalysts are geared towards acidic environments, and earth abundant oxygen catalyst are available for alkaline environments, while the opposite environments are present in the combined electrolysis/acid-base production.<sup>196</sup> That limits the options for electrocatalytic material (*e.g.*, platinum and ruthenium), which can pose resource limitations as a relatively large electrode area is required. On the contrary, up scaling can be done easily for BPMED capture method by repeating multiple cell pairs within a single electrode pair.

(2) When using BPMED, despite its uncomplicated up scaling, the typical energy consumption in Table 1 is still 2–3 times more than theoretically expected in Fig. 14a. These losses are due to the involved non-idealities in charged membranes (*e.g.*, high resistivity, co-ion leakage, low chemical stability), the high over potential of water dissociation in BPM, or carbonate feed (requiring 2 H<sup>+</sup> per molecule to acidify to H<sub>2</sub>CO<sub>3</sub>) instead of bicarbonate. Thankfully, achieving a lower energy consumption is possible both through process optimization and material engineering. Process optimizations can be done by *e.g.*, controlling the applied current density ( $i$ ), feed flow rate (residence time in the cell), electrolyte conductivity/pH, cell configuration, flow path mode, and operation pressure/temperature, while water dissociation can be improved through material engineering.<sup>197,198</sup> The current minimum economic cost of BPMED is at least twice of the cost of the wet-scrubbing rival.<sup>3</sup> However, the cost can significantly decrease if improvements in the cost of renewable energies, cost and availability of ion exchange membrane, membrane life time and membrane selectivity is achieved. Finally, the total capture cost does not only depend on the method, but also on the source of the capture. For example, depending on the pumping facilities and plant location, indirect ocean capture (IOC) can be

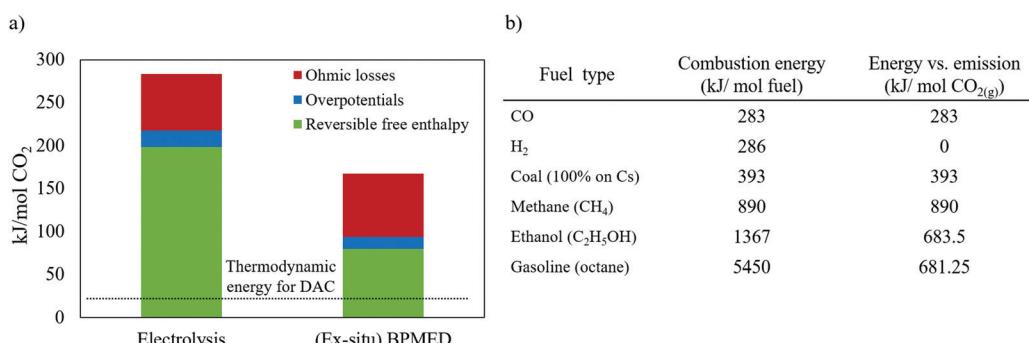


Fig. 14 (a) Electrical energy consumption for direct air capture (DAC) through (membrane) electrolysis. Current density of 20 mA cm<sup>-2</sup> and ΔpH = 14 is assumed for both cases. See Section S2 of the ESI† for detailed calculations. The thermodynamic work required for DAC (assuming 400 ppm CO<sub>2(g)</sub>) is 20 kJ mol<sup>-1</sup> CO<sub>2</sub>.<sup>15</sup> (b) The combustion heat of common fuels and their CO<sub>2(g)</sub> emission, obtained from ref. 195 and stoichiometric combustion reactions.



economically favored relative to direct air capture (DAC), or *vice versa*.<sup>199</sup>

(3) The reversible free enthalpy in Fig. 14a is based on a  $\Delta\text{pH} = 14$ . Using lower  $\Delta\text{pH}$ , a lower reversible free enthalpy is involved.<sup>84</sup> Although it is theoretically possible to perform a pH swing between pH 4–7, potentially reducing the energy consumption to values close to the thermodynamic limits, this low energy consumption is not obtained in practical BPMED at medium to high current density.

(4) Membrane capacitive deionization (MCDI) is recently demonstrated to capture CO<sub>2</sub> from a CO<sub>2</sub>(g) + N<sub>2</sub>(g) mixture, using only demineralized water<sup>37,156</sup> with the lowest capture energy among other methods ( $\sim 40\text{--}50 \text{ kJ mol}^{-1} \text{ CO}_2$ ), see Table 1. However, the obtained current density is extremely low ( $\sim 0.02\text{--}0.06 \text{ mA cm}^{-2}$ ) and there is a long way to go before (M)CDI becomes a competitive means of CO<sub>2</sub> capture as the stability and performance of the large-scale CDI applications are yet unknown. Future work is suggested to investigate the physical and chemical effects of weak electrolyte solutions in CDI.<sup>156</sup>

(5) Only a few works on CO<sub>2</sub> capture through electrodeionization (EDI) show lab scale feasibility<sup>76,121,200</sup> as summarized in Table 1. However, no data on the energy consumption of those systems is available. CO<sub>2</sub> capture through EDI is limited due to the cost of ion exchange resins, their poor stability and their sensitivity to fouling.<sup>127</sup>

(6) Electrochemical methods that use redox-active carriers are shown to be less energy intensive ( $\sim 100 \text{ kJ mol}^{-1} \text{ CO}_2$ ). However, these results have been only obtained using synthetic flue gas. Quinones, used as binding agents for CO<sub>2</sub>, are highly sensitive to water and oxygen, making the applications for real flue gas (or direct air capture) impractical. Moreover, most redox carriers need organic solvents electrolytes that suffer from a low ionic conductivity which limit the current density. When using quinones as carriers, the total CO<sub>2</sub> carrying capacity is limited by the solubility of quinone in the solvent, the applied electrode potentials, evaporative solvent losses and consequent drying of the electrodes.<sup>144</sup> Luckily, the efficiency of the CO<sub>2</sub> absorption and desorption in such systems can be increased by combining a pH-swing through electrochemical reactions,<sup>136</sup> where proton coupled electron transfer (PCET) takes place. However, the practicality of this approach still awaits the improvement of electrochemical redox kinetics. The low solubility of PCET organics limits its capture

capacity.<sup>135</sup> Furthermore, PCET carriers are also very sensitive to gasses such as O<sub>2</sub> and sulfur, posing again challenges for (real) gas CO<sub>2</sub> capture application.<sup>135</sup> Upscaling can be done by using a larger electrode surface area.

All electrochemical CO<sub>2</sub> capture methods are still under development (TRL 5 to 6), although they enable high CO<sub>2</sub> recovery rate (>80%). In order to provide a framework of comparison between these methods and the conventional (non-electrochemical) processes – which have already been commercialized – the conventional processes are described further in the next section.

## 4 Combining electrochemical methods with conventional capture technologies

Conventionally, the capture industry only targeted CO<sub>2</sub> capture from centralized CO<sub>2</sub> emitters such as fossil fueled power plants, iron, steel, and cement industries. However, this approach is impotent to achieve a net zero CO<sub>2</sub> emission because, as shown in Table 2, decentralized sources still constitute a large part of the total emission (total GHG emission of 55 Gt CO<sub>2eq</sub> in 2019<sup>201</sup>). Therefore, currently DAC and IOC are gaining attention (Table 3). For achieving climate targets, CO<sub>2</sub> removal within a gigaton order of magnitude is needed.<sup>202,203</sup>

The (centralized) capture technologies are often grouped in main categories of;<sup>18</sup> (1) oxy-fuel combustion, (2) pre-combustion, (3) post-combustion and (4) chemical looping (combustion) as discussed in Table 4. In addition, capture by algae,<sup>214–220</sup> biochar<sup>221–226</sup> and charcoal<sup>227</sup> are recently demonstrated. While there are many CO<sub>2</sub> capture methods, introducing all of them are out of scope of this work and we refer the reader to various available literature on this topic.<sup>13,17–25,228,229</sup> For an overview of the current state-of-the-art of CO<sub>2</sub> capture, transport, utilisation and storage see ref. 230. Among the available methods, most research focus has been given to the post-combustion methods as they can be retrofitted more easily to the existing industrial units, compared to the oxy-fuel and pre-combustion methods.<sup>229</sup> Traditional post-combustion capture methods are absorption,<sup>18,19,231–236</sup> adsorption,<sup>13,18,237–239</sup> membrane gas separation,<sup>240–246</sup> calcium looping<sup>19,247–249</sup> and mineral carbonation,<sup>110,250–260</sup> see Table 4. These methods are combined

Table 2 Thermodynamically required energy, properties and the scale of main capture feeds

Source	Thermodynamic properties & required energy	Emission & capture scale
Centralized	<ul style="list-style-type: none"> <li><b>Flue gas:</b> <ul style="list-style-type: none"> <li>- <math>150 &lt; T &lt; 1200^\circ\text{C}</math>, <math>p_{\text{CO}_2} \sim 0.03\text{--}0.15 \text{ atm}</math><sup>204,205</sup></li> <li>- <math>7 \text{ kJ mol}^{-1} \text{ CO}_2</math> for 13% flue gas<sup>206</sup></li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>&gt; 58% of total emission, see Fig. 1</li> <li>Current post-combustion capture &gt; 2.4 Mt CO<sub>2</sub> per year<sup>207</sup></li> </ul>
Decentralized	<ul style="list-style-type: none"> <li><b>Direct air capture (DAC):</b> <ul style="list-style-type: none"> <li>- Ambient <math>T</math>, <math>p_{\text{CO}_2} \sim 0.0004 \text{ atm}</math> (<math>\sim 400 \text{ ppm}</math>)</li> <li>- <math>20 \text{ kJ mol}^{-1} \text{ CO}_2</math><sup>15,206,208</sup></li> </ul> </li> <li><b>Indirect ocean capture (IOC):</b> <ul style="list-style-type: none"> <li>- <math>5 &lt; T &lt; 35^\circ\text{C}</math>, <math>p_{\text{CO}_2} \sim 0.072 \text{ atm}</math> (<math>\sim 2.5 \text{ mM DIC}</math>)</li> <li>- Same thermodynamically required energy as DAC<sup>199</sup></li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>&lt; 42% of total emission, see Fig. 1</li> <li>Current DAC capture shown in Table 3, but no large scale IOC, yet<sup>209</sup></li> </ul>



Table 3 Large scale DAC companies

Company	Process mechanism	Capacity (tonne CO <sub>2</sub> per year)
Carbon Engineering <sup>210</sup>	(KOH) absorption + high temperature calcination	1 000 000
Global Thermostat <sup>211</sup>	(Amine based) adsorption + thermal & pressure swing regeneration	4000
Climeworks <sup>212,213</sup>	(Amine based) adsorption + thermal swing regeneration	900

Table 4 Dominant non-electrochemical CO<sub>2</sub> capture methods (continued)

Capture method	Process mechanism	Challenges
Oxy-fuel <sup>261–263</sup>	Instead of air, pure O <sub>2</sub> (g) or a CO <sub>2</sub> (g)/O <sub>2</sub> (g) mixture is used for fuel combustion. 75–80% CO <sub>2</sub> is produced as opposed to combustion in normal air where 3–15% CO <sub>2</sub> is produced	<ul style="list-style-type: none"> <li>High oxygen production energy costs (<i>ca.</i> 200–220 kW h per tonne of oxygen generated by cryogenic air separation<sup>263</sup>)</li> <li>High sensitivity to air leakage into the system</li> <li>Although an efficient capture method,<sup>264</sup> difficult to retrofit compared to post-combustion method</li> <li>Special materials are needed to resist the high flame temperature (<i>ca.</i> 3500 °C). Although, the recycled CO<sub>2</sub> can be used to moderate this temperature<sup>18</sup></li> </ul>
Pre-combustion <sup>265–268</sup>	CO <sub>2</sub> is separated from H <sub>2</sub> -rich fuel before combustion. For example, synthetic gas is produced from fossil fuel by adding steam or pure oxygen at high temperature and pressure (1400 °C and 25–55 atm) and a subsequent water-gas shift reaction.	<ul style="list-style-type: none"> <li>Retrofit to existing plants is costly and more difficult compared to oxy-fuel and post-combustion</li> <li>Reaction CO + steam ⇌ CO<sub>2</sub> + H<sub>2</sub> produces 15–40% CO<sub>2</sub> at 14–40 atm. The produced H<sub>2</sub> can be used for power generation, but CO<sub>2</sub> needs to be removed using a subsequent separation technique</li> </ul>
Post-combustion: Absorption <sup>18,19,231–236</sup>	CO <sub>2</sub> (g) (from flue gas or air) is absorbed ( <i>i.e.</i> , chemically or physically) in an absorbent. Pure CO <sub>2</sub> (g) is subsequently recovered through temperature swing desorption while the absorbent will be regenerated. Currently, amine based capture is the most mature method for CO <sub>2</sub> capture	<ul style="list-style-type: none"> <li>Limited CO<sub>2</sub> absorbing capacity resulted from the reaction stoichiometry and dependent on the absorbent type (<i>e.g.</i>, low capacity as 0.4 kg CO<sub>2</sub> per kg-MEA or higher as 1.2 kg CO<sub>2</sub> per kg-NH<sub>3</sub><sup>18,269</sup>)</li> <li>High absorbent regeneration (<i>i.e.</i>, CO<sub>2</sub> desorption) energy</li> <li>Solvent losses caused by volatility or thermal/chemical degradation, the subsequent equipment corrosion &amp; negative environmental impacts of solvent emissions</li> <li>High sensitivity to flue gas temperature, pressure and presence of impurities, such as NO<sub>x</sub>, SO<sub>x</sub> and oxygen (<i>i.e.</i>, oxidative degradation)<sup>270</sup></li> </ul>
Absorption <sup>13,18,237–239</sup>	CO <sub>2</sub> (g) is adsorbed on solid materials and will be recovered through temperature, pressure or vacuum swing desorption	<ul style="list-style-type: none"> <li>When used for flue gas, pre-treatments to remove impurities, such as NO<sub>x</sub>, SO<sub>x</sub> and H<sub>2</sub>O and to decrease gas temperature are needed</li> <li>Possible loss in the adsorption capacity of the adsorbent after desorption step (<i>e.g.</i>, 4–9% loss for amine immobilized onto solid silica)</li> <li>Sorbent degradation in cyclic operation</li> </ul>
Membrane gas separation <sup>13,240,241,244,246,271,272</sup>	Process is driven by partial pressure difference of the gas molecules to be separated. Gas molecules permeate according to their size, diffusivity, or solubility through the membrane.	<ul style="list-style-type: none"> <li>Not feasible for streams with low CO<sub>2</sub> partial pressure and concentration</li> <li>To accommodate the high flow rate of industrial flue gas, high membrane surface area is required</li> <li>Sensitivity to presence of moisture (<i>i.e.</i>, lower selectivity)</li> <li>On-going research on new membranes with high selectivity and permeability<sup>273–275</sup></li> </ul>
Calcium looping <sup>13,248,276</sup>	A variant of chemical looping (combustion) that involves carbonation and calcination. Metal oxides <i>e.g.</i> , CuO, Mn <sub>2</sub> O <sub>3</sub> , NiO, and Fe <sub>2</sub> O <sub>3</sub> are used instead of O <sub>2</sub> (g) in oxy-fuel combustion	<ul style="list-style-type: none"> <li>Rapid decrease in the limestone (<i>i.e.</i>, sorbent) capacity after a number of cycles of reaction with CO<sub>2</sub></li> <li>Environmental concerns caused by limestone mining, the waste from Ca-looping (<i>i.e.</i>, the spent CaO) and the need for high temperatures for the operation</li> <li>Need for air separation unit to obtain pure O<sub>2</sub> for calcination</li> </ul>

with thermal swing, pressure swing or vacuum swing for CO<sub>2</sub> desorption.

The conventional absorption and adsorption based captures can be combined with electrochemical methods to decrease (or

eliminate) the required thermal energy for the regeneration step as discussed in Sections 4.1.3 and 4.2.1. No available work have been found on electrochemical enhancement of the other conventional methods.



#### 4.1 Absorption (wet scrubbing)

$\text{CO}_2$  is a weak acid. Therefore, substrates that contain basic moieties such as amine groups (*e.g.*, alkanolamines) are efficient absorbents for  $\text{CO}_2$  capture.<sup>277</sup> Amines are derivatives of ammonia ( $\text{NH}_3$ ), containing a basic nitrogen atom, where one ( $\text{R}-\text{NH}_2$ ) or more hydrogen atoms have been replaced by a substituent. Amines act as a nucleophiles (*i.e.*, electron pair donors also known as Lewis bases), reacting with  $\text{CO}_2$  at the electrophilic (*i.e.*, electron pair acceptor) carbon center to form a carbamate (derivatives of carbamic acid  $\text{H}_2\text{NCOOH}$  where one or more hydrogens are replaced by other organic functional groups).<sup>49,167,278</sup> Although the amine capture processes are extensively studied, the reaction mechanism is not yet fully understood. For a detailed description see ref. 279.

The post-combustion  $\text{CO}_2$  capture is dominated by amine-based absorption, using aqueous solutions of mono-, di-, tri-ethanolamine or hindered amines to absorb  $\text{CO}_2$  in gas form.<sup>232,278,280–283</sup> Aqueous solutions are often used in order to control the density, viscosity, surface tension, and the thermal expansion coefficient of the pure amines.<sup>284–286</sup> This is while, the energy consumption for solvent regeneration decreases substantially with increasing the amine concentration (due to an improved  $\text{CO}_2$  reaction rate and absorption capacity<sup>287</sup>). However, such high concentrations also increase the degradation rate, viscosity and the involved environmental concerns, posing challenges on the overall capture process.<sup>285,287</sup> In addition to aqueous solutions, both non- and low-aqueous solvents (*i.e.*, water-lean solvent) are viable.<sup>284,288,289</sup> These alternatives are not well studied yet although they have gained interests recently. All currently assessed water-lean solvents have shown lower  $\text{CO}_2$  solubilities than aqueous monoethanolamine (MEA). However, because the heat of absorption is not much affected, solvents with the lower volatility than water could potentially offer opportunities for processes with overall less reboiler heat duties than that of ordinary aqueous MEA.<sup>284</sup>

Amines have been used for  $\text{CO}_2$  capture since 1930.<sup>278</sup> Monoethanolamine (MEA) scrubbing technology is seen as a benchmark technology for  $\text{CO}_2$  capture from flue gas of large-scale power plants.<sup>187,190,290,291</sup> In this method,  $\text{CO}_2(\text{g})$  is chemically absorbed at low temperatures (~40 to 60 °C) in the absorbent and is extracted in a desorber column later, generally *via* a temperature swing at high temperatures (~120 °C), where the absorbent is also regenerated.<sup>186,292</sup> The energy consumption of  $\text{CO}_2$  capture (from flue gas) *via* aqueous monoethanolamine (MEA) thermal swing is between ~170–300 kJ mol<sup>-1</sup>  $\text{CO}_2$ .<sup>184–190</sup>

To address the drawbacks discussed in Table 4, for  $\text{CO}_2$  capture *via* chemical absorption, other inorganic solvents, such as aqueous potassium and sodium carbonate,<sup>167</sup> ammonia solution and alkali hydroxide solution have been investigated.<sup>293,294</sup> When using alkaline or carbonate based solution, hydration of  $\text{CO}_2$  takes place rather than carbamate formation.<sup>167</sup> However,  $\text{CO}_2$  absorption in carbonate is very slow compared to that of amines.<sup>270</sup> Increasing the absorbent pH (*i.e.*, applying a wide range pH-swing), can enhance the kinetics substantially.

**4.1.1 pH-swing vs. thermal swing.** All available large-scale  $\text{CO}_2$  capture processes rely on heating or using a combination

of heat and vacuum to release the captured  $\text{CO}_2$ .<sup>27,294</sup> Given the initial focus was to capture  $\text{CO}_2$  from flue gas of fossil fuel power stations, heat integration is relatively straightforward. However, as an alternative to this thermal swing, an (electrochemical) pH-swing approach can be applied for  $\text{CO}_2$  recovery and absorbent regeneration.<sup>3</sup>

In a thermal swing absorption process, the energy performance is dominated by (1) absorbent absorption capacity, (2) absorption rate, (3) heat of absorption and (4) thermal degradation.<sup>270</sup> The required thermal energy is often exacerbated due to use of aqueous solutions in which the capturing agent is contained (*e.g.*, water for the case of MEA<sup>270</sup>).<sup>49</sup> Furthermore, the required heat is normally generated from combustion of fossil fuels, decreasing the net captured  $\text{CO}_2$  in the conventional processes.<sup>108</sup>

Alternatively a pH-swing can be used, to absorb and desorb  $\text{CO}_2$ . The cost of absorbent regeneration through pH-swing *via* BPMED in wet scrubbing (using KOH absorbent) is estimated to be ~773 \$ per tonne  $\text{CO}_2$ . That is more than three times of the cost of the thermal swing rival. However, the cost can significantly decrease if the cost of renewable energy decreases (*e.g.*, from 0.06 to 0.018 \$ per kW h), cost of membrane decreases (to lower than 100 \$ m<sup>-2</sup>), membrane life time increases from around 3 years<sup>295</sup> to 15 years and the process is optimized.<sup>3</sup>

**4.1.2 Physical absorption.** The advantage of the physical absorption to chemical absorption explained above is its lower heat consumption in the solvent regeneration step.<sup>21,22</sup> Solvents, such as methanol, poly(ethylene glycol) and dimethyl ether can be used to absorb  $\text{CO}_2(\text{g})$  physically. Recently, ionic liquids have been proposed as alternatives to the conventional absorption solvents.<sup>296–298</sup> Ionic liquids are molten salts that exist as liquids near room temperature, often composed of an organic cation with an inorganic or organic anion and featuring polar properties.<sup>25</sup> Ionic liquids are referred to as green solvents due to their low volatility, exceptional thermal stability, non-flammability and environmentally benign character.<sup>299</sup> The capture using ionic liquids is often based on physisorption although some ionic liquids react with  $\text{CO}_2$  in a chemisorption mechanism.<sup>22</sup>

**4.1.3 Electrochemical enhancement of amine based absorption.** Electrochemical methods provide alternative routes to the conventional thermal regeneration step in absorption based capture. Such electrochemical enhancements are shown feasible through (1) pre-concentrating the  $\text{CO}_2$  rich amine stream, (2) substituting  $\text{CO}_2$  with suitable metallic species or (3) pH-swing. These three routes are explained below.

For pre-concentrating the  $\text{CO}_2$  rich amine stream, a capacitive deionization unit (CDI) can be used. Inside the CDI cell, when current is applied, ionic species (*i.e.*,  $\text{MEAH}^+$  and  $\text{MEACOO}^-$  in case of monoethanolamine absorption) are adsorbed at the electrodes, creating an ion-free solution (mainly water<sup>270</sup>) that can be sent back to the absorber column without the need to undergo the thermal desorption step. Subsequently, when power is switched off or reversed, the adsorbed ions will be released back from the porous electrodes, creating a carbon rich stream that can then be sent to the



stripper column. When applying thermal regeneration, the concentrated solution from the CDI unit then requires 50% lower solvent regeneration heat energy because of its high CO<sub>2</sub> loading.<sup>300</sup>

As an alternative approach, the conventional temperature swing step in the amine absorption process can be replaced by metal ion substitution in an electrochemical cell.<sup>29,30,301</sup> Such a cell consists of multiple anode and cathode chambers made of copper. At the anode, Cu<sup>2+</sup> reacts with the amines, displacing the CO<sub>2</sub> as shown in Fig. 15. CO<sub>2</sub> is subsequently removed in flash tanks after the anode chambers and the amines are regenerated by subsequent reduction of the Cu<sup>2+</sup> to Cu in the cathodes. The process allows for higher CO<sub>2</sub> desorption pressures, smaller absorber columns and lower energy demands.

There are few works available on using a pH-swing to regenerate amine based absorbents; The early work of Zabolotskii *et al.* shows the feasibility of a low-temperature BPMED for regeneration of aqueous monoethanolamine (MEA) sorbent.<sup>303</sup> Huang *et al.* demonstrated a pH-swing for amine based absorbents, doing so electrochemically (for flue gas desulfurization)<sup>304</sup> and Feng *et al.* by simply adding a (weak) acid to the rich amine stream (for CO<sub>2</sub> capture).<sup>236</sup> Such addition of acid is reported to have the potential to increase the volume of the released CO<sub>2</sub> and to decrease the absorbent regeneration heat energy. Both contributing to a higher energy efficiency.<sup>236</sup>

## 4.2 Adsorption

CO<sub>2</sub> can be adsorbed on solid porous materials, where CO<sub>2</sub>(g) is subsequently recovered and the adsorbent is regenerated through a temperature, pressure,<sup>305</sup> vacuum<sup>306–315</sup> or electric swing desorption.<sup>316</sup> Previous work has shown CO<sub>2</sub> adsorption on metal–organic frameworks (MOF's), silica, zeolites,

immobilized amine, alumina, polymeric resins, molecular sieves and activated carbon. Adsorption is possible through both physical (*e.g.*, on zeolite, graphene, MOF's, silica) and chemical (*e.g.*, amine and calcium based materials) bonding with CO<sub>2</sub>.

An advantage of adsorption based capture is that using solid adsorbents (instead of the mature aqueous monoethanolamine (MEA) technology) in capturing systems reduce the regeneration heat (due to the much lower heat capacity of solid adsorbents and the avoidance of water evaporation in the regenerator).<sup>187</sup> The (calculated) regeneration heat for polyethyleneimine (PEI)/silica adsorbent based capture is reported to be around 2.46 GJ per tonne CO<sub>2</sub>, which is much lower than the value of 3.3–3.9 GJ per tonne CO<sub>2</sub> for a typical aqueous MEA system.<sup>187</sup> In general, adsorption also has higher CO<sub>2</sub> adsorption capacity compared to that of absorption *e.g.*, ca. 88–176 kg CO<sub>2</sub> per kg adsorbent<sup>305</sup> vs. 0.4–1.2 kg CO<sub>2</sub> per kg adsorbent.<sup>18,269,317</sup>

**4.2.1 Electrochemical enhancement of adsorption.** Similar to absorbents, the CO<sub>2</sub> capture and recovery of recent adsorbents has been assessed *via* electrochemical swings instead of the conventional pressure or temperature swings.<sup>39,318</sup> As an example, the redox active carriers described in Section 3.3 can be employed as solid adsorbents, immobilized on surface of electrodes. Such electro-swing systems normally operate in charge/discharge cycles where changing the cell polarity regulates the activation and deactivation of the carrier.<sup>39</sup> The significant advantage of the electro-swing process with respect to pressure swing adsorption (PSA) and temperature swing adsorption (TSA) is that the CO<sub>2</sub> capacity of these solid adsorbents does not depend on the feed concentration, making them suitable for CO<sub>2</sub> capture even from very dilute streams.<sup>39</sup> Moreover, up-scaling is easily achievable in electro-swing adsorption by using multiple anode and cathode chambers repeating within one cell.

Alternative to the electrochemical electro swing approach described above and in ref. 39, the electrochemical process can induce a temperature swing. In that case, a low voltage passes through a conductor to change the sorbent temperature *via* Joule heating (*i.e.*, resistance turning electric energy into heat).<sup>318–322</sup>

## 5 CO<sub>2</sub> utilization

After CO<sub>2</sub> is captured, it can be stored or utilized, see Fig. 16. CO<sub>2</sub> is an inexpensive, non-toxic, renewable commodity.<sup>323,324</sup> The market for CO<sub>2</sub> use is projected to grow from 0.23 gigatonnes (Gt) per year today to 7 Gt per year by 2030.<sup>325</sup>

In addition to fuels, chemicals such as ethylene, alcohols, formic acid (or formate), syngas, urea and other organic materials can be produced from CO<sub>2</sub>, electrochemically, thermo-chemically or by other approaches.<sup>323,329–337</sup> Such organic chemicals are often more expensive than fuels and may offer advantages in the techno-economic analysis. However, the global demand for them are much lower than fuels as shown in Fig. 17.

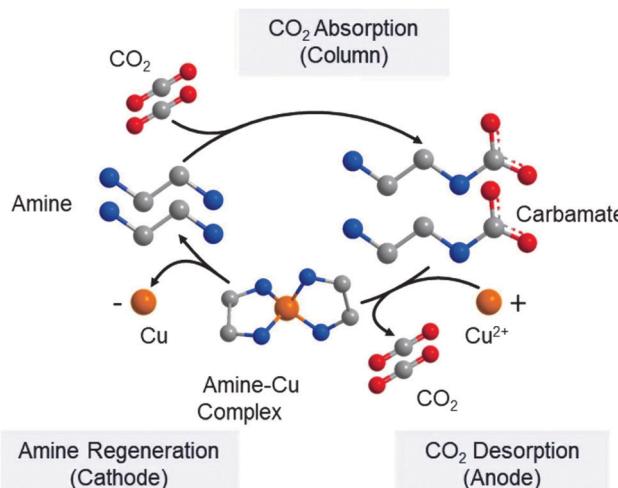
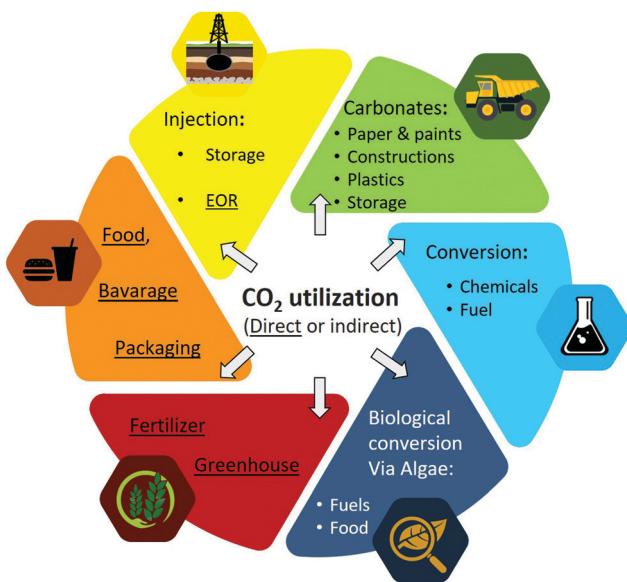
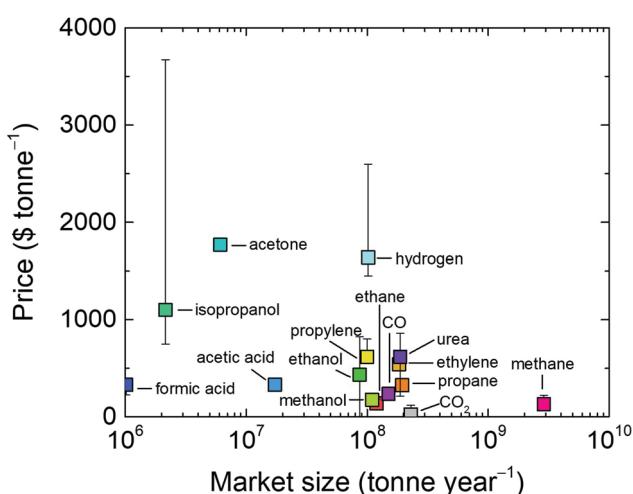


Fig. 15 Electrochemically-mediated amine regeneration (EMAR) using copper. Reprinted from ref. 302, Copyright (2019), with permission from Elsevier. The conventional thermal swing is replaced with an electrochemical step. In addition to Cu/Cu<sup>2+</sup>, many possible chemistries can be utilized in such separation processes as discussed further in ref. 29, 30 and 301.





**Fig. 16** Schematic of direct and indirect (*i.e.*, via conversion) utilization of  $\text{CO}_2$ . Alternative to gaseous  $\text{CO}_2$ , carbonate minerals (e.g.,  $\text{CaCO}_3$ ) can be utilized<sup>326</sup> in paper industry, coating, plastics,<sup>327</sup> paints, adhesive/sealants, rubber, cement and construction materials.<sup>328</sup>



**Fig. 17** Average price of  $\text{CO}_2$  utilization products as a function of their market size. Error bars indicate anomalies in some regions (see the ESI,† Table S1 for values).  $\text{CO}_2$  and  $\text{H}_2$  are included for reference.

For instance, the global demand for one of the largest chemical markets, ethylene, is 184 Mt per year.<sup>338</sup> Ethylene manufacture also stands as the prime contributor for  $\text{CO}_2$  emissions among carbon-based chemicals, with a  $\text{CO}_2$  emissions rate of 184.3–213 Mt in 2015, which could reach 1.34 Gt per year by 2030.<sup>339</sup>

Production of synthetic hydrocarbon fuels and chemicals often requires high purity  $\text{CO}_2$  feeds. Many  $\text{CO}_2$  capture facilities using centralized sources simultaneously capture sulfur-containing compounds, such as hydrogen sulfide ( $\text{H}_2\text{S}$ ) that must be removed upstream to avoid catalyst poisoning.<sup>340</sup> The process of desulfurization typically involves liquid phase oxidation to promote  $\text{H}_2\text{S}$  oxidation to sulfur, followed by sulfur separation

from the gas stream.<sup>341</sup> Chemical adsorption using high surface area  $\text{ZnO}$ -based adsorbents may be used in sequence to further eliminate  $\text{H}_2\text{S}$  prior to pipeline transmission.<sup>342,343</sup> Alternatively,  $\text{CO}_2$  conversion can take place *via* biocatalytic routes with both natural and engineered microorganisms<sup>344,345</sup> that generally have higher tolerance for impurities.<sup>346</sup>  $\text{CO}_2$  capture from dilute sources, such as from air and seawater, usually contains non-negligible amount of  $\text{O}_2$  and  $\text{N}_2$ .<sup>28,45</sup> While  $\text{N}_2$  is an inert gas and may not negatively impact the  $\text{CO}_2$  conversion, a trace amount of  $\text{O}_2$  may lower the catalytic turnover through the unwanted reaction with hydrogen in the thermochemical process,<sup>347</sup> or through the preferential reaction of oxygen reduction in the electrochemical process.<sup>45</sup> Strategies for  $\text{O}_2$  removal from  $\text{CO}_2$  stream include catalytic oxidation of hydrogen<sup>348</sup> or methane<sup>349</sup> on noble metal catalysts such as Pt or Pd,<sup>350</sup> chemical adsorption of  $\text{O}_2$  on Cu surfaces at elevated temperatures,<sup>348</sup> and electrochemical reduction of  $\text{O}_2$  on Ag catalysts.<sup>45</sup>

A pressurized  $\text{CO}_2(\text{aq})$  stream is beneficial for a subsequent  $\text{CO}_2$  conversion step. In a  $\text{CO}_2$  electrolyser for methanol production, when the produced  $\text{CO}_2$  remains dissolved due to an applied pressure, the avoided typical gas regeneration step and  $\text{CO}(\text{g})$  compression step save more than 150  $\text{kJ mol}^{-1}$   $\text{CO}_2$ .<sup>46</sup> High pressure electrolyser (up to 40 bar) is also reported to increase the current efficiency of  $\text{CO}_2$  reduction to formic acid/formate.<sup>351,352</sup> Moreover, a high pressure  $\text{CO}_2(\text{g})$  is required for the transportation in the pipes, enhanced oil recovery or geological  $\text{CO}_2$  sequestration for underground injection. Supercritical  $\text{CO}_2$  (above its critical temperature 31.0 °C and pressure 72.8 atm) with its low density and viscosity plays a significant role in the extraction of oil.<sup>353–355</sup> Furthermore, supercritical  $\text{CO}_2$  can be used in the enhanced geothermal system for heat exchange.<sup>247,356</sup>

The electrochemical  $\text{CO}_2$  conversion lacks studies that demonstrate the capability of the technology at scales large enough for industrial implementation.<sup>357</sup> As an alternative,  $\text{CO}_2$  can be converted biologically to organic carbon in plants or microalgae, through photosynthesis, resulting in various products, such as biofuel or animal feed.<sup>358,359</sup>

Gaseous  $\text{CO}_2$  can be stored (*i.e.*, sequestered) in deep geological layers or in the ocean.<sup>19,360–362</sup> In 2019, from the 19 in operation large-scale carbon capture & storage (CCS) facilities, 33.2 Mt per year of  $\text{CO}_2$  were captured and stored<sup>363</sup> (*i.e.*, less than 0.1% of the total global emissions).<sup>364</sup> By addition of the already in constructions facilities, this value is estimated to be doubled, within the coming years. Most of this storage is done through enhanced oil recovery (EOR) application (*i.e.*, over 260 Mt of anthropogenic  $\text{CO}_2$  by 2019).<sup>363</sup>

As an alternative to sequestration of gaseous  $\text{CO}_2$ ,  $\text{CO}_2(\text{g})$  can first be converted to bicarbonate ion and, subsequently, be stored as already abundant forms of ocean alkalinity, through electrogeochemistry.<sup>71,75,78,112</sup>

There are social concerns associated with the gas sequestration including fear of  $\text{CO}_2$  leakages, lack of suitable locations, required site monitoring, unknown impacts on living organisms and limitations involved with  $\text{CO}_2$  transportation and injection to storage sites. Alternatively, solid (carbonates) storage can be

used. Such mineral carbonate sequestration is permanent, safe, has a large worldwide storage capacity and is less subject to social opposition.<sup>328,365,366</sup>

## 6 Conclusions

Electrochemical CO<sub>2</sub> capture methods are undergoing a renaissance as their applications expand due to their higher energy efficiency, flexibility and sustainability compared to the conventional approaches. Electrochemical CO<sub>2</sub> capture is classified into four categories; (1) methods that apply a pH-swing to capture and recover the CO<sub>2</sub>, (2) methods that rely on the binding affinity of CO<sub>2</sub> molecules to redox-active species, (3) molten carbonate cells and (4) hybrid electrochemical processes that combine CO<sub>2</sub> capture and *e.g.*, direct conversion. Among the electrochemical capture methods, pH-swing based approaches, leveraging the carbonate equilibrium, are most widely studied, due to their straightforward operation and the absence of toxic or expensive chemicals. In theory, a mild pH-swing over *ca.* 2–3 pH units would allow to capture *>*98% of the CO<sub>2</sub>. However, in practice, to improve the slow kinetics associated with such a mild swing, either a wider pH range (*ca.* 5–6 pH units) or catalytic enzymes (*e.g.*, carbonic anhydrase) need to be applied.

An electrochemical pH-swing is induced *via* electrolysis, bipolar membrane electrodialysis (BPMED), redox active molecules that undergo proton coupled electron transfer (PCET) or capacitive deionization. Among all, electrolysis is the earliest method (used for alkaline absorbent regeneration), but is still rather energy intensive due to the intrinsic irreversibility of the gas evolution redox reactions. However, the produced H<sub>2</sub>(g) (through water electrolysis) can be used to offset the total energy consumption. Capture *via* PCET active agents enable high current efficiencies, but are at the moment limited by slow electrode kinetics, low solubility of PCET organics and the sensitivity of the process to impurities in the flue gas such as O<sub>2</sub>, water and sulfur. Using (membrane) capacitive deionization (MCDI) enables capture with an electrical energy consumption as low as 40 kJ mol<sup>-1</sup> using only deionized water. However, (M)CDI capture is so far only applied at very low current densities, is still in the very early stage of the lab-scale research (TRL of 3) and its large scale applications await more performance studies. All electrochemical capture methods can be used easily as plug-and-play units. Among the four technology for electrochemical pH-swing, BPMED has the advantage of keeping a small footprint upon up scaling. At present, the cost of using BPMED for CO<sub>2</sub> desorption and alkaline (re)generation in alkaline wet scrubbing is estimated to be 2–3 times more than the conventional thermal swing desorption rival. However, the cost can significantly decrease if improvements in the cost of renewable energies and ion exchange membranes, membrane life time and their permselectivity and resistivity are achieved.

Despite of the successful lab-scale demonstrations, both CO<sub>2</sub> capture *via* electrolysis and BPMED have achieved TRL of 5–6 and are not yet commercialized. This is while, the

conventional post-combustion CO<sub>2</sub> capture methods, such as absorption, adsorption, membrane separation and chemical looping have found their way to industrial applications. As opposed to the electrochemical captures, conventional methods are mainly designed to capture CO<sub>2</sub> from centralized emitters such as fossil fueled power plants. These methods have a larger footprint and are not geared for efficient decentralised emitted CO<sub>2</sub>. However, in the last decade, to benefit from the high efficiency and selectivity of the electrochemical processes, conventional methods are also promoted to be combined with electrochemical process. Substituting the temperature or pressure swings with an electrochemical swing in an amine based absorption capture is shown to halve the energy consumption of the CO<sub>2</sub> desorption step while decreasing the footprint of the unit. The framework established in this paper can be the basis for future studies on the energetics of electrochemical CO<sub>2</sub> capture processes, not only for flue gas separations, but also for a range of other applications, such as seawater CO<sub>2</sub> capture and direct air capture.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

This work was performed in the NWO-cooperation framework of Wetsus, Centre of Excellence for Sustainable Water Technology ([www.wetsus.nl](http://www.wetsus.nl)). Wetsus is funded by the Dutch Ministry of Economic Affairs, the European Union Regional Development Fund, the Province of Fryslân, the City of Leeuwarden and the EZ/Kompas program of the “Samenwerkingsverband Noord-Nederland”. The authors like to thank the participants of the research theme “Concentrates” in Wetsus and research group “Transport phenomena” in faculty of applied sciences at TU Delft for the discussions and their (financial) support. This research received funding from the Netherlands Organization for Scientific Research (NWO) in the framework of the project ALW.2016.004. The work on aqueous carbonate equilibrium and CO<sub>2</sub> utilization is based on work performed by the Liquid Sunlight Alliance, which is supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, Fuels from Sunlight Hub under Award Number DE-SC0021266. The authors also thank the support from SoCalGas.

## References

- 1 M. Fajard, A. Köberle, N. Mac Dowell and A. Fantuzzi, *BECCS-deployment: a-reality-check*, 2018.
- 2 J. P. Mulligan, *Carbon Dioxide Emissions*, Nova Science, 2010.
- 3 F. Sabatino, M. Mehta, A. Grimm, M. Gazzani, F. Gallucci, G. J. Kramer and M. van Sint Annaland, Evaluation of a Direct Air Capture Process Combining Wet Scrubbing and



- Bipolar Membrane Electrodialysis, *Ind. Eng. Chem. Res.*, 2020, **59**(15), 7007–7020, DOI: 10.1021/acs.iecr.9b05641.
- 4 S. Nanda, S. N. Reddy, S. K. Mitra and J. A. Kozinski, The progressive routes for carbon capture and sequestration, *Energy Sci. Eng.*, 2016, **4**(2), 99–122, DOI: 10.1002/ese3.117.
  - 5 IPCC, in *Summary for Policymakers*, ed. T. Stocker, *et al.*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013, ch. SPM, pp. 1–30, DOI: 10.1017/CBO9781107415324.004, URL: www.climatechange2013.org, ISBN: 978-1-107-66182-0.
  - 6 C. Fernández-Dacosta, V. Stojcheva and A. Ramirez, Closing carbon cycles: Evaluating the performance of multi-product CO<sub>2</sub> utilisation and storage configurations in a refinery, *J. CO<sub>2</sub> Util.*, 2018, **23**, 128–142, DOI: 10.1016/j.jcou.2017.11.008, URL: http://www.sciencedirect.com/science/article/pii/S2212982017305589, ISSN: 2212-9820.
  - 7 A. Fane, A grand challenge for membrane desalination: More water, less carbon, *Desalination*, 2018, **426**, 155–163, DOI: 10.1016/j.desal.2017.11.002, URL: http://www.sciencedirect.com/science/article/pii/S0011916417320866, ISSN: 0011-9164.
  - 8 C.-F. de Lannoy, M. D. Eisaman, A. Jose, S. D. Karnitz, R. W. DeVaul, K. Hannun and J. L. Rivest, Indirect ocean capture of atmospheric CO<sub>2</sub>: Part I. Prototype of a negative emissions technology, *Int. J. Greenhouse Gas Control*, 2018, **70**, 243–253, DOI: 10.1016/j.ijggc.2017.10.007, URL: http://www.sciencedirect.com/science/article/pii/S1750583617304-322, ISSN: 1750-5836.
  - 9 S. E. Tanzer and A. Ramírez, When are negative emissions negative emissions?, *Energy Environ. Sci.*, 2019, **12**, 1210–1218, DOI: 10.1039/C8EE03338B.
  - 10 O. Edenhofer, *Climate change 2014: mitigation of climate change*, Cambridge University Press, 2015, vol. 3.
  - 11 C. Le Quéré, *et al.*, Global Carbon Budget 2018, *Earth Syst. Sci. Data*, 2018, **10**(4), 2141–2194, DOI: 10.5194/essd-10-2141-2018, URL: https://www.earth-syst-sci-data.net/10/2141/2018/.
  - 12 A. Alonso, J. Moral-Vico, A. A. Markeb, M. Busquets-Fité, D. Komilis, V. Puntes, A. Sánchez and X. Font, Critical review of existing nanomaterial adsorbents to capture carbon dioxide and methane, *Sci. Total Environ.*, 2017, **595**, 51–62.
  - 13 C. Song, Q. Liu, N. Ji, S. Deng, J. Zhao, Y. Li, Y. Song and H. Li, Alternative pathways for efficient CO<sub>2</sub> capture by hybrid processes—A review, *Renewable Sustainable Energy Rev.*, 2018, **82**, 215–231, DOI: 10.1016/j.rser.2017.09.040, URL: http://www.sciencedirect.com/science/article/pii/S1364032117312947, ISSN: 1364-0321.
  - 14 A. Al-Mamoori, A. Krishnamurthy, A. A. Rownaghi and F. Rezaei, Carbon Capture and Utilization Update, *Energy Technol.*, 2017, **5**(6), 834–849, DOI: 10.1002/ente.201600747, URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/ente.201600747.
  - 15 K. Z. House, A. C. Baclig, M. Ranjan, E. A. van Nierop, J. Wilcox and H. J. Herzog, Economic and energetic analysis of capturing CO<sub>2</sub> from ambient air, *Proc. Natl. Acad. Sci. U. S. A.*, 2011, **108**(51), 20428–20433, DOI: 10.1073/pnas.1012253108.
  - 16 J. Míguez, J. Porteiro, R. Pérez-Orozco, D. Patiño and S. Rodríguez, Evolution of CO<sub>2</sub> capture technology between 2007 and 2017 through the study of patent activity, *Appl. Energy*, 2018, **211**, 1282–1296, DOI: 10.1016/j.apenergy.2017.11.107, URL: http://www.sciencedirect.com/science/article/pii/S0306261917317087, ISSN: 0306-2619.
  - 17 R. S. Haszeldine, Carbon Capture and Storage: How Green Can Black Be?", *Science*, 2009, **325**(5948), 1647–1652, DOI: 10.1126/science.1172246, URL: https://science.sciencemag.org/content/325/5948/1647.
  - 18 B. P. Spigarelli and S. K. Kawatra, Opportunities and challenges in carbon dioxide capture, *J. CO<sub>2</sub> Util.*, 2013, **1**, 69–87, DOI: 10.1016/j.jcou.2013.03.002, URL: http://www.sciencedirect.com/science/article/pii/S2212982013000-05X, ISSN: 2212-9820.
  - 19 D. Y. Leung, G. Caramanna and M. M. Maroto-Valer, An overview of current status of carbon dioxide capture and storage technologies, *Renewable Sustainable Energy Rev.*, 2014, **39**, 426–443, DOI: 10.1016/j.rser.2014.07.093, URL: http://www.sciencedirect.com/science/article/pii/S1364032114005450, ISSN: 1364-0321.
  - 20 E. J. Granite and T. O'Brien, Review of novel methods for carbon dioxide separation from flue and fuel gases, *Fuel Process. Technol.*, 2005, **86**(14), 1423–1434, DOI: 10.1016/j.fuproc.2005.01.001, URL: http://www.sciencedirect.com/science/article/pii/S0378382005000123, ISSN: 0378-3820.
  - 21 M. M. Abu-Khader, Recent Progress in CO<sub>2</sub> Capture/Sequestration: A Review, *Energy Sources, Part A*, 2006, **28**(14), 1261–1279, DOI: 10.1080/009083190933825.
  - 22 D. M. D'Alessandro, B. Smit and J. R. Long, Carbon Dioxide Capture: Prospects for New Materials, *Angew. Chem., Int. Ed.*, 2010, **49**(35), 6058–6082, DOI: 10.1002/anie.201000431.
  - 23 Y. Surampalli Rao, Environmental and Water Resources Institute (U.S.) and Carbon Capture and Storage Task Committee, English, Reston, Virginia: American Society of Civil Engineers, 2015, URL: https://app.knovel.com/web/toc.v/cid:kpCCSPCBM8/viewerType:toc/root\_slug:carbon-capture-storage.
  - 24 M. Songolzadeh, M. Soleimani, M. T. Ravanchi and R. Songolzadeh, Carbon Dioxide Separation from Flue Gases: A Technological Review Emphasizing Reduction in Greenhouse Gas Emissions, *Sci. World J.*, 2014, **2014**, 1–34, DOI: 10.1155/2014/828131.
  - 25 A. S. R. Machado and M. N. da Ponte, CO<sub>2</sub> capture and electrochemical conversion, *Curr. Opin. Green Sustainable Chem.*, 2018, **11**, 86–90, DOI: 10.1016/j.cogsc.2018.05.009, URL: http://www.sciencedirect.com/science/article/pii/S2452223617301207, ISSN: 2452-2236.
  - 26 Y. Ishimoto, M. Sugiyama, E. Kato, R. Moriyama, K. Tsuzuki and A. Kurosawa, Putting Costs of Direct Air Capture in Context, *SSRN Electron. J.*, 2017, DOI: 10.2139/ssrn.2982422, URL: https://papers.ssrn.com/sol3/papers.cfm?abstract\_id=2982422.



- 27 National Academies of Sciences, Engineering and Medicine, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda, The National Academies Press, Washington, DC, 2019, ISBN: 978-0-309-48452-7, DOI: 10.17226/25259, URL: <https://www.nap.edu/catalog/25259/negative-emissionstechnologies-and-reliable-sequestration-a-research-agenda>.
- 28 D. W. Keith, G. Holmes, D. S. Angelo and K. Heidel, A Process for Capturing CO<sub>2</sub> from the Atmosphere, *Joule*, 2018, 2(8), 1573–1594, DOI: 10.1016/j.joule.2018.05.006, URL: <http://www.sciencedirect.com/science/article/pii/S2542435118302253>, ISSN: 2542-4351.
- 29 M. C. Stern, F. Simeon, H. Herzog and T. A. Hatton, Post-combustion carbon dioxide capture using electrochemically mediated amine regeneration, *Energy Environ. Sci.*, 2013, **6**, 2505–2517, DOI: 10.1039/C3EE41165F.
- 30 M. Wang, H. J. Herzog and T. A. Hatton, CO<sub>2</sub> Capture Using Electrochemically Mediated Amine Regeneration, *Ind. Eng. Chem. Res.*, 2020, **59**(15), 7087–7096, DOI: 10.1021/acs.iecr.9b05307.
- 31 H. Rg and A. Babinsky, Electrochemical concentration and separation of carbon dioxide for advanced life support systems-carbonation cell system, *SAE Trans.*, 1969, **78**, 151.
- 32 M. P. Kang and J. Winnick, Concentration of carbon dioxide by a high-temperature electrochemical membrane cell, *J. Appl. Electrochem.*, 1985, **15**(3), 431–439, DOI: 10.1007/BF00615996, ISSN: 1572-8838.
- 33 L. Walke, K. Atkinson, D. Clark, D. Scardaville and J. Winnick, Recovery of CO<sub>2</sub> from flue gas using an electrochemical membrane, *Gas Sep. Purif.*, 1988, **2**(2), 72–76, DOI: 10.1016/0950-4214(88)80015-X, URL: <http://www.sciencedirect.com/science/article/pii/095042148880-015X>, ISSN: 0950-4214.
- 34 J. Winnick, *Electrochemical membrane gas separation*, 1990.
- 35 M. Eisaman, D. E. Schwartz, S. Amic, D. Larner, J. Zesch, F. Torres and K. Littau, Energy-efficient electrochemical CO<sub>2</sub> capture from the atmosphere, Technical Proceedings of the 2009 Clean Technology Conference and Trade Show, 2009.
- 36 F. F. Dimascio, H. Willauer, D. Hardy, K. Lewis and F. Williams, Extraction of Carbon Dioxide from Seawater by an Electrochemical Acidification Cell, Part 1 – Initial Feasibility Studies, 2010, vol. 25.
- 37 L. Legrand, O. Schaetzle, R. C. F. de Kler and H. V. M. Hamelers, Solvent-Free CO<sub>2</sub> Capture Using Membrane Capacitive Deionization, *Environ. Sci. Technol.*, 2018, **52**(16), 9478–9485, DOI: 10.1021/acs.est.8b00980, PMID: 29993236.
- 38 M. H. Youn, *et al.*, Carbon dioxide sequestration process for the cement industry, *J. CO<sub>2</sub> Util.*, 2019, **34**, 325–334, DOI: 10.1016/j.jcou.2019.07.023, URL: <http://www.sciencedirect.com/science/article/pii/S221298201930410X>, ISSN: 2212-9820.
- 39 S. Voskian and T. A. Hatton, Faradaic electro-swing reactive adsorption for CO<sub>2</sub> capture, *Energy Environ. Sci.*, 2019, **12**, 3530–3547, DOI: 10.1039/C9EE02412C.
- 40 R. A. Shaw and T. A. Hatton, Electrochemical CO<sub>2</sub> capture thermodynamics, *Int. J. Greenhouse Gas Control*, 2020, **95**, 102878, DOI: 10.1016/j.ijggc.2019.102878, URL: <http://www.sciencedirect.com/science/article/pii/S175058361930427X>, ISSN: 1750-5836.
- 41 M. C. Stern, F. Simeon, T. Hammer, H. Landes, H. J. Herzog and T. A. Hatton, Electrochemically mediated separation for carbon capture, *Energy Procedia* 4, 10th International Conference on Greenhouse Gas Control Technologies, 2011, pp. 860–867, ISSN: 1876-6102, DOI: 10.1016/j.egypro.2011.01.130, URL: <http://www.sciencedirect.com/science/article/pii/S1876610211001329>.
- 42 S. Datta, *et al.*, Electrochemical CO<sub>2</sub> Capture Using Resin-Wafer Electrodeionization, *Ind. Eng. Chem. Res.*, 2013, **52**(43), 15177–15186, DOI: 10.1021/ie402538d.
- 43 M. D. Eisaman, L. Alvarado, D. Larner, P. Wang and K. A. Littau, CO<sub>2</sub> desorption using high-pressure bipolar membrane electrodialysis, *Energy Environ. Sci.*, 2011, **4**, 4031–4037, DOI: 10.1039/C1EE01336J.
- 44 B. Mot, J. Hereijgers, M. Duarte and T. Breugelmans, Influence of flow and pressure distribution inside a gas diffusion electrode on the performance of a flow-by CO<sub>2</sub> electrolyzer, *Chem. Eng. J.*, 2019, **378**, 122224, DOI: 10.1016/j.cej.2019.122224, URL: <http://www.sciencedirect.com/science/article/pii/S1385894719316183>, ISSN: 1385-8947.
- 45 I. A. Digdaya, I. Sullivan, M. Lin, L. Han, W.-H. Cheng, H. A. Atwater and C. Xiang, A direct coupled electrochemical system for capture and conversion of CO<sub>2</sub> from oceanwater, *Nat. Commun.*, 2020, **11**(1), 1–10.
- 46 W. A. Smith, T. Burdyny, D. A. Vermaas and H. Geerlings, Pathways to Industrial-Scale Fuel Out of Thin Air from CO<sub>2</sub> Electrolysis, *Joule*, 2019, **3**(8), 1822–1834, DOI: 10.1016/j.joule.2019.07.009, URL: <http://www.sciencedirect.com/science/article/pii/S2542435119303538>, ISSN: 2542-4351.
- 47 T. Li, E. W. Lees, M. Goldman, D. A. Salvatore, D. M. Weekes and C. P. Berlinguette, Electrolytic Conversion of Bicarbonate into CO in a Flow Cell, *Joule*, 2019, **3**(6), 1487–1497, DOI: 10.1016/j.joule.2019.05.021, URL: <http://www.sciencedirect.com/science/article/pii/S2542435119303538>, ISSN: 2542-4351.
- 48 E. W. Lees, M. Goldman, A. G. Fink, D. J. Dvorak, D. A. Salvatore, Z. Zhang, N. W. X. Loo and C. P. Berlinguette, Electrodes Designed for Converting Bicarbonate into CO, *ACS Energy Lett.*, 2020, **5**(7), 2165–2173, DOI: 10.1021/acsenergylett.0c00898.
- 49 J. H. Rheinhardt, P. Singh, P. Tarakeshwar and D. A. Buttry, Electrochemical Capture and Release of Carbon Dioxide, *ACS Energy Lett.*, 2017, **2**(2), 454–461, DOI: 10.1021/acsenergylett.6b00608.
- 50 P. Kuntke, M. Rodríguez Arredondo, L. Widjakristi, A. ter Heijne, T. H. J. A. Sleutels, H. V. M. Hamelers and C. J. N. Buisman, Hydrogen Gas Recycling for Energy Efficient Ammonia Recovery in Electrochemical Systems, *Environ. Sci. Technol.*, 2017, **51**(5), 3110–3116, DOI: 10.1021/acs.est.6b06097.
- 51 P. Kuntke, M. Rodrigues, T. Sleutels, M. Saakes, H. V. M. Hamelers and C. J. N. Buisman, Energy-Efficient

- Ammonia Recovery in an Up-Scaled Hydrogen Gas Recycling Electrochemical System, *ACS Sustainable Chem. Eng.*, 2018, **6**(6), 7638–7644, DOI: 10.1021/acssuschemeng.8b00457.
- 52 Y. Lei, S. Narsing, M. Saakes, R. D. van der Weijden and C. J. N. Buisman, Calcium Carbonate Packed Electrochemical Precipitation Column: New Concept of Phosphate Removal and Recovery, *Environ. Sci. Technol.*, 2019, **53**(18), 10774–10780, DOI: 10.1021/acs.est.9b03795.0.
- 53 V. L. Snoeyink and D. Jenkins, *Water chemistry*, John Wiley & Sons, Ltd, 1980.
- 54 J. Butler, *Carbon dioxide equilibria and their applications*, 1982.
- 55 J. J. Morgan and W. Stumm, *Aquatic chemistry: chemical equilibria and rates in natural waters*, Wiley, 1996.
- 56 J. W. Murray, Ocean Carbonate Chemistry: The Aquatic Chemistry Fundamentals, in *The Ocean Carbon Cycle and Climate*, ed. M. Follows and T. Oguz, Springer Netherlands, Dordrecht, 2004, pp. 1–29.
- 57 M. J. Mitchell, O. E. Jensen, K. A. Cliffe and M. M. Maroto-Valer, A model of carbon dioxide dissolution and mineral carbonation kinetics, *Proc. R. Soc. A*, 2010, **466**(2117), 1265–1290, URL: <http://www.jstor.org/stable/25661496>, ISSN: 13645021.
- 58 C. A. Rochelle, I. Czernichowski-Lauriol and A. E. Milodowski, *The impact of chemical reactions on CO<sub>2</sub> storage in geological formations: a brief review*, Geological Society, London, 2004, Special Publications, vol. 233(issue 1), pp. 87–106, DOI: 10.1144/GSL.SP.2004.233.01.07, eprint: <https://sp.lyellcollection.org/content/233/1/87.full.pdf>, ISSN: 0305-8719.
- 59 X. Wang, W. Conway, R. Burns, N. McCann and M. Maeder, Comprehensive study of the hydration and dehydration reactions of carbon dioxide in aqueous solution, *J. Phys. Chem. A*, 2010, **114**(4), 1734–1740, DOI: 10.1021/jp909019u, ISSN: 1089-5639.
- 60 Y. Pocker and D. W. Bjorkquist, Stopped-Flow Studies of Carbon Dioxide Hydration and Bicarbonate Dehydration in H<sub>2</sub>O and D<sub>2</sub>O. Acid–Base and Metal Ion Catalysis, *J. Am. Chem. Soc.*, 1977, **99**(20), 6537–6543, DOI: 10.1021/ja00462a012, ISSN: 15205126.
- 61 A. G. Dickson, C. L. Sabine and J. R. Christian, *Guide to best practices for ocean CO<sub>2</sub> measurements*, North Pacific Marine Science Organization, 2007.
- 62 R. Zeebe and D. Wolf-Gladrow, *CO<sub>2</sub> in Seawater: Equilibrium, Kinetics, Isotopes*, 2001.
- 63 F. J. Millero, The thermodynamics of the carbonate system in seawater, *Geochim. Cosmochim. Acta*, 1979, **43**(10), 1651–1661, DOI: 10.1016/0016-7037(79)90184-4, ISSN: 0016-7037.
- 64 A. Dickson and J. Riley, The estimation of acid dissociation constants in seawater media from potentiometric titrations with strong base. I. The ionic product of water—K<sub>w</sub>, *Mar. Chem.*, 1979, **7**(2), 89–99, DOI: 10.1016/0304-4203(79)90001-X, URL: <http://www.sciencedirect.com/science/article/pii/030442037990001X>, ISSN: 0304-4203.
- 65 K. Schulz, U. Riebesell, B. Rost, S. Thoms and R. Zeebe, Determination of the rate constants for the carbon dioxide to bicarbonate inter-conversion in pH-buffered seawater systems, *Mar. Chem.*, 2006, **100**(1), 53–65, DOI: 10.1016/j.marchem.2005.11.001, URL: <http://www.sciencedirect.com/science/article/pii/S0304420305001684>, ISSN: 0304-4203.
- 66 S. Lindskog, The catalytic mechanism of carbonic anhydrase, *Inorg. Chim. Acta*, 1983, **79**, 36, DOI: 10.1016/S0020-1693(00)95058-8, URL: <http://www.sciencedirect.com/science/article/pii/S0020169300950588>, ISSN: 0020-1693.
- 67 J. da Costa Ores, L. Sala, G. P. Cerveira and S. J. Kalil, Purification of carbonic anhydrase from bovine erythrocytes and its application in the enzymic capture of carbon dioxide, *Chemosphere*, 2012, **88**(2), 255–259.
- 68 I. M. Power, A. L. Harrison, G. M. Dipple and G. Southam, Carbon sequestration via carbonic anhydrase facilitated magnesium carbonate precipitation, *Int. J. Greenhouse Gas Control*, 2013, **16**, 145–155, DOI: 10.1016/j.ijggc.2013.03.011, URL: <http://www.sciencedirect.com/science/article/pii/S175058361300131X>, ISSN: 1750-5836.
- 69 H. Yun, Y. E. Kim, W. Lee, M. H. Youn, S. K. Jeong, K. T. Park and K. B. Lee, Simultaneous Sodium Hydroxide Production by Membrane Electrolysis and Carbon Dioxide Capture, *Chem. Eng. Technol.*, 2017, **40**(12), 2204–2211, DOI: 10.1002/ceat.201700151.
- 70 H. Park, J. S. Lee, J. Han, S. Park, J. Park and B. Min, CO Fixation by Membrane Separated NaCl Electrolysis, *Energies*, 2015, **8**, 8704–8715, DOI: 10.3390/en8088704.
- 71 G. H. Rau, Electrochemical Splitting of Calcium Carbonate to Increase Solution Alkalinity: Implications for Mitigation of Carbon Dioxide and Ocean Acidity, *Environ. Sci. Technol.*, 2008, **42**(23), 8935–8940, DOI: 10.1021/es800366q, PMID: 19192821.
- 72 A. Mehmood, M. I. Iqbal, J.-Y. Lee, J. Hwang, K.-D. Jung and H. Y. Ha, A novel high performance configuration of electrochemical cell to produce alkali for sequestration of carbon dioxide, *Electrochim. Acta*, 2016, **219**, 655–663, DOI: 10.1016/j.electacta.2016.09.123, URL: <http://www.sciencedirect.com/science/article/pii/S0013468616320436>, ISSN: 0013-4686.
- 73 J. Way, et al., Low-Voltage Electrochemical Process for Direct Carbon Dioxide Sequestration, *J. Electrochem. Soc.*, 2012, **159**, B627–B628, DOI: 10.1149/2.033206jes.
- 74 S. Stucki, A. Schuler and M. Constantinescu, Coupled CO<sub>2</sub> recovery from the atmosphere and water electrolysis: Feasibility of a new process for hydrogen storage, *Int. J. Hydrogen Energy*, 1995, **20**(8), 653–663, DOI: 10.1016/0360-3199(95)00007-Z, URL: <http://www.sciencedirect.com/science/article/pii/036031999500007Z>, ISSN: 0360-3199.
- 75 G. H. Rau, Electrochemical CO<sub>2</sub> capture and storage with hydrogen generation, *Energy Procedia*, 2009, **1**(1), 823–828, DOI: 10.1016/j.egypro.2009.01.109, URL: <http://www.sciencedirect.com/science/article/pii/S1876610209001106>, ISSN: 1876-6102.
- 76 H. D. Willauer, F. DiMascio and D. R. Hardy, Extraction of Carbon Dioxide and Hydrogen from Seawater By an Electrolytic Cation Exchange Module (E-CEM) Part 5: E-CEM



- Effluent Discharge Composition as a Function of Electrode Water Composition, Tech. Rep. Naval Research Lab, Washington D.C., USA, 2017.
- 77 A. Bard and L. Faulkner, *Electrochemical Methods: Fundamentals and Applications*, Wiley Textbooks, 2nd edn, 2000, ISBN: 9781118312803, URL: <https://books.google.nl/books?id=hQoCAAAQBAJ>.
- 78 G. H. Rau, CO<sub>2</sub> Mitigation via Capture and Chemical Conversion in Seawater, *Environ. Sci. Technol.*, 2011, **45**(3), 1088–1092, DOI: 10.1021/es102671x, PMID: 21189009.
- 79 National Research Council and National Academy of Engineering, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, The National Academies Press, Washington, DC, 2004, DOI: 10.17226/10922, URL: <https://www.nap.edu/catalog/10922/the-hydrogen-economy-opportunities-costs-barriers-and-rd-needs>, ISBN: 978-0-309-09163-3.
- 80 H. D. Willauer, F. DiMascio, D. R. Hardy, M. K. Lewis and F. W. Williams, Development of an Electrochemical Acidification Cell for the Recovery of CO<sub>2</sub> and H<sub>2</sub> from Seawater II. Evaluation of the Cell by Natural Seawater, *Ind. Eng. Chem. Res.*, 2012, **51**(34), 11254–11260, DOI: 10.1021/ie301006y.
- 81 H. D. Willauer, F. DiMascio, D. R. Hardy and F. W. Williams, Feasibility of CO<sub>2</sub> Extraction from Seawater and Simultaneous Hydrogen Gas Generation Using a Novel and Robust Electrolytic Cation Exchange Module Based on Continuous Electrodeionization Technology, *Ind. Eng. Chem. Res.*, 2014, **53**(31), 12192–12200, DOI: 10.1021/ie502128x.
- 82 C. Wang, H. Liu, X. Li and L. Zheng, Importance of Ambient O<sub>2</sub> for Electrochemical Enrichment of Atmospheric CO<sub>2</sub>, *Ind. Eng. Chem. Res.*, 2013, **52**(7), 2470–2476, DOI: 10.1021/ie302999y.
- 83 H. W. Pennline, E. J. Granite, D. R. Luebke, J. R. Kitchin, J. Landon and L. M. Weiland, Separation of CO<sub>2</sub> from flue gas using electrochemical cells, *Fuel*, 2010, **89**(6), 1307–1314, DOI: 10.1016/j.fuel.2009.11.036, URL: <http://www.sciencedirect.com/science/article/pii/S0016236109005584>, ISSN: 0016-2361.
- 84 S. Z. Oener, S. Ardo and S. W. Boettcher, Ionic Processes in Water Electrolysis: The Role of Ion-Selective Membranes, *ACS Energy Lett.*, 2017, **2**(11), 2625–2634, DOI: 10.1021/acsenergylett.7b00764.
- 85 H. Strathmann, J. Krol, H.-J. Rapp and G. Eigenberger, Limiting current density and water dissociation in bipolar membranes, *J. Membr. Sci.*, 1997, **125**(1), 123–142, DOI: 10.1016/S0376-7388(96)00185-8, URL: <http://www.sciencedirect.com/science/article/pii/S0376738896001858>, ISSN: 0376-7388.
- 86 T. Xu, W. Yang and B. He, Water dissociation phenomena in a bipolar membrane, *Sci. China, Ser. B: Chem.*, 1999, **42**(6), 589–598, DOI: 10.1007/BF02874323, ISSN: 1862-2771.
- 87 D. A. Vermaas and W. A. Smith, Synergistic Electrochemical CO<sub>2</sub> Reduction and Water Oxidation with a Bipolar Membrane, *ACS Energy Lett.*, 2016, **1**(6), 1143–1148, DOI: 10.1021/acsenergylett.6b00557.
- 88 D. A. Vermaas, S. Wiegman, T. Nagaki and W. A. Smith, Ion transport mechanisms in bipolar membranes for (photo)-electrochemical water splitting, *Sustainable Energy Fuels*, 2018, **2**, 2006–2015, DOI: 10.1039/C8SE00118A.
- 89 W. J. van Egmond, M. Saakes, I. Noor, S. Porada, C. J. N. Buisman and H. Hamelers, Performance of an environmentally benign acid base flow battery at high energy density, *Int. J. Energy Res.*, 2018, **42**(4), 1524–1535, DOI: 10.1002/er.3941.
- 90 J.-H. Han, et al., Reverse electrodialysis (RED) using a bipolar membrane to suppress inorganic fouling around the cathode, *Water Res.*, 2019, **115078**, DOI: 10.1016/j.watres.2019.115078, URL: <http://www.sciencedirect.com/science/article/pii/S0043135419308528>, ISSN: 0043-1354.
- 91 A. Bandi, M. Specht, T. Weimer and K. Schaber, CO<sub>2</sub> recycling for hydrogen storage and transportation—Electrochemical CO<sub>2</sub> removal and fixation, *Energy Convers. Manage.*, 1995, **36**(6), 899–902, DOI: 10.1016/0196-8904(95)00148-7, URL: <http://www.sciencedirect.com/science/article/pii/0196890495001487>, ISSN: 0196-8904.
- 92 M. D. Eisaman, L. Alvarado, D. Larner, P. Wang, B. Garg and K. A. Littau, CO<sub>2</sub> separation using bipolar membrane electrodialysis, *Energy Environ. Sci.*, 2011, **4**, 1319–1328, DOI: 10.1039/C0EE00303D.
- 93 R. E. Moussaoui, G. Pourcelly, M. Maeck, H. D. Hurwitz and C. Gavach, Co-ion leakage through bipolar membranes Influence on I–V responses and water-splitting efficiency, *J. Membr. Sci.*, 1994, **90**(3), 283–292, DOI: 10.1016/0376-7388(94)80078-2, URL: <http://www.sciencedirect.com/science/article/pii/0376738894800782>, ISSN: 0376-7388.
- 94 Y. Tanaka, Acceleration of water dissociation generated in an ion exchange membrane, *J. Membr. Sci.*, 2007, **303**(1), 234–243, DOI: 10.1016/j.memsci.2007.07.020, URL: <http://www.sciencedirect.com/science/article/pii/S037673880700484X>, ISSN: 0376-7388.
- 95 Y. Tanaka, Water dissociation reaction generated in an ion exchange membrane, *J. Membr. Sci.*, 2010, **350**(1), 347–360, DOI: 10.1016/j.memsci.2010.01.010, URL: <http://www.sciencedirect.com/science/article/pii/S0376738810000190>, ISSN: 0376-7388.
- 96 T. Luo, S. Abdu and M. Wessling, Selectivity of ion exchange membranes: A review, *J. Membr. Sci.*, 2018, **555**, 429–454, DOI: 10.1016/j.memsci.2018.03.051, URL: <http://www.sciencedirect.com/science/article/pii/S0376738817335779>, ISSN: 0376-7388.
- 97 A. Alcaraz, P. Ramírez, J. Manzanares and S. Mafé, Conductive and Capacitive Properties of the Bipolar Membrane Junction Studied by AC Impedance Spectroscopy, *J. Phys. Chem. B*, 2001, **105**, 11669, DOI: 10.1021/jp011581x.
- 98 P. Ramírez, V. Aguilera, J. Manzanares and S. Mafé, Effects of temperature and ion transport on water splitting in bipolar membranes, *J. Membr. Sci.*, 1992, **73**(2), 191–201, DOI: 10.1016/0376-7388(92)80129-8, URL: <http://www.sciencedirect.com/science/article/pii/S0376738892801298>.

- [cedirect.com/science/article/pii/0376738892801298](http://cedirect.com/science/article/pii/0376738892801298), ISSN: 0376-7388.
- 99 R. Pärnamäe, S. Mareev, V. Nikonenko, S. Melnikov, N. Sheldeshov, V. Zabolotskii, H. Hamelers and M. Tedesco, Bipolar membranes: A review on principles, latest developments, and applications, *J. Membr. Sci.*, 2021, **617**, 118538, DOI: 10.1016/j.memsci.2020.118538, URL: <http://www.sciencedirect.com/science/article/pii/S0376738820311157>, ISSN: 0376-7388.
- 100 R. Wiebe and V. L. Gaddy, The Solubility of Carbon Dioxide in Water at Various Temperatures from 12 to 40° and at Pressures to 500 Atmospheres. Critical Phenomena, *J. Am. Chem. Soc.*, 1940, **62**(4), 815–817, DOI: 10.1021/ja01861a033.
- 101 L. Diamond and N. Akinfiev, Solubility of CO<sub>2</sub> in water from –1.5 to 100 °C and from 0.1 to 100 MPa: Evaluation of literature data and thermodynamic modelling, *Fluid Phase Equilib.*, 2003, **208**, 265–290, DOI: 10.1016/S0378-3812(03)00041-4.
- 102 S. Hangx, Behaviour of the CO<sub>2</sub>-H<sub>2</sub>O system and preliminary mineralisation model and experiments, *CATO Workpackage WP 4.1*, 2005, pp. 1–43.
- 103 M. Vandiver, B. Caire, J. Carver, K. Waldrop, M. Hibbs, J. Varcoe, A. Herring and M. Liberatore, Mechanical Characterization of Anion Exchange Membranes by Extensional Rheology under Controlled Hydration, *J. Electrochem. Soc.*, 2014, **161**, H677–H683, DOI: 10.1149/2.0971410jes.
- 104 J. Peron, *et al.*, Properties of Nafion® NR-211 membranes for PEMFCs, *J. Membr. Sci.*, 2010, **356**(1), 44–51, DOI: 10.1016/j.memsci.2010.03.025, URL: <http://www.sciencedirect.com/science/article/pii/S0376738810002437>, ISSN: 0376-7388.
- 105 H. Nagasawa, A. Yamasaki, A. Iizuka, K. Kumagai and Y. Yanagisawa, A New Recovery Process of Carbon Dioxide from Alkaline Carbonate Solution via Electrodialysis, *AICHe J.*, 2009, **55**, 3286–3293, DOI: 10.1002/aic.11907.
- 106 A. Iizuka, K. Hashimoto, H. Nagasawa, K. Kumagai, Y. Yanagisawa and A. Yamasaki, Carbon dioxide recovery from carbonate solutions using bipolar membrane electrodialysis, *Sep. Purif. Technol.*, 2012, **101**, 49–59, DOI: 10.1016/j.seppur.2012.09.016.
- 107 Y. Zhao, J. Wang, Z. Ji, J. Liu, X. Guo and J. Yuan, A novel technology of carbon dioxide adsorption and mineralization via seawater decalcification by bipolar membrane electrodialysis system with a crystallizer, *Chem. Eng. J.*, 2020, **381**, 122542, DOI: 10.1016/j.cej.2019.122542, URL: <http://www.sciencedirect.com/science/article/pii/S138589471931945X>, ISSN: 1385-8947.
- 108 C. Jiang, S. Li, D. Zhang, Z. Yang, D. Yu, X. Chen, Y. Wang and T. Xu, Mathematical modelling and experimental investigation of CO<sub>2</sub> absorber recovery using an electro-acidification method, *Chem. Eng. J.*, 2019, **360**, 654–664, DOI: 10.1016/j.cej.2018.12.006, URL: <http://www.sciencedirect.com/science/article/pii/S1385894718324781>, ISSN: 1385-8947.
- 109 H. Li, Z. Tang, X. Xing, D. Guo, L. Cui and X.-z. Mao, Study of CO<sub>2</sub> capture by seawater and its reinforcement, *Energy*, 2018, **164**, 1135–1144, DOI: 10.1016/j.energy.2018.09.066, URL: <http://www.sciencedirect.com/science/article/pii/S0360-544218318309>, ISSN: 0360-5442.
- 110 S. A. Rackley, 10-Mineral carbonation, *Carbon Capture and Storage*, ed. S. A. Rackley, Butterworth-Heinemann, Boston, 2nd edn, 2017, pp. 253–282, DOI: 10.1016/B978-0-12-812041-5.00010-6, URL: <http://www.sciencedirect.com/science/article/pii/B9780128120415000106>, ISBN: 978-0-12-812041-5.
- 111 T. Coffey, D. R. Hardy, G. E. Besenbruch, K. R. Schultz, L. C. Brown and J. P. Dahlburg, Hydrogen as a Fuel for DOD, *Defense Horizons*, 2003, p. 1.
- 112 G. H. Rau, H. D. Willauer and Z. J. Ren, The global potential for converting renewable electricity to negative-CO<sub>2</sub>-emissions hydrogen, *Nat. Clim. Change*, 2018, **8**(7), 621–625.
- 113 M. D. Eisaman, K. Parajuly, A. Tuganov, C. Eldershaw, N. Chang and K. A. Littau, CO<sub>2</sub> extraction from seawater using bipolar membrane electrodialysis, *Energy Environ. Sci.*, 2012, **5**, 7346–7352, DOI: 10.1039/C2EE03393C.
- 114 M. L. Druckenmiller and M. M. Maroto-Valer, Carbon sequestration using brine of adjusted pH to form mineral carbonates, *Fuel Process. Technol.*, 2005, **86**(14–15), 1599–1614.
- 115 W. Wang, M. Hu, Y. Zheng, P. Wang and C. Ma, CO<sub>2</sub> Fixation in Ca<sup>2+</sup>-/Mg<sup>2+</sup>-Rich Aqueous Solutions through Enhanced Carbonate Precipitation, *Ind. Eng. Chem. Res.*, 2011, **50**(13), 8333–8339, DOI: 10.1021/ie1025419.
- 116 D. Desai, *et al.*, Electrochemical Desalination of Seawater and Hypersaline Brines with Coupled Electricity Storage, *ACS Energy Lett.*, 2018, **3**(2), 375–379, DOI: 10.1021/acsenergylett.407b01220.
- 117 M. D. Eisaman, J. L. Rivest, S. D. Karnitz, C.-F. de Lannoy, A. Jose, R. W. DeVaul and K. Hannun, Indirect ocean capture of atmospheric CO<sub>2</sub>: Part II. Understanding the cost of negative emissions, *Int. J. Greenhouse Gas Control*, 2018, **70**, 254–261, DOI: 10.1016/j.ijggc.2018.02.020, URL: <http://www.sciencedirect.com/science/article/pii/S1750583-61730436X>, ISSN: 1750-5836.
- 118 W. Omar, J. Chen and J. Ulrich, Application of seeded batch crystallization methods for reduction of the scaling tendency of seawater—A study of growth kinetics of calcium carbonate in seawater, *Cryst. Res. Technol.*, 2009, **44**(5), 469–476.
- 119 A. Kirchofer, A. Brandt, S. Krevor, V. Prigobbe and J. Wilcox, Impact of alkalinity sources on the life-cycle energy efficiency of mineral carbonation technologies, *Energy Environ. Sci.*, 2012, **5**, 8631–8641, DOI: 10.1039/C2EE22180B.
- 120 G. C. Ganzi, J. H. Wood and C. S. Griffin, Water purification and recycling using the CDI process, *Environ. Prog.*, 1992, **11**(1), 49–53, DOI: 10.1002/ep.670110117, URL: <https://aiche.onlinelibrary.wiley.com/doi/abs/10.1002/ep.670110117>.
- 121 R. Datta, Y. Lin, D. Burke and S.-P. Tsai, *Electrodeionization substrate, and device for electrodeionization treatment*, 2002.



- 122 Y. J. Lin, M. P. Henry and S. W. Snyder, *Electronically and ionically conductive porous material and method for manufacture of resin wafers therefrom*, 2011.
- 123 S.-Y. Pan, S. W. Snyder, H.-W. Ma, Y. J. Lin and P.-C. Chiang, Development of a Resin Wafer Electrodeionization Process for Impaired Water Desalination with High Energy Efficiency and Productivity, *ACS Sustainable Chem. Eng.*, 2017, 5(4), 2942–2948, DOI: 10.1021/acssuschemeng.6b02455.
- 124 I. N. Widiasa, P. D. Sutrisna and I. Wenten, *Performance of a novel electrodeionization technique during citric acid recovery*, 2004.
- 125 L. Alvarado and A. Chen, Electrodeionization: Principles, Strategies and Applications, *Electrochim. Acta*, 2014, 132, 583–597, DOI: 10.1016/j.electacta.2014.03.165, ISSN: 0013-4686.
- 126 M. Parvazinia, S. Garcia and M. Maroto-Valer, CO<sub>2</sub> capture by ion exchange resins as amine functionalized adsorbents, *Chem. Eng. J.*, 2018, 331, 335–342, DOI: 10.1016/j.cej.2017.08.087, URL: <http://www.sciencedirect.com/science/article/pii/S1385894717314316>, ISSN: 1385-8947.
- 127 G. Zeng, J. Ye and M. Yan, Application of Electrodeionization Process for Bioproduct Recovery and CO<sub>2</sub> Capture and Storage, *Curr. Org. Chem.*, 2016, 20, 1, DOI: 10.2174/1385272820666160513153326.
- 128 J. Wang, S. Wang and M. Jin, A study of the electrodeionization process—high-purity water production with a RO/EDI system, *Desalination*, 2000, 132(1), 349–352, DOI: 10.1016/S0011-9164(00)00171-5, URL: <http://www.sciencedirect.com/science/article/pii/S0011916400001715>, ISSN: 0011-9164.
- 129 K. H. Yeon, J. H. Seong, S. Rengaraj and S. H. Moon, Electrochemical Characterization of Ion-Exchange Resin Beds and Removal of Cobalt by Electrodeionization for High Purity Water Production, *Sep. Sci. Technol.*, 2003, 38(2), 443–462, DOI: 10.1081/SS-120016584.
- 130 Ö. Arar, Ü. Yüksel, N. Kabay and M. Yüksel, Various applications of electrodeionization (EDI) method for water treatment—A short review, *Desalination*, 2014, 342, 16–22, DOI: 10.1016/j.desal.2014.01.028, URL: <http://www.sciencedirect.com/science/article/pii/S0011916414000745>, ISSN: 0011-9164.
- 131 R. N. Gurram, S. Datta, Y. J. Lin, S. W. Snyder and T. J. Menkhaus, Removal of enzymatic and fermentation inhibitory compounds from biomass slurries for enhanced biorefinery process efficiencies, *Bioresour. Technol.*, 2011, 102(17), 7850–7859, DOI: 10.1016/j.biortech.2011.05.043, URL: <http://www.sciencedirect.com/science/article/pii/S0960-852411007036>, ISSN: 0960-8524.
- 132 W. R. Alesi and J. R. Kitchin, Evaluation of a Primary Amine-Functionalized Ion-Exchange Resin for CO<sub>2</sub> Capture, *Ind. Eng. Chem. Res.*, 2012, 51(19), 6907–6915, DOI: 10.1021/ie300452c.
- 133 R. Veneman, N. Frigka, W. Zhao, Z. Li, S. Kersten and W. Brilman, Adsorption of H<sub>2</sub>O and CO<sub>2</sub> on supported amine sorbents, *Int. J. Greenhouse Gas Control*, 2015, 41, 268–275, DOI: 10.1016/j.ijggc.2015.07.014, URL: <http://www.sciencedirect.com/science/article/pii/S1750583615300219>, ISSN: 1750-5836.
- 134 K. Afrasiabi, *Wafer Enhanced Electrodeionization for Conversion of CO<sub>2</sub> into Bicarbonate Feed for Algae Cultured Photobioreactors*, 2018.
- 135 H. Xie, Y. Wu, T. Liu, F. Wang, B. Chen and B. Liang, Low-energy-consumption electrochemical CO<sub>2</sub> capture driven by biomimetic phenazine derivatives redox medium, *Appl. Energy*, 2020, 259, 114119, DOI: 10.1016/j.apenergy.2019.114119, URL: <http://www.sciencedirect.com/science/article/pii/S0306261919318069>, ISSN: 0306-2619.
- 136 J. D. Watkins, N. S. Siebert, X. Zhou, C. R. Myers, J. R. Kitchin, D. P. Hopkinson and H. B. Nulwala, Redox-Mediated Separation of Carbon Dioxide from Flue Gas, *Energy Fuels*, 2015, 29(11), 7508–7515, DOI: 10.1021/acs.energyfuels.5b01807.
- 137 B. P. Sullivan, K. Krist and H. Guard, *Electrochemical and electrocatalytic reactions of carbon dioxide*, Elsevier, 2012.
- 138 M. Robert, Proton-coupled electron transfer, *Energy Environ. Sci.*, 2012, 5, 7695, DOI: 10.1039/C2EE90013K.
- 139 C. Costentin, Electrochemical Approach to the Mechanistic Study of Proton-Coupled Electron Transfer, *Chem. Rev.*, 2008, 108(7), 2145–2179, DOI: 10.1021/cr068065t.
- 140 C. Huang, C. Liu, K. Wu, H. Yue, S. Tang, H. Lu and B. Liang, CO<sub>2</sub> Capture from Flue Gas Using an Electrochemically Reversible Hydroquinone/Quinone Solution, *Energy Fuels*, 2019, 33(4), 3380–3389, DOI: 10.1021/acs.energyfuels.8b04419.
- 141 P. Scovazzo, J. Poshusta, D. DuBois, C. Koval and R. Noble, Electrochemical Separation and Concentration of 1% Carbon Dioxide from Nitrogen, *J. Electrochem. Soc.*, 2003, 150(5), D91, DOI: 10.1149/1.1566962.
- 142 H. Ishida, T. Ohba, T. Yamaguchi and K. Ohkubo, Interaction between CO<sub>2</sub> and Electrochemically Reduced Species of N-propyl-4,4-bipyridinium Cation, *Chem. Lett.*, 1994, 23(5), 905–908, DOI: 10.1246/cl.1994.905.
- 143 R. Ranjan, J. Olson, P. Singh, E. D. Lorance, D. A. Buttry and I. R. Gould, Reversible electrochemical trapping of carbon dioxide using 4,4-bipyridine that does not require thermal activation, *J. Phys. Chem. Lett.*, 2015, 6(24), 4943–4946.
- 144 B. Gurkan, F. Simeon and T. A. Hatton, Quinone Reduction in Ionic Liquids for Electrochemical CO<sub>2</sub> Separation, *ACS Sustainable Chem. Eng.*, 2015, 3(7), 1394–1405, DOI: 10.1021/acssuschemeng.5b00116.
- 145 D. H. Apaydin, E. D. Glowacki, E. Portenkirchner and N. S. Sariciftci, Direct Electrochemical Capture and Release of Carbon Dioxide Using an Industrial Organic Pigment: Quinacridone, *Angew. Chem., Int. Ed.*, 2014, 53(26), 6819–6822, DOI: 10.1002/anie.201403618.
- 146 M. Mizen and M. Wrighton, Reductive Addition of CO<sub>2</sub> to 9,10-Phenanthrenequinone, *J. Electrochem. Soc.*, 1989, 136, 941, URL: <http://jes.ecsdl.org/content/136/4/941.abstract>.
- 147 Y. Liu, H.-Z. Ye, K. Diederichsen, T. Voorhis and T. Hatton, Electrochemically mediated carbon dioxide separation with quinone chemistry in salt-concentrated aqueous



- media, *Nat. Commun.*, 2020, **11**, 2278, DOI: 10.1038/s41467-020-16150-7.
- 148 G. P. Moss, P. A. S. Smith and D. Tavernier, Glossary of class names of organic compounds and reactivity intermediates based on structure (IUPAC Recommendations 1995), *Pure Appl. Chem.*, 1995, **67**(8–9), 1307–1375, URL: <https://www.degruyter.com/view/journals/pac/67/8-9/article-p1307.xml>.
- 149 P. S. Guin, S. Das and P. C. Mandal, Electrochemical Reduction of Quinones in Different Media: A Review, *Int. J. Electrochem.*, 2011, **2011**, 816202, DOI: 10.4061/2011/816202.
- 150 L. F. Fieser, The Tautomerism of Hydroxy Quinones, *J. Am. Chem. Soc.*, 1928, **50**(2), 439–465, DOI: 10.1021/ja01389a033.
- 151 E. Lavoron, Electrochemical reactions with protonations at equilibrium: Part XII. The 2e, 2H<sup>+</sup> homogeneous isotopic electron exchange reaction (nine-member square scheme), *J. Electroanal. Chem. Interfacial Electrochem.*, 1984, **169**(1), 29–46, DOI: 10.1016/0022-0728(84)80071-6, URL: <http://www.sciencedirect.com/science/article/pii/0022072884800716>.
- 152 M. Quan, D. Sanchez, M. F. Wasylkiw and D. K. Smith, Voltammetry of Quinones in Unbuffered Aqueous Solution: Reassessing the Roles of Proton Transfer and Hydrogen Bonding in the Aqueous Electrochemistry of Quinones, *J. Am. Chem. Soc.*, 2007, **129**(42), 12847–12856, DOI: 10.1021/ja0743083.
- 153 D. R. Weinberg, *et al.*, Proton-Coupled Electron Transfer, *Chem. Rev.*, 2012, **112**(7), 4016–4093, DOI: 10.1021/cr200177j.
- 154 B. Trumpower, The protonmotive Q cycle. Energy transduction by coupling of proton translocation to electron transfer by the cytochrome bc1 complex, *J. Biol. Chem.*, 1990, **265**(20), 11409–11412.
- 155 Y. Lei, B. Song, R. D. van der Weijden, M. Saakes and C. J. N. Buisman, Electrochemical Induced Calcium Phosphate Precipitation: Importance of Local pH, *Environ. Sci. Technol.*, 2017, **51**(19), 11156–11164, DOI: 10.1021/acs.est.7b03909, PMID: 28872838.
- 156 L. Legrand, Q. Shu, M. Tedesco, J. Dykstra and H. Hamelers, Role of ion exchange membranes and capacitive electrodes in membrane capacitive deionization (MCDI) for CO<sub>2</sub> capture, *J. Colloid Interface Sci.*, 2020, **564**, 478–490, DOI: 10.1016/j.jcis.2019.12.039, URL: <http://www.sciencedirect.com/science/article/pii/S0021979719314985>, ISSN: 0021-9797.
- 157 W. Xing, *et al.*, Versatile applications of capacitive deionization (CDI)-based technologies, *Desalination*, 2020, **482**, 114390, DOI: 10.1016/j.desal.2020.114390, URL: <http://www.sciencedirect.com/science/article/pii/S0011916419322519>, ISSN: 0011-9164.
- 158 D. Vermaas, M. Saakes and K. Nijmeijer, Capacitive Electrodes for Energy Generation by Reverse Electrodialysis, *Procedia Eng.*, 2012, **44**, 496–497, DOI: 10.1016/j.proeng.2012.08.463, URL: <http://www.sciencedirect.com/science/article/pii/S1877705812034753>, ISSN: 1877-7058.
- 159 Z.-H. Huang, Z. Yang, F. Kang and M. Inagaki, Carbon electrodes for capacitive deionization, *J. Mater. Chem. A*, 2017, **5**, 470–496, DOI: 10.1039/C6TA06733F.
- 160 P. Ratajczak, M. E. Suss, F. Kaasik and F. Béguin, Carbon electrodes for capacitive technologies, *Energy Storage Mater.*, 2019, **16**, 126–145, DOI: 10.1016/j.ensm.2018.04.031, URL: <http://www.sciencedirect.com/science/article/pii/S2405829717307171>, ISSN: 2405-8297.
- 161 K. Singh, Z. Qian, P. Biesheuvel, H. Zuilhof, S. Porada and L. C. Smet, Nickel hexacyanoferrate electrodes for high mono/divalent ion-selectivity in capacitive deionization, *Desalination*, 2020, **481**, 114346, DOI: 10.1016/j.desal.2020.114346, URL: <http://www.sciencedirect.com/science/article/pii/S0011916419321538>, ISSN: 0011-9164.
- 162 P. Biesheuvel, R. Zhao, S. Porada and A. van der Wal, Theory of membrane capacitive deionization including the effect of the electrode pore space, *J. Colloid Interface Sci.*, 2011, **360**(1), 239–248, DOI: 10.1016/j.jcis.2011.04.049, URL: <http://www.sciencedirect.com/science/article/pii/S0021979711004796>, ISSN: 0021-9797.
- 163 R. Zhao, P. M. Biesheuvel and A. van der Wal, Energy consumption and constant current operation in membrane capacitive deionization, *Energy Environ. Sci.*, 2012, **5**, 9520–9527, DOI: 10.1039/C2EE21737F.
- 164 P. Długołęcki and A. van der Wal, Energy Recovery in Membrane Capacitive Deionization, *Environ. Sci. Technol.*, 2013, **47**(9), 4904–4910, DOI: 10.1021/es3053202, PMID: 23477563.
- 165 S. Porada, R. Zhao, A. van der Wal, V. Presser and P. Biesheuvel, Review on the science and technology of water desalination by capacitive deionization, *Prog. Mater. Sci.*, 2013, **58**(8), 1388–1442, DOI: 10.1016/j.pmatsci.2013.03.005, URL: <http://www.sciencedirect.com/science/article/pii/S0079642513000340>, ISSN: 0079-6425.
- 166 A. Ullah, M. W. Saleem and W.-S. Kim, Performance and energy cost evaluation of an integrated NH<sub>3</sub>-based CO<sub>2</sub> capture-capacitive deionization process, *Int. J. Greenhouse Gas Control*, 2017, **66**, 85–96, DOI: 10.1016/j.ijgge.2017.09.013, URL: <http://www.sciencedirect.com/science/article/pii/S1750583617303699>, ISSN: 1750-5836.
- 167 M. Rahimi, G. Catalini, S. Hariharan, M. Wang, M. Puccini and T. A. Hatton, Carbon Dioxide Capture Using an Electrochemically Driven Proton Concentration Process, *Cell. Rep. Phys. Sci.*, 2020, **100033**, DOI: 10.1016/j.xcrp.2020.100033, URL: <http://www.sciencedirect.com/science/article/pii/S2666386420300230>, ISSN: 2666-3864.
- 168 J. Winnick, H. Toghiani and P. Quattrone, Carbon dioxide concentration for manned spacecraft using a molten carbonate electrochemical cell, *AIChE J.*, 1982, **28**(1), 103–111.
- 169 J. Rosen, *et al.*, Molten Carbonate Fuel Cell Performance for CO<sub>2</sub> Capture from Natural Gas Combined Cycle Flue Gas, *J. Electrochem. Soc.*, 2020, **167**(6), 064505, DOI: 10.1149/1945-7111/ab7a9f.
- 170 M. Spinelli, D. Bona, M. Gatti, E. Martelli, F. Viganò and S. Consonni, Assessing the potential of molten carbonate fuel cell-based schemes for carbon capture in natural gas-fired combined cycle power plants, *J. Power Sources*, 2020, **448**, 227223, DOI: 10.1016/j.jpowsour.2019.227223, URL: <http://www.sciencedirect.com/science/article/pii/S0378775319312169>, ISSN: 0378-7753.



- 171 P. Greppi, B. Bosio and E. Arato, Membranes and Molten Carbonate Fuel Cells to Capture CO<sub>2</sub> and Increase Energy Production in Natural Gas Power Plants, *Ind. Eng. Chem. Res.*, 2013, **52**(26), 8755–8764, DOI: 10.1021/ie302725a.
- 172 K. Sugiura, K. Takei, K. Tanimoto and Y. Miyazaki, The carbon dioxide concentrator by using MCFC, *J. Power Sources*, 2003, **118**(1), 218–227, DOI: 10.1016/S0378-7753(03)00084-3, URL: <http://www.sciencedirect.com/science/article/pii/S0378775303000843>, ISSN: 0378-7753.
- 173 D. Shekhawat, D. R. Luebke and H. W. Pennline, A Review of Carbon Dioxide Selective Membranes: A Topical Report, 2003, DOI: 10.2172/819990, URL: <https://www.osti.gov/biblio/819990>.
- 174 Z. Rui, M. Anderson, Y. Lin and Y. Li, Modeling and analysis of carbon dioxide permeation through ceramic-carbonate dual-phase membranes, *J. Membr. Sci.*, 2009, **345**(1), 110–118, DOI: 10.1016/j.memsci.2009.08.034, URL: <http://www.sciencedirect.com/science/article/pii/S0376738809006310>, ISSN: 0376-7388.
- 175 Z. Rui, H. Ji and Y. Lin, Modeling and analysis of ceramic-carbonate dual-phase membrane reactor for carbon dioxide reforming with methane, *Int. J. Hydrogen Energy*, 2011, **36**(14), 8292–8300, DOI: 10.1016/j.ijhydene.2011.02.110, URL: <http://www.sciencedirect.com/science/article/pii/S03603199110-04678>, ISSN: 0360-3199.
- 176 H. Bae, J.-S. Park, S. Senthilkumar, S. M. Hwang and Y. Kim, Hybrid seawater desalination–carbon capture using modified seawater battery system, *J. Power Sources*, 2019, **410**–411, 99–105, DOI: 10.1016/j.jpowsour.2018.11.009, URL: <https://linkinghub.elsevier.com/retrieve/pii/S0378775318312382>.
- 177 A. Khurram, M. He and B. M. Gallant, Tailoring the Discharge Reaction in Li-CO<sub>2</sub> Batteries through Incorporation of CO<sub>2</sub> Capture Chemistry, *Joule*, 2018, **2**(12), 2649–2666, DOI: 10.1016/j.joule.2018.09.002, URL: <http://www.sciencedirect.com/science/article/pii/S2542435118304057>, ISSN: 2542-4351.
- 178 Y. Li, A. Khurram and B. M. Gallant, A High-Capacity Lithium–Gas Battery Based on Sulfur Fluoride Conversion, *J. Phys. Chem. C*, 2018, **122**(13), 7128–7138, DOI: 10.1021/acs.jpcc.8b00569.
- 179 H. Yin, X. Mao, D. Tang, W. Xiao, L. Xing, H. Zhu, D. Wang and D. R. Sadoway, Capture and electrochemical conversion of CO<sub>2</sub> to value-added carbon and oxygen by molten salt electrolysis, *Energy Environ. Sci.*, 2013, **6**, 1538–1545, DOI: 10.1039/C3EE24132G.
- 180 N. Hollingsworth, S. F. R. Taylor, M. T. Galante, J. Jacquemin, C. Longo, K. B. Holt, N. H. de Leeuw and C. Hardacre, CO<sub>2</sub> capture and electrochemical conversion using superbasic [P66614][124Triz], *Faraday Discuss.*, 2015, **183**, 389–400, DOI: 10.1039/C5FD00091B.
- 181 S. Kar, A. Goeppert and G. K. S. Prakash, Integrated CO<sub>2</sub> Capture and Conversion to Formate and Methanol: Connecting Two Threads, *Acc. Chem. Res.*, 2019, **52**(10), 2892–2903, DOI: 10.1021/acs.accounts.9b00324, PMID: 31487145.
- 182 P. Zhang, J. Tong and K. Huang, Electrochemical CO<sub>2</sub> Capture and Conversion, *Materials and Processes for CO<sub>2</sub> Capture, Conversion, and Sequestration*, John Wiley Sons, Ltd, 2018, ch. 5, pp. 213–266, DOI: 10.1002/9781119231059.ch5, URL: <https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119231059.ch5>, ISBN: 9781119231059.
- 183 N. Li, X. Chen, W.-J. Ong, D. R. MacFarlane, X. Zhao, A. K. Cheetham and C. Sun, Understanding of Electrochemical Mechanisms for CO<sub>2</sub> Capture and Conversion into Hydrocarbon Fuels in Transition-Metal Carbides (MXenes), *ACS Nano*, 2017, **11**(11), 10825–10833, DOI: 10.1021/acsnano.7b03738, PMID: 28892617.
- 184 J. Choi, H. Cho, S. Yun, M.-G. Jang, S.-Y. Oh, M. Binns and J.-K. Kim, Process design and optimization of MEA-based CO<sub>2</sub> capture processes for non-power industries, *Energy*, 2019, **185**, 971–980, DOI: 10.1016/j.energy.2019.07.092, URL: <http://www.sciencedirect.com/science/article/pii/S0360544219314331>, ISSN: 0360-5442.
- 185 R. Notz, H. P. Mangalapally and H. Hasse, Post combustion CO<sub>2</sub> capture by reactive absorption: Pilot plant description and results of systematic studies with MEA, *Int. J. Greenhouse Gas Control*, 2012, **6**, 84–112.
- 186 T. Yokoyama, Analysis of reboiler heat duty in MEA process for CO<sub>2</sub> capture using equilibrium-staged model, *Sep. Purif. Technol.*, 2012, **94**, 97–103, DOI: 10.1016/j.seppur.2011.12.029, URL: <http://www.sciencedirect.com/science/article/pii/S1383586611007398>, ISSN: 1383-5866.
- 187 W. Zhang, H. Liu, Y. Sun, J. Cakstins, C. Sun and C. E. Snape, Parametric study on the regeneration heat requirement of an amine-based solid adsorbent process for post-combustion carbon capture, *Appl. Energy*, 2016, **168**, 394–405, DOI: 10.1016/j.apenergy.2016.01.049, URL: <http://www.sciencedirect.com/science/article/pii/S03062621151600290>, ISSN: 0306-2619.
- 188 H. P. Mangalapally, R. Notz, S. Hoch, N. Asprion, G. Sieder, H. Garcia and H. Hasse, Pilot plant experimental studies of post combustion CO<sub>2</sub> capture by reactive absorption with MEA and new solvents, *Energy Procedia*, 2009, **1**(1), 963–970.
- 189 S.-Y. Oh, M. Binns, H. Cho and J.-K. Kim, Energy minimization of MEA-based CO<sub>2</sub> capture process, *Appl. Energy*, 2016, **169**, 353–362, DOI: 10.1016/j.apenergy.2016.02.046, URL: <http://www.sciencedirect.com/science/article/pii/S0306261916301696>, ISSN: 0306-2619.
- 190 M. R. Abu-Zahra, L. H. Schneiders, J. P. Niederer, P. H. Feron and G. F. Versteeg, CO<sub>2</sub> capture from power plants: Part I. A parametric study of the technical performance based on monoethanolamine, *Int. J. Greenhouse Gas Control*, 2007, **1**(1), 37–46.
- 191 J. Thomas and W. Echt, The evolution of performance solvents for gas treating, Petroenergy Conference, 1989, vol. 24.
- 192 M. Clausse, J. Merel and F. Meunier, Numerical parametric study on CO<sub>2</sub> capture by indirect thermal swing adsorption, *Int. J. Greenhouse Gas Control*, 2011, **5**(5), 1206–1213.
- 193 J. K. Stolaroff, D. W. Keith and G. V. Lowry, Carbon Dioxide Capture from Atmospheric Air Using Sodium Hydroxide Spray, *Environ. Sci. Technol.*, 2008, **42**(8), 2728–2735, DOI: 10.1021/es702607w.



- 194 H. D. Willauer, F. Dimascio, D. R. Hardy, M. K. Lewis and F. W. Williams, Development of an electrochemical acidification cell for the recovery of CO<sub>2</sub> and H<sub>2</sub> from seawater, *Ind. Eng. Chem. Res.*, 2011, **50**(17), 9876–9882, DOI: 10.1021/ie2008136, ISSN: 08885885.
- 195 E. ToolBox, Heat of combustion [online], [https://www.engineeringtoolbox.com/standard-heatof-combustion-energy-content-d\\_1987.html](https://www.engineeringtoolbox.com/standard-heatof-combustion-energy-content-d_1987.html), 2017.
- 196 C. C. L. McCrory, S. Jung, I. M. Ferrer, S. M. Chatman, J. C. Peters and T. F. Jaramillo, Benchmarking Hydrogen Evolving Reaction and Oxygen Evolving Reaction Electrocatalysts for Solar Water Splitting Devices, *J. Am. Chem. Soc.*, 2015, **137**(13), 4347–4357, DOI: 10.1021/ja510442p, PMID: 25668483.
- 197 S. Z. Oener, M. J. Foster and S. W. Boettcher, Accelerating water dissociation in bipolar membranes and for electrocatalysis, *Science*, 2020, **369**(6507), 1099–1103, DOI: 10.1126/science.aaz1487, URL: <https://science.sciencemag.org/content/369/6507/1099>, ISSN: 0036-8075.
- 198 M. L. Jordan, L. Valentino, N. Nazryrbekova, V. M. Palakkal, S. Kole, D. Bhattacharya, Y. J. Lin and C. G. Arges, Promoting water-splitting in Janus bipolar ion-exchange resin wafers for electrodeionization, *Mol. Syst. Des. Eng.*, 2020, **5**, 922–935, DOI: 10.1039/C9ME00179D.
- 199 M. D. Eisaman, Negative Emissions Technologies: The Tradeoffs of Air-Capture Economics, *Joule*, 2020, **4**(3), 516–520, DOI: 10.1016/j.joule.2020.02.007, URL: <http://www.sciencedirect.com/science/article/pii/S254243512030-0854>, ISSN: 2542-4351.
- 200 M. L. Jordan, L. Valentino, N. Nazryrbekova, V. M. Palakkal, S. Kole, D. Bhattacharya, Y. J. Lin and C. G. Arges, Promoting water-splitting in Janus bipolar ion-exchange resin wafers for electrodeionization, *Mol. Syst. Des. Eng.*, 2020, **5**(5), 922–935, DOI: 10.1039/C9ME00179D, URL: <http://dx.doi.org/10.1039/C9ME00179D>.
- 201 J. G. J. Olivier and J. A. H. W. Peters, Trends in global CO<sub>2</sub> and total greenhouse gas emissions 2019 Report, PBL Netherlands Environmental Assessment Agency, 2020.
- 202 G. Realmonte, L. Drouet, A. Gambhir, J. Glynn, A. Hawkes, A. C. Köberle and M. Tavoni, An inter-model assessment of the role of direct air capture in deep mitigation pathways, *Nat. Commun.*, 2019, **10**(1), 1–12.
- 203 C. Beutler, L. Charles and J. Wurzbacher, The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions, *Front. Clim.*, 2019, **1**, 10, DOI: 10.3389/fclim.2019.00010, URL: <https://www.frontiersin.org/article/10.3389/fclim.2019.00010>, ISSN: 2624-9553.
- 204 G. Reiter and J. Lindorfer, Evaluating CO<sub>2</sub> sources for power-to-gas applications—A case study for Austria, *J. CO<sub>2</sub> Util.*, 2015, **10**, 40–49.
- 205 E. I. Koitsoumpa, C. Bergins and E. Kakaras, The CO<sub>2</sub> economy: Review of CO<sub>2</sub> capture and reuse technologies, *J. Supercrit. Fluids*, 2018, **132**, 3–16, DOI: 10.1016/j.supflu.2017.07.029, URL: <http://www.sciencedirect.com/science/article/pii/S0896844617300694>, ISSN: 0896-8446.
- 206 K. S. Lackner, The thermodynamics of direct air capture of carbon dioxide, *Energy*, 2013, **50**, 38–46.
- 207 I. Paris, The role of CCUS in low-carbon power systems, 2020, URL: <https://www.iea.org/reports/the-role-of-ccus-in-low-carbon-power-systems>.
- 208 C. Pritchard, A. Yang, P. Holmes and M. Wilkinson, Thermodynamics, economics and systems thinking: What role for air capture of CO<sub>2</sub>?, *Process Saf. Environ. Prot.*, 2015, **94**, 188–195, DOI: 10.1016/j.psep.2014.06.011, URL: <http://www.sciencedirect.com/science/article/pii/S095758201400-0913>, ISSN: 0957-5820.
- 209 I. Paris, Direct Air Capture, 2020, <https://www.iea.org/reports/direct-air-capture>.
- 210 K. Heidel, D. Keith, A. Singh and G. Holmes, Process design and costing of an air-contactor for air-capture, *Energy Procedia* 4, 10th International Conference on Greenhouse Gas Control Technologies, 2011, pp. 2861–2868, DOI: 10.1016/j.egypro.2011.02.192, URL: <http://www.sciencedirect.com/science/article/pii/S1876610211003894>, ISSN: 1876-6102.
- 211 G. Thermostat and M. I. New, Global Thermostat, 2018.
- 212 J. Wurzbacher, Capturing CO<sub>2</sub> from air, *Internationaler Motorenkongress 2017*, Springer, 2017, pp. 499–511.
- 213 A. Kiani, K. Jiang and P. Feron, Techno-Economic Assessment for CO<sub>2</sub> Capture From Air Using a Conventional Liquid-Based Absorption Process, *Front. Energy Res.*, 2020, **8**, 92, DOI: 10.3389/fenrg.2020.00092, URL: <https://www.frontiersin.org/article/10.3389/fenrg.2020.00092>, ISSN: 2296-598X.
- 214 D. Moreira and J. C. Pires, Atmospheric CO<sub>2</sub> capture by algae: negative carbon dioxide emission path, *Bioresour. Technol.*, 2016, **215**, 371–379.
- 215 D. D.-W. Tsai, P. H. Chen and R. Ramaraj, The potential of carbon dioxide capture and sequestration with algae, *Ecol. Eng.*, 2017, **98**, 17–23.
- 216 M. K. Lam, K. T. Lee and A. R. Mohamed, Current status and challenges on microalgae-based carbon capture, *Int. J. Greenhouse Gas Control*, 2012, **10**, 456–469.
- 217 A. Ghorbani, H. R. Rahimpour, Y. Ghasemi, S. Zoughi and M. R. Rahimpour, A review of carbon capture and sequestration in Iran: microalgal biofixation potential in Iran, *Renewable Sustainable Energy Rev.*, 2014, **35**, 73–100.
- 218 A. Ghosh and B. Kiran, Carbon concentration in algae: reducing CO<sub>2</sub> from exhaust gas, *Trends Biotechnol.*, 2017, **35**(9), 806–808.
- 219 W. Zhou, et al., Bio-mitigation of carbon dioxide using microalgal systems: advances and perspectives, *Renewable Sustainable Energy Rev.*, 2017, **76**, 1163–1175.
- 220 K. Zhou, S. Chaemchuen and F. Verpoort, Alternative materials in technologies for Biogas upgrading via CO<sub>2</sub> capture, *Renewable Sustainable Energy Rev.*, 2017, **79**, 1414–1441.
- 221 M. Waqas, A. Aburizaiza, R. Miandad, M. Rehan, M. Barakat and A. Nizami, Development of biochar as fuel and catalyst in energy recovery technologies, *J. Cleaner Prod.*, 2018, **188**, 477–488.



- 222 X.-f. Tan, *et al.*, Biochar-based nano-composites for the decontamination of wastewater: a review, *Bioresour. Technol.*, 2016, **212**, 318–333.
- 223 N. A. Qambrani, M. M. Rahman, S. Won, S. Shim and C. Ra, Biochar properties and eco-friendly applications for climate change mitigation, waste management, and wastewater treatment: A review, *Renewable Sustainable Energy Rev.*, 2017, **79**, 255–273.
- 224 A. E. Creamer, B. Gao and S. Wang, Carbon dioxide capture using various metal oxyhydroxide–biochar composites, *Chem. Eng. J.*, 2016, **283**, 826–832.
- 225 S. P. Galinato, J. K. Yoder and D. Granatstein, The economic value of biochar in crop production and carbon sequestration, *Energy Policy*, 2011, **39**(10), 6344–6350.
- 226 S. Gupta, H. W. Kua and C. Y. Low, Use of biochar as carbon sequestering additive in cement mortar, *Cem. Concr. Compos.*, 2018, **87**, 110–129.
- 227 P.-H. Huang, H.-H. Cheng and S.-H. Lin, Adsorption of carbon dioxide onto activated carbon prepared from coconut shells, *J. Chem.*, 2015, **2015**, 1–10, DOI: 10.1155/2015/106590.
- 228 M. Asif, M. Suleman, I. Haq and S. A. Jamal, Post-combustion CO<sub>2</sub> capture with chemical absorption and hybrid system: current status and challenges, *Greenhouse Gases: Sci. Technol.*, 2018, **8**(6), 998–1031, DOI: 10.1002/ghg.1823, URL: <https://onlinelibrary.wiley.com/doi/abs/10.1002/ghg.1823>.
- 229 B. Dutcher, M. Fan and A. G. Russell, Amine-Based CO<sub>2</sub> Capture Technology Development from the Beginning of 2013—A Review, *ACS Appl. Mater. Interfaces*, 2015, **7**(4), 2137–2148, DOI: 10.1021/am507465f.
- 230 M. Bui, *et al.*, Carbon capture and storage (CCS): the way forward, *Energy Environ. Sci.*, 2018, **11**(5), 1062–1176, DOI: 10.1039/C7EE02342A.
- 231 I. Sreedhar, T. Nahar, A. Venugopal and B. Srinivas, Carbon capture by absorption-path covered and ahead, *Renewable Sustainable Energy Rev.*, 2017, **76**, 1080–1107.
- 232 J. T. Yeh, H. W. Pennline and K. P. Resnik, Study of CO<sub>2</sub> Absorption and Desorption in a Packed Column, *Energy Fuels*, 2001, **15**(2), 274–278, DOI: 10.1021/ef0002389.
- 233 V. Nikulshina, D. Hirsch, M. Mazzotti and A. Steinfeld, CO<sub>2</sub> capture from air and co-production of H<sub>2</sub> via the Ca(OH)<sub>2</sub>–CaCO<sub>3</sub> cycle using concentrated solar power–Thermodynamic analysis, *Energy*, 2006, **31**(12), 1715–1725, DOI: 10.1016/j.energy.2005.09.014, URL: <http://www.sciencedirect.com/science/article/pii/S0360544205001891>, ISSN: 0360-5442.
- 234 V. Nikulshina, M. Gálvez and A. Steinfeld, Kinetic analysis of the carbonation reactions for the capture of CO<sub>2</sub> from air via the Ca(OH)<sub>2</sub>–CaCO<sub>3</sub>–CaO solar thermochemical cycle, *Chem. Eng. J.*, 2007, **129**(1), 75–83, DOI: 10.1016/j.cej.2006.11.003, URL: <http://www.sciencedirect.com/science/article/pii/S1385894706004955>, ISSN: 1385-8947.
- 235 V. Nikulshina, N. Ayesa, M. Gálvez and A. Steinfeld, Feasibility of Na-based thermochemical cycles for the capture of CO<sub>2</sub> from air—Thermodynamic and thermogravimetric analyses, *Chem. Eng. J.*, 2008, **140**(1), 62–70, DOI: 10.1016/j.cej.2007.09.007, URL: <http://www.sciencedirect.com/science/article/pii/S1385894707006134>, ISSN: 1385-8947.
- 236 B. Feng, M. Du, T. J. Dennis, K. Anthony and M. J. Perumal, Reduction of Energy Requirement of CO<sub>2</sub> Desorption by Adding Acid into CO<sub>2</sub>-Loaded Solvent, *Energy Fuels*, 2010, **24**(1), 213–219, DOI: 10.1021/ef900564x.
- 237 A. Samanta, A. Zhao, G. K. H. Shimizu, P. Sarkar and R. Gupta, Post-Combustion CO<sub>2</sub> Capture Using Solid Sorbents: A Review, *Ind. Eng. Chem. Res.*, 2012, **51**(4), 1438–1463, DOI: 10.1021/ie200686q.
- 238 Q. Cen, M. Fang, T. Wang, I. Majchrzak-Kucęba, D. Wawryńczak and Z. Luo, Thermodynamics and regeneration studies of CO<sub>2</sub> adsorption on activated carbon, *Greenhouse Gases: Sci. Technol.*, 2016, **6**(6), 787–796, DOI: 10.1002/ghg.1621, URL: <https://onlinelibrary.wiley.com/doi/abs/10.1002/ghg.1621>.
- 239 S. Choi, J. H. Drese and C. W. Jones, Adsorbent Materials for Carbon Dioxide Capture from Large Anthropogenic Point Sources, *ChemSusChem*, 2009, **2**(9), 796–854, DOI: 10.1002/cssc.200900036.
- 240 P. Pandey and R. Chauhan, Membranes for gas separation, *Prog. Polym. Sci.*, 2001, **26**(6), 853–893, DOI: 10.1016/S0079-6700(01)00009-0, URL: <http://www.sciencedirect.com/science/article/pii/S0079670001000090>, ISSN: 0079-6700.
- 241 P. Bernardo, E. Drioli and G. Golemme, Membrane Gas Separation: A Review/State of the Art, *Ind. Eng. Chem. Res.*, 2009, **48**(10), 4638–4663, DOI: 10.1021/ie8019032.
- 242 T. C. Merkel, H. Lin, X. Wei and R. Baker, Power plant post-combustion carbon dioxide capture: An opportunity for membranes, *J. Membr. Sci.*, 2010, **359**(1), 126–139, DOI: 10.1016/j.memsci.2009.10.041, URL: <http://www.sciencedirect.com/science/article/pii/S0376738809007832>, ISSN: 0376-7388.
- 243 T. C. Merkel, X. Wei, Z. He, L. S. White, J. G. Wijmans and R. W. Baker, Selective Exhaust Gas Recycle with Membranes for CO<sub>2</sub> Capture from Natural Gas Combined Cycle Power Plants, *Ind. Eng. Chem. Res.*, 2013, **52**(3), 1150–1159, DOI: 10.1021/ie302110z.
- 244 G. Russo, G. Prpic, E. J. Anthony, F. Montagnaro, N. Jurado, G. D. Lorenzo and H. G. Darabkhani, Selective-exhaust gas recirculation for CO<sub>2</sub> capture using membrane technology, *J. Membr. Sci.*, 2018, **549**, 649–659, DOI: 10.1016/j.memsci.2017.10.052, URL: <http://www.sciencedirect.com/science/article/pii/S0376738817308505>, ISSN: 0376-7388.
- 245 X. Feng and J. Ivory, Development of hollow fiber membrane systems for nitrogen generation from combustion exhaust gas: Part I. Effects of module configurations, *J. Membr. Sci.*, 2000, **176**(2), 197–207, DOI: 10.1016/S0376-7388(00)00445-2, URL: <http://www.sciencedirect.com/science/article/pii/S0376738800004452>, ISSN: 0376-7388.
- 246 U. W. Siagian, A. Raksaati, N. F. Himma, K. Khoiruddin and I. Wenten, Membrane-based carbon capture technologies: Membrane gas separation vs. membrane contactor, *J. Nat. Gas Sci. Eng.*, 2019, **67**, 172–195, DOI: 10.1016/j.jngse.2019.04.008, URL: <http://www.sciencedirect.com/science/article/pii/S1875510019301039>, ISSN: 1875-5100.

- 247 M. Anwar, *et al.*, CO<sub>2</sub> capture and storage: A way forward for sustainable environment, *J. Environ. Manage.*, 2018, **226**, 131–144, DOI: 10.1016/j.jenvman.2018.08.009, URL: <http://www.sciencedirect.com/science/article/pii/S0301479718308788>, ISSN: 0301-4797.
- 248 J. Blamey, E. Anthony, J. Wang and P. Fennell, The calcium looping cycle for large-scale CO<sub>2</sub> capture, *Prog. Energy Combust. Sci.*, 2010, **36**(2), 260–279, DOI: 10.1016/j.pecs.2009.10.001, URL: <http://www.sciencedirect.com/science/article/pii/S0360128509000574>, ISSN: 0360-1285.
- 249 M. Erans, V. Manovic and E. J. Anthony, Calcium looping sorbents for CO<sub>2</sub> capture, *Appl. Energy*, 2016, **180**, 722–742, DOI: 10.1016/j.apenergy.2016.07.074, URL: <http://www.sciencedirect.com/science/article/pii/S0306261916310157>, ISSN: 0306-2619.
- 250 P. R. Jeon, J. Choi, T. S. Yun and C.-H. Lee, Sorption equilibrium and kinetics of CO<sub>2</sub> on clay minerals from subcritical to supercritical conditions: CO<sub>2</sub> sequestration at nanoscale interfaces, *Chem. Eng. J.*, 2014, **255**, 705–715, DOI: 10.1016/j.cej.2014.06.090, URL: <http://www.sciencedirect.com/science/article/pii/S1385894714008390>.
- 251 A. A. Olajire, A review of mineral carbonation technology in sequestration of CO<sub>2</sub>, *J. Pet. Sci. Eng.*, 2013, **109**, 364–392, DOI: 10.1016/j.petrol.2013.03.013, URL: <http://www.sciencedirect.com/science/article/pii/S0920410513000673>.
- 252 A.-H. A. Park and L.-S. Fan, CO<sub>2</sub> mineral sequestration: physically activated dissolution of serpentine and pH swing process, *Chem. Eng. Sci.*, 2004, **59**(22), 5241–5247, DOI: 10.1016/j.ces.2004.09.008, URL: <http://www.sciencedirect.com/science/article/pii/S0009250904006773>, ISSN: 0009-2509.
- 253 S. Kodama, T. Nishimoto, N. Yamamoto, K. Yogo and K. Yamada, Development of a new pH-swing CO<sub>2</sub> mineralization process with a recyclable reaction solution, *Energy*, 2008, **33**(5), 776–784, DOI: 10.1016/j.energy.2008.01.005, URL: <http://www.sciencedirect.com/science/article/pii/S0360544208000273>, ISSN: 0360-5442.
- 254 S. Eloneva, A. Said, C.-J. Fogelholm and R. Zevenhoven, Preliminary assessment of a method utilizing carbon dioxide and steelmaking slags to produce precipitated calcium carbonate, *Appl. Energy*, 2012, **90**(1), 329–334, DOI: 10.1016/j.apenergy.2011.05.045, URL: <http://www.sciencedirect.com/science/article/pii/S0306261911003400>, ISSN: 0306-2619.
- 255 A. Sanna, M. Dri and M. Maroto-Valer, Carbon dioxide capture and storage by pH swing aqueous mineralisation using a mixture of ammonium salts and antigorite source, *Fuel*, 2013, **114**, 153–161, DOI: 10.1016/j.fuel.2012.08.014, URL: <http://www.sciencedirect.com/science/article/pii/S0016236112006503>, ISSN: 0016-2361.
- 256 A. Azdarpour, M. Asadullah, E. Mohammadian, H. Hamidi, R. Junin and M. A. Karaei, A review on carbon dioxide mineral carbonation through pH-swing process, *Chem. Eng. J.*, 2015, **279**, 615–630, DOI: 10.1016/j.cej.2015.05.064, URL: <http://www.sciencedirect.com/science/article/pii/S1385894715007408>, ISSN: 1385-8947.
- 257 V. Prigobbe, M. Hänenchen, M. Werner, R. Baciocchi and M. Mazzotti, Mineral carbonation process for CO<sub>2</sub> sequestration, *Energy Procedia*, 2009, **1**(1), 4885–4890, DOI: 10.1016/j.egypro.2009.02.318, URL: <http://www.sciencedirect.com/science/article/pii/S1876610209009618>, ISSN: 1876-6102.
- 258 S. J. Gerdemann, W. K. O'Connor, D. C. Dahlin, L. R. Penner and H. Rush, *Ex Situ* Aqueous Mineral Carbonation, *Environ. Sci. Technol.*, 2007, **41**(7), 2587–2593, DOI: 10.1021/es0619253.
- 259 A. Azdarpour, M. Asadullah, E. Mohammadian, R. Junin, H. Hamidi, M. Manan and A. R. M. Daud, Mineral carbonation of red gypsum via pH-swing process: Effect of CO<sub>2</sub> pressure on the efficiency and products characteristics, *Chem. Eng. J.*, 2015, **264**, 425–436, DOI: 10.1016/j.cej.2014.11.125, URL: <http://www.sciencedirect.com/science/article/pii/S1385894714015939>, ISSN: 1385-8947.
- 260 G. L. A. Ferrufino, S. Okamoto, J. C. Santos, J. A. Carvalho, I. Avila, C. M. Luna and T. S. Neto, CO<sub>2</sub> sequestration by pH-swing mineral carbonation based on HCl/NH<sub>4</sub>OH system using iron-rich lizardite 1T, *J. CO<sub>2</sub> Util.*, 2018, **24**, 164–173, DOI: 10.1016/j.jcou.2018.01.001, URL: <http://www.sciencedirect.com/science/article/pii/S221298201730272X>, ISSN: 2212-9820.
- 261 R. Stanger, *et al.*, Oxyfuel combustion for CO<sub>2</sub> capture in power plants, *Int. J. Greenhouse Gas Control*, 2015, **40**, 55–125, DOI: 10.1016/j.ijggc.2015.06.010, URL: <http://www.sciencedirect.com/science/article/pii/S1750583615002637>, ISSN: 1750-5836.
- 262 G. Scheffknecht, L. Al-Makhadmeh, U. Schnell and J. Maier, Oxy-fuel coal combustion—A review of the current state-of-the-art, *Int. J. Greenhouse Gas Control*, 2011, **5**, S16–S35, DOI: 10.1016/j.ijggc.2011.05.020, URL: <http://www.sciencedirect.com/science/article/pii/S1750583611000806>, ISSN: 1750-5836.
- 263 L. Zheng, 1-Overview of oxy-fuel combustion technology for carbon dioxide (CO<sub>2</sub>) capture, in *Oxy-Fuel Combustion for Power Generation and Carbon Dioxide (CO<sub>2</sub>) Capture*, ed. L. Zheng, Woodhead Publishing Series in Energy, Woodhead Publishing, 2011, pp. 1–13, DOI: 10.1533/9780857090980.1, URL: <http://www.sciencedirect.com/science/article/pii/B9781845696719500016>, ISBN: 978-1-84569-671-9.
- 264 B. Metz, O. Davidson, H. De Coninck, M. Loos and L. Meyer, IPCC special report on carbon dioxide capture and storage, Tech. Rep., Intergovernmental Panel on Climate Change, Geneva (Switzerland), 2005.
- 265 C. F. Song, Y. Kitamura and S. H. Li, Evaluation of Stirling cooler system for cryogenic CO<sub>2</sub> capture, *Appl. Energy*, 2012, **98**, 491–501.
- 266 T. F. Wall, Combustion processes for carbon capture, *Proc. Combust. Inst.*, 2007, **31**(1), 31–47.
- 267 R. Pardemann and B. Meyer, Pre-Combustion Carbon Capture, *Handbook of Clean Energy Systems*, American Cancer Society, 2015, DOI: 10.1002/9781118991978.hces061, URL: <https://onlinelibrary.wiley.com/doi/abs/10.1002/9781118991978.hces061>, ISBN: 9781118991978.



- 268 O. d. Q. F. Araújo and J. L. de Medeiros, Carbon capture and storage technologies: present scenario and drivers of innovation, *Curr. Opin. Chem. Eng.*, 2017, **17**, 22–34.
- 269 A. C. Yeh and H. Bai, Comparison of ammonia and monoethanolamine solvents to reduce CO<sub>2</sub> greenhouse gas emissions, *Sci. Total Environ.*, 1999, **228**(2), 121–133, DOI: 10.1016/S0048-9697(99)00025-X, URL: <http://www.sciencedirect.com/science/article/pii/S004896979900025X>, ISSN: 0048-9697.
- 270 G. Rochelle, 3-Conventional amine scrubbing for CO<sub>2</sub> capture, in *Absorption-Based Post-combustion Capture of Carbon Dioxide*, ed. P. H. Feron, Woodhead Publishing, 2016, pp. 35–67, DOI: 10.1016/B978-0-08-100514-9.00003-2, URL: <http://www.sciencedirect.com/science/article/pii/B9780081005149000032>, ISBN: 978-0-08-100514-9.
- 271 M. T. Ho, G. W. Allinson and D. E. Wiley, Reducing the Cost of CO<sub>2</sub> Capture from Flue Gases Using Membrane Technology, *Ind. Eng. Chem. Res.*, 2008, **47**(5), 1562–1568, DOI: 10.1021/ie070541y, URL: <https://doi.org/10.1021/ie070541y>.
- 272 C. E. Powell and G. G. Qiao, Polymeric CO<sub>2</sub>/N<sub>2</sub> gas separation membranes for the capture of carbon dioxide from power plant flue gases, *J. Membr. Sci.*, 2006, **279**(1), 1–49, DOI: 10.1016/j.memsci.2005.12.062, URL: <http://www.sciencedirect.com/science/article/pii/S0376738806000068>, ISSN: 0376-7388.
- 273 Y. Peng, Y. Li, Y. Ban and W. Yang, Two-Dimensional Metal–Organic Framework Nanosheets for Membrane-Based Gas Separation, *Angew. Chem., Int. Ed.*, 2017, **56**(33), 9757–9761, DOI: 10.1002/anie.201703959.
- 274 X. Zou and G. Zhu, Microporous Organic Materials for Membrane-Based Gas Separation, *Adv. Mater.*, 2018, **30**(3), 1700750, DOI: 10.1002/adma.201700750.
- 275 J. Wang, J. Luo, S. Feng, H. Li, Y. Wan and X. Zhang, Recent development of ionic liquid membranes, *Green Energy Environ.*, 2016, **1**(1), 43–61, DOI: 10.1016/j.gee.2016.05.002, URL: <http://www.sciencedirect.com/science/article/pii/S246802571630022X>, ISSN: 2468-0257.
- 276 A. Perejón, L. M. Romeo, Y. Lara, P. Lisbona, A. Martínez and J. M. Valverde, The Calcium-Looping technology for CO<sub>2</sub> capture: On the important roles of energy integration and sorbent behavior, *Appl. Energy*, 2016, **162**, 787–807, DOI: 10.1016/j.apenergy.2015.10.121, URL: <http://www.sciencedirect.com/science/article/pii/S0306261915013616>, ISSN: 0306-2619.
- 277 C. Verma and E. E. Ebenso, Ionic liquid-mediated functionalization of graphene-based materials for versatile applications: a review, *Graphene Technol.*, 2019, **4**(1–2), 1–15.
- 278 G. T. Rochelle, Amine Scrubbing for CO<sub>2</sub> Capture, *Science*, 2009, **325**(5948), 1652–1654, DOI: 10.1126/science.1176731, URL: <http://science.sciencemag.org/content/325/5948/1652>, ISSN: 0036-8075.
- 279 S. Kim, H. Shi and J. Y. Lee, CO<sub>2</sub> absorption mechanism in amine solvents and enhancement of CO<sub>2</sub> capture capability in blended amine solvent, *Int. J. Greenhouse Gas Control*, 2016, **45**, 181–188, DOI: 10.1016/j.ijggc.2015.12.024, URL: <http://www.sciencedirect.com/science/article/pii/S1750583615301675>, ISSN: 1750-5836.
- 280 G. Sartori and D. W. Savage, Sterically hindered amines for carbon dioxide removal from gases, *Ind. Eng. Chem. Fundam.*, 1983, **22**(2), 239–249, DOI: 10.1021/i100010a016.
- 281 A. Dibenedetto, M. Aresta, C. Fragale and M. Narracci, Reaction of silylalkylmono- and silylalkyldiamines with carbon dioxide: evidence of formation of inter- and intramolecular ammonium carbamates and their conversion into organic carbamates of industrial interest under carbon dioxide catalysis, *Green Chem.*, 2002, **4**, 439–443, DOI: 10.1039/B205319P.
- 282 G. Puxty, R. Rowland, A. Allport, Q. Yang, M. Bown, R. Burns, M. Maeder and M. Attalla, Carbon Dioxide Postcombustion Capture: A Novel Screening Study of the Carbon Dioxide Absorption Performance of 76 Amines, *Environ. Sci. Technol.*, 2009, **43**(16), 6427–6433, DOI: 10.1021/es901376a.
- 283 H. Ahn, M. Luberti, Z. Liu and S. Brandani, Process configuration studies of the amine capture process for coal-fired power plants, *Int. J. Greenhouse Gas Control*, 2013, **16**, 29–40, DOI: 10.1016/j.ijggc.2013.03.002, URL: <http://www.sciencedirect.com/science/article/pii/S1750583613001229>, ISSN: 1750-5836.
- 284 R. R. Wanderley, D. D. Pinto and H. K. Knuutila, Investigating opportunities for water-lean solvents in CO<sub>2</sub> capture: VLE and heat of absorption in water-lean solvents containing MEA, *Sep. Purif. Technol.*, 2020, **231**, 115883, DOI: 10.1016/j.seppur.2019.115883, URL: <http://www.sciencedirect.com/science/article/pii/S1383586619327583>, ISSN: 1383-5866.
- 285 H. Karunaratne, D. Eimer and L. Øi, Physical Properties of MEA + Water + CO<sub>2</sub> Mixtures in Postcombustion CO<sub>2</sub> Capture: A Review of Correlations and Experimental Studies, *J. Eng.*, 2020, **2020**, 1–17, DOI: 10.1155/2020/7051368.
- 286 P. Luis, Use of monoethanolamine (MEA) for CO<sub>2</sub> capture in a global scenario: Consequences and alternatives, *Desalination*, 2016, **380**, 93–99, DOI: 10.1016/j.desal.2015.08.004, URL: <http://www.sciencedirect.com/science/article/pii/S001191641500418X>, ISSN: 0011-9164.
- 287 K. Li, A. Cousins, H. Yu, P. Feron, M. Tade, W. Luo and J. Chen, Systematic study of aqueous monoethanolamine based CO<sub>2</sub> capture process: model development and process improvement, *Energy Sci. Eng.*, 2016, **4**(1), 23–39, DOI: 10.1002/ese3.101.
- 288 I. M. Bernhardsen and H. K. Knuutila, A review of potential amine solvents for CO<sub>2</sub> absorption process: Absorption capacity, cyclic capacity and pKa, *Int. J. Greenhouse Gas Control*, 2017, **61**, 27–48.
- 289 S. Singto, T. Supap, R. Idem, P. Tontiwachwuthikul and S. Tantayanon, The effect of chemical structure of newly synthesized tertiary amines used for the post combustion capture process on carbon dioxide (CO<sub>2</sub>): Kinetics of CO<sub>2</sub> absorption using the stopped-flow apparatus and regeneration, and heat input of CO<sub>2</sub> regeneration, *Energy Procedia*, 2017, **114**, 852–859.

- 290 M. K. Mondal, H. K. Balsora and P. Varshney, Progress and trends in CO<sub>2</sub> capture/separation technologies: a review, *Energy*, 2012, **46**(1), 431–441.
- 291 C. Han, K. Graves, J. Neatherly and K. Liu, Simulation of the Energy Consumption of CO<sub>2</sub> Capture by Aqueous Monoethanolamine in Pilot Plant, *Energy Environ. Res.*, 2011, **1**(1), 67.
- 292 F. A. Chowdhury, H. Yamada, T. Higashii, K. Goto and M. Onoda, CO<sub>2</sub> Capture by Tertiary Amine Absorbents: A Performance Comparison Study, *Ind. Eng. Chem. Res.*, 2013, **52**(24), 8323–8331, DOI: 10.1021/ie400825u.
- 293 M. Mahmoudkhani and D. W. Keith, Low-energy sodium hydroxide recovery for CO<sub>2</sub> capture from atmospheric air—Thermodynamic analysis, *Int. J. Greenhouse Gas Control*, 2009, **3**(4), 376–384, DOI: 10.1016/j.ijggc.2009.02.003, URL: <http://www.sciencedirect.com/science/article/pii/S1750583609000176>, ISSN: 1750-5836.
- 294 F. Zeman, Energy and Material Balance of CO<sub>2</sub> Capture from Ambient Air, *Environ. Sci. Technol.*, 2007, **41**(21), 7558–7563, DOI: 10.1021/es070874m.
- 295 Y. Tanaka, 17-Bipolar Membrane Electrodialysis, in *Ion Exchange Membranes*, ed. Y. Tanaka, Elsevier, Amsterdam, 2nd edn, 2015, pp. 369–392, DOI: 10.1016/B978-0-444-63319-4.00017-1, URL: <http://www.sciencedirect.com/science/article/pii/B9780444633194000171>, ISBN: 978-0-444-63319-4.
- 296 E. D. Bates, R. D. Mayton, I. Ntai and J. H. Davis, CO<sub>2</sub> Capture by a Task-Specific Ionic Liquid, *J. Am. Chem. Soc.*, 2002, **124**(6), 926–927, DOI: 10.1021/ja017593d, PMID: 11829599.
- 297 M. Ramdin, T. W. de Loos and T. J. Vlugt, State-of-the-Art of CO<sub>2</sub> Capture with Ionic Liquids, *Ind. Eng. Chem. Res.*, 2012, **51**(24), 8149–8177, DOI: 10.1021/ie3003705.
- 298 K. Huang, F.-F. Chen, D.-J. Tao and S. Dai, Ionic liquid-formulated hybrid solvents for CO<sub>2</sub> capture, *Curr. Opin. Green Sustainable Chem.*, 2017, **5**, 67–73, DOI: 10.1016/j.cogsc.2017.03.016, URL: <http://www.sciencedirect.com/science/article/pii/S2452223616300931>, ISSN: 2452-2236.
- 299 M. Smiglak, A. Metlen and R. D. Rogers, The Second Evolution of Ionic Liquids: From Solvents and Separations to Advanced Materials—Energetic Examples from the Ionic Liquid Cookbook, *Acc. Chem. Res.*, 2007, **40**(11), 1182–1192, DOI: 10.1021/ar7001304, PMID: 17979252.
- 300 Y. A. C. Jande, M. Asif, S. M. Shim and W. S. Kim, Energy minimization in monoethanolamine based CO<sub>2</sub> capture using capacitive deionization, *Int. J. Energy Res.*, 2014, **38**(12), 1531–1540, DOI: 10.1002/er.3168.
- 301 M. C. Stern, F. Simeon, H. Herzog and T. A. Hatton, An Electrochemically-mediated Gas Separation Process for Carbon Abatement, *Energy Procedia*, 2013, **37**, 1172–1179, DOI: 10.1016/j.egypro.2013.05.214, URL: <http://www.sciencedirect.com/science/article/pii/S1876610213002245>, ISSN: 1876-6102.
- 302 M. Wang, M. Rahimi, A. Kumar, S. Hariharan, W. Choi and T. A. Hatton, Flue gas CO<sub>2</sub> capture via electrochemically mediated amine regeneration: System design and performance, *Appl. Energy*, 2019, **255**, 113879, DOI: 10.1016/j.apenergy.2019.113879, URL: <http://www.sciencedirect.com/science/article/pii/S0306261919315661>, ISSN: 0306-2619.
- 303 V. I. Zabolotskii, L. F. El'nikova, N. P. Gnusin and Y. N. Omel'chenko, Regeneration of monoethanolamine-based sorbents of carbon dioxide by electrodialysis with bipolar membranes, *J. Appl. Chem. USSR (Engl. Transl.)*, 1986, **58**(10 Pt 2), <https://www.osti.gov/biblio/6848071>.
- 304 C. Huang, T. Xu and X. Yang, Regenerating Fuel-Gas Desulfurizing Agents by Using Bipolar Membrane Electrodialysis (BMED): Effect of Molecular Structure of Alkanolamines on the Regeneration Performance, *Environ. Sci. Technol.*, 2007, **41**(3), 984–989, DOI: 10.1021/es061918e.
- 305 M. T. Ho, G. W. Allinson and D. E. Wiley, Reducing the Cost of CO<sub>2</sub> Capture from Flue Gases Using Pressure Swing Adsorption, *Ind. Eng. Chem. Res.*, 2008, **47**(14), 4883–4890, DOI: 10.1021/ie070831e.
- 306 R. T. Yang, Cyclic Gas Separation Processes, *Gas Separation by Adsorption Processes*, ed. R. T. Yang, Butterworth-Heinemann, 1987, ch. 6, pp. 201–235, DOI: 10.1016/B978-0-409-90004-0.50009-X, URL: <http://www.sciencedirect.com/science/article/pii/B978040990004050009X>, ISBN: 978-0-409-90004-0.
- 307 E. S. Kikkinides and R. T. Yang, Concentration and Recovery of CO<sub>2</sub> from Flue Gas by Pressure Swing Adsorption (PSA), *Ind. Eng. Chem. Res.*, 1993, **32**, 2714.
- 308 K. T. Chue, J. N. Kim, Y. J. Yoo, S. H. Cho and R. T. Yang, Comparison of Activated Carbon and Zeolite 13X for CO<sub>2</sub> Recovery from Flue Gas by Pressure Swing Adsorption, *Ind. Eng. Chem. Res.*, 1995, **34**, 591.
- 309 S. J. Doong and R. T. Yang, Bulk Separation of Multi-component Gas Mixtures by Pressure Swing Adsorption: Pore Surface Diffusion and Equilibrium Models, *AICHE J.*, 1986, **32**, 397.
- 310 D. Ko, R. Sirwardane and L. Biegler, Optimization of Pressure Swing Adsorption and Fractionated Vacuum Pressure Swing Adsorption Processes for CO<sub>2</sub> Sequestration, *Ind. Eng. Chem. Res.*, 2005, **44**, 8084.
- 311 D. Ko, R. Sirwardane and L. Biegler, Optimization of Pressure Swing Adsorption Process Using Zeolite 13X for CO<sub>2</sub> Sequestration, *Ind. Eng. Chem. Res.*, 2003, **42**, 339.
- 312 C. Chou and C. Chen, Carbon Dioxide Recovery by Vacuum Swing Adsorption, *J. Chin. Inst. Chem. Eng.*, 2003, **34**, 135.
- 313 W. K. Choi, T. I. Kwon, Y. K. Yeo, H. Lee, B. K. Na and H. K. Song, Optimal Operation of the Pressure Swing Adsorption Process for CO<sub>2</sub> Recovery, *Korean J. Chem. Eng.*, 2003, **20**, 617.
- 314 J. Zhang, P. A. Webley and P. Xiao, Effect of Process Parameters on the Power Requirements of Vacuum Swing Adsorption Technology for CO<sub>2</sub> Capture from Flue Gas, *Energy Convers. Manage.*, 2008, **49**, 346.
- 315 A. Kapoor and R. T. Yang, Kinetic Separation of Methane-Carbon Dioxide Mixture by Adsorption on Molecular Sieve Carbon, *Chem. Eng. Sci.*, 1989, **44**, 1723.
- 316 C.-H. Yu, C.-H. Huang and C.-S. Tan, A Review of CO<sub>2</sub> Capture by Absorption and Adsorption, *Aerosol Air Qual. Res.*, 2012,



- 12(5), 745–769, DOI: 10.4209/aaqr.2012.05.0132, URL: <https://doi.org/10.4209/aaqr.2012.05.0132>.
- 317 J. Huertas and J. Garzon, CO<sub>2</sub> Absorbing Capacity of MEA, *J. Chem.*, 2015, **2015**, 1–7, DOI: 10.1155/2015/965015.
- 318 C. A. Grande and A. E. Rodrigues, Electric Swing Adsorption for CO<sub>2</sub> removal from flue gases, *Int. J. Greenhouse Gas Control*, 2008, **2**(2), 194–202, DOI: 10.1016/S1750-5836(07)00116-8, URL: <http://www.sciencedirect.com/science/article/pii/S1750583607001168>, ISSN: 1750-5836.
- 319 H. An, B. Feng and S. Su, CO<sub>2</sub> capture by electrothermal swing adsorption with activated carbon fibre materials, *Int. J. Greenhouse Gas Control*, 2011, **5**(1), 16–25, DOI: 10.1016/j.ijggc.2010.03.007, URL: <http://www.sciencedirect.com/science/article/pii/S1750583610000447>, ISSN: 1750-5836.
- 320 N. Tlili, G. Grévillot, A. Latifi and C. Vallières, Electrical Swing Adsorption Using New Mixed Matrix Adsorbents for CO<sub>2</sub> Capture and Recovery: Experiments and Modeling, *Ind. Eng. Chem. Res.*, 2012, **51**(48), 15729–15737, DOI: 10.1021/ie3016818.
- 321 M. Petkovska, D. Tondeur, G. Grevillot, J. Granger and M. Mitrović, Temperature-Swing Gas Separation with Electrothermal Desorption Step, *Sep. Sci. Technol.*, 1991, **26**(3), 425–444, DOI: 10.1080/01496399108050482.
- 322 M. Rahimi, J. K. Singh and F. Müller-Plathe, CO<sub>2</sub> Adsorption on Charged Carbon Nanotube Arrays: A Possible Functional Material for Electric Swing Adsorption, *J. Phys. Chem. C*, 2015, **119**(27), 15232–15239, DOI: 10.1021/acs.jpcc.5b02874.
- 323 R. M. Cuéllar-Franca and A. Azapagic, Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts, *J. CO<sub>2</sub> Util.*, 2015, **9**, 82–102, DOI: 10.1016/j.jcou.2014.12.001, URL: <http://www.sciencedirect.com/science/article/pii/S2212982014000626>, ISSN: 2212-9820.
- 324 K. M. K. Yu, I. Curcic, J. Gabriel and S. C. E. Tsang, Recent Advances in CO<sub>2</sub> Capture and Utilization, *ChemSusChem*, 2008, **1**(11), 893–899, DOI: 10.1002/cssc.200800169.
- 325 I. Paris, Putting CO<sub>2</sub> to use – Creating value from emissions, 2019, URL: <https://www.iea.org/reports/putting-co2-to-use>.
- 326 C. M. Woodall, N. McQueen, H. Pilorgé and J. Wilcox, Utilization of mineral carbonation products: current state and potential, *Greenhouse Gases: Sci. Technol.*, 2019, **9**(6), 1096–1113, DOI: 10.1002/ghg.1940.
- 327 J. van Heek, K. Arning and M. Ziefle, Reduce, reuse, recycle: Acceptance of CO<sub>2</sub>-utilization for plastic products, *Energy Policy*, 2017, **105**, 53–66, DOI: 10.1016/j.enpol.2017.02.016, URL: <http://www.sciencedirect.com/science/article/pii/S0301421517300915>, ISSN: 0301-4215.
- 328 R. Chang, S. Kim, S. Lee, S. Choi, M. Kim and Y. Park, Calcium Carbonate Precipitation for CO<sub>2</sub> Storage and Utilization: A Review of the Carbonate Crystallization and Polymorphism, *Front. Energy Res.*, 2017, **5**, 17, DOI: 10.3389/fenrg.2017.00017.
- 329 M. Ramdin, et al., High Pressure Electrochemical Reduction of CO<sub>2</sub> to Formic Acid/Formate: A Comparison between Bipolar Membranes and Cation Exchange Membranes, *Ind. Eng. Chem. Res.*, 2019, **58**(5), 1834–1847, DOI: 10.1021/acs.iecr.8b04944.
- 330 A. Adamu, F. Russo-Abegão and K. Boodhoo, Process intensification technologies for CO<sub>2</sub> capture and conversion – a review, *BMC Chem. Eng.*, 2020, **2**(1), 1–18.
- 331 H. Hashiba, L.-C. Weng, Y. Chen, H. K. Sato, S. Yotsuhashi, C. Xiang and A. Z. Weber, Effects of Electrolyte Buffer Capacity on Surface Reactant Species and the Reaction Rate of CO<sub>2</sub> in Electrochemical CO<sub>2</sub> Reduction, *J. Phys. Chem. C*, 2018, **122**(7), 3719–3726, DOI: 10.1021/acs.jpcc.7b11316.
- 332 Y. Hori, K. Kikuchi and S. Suzuki, Production of CO and CH<sub>4</sub> in electrochemical reduction of CO<sub>2</sub> at metal electrodes in aqueous hydrogencarbonate solution, *Chem. Lett.*, 1985, 1695–1698, DOI: 10.1246/cl.1985.1695.
- 333 K. P. Kuhl, E. R. Cave, D. N. Abram and T. F. Jaramillo, New insights into the electrochemical reduction of carbon dioxide on metallic copper surfaces, *Energy Environ. Sci.*, 2012, **5**, 7050–7059, DOI: 10.1039/C2EE21234J.
- 334 Y. Song, et al., High-Selectivity Electrochemical Conversion of CO<sub>2</sub> to Ethanol using a Copper Nanoparticle/N-Doped Graphene Electrode, *ChemistrySelect*, 2016, **1**(19), 6055–6061, DOI: 10.1002/slct.201601169.
- 335 Y. C. Li, et al., CO<sub>2</sub> Electroreduction from Carbonate Electrolyte, *ACS Energy Lett.*, 2019, **4**(6), 1427–1431, DOI: 10.1021/acsenergylett.9b00975.
- 336 J. Lee, J. Lim, C.-W. Roh, H. S. Whang and H. Lee, Electrochemical CO<sub>2</sub> reduction using alkaline membrane electrode assembly on various metal electrodes, *J. CO<sub>2</sub> Util.*, 2019, **31**, 244–250, DOI: 10.1016/j.jcou.2019.03.022, URL: <http://www.sciencedirect.com/science/article/pii/S2212982019300216>, ISSN: 2212-9820.
- 337 J. Qiao, Y. Liu and J. Zhang, *Electrochemical reduction of carbon dioxide: fundamentals and technologies*, CRC Press, Boca Raton, 2016.
- 338 D. Knuth, Rapid changes in the ethylene capacity world order, 2019, URL: <https://www.woodmac.com/news/opinion/rapid-changes-in-the-ethylene-capacity-world-order/>, August 2020.
- 339 L. A. Hamilton, et al., *Plastic & Climate: The Hidden Costs of a Plastic Planet*, Center for International Environmental Law (CIEL), 2019.
- 340 D. Méndez-Mateos, V. L. Barrio, J. M. Requies and J. F. Cambra, A study of deactivation by H<sub>2</sub>S and regeneration of a Ni catalyst supported on Al<sub>2</sub>O<sub>3</sub>, during methanation of CO<sub>2</sub>. Effect of the promoters Co, Cr, Fe and Mo, *RSC Adv.*, 2020, **10**(28), 16551–16564.
- 341 X. Zhang, Y. Tang, S. Qu, J. Da and Z. Hao, H<sub>2</sub>S-selective catalytic oxidation: catalysts and processes, *ACS Catal.*, 2015, **5**(2), 1053–1067.
- 342 M. Davidson, C. H. Lawrie and K. Sohail, Kinetics of the absorption of hydrogen sulfide by high purity and doped high surface area zinc oxide, *Ind. Eng. Chem. Res.*, 1995, **34**(9), 2981–2989.
- 343 P. Spath, A. Aden, T. Eggeman, M. Ringer, B. Wallace and J. Jechura, Biomass to hydrogen production detailed



- design and economics utilizing the Battelle Columbus Laboratory indirectly-heated gasifier, Tech. Rep., National Renewable Energy Lab., Golden, CO (US), 2005.
- 344 J. C. Liao, L. Mi, S. Pontrelli and S. Luo, Fuelling the future: microbial engineering for the production of sustainable biofuels, *Nat. Rev. Microbiol.*, 2016, **14**(5), 288–304.
- 345 T. Haas, R. Krause, R. Weber, M. Demler and G. Schmid, Technical photosynthesis involving CO<sub>2</sub> electrolysis and fermentation, *Nat. Catal.*, 2018, **1**(1), 32–39.
- 346 M. Götz, J. Lefebvre, F. Mörs, A. M. Koch, F. Graf, S. Bajohr, R. Reimert and T. Kolb, Renewable Power-to-Gas: A technological and economic review, *Renewable Energy*, 2016, **85**, 1371–1390.
- 347 K. Müller, M. Fleige, F. Rachow and D. Schmeißer, Sabatier based CO<sub>2</sub>-methanation of flue gas emitted by conventional power plants, *Energy Procedia*, 2013, **40**, 240–248.
- 348 Z. Abbas, T. Mezher and M. R. Abu-Zahra, Evaluation of CO<sub>2</sub> purification requirements and the selection of processes for impurities deep removal from the CO<sub>2</sub> product stream, *Energy Procedia*, 2013, **37**, 2389–2396.
- 349 Q. Zheng, S. Zhou, M. Lail and K. Amato, Oxygen removal from oxy-combustion flue gas for CO<sub>2</sub> purification via catalytic methane oxidation, *Ind. Eng. Chem. Res.*, 2018, **57**(6), 1954–1960.
- 350 N. Chambron, A. Darde, R. Dubettier-Grenier and M. Leclerc, *Method and unit for removing oxygen from a gas flow comprising CO<sub>2</sub>*, US Pat., 14/438,309, 2015.
- 351 M. Ramdin, *et al.*, High-Pressure Electrochemical Reduction of CO<sub>2</sub> to Formic Acid/Formate: Effect of pH on the Downstream Separation Process and Economics, *Ind. Eng. Chem. Res.*, 2019, **58**(51), 22718–22740, DOI: 10.1021/acs.iecr.9b03970.
- 352 M. Ramdin, *et al.*, High Pressure Electrochemical Reduction of CO<sub>2</sub> to Formic Acid/Formate: A Comparison between Bipolar Membranes and Cation Exchange Membranes, *Ind. Eng. Chem. Res.*, 2019, **58**(5), 1834–1847, DOI: 10.1021/acs.iecr.8b04944.
- 353 Z. Zhang and D. Huisingsh, Carbon dioxide storage schemes: technology, assessment and deployment, *J. Cleaner Prod.*, 2017, **142**, 1055–1064.
- 354 R. C. Ferguson, C. Nichols, T. V. Leeuwen and V. A. Kuuskraa, Storing CO<sub>2</sub> with enhanced oil recovery, *Energy Procedia*, 2009, **1**(1), 1989–1996, DOI: 10.1016/j.egy-pro.2009.01.259, URL: <http://www.sciencedirect.com/science/article/pii/S1876610209002604>, ISSN: 1876-6102.
- 355 S. Lee and S. Kam, Enhanced Oil Recovery by Using CO<sub>2</sub> Foams: Fundamentals and Field Applications, in *Enhanced Oil Recovery Field Case Studies*, ed. J. J. Sheng, Gulf Professional Publishing, Boston, 2013, ch. 2, pp. 23–61, DOI: 10.1016/B978-0-12-386545-8.00002-6, URL: <http://www.sciencedirect.com/science/article/pii/B9780123865458000-026>, ISBN: 978-0-12-386545-8.
- 356 C. Xu, P. Dowd and Q. Li, Carbon sequestration potential of the Habanero reservoir when carbon dioxide is used as the heat exchange fluid, *J. Rock Mech. Geotech. Eng.*, 2016, **8**(1), 50–59.
- 357 J. Durst, *et al.*, Electrochemical CO<sub>2</sub> reduction—a critical view on fundamentals, materials and applications, *Chimia Int. J. Chem.*, 2015, **69**(12), 769–776.
- 358 L. Brennan and P. Owende, Biofuels from microalgae—A review of technologies for production, processing, and extractions of biofuels and co-products, *Renewable Sustainable Energy Rev.*, 2010, **14**(2), 557–577, DOI: 10.1016/j.rser.2009.10.009, URL: <http://www.sciencedirect.com/science/article/pii/S1364032109002408>, ISSN: 1364-0321.
- 359 P. Styring, D. Jansen, H. De Coninck, H. Reith and K. Armstrong, *Carbon Capture and Utilisation in the green economy*, Centre for Low Carbon Futures, New York, 2011.
- 360 K. Michael, A. Golab, V. Shulakova, J. Ennis-King, G. Allinson, S. Sharma and T. Aiken, Geological storage of CO<sub>2</sub> in saline aquifers—A review of the experience from existing storage operations, *Int. J. Greenhouse Gas Control*, 2010, **4**(4), 659–667, DOI: 10.1016/j.ijggc.2009.12.011, URL: <http://www.sciencedirect.com/science/article/pii/S175058361000071> ISSN: 1750-5836.
- 361 F. Yang, B. Bai, D. Tang, D.-N. Shari and W. David, Characteristics of CO<sub>2</sub> sequestration in saline aquifers, *Pet. Sci.*, 2010, **7**(1), 83–92, DOI: 10.1007/s12182-010-0010-3, ISSN: 1995-8226.
- 362 K. Asghari, A. Al-Dliwe and N. Mahinpey, Effect of Operational Parameters on Carbon Dioxide Storage Capacity in a Heterogeneous Oil Reservoir: A Case Study, *Ind. Eng. Chem. Res.*, 2006, **45**(8), 2452–2456, DOI: 10.1021/ie050572y.
- 363 G. C. Institute, Global status of CCS 2019, 2019, URL: <https://www.globalccsinstitute.com/resources/global-status-report/>.
- 364 R. G. Grim, Z. Huang, M. T. Guarnieri, J. R. Ferrell, L. Tao and J. A. Schaidle, Transforming the carbon economy: challenges and opportunities in the convergence of low-cost electricity and reductive CO<sub>2</sub> utilization, *Energy Environ. Sci.*, 2020, **13**, 472–494, DOI: 10.1039/C9EE02410G.
- 365 A. Sanna, M. Uibu, G. Caramanna, R. Kuusik and M. M. Maroto-Valer, A review of mineral carbonation technologies to sequester CO<sub>2</sub>, *Chem. Soc. Rev.*, 2014, **43**, 8049–8080, DOI: 10.1039/C4CS00035H.
- 366 B. Smit, J. A. Reimer, C. M. Oldenburg and I. C. Bourg, *Introduction to Carbon Capture and Sequestration*, Imperial College Press, 2014, DOI: 10.1142/p911, URL: <https://www.worldscientific.com/doi/abs/10.1142/p911>.

