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Techno-economic feasibility assessment of CO_2 capture from coal-fired power plants using molecularly imprinted polymer

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ABSTRACT

Mature CO_2 capture technologies would reduce the net thermal efficiency of the coal-fired power plant by 7–13% points, leading to an electricity cost increase of at least 60%. To minimise the energy-intensity of CO_2 capture, novel technologies and CO_2 capture materials are being developed. This study assessed the techno-economic feasibility of the CO_2 capture system using acrylamide-based molecularly imprinted polymer (MIP) sorbent in a 580 MW_{el} coal-fired power plant retrofit scenario. Under the initial design basis, the net efficiency penalty and the energy penalty of the MIP retrofit scenario were estimated to be 5.3%$_{HHV}$ points and 14.1%, respectively. Furthermore, the cost of CO_2 avoided was estimated to be 29.3 £/tCO_2. Such techno-economic performance was found to be superior to the CO_2 capture system using chemical solvents. The parametric study revealed that the thermodynamic performance of the MIP retrofit scenario is mainly affected by the sorbent capacity, as the net efficiency penalty was found to increase from 4.4 to 8.9%$_{HHV}$ points on reduction of the sorbent capacity from 1 to 0.2 mmol CO_2/g. Moreover, the economic performance was not only found to be affected by sorbent capacity, but primarily on the cyclic performance of the MIP sorbent. It was shown that the cost of CO_2 avoided would increase linearly with increase of the MIP sorbent make-up at a rate of 6.8 £/tCO_2 per 0.1% of sorbent make-up.

1. Introduction

Carbon capture and storage (CCS) is expected to play a pivotal role in the reduction of greenhouse gas emissions from the power sector and is expected to result in a 13% cumulative reduction of CO_2 emission between 2012 and 2050 [1,2]. However, rapid development and demonstration of CCS technologies are required if they are to be deployed after 2020 to meet 2DS objectives [3]. Unfortunately, a first-of-a-kind large-scale demonstration plant retrofitted to the coal-fired power plant was only commissioned in 2014 [4]. A main challenge that keeps CCS from large-scale deployment in the power sector is its considerable capital and operating cost that would affect the cost of electricity.

The post-combustion technologies are claimed to have a large potential for decarbonising the power sector in the short- to mid-term, as they can be both easily retrofitted to the existing power plant fleet and integrated to new greenfield systems [5–8]. Thus far, chemical solvent scrubbing has been perceived as the technology of choice for decarbonisation of coal-fired power plants [5–11]. Yet, retrofit of this technology to coal-fired power plants was shown to impose a net thermal efficiency penalty of 7–13% points [12,13], which is expected to cause an increase in the cost of electricity by at least 60% [14–18]. Although other CO_2 capture and separation technologies, such as adsorption or membrane separation, have been successfully implemented in other industries, these have thus far not been considered efficient options for coal-fired power plants due to high impurities content and low CO_2 concentration in, and atmospheric pressure of, flue gas [7,8,11]. Yet, the recent progress in development of these technologies indicates that other technologies could result in lower parasitic load on the power plant performance compared to chemical solvent absorption, and thus may bring higher improvements to the economics of CCS.

As opposed to the absorption process, in which CO_2 molecules dissolve in the bulk of the solvent, adsorption of CO_2 takes place at the surface of a solid sorbent. This is typically conducted in a fixed or fluidised bed reactor using zeolites, activated carbon, metal oxides or alumina, as well as new materials, such as functionalised amine-based sorbents, metal-organic frameworks, and polymer-based sorbents [13,19–23]. Compared to chemical solvents, such as monoethanolamine, solid sorbents are neither corrosive nor toxic, and are characterised by the need for lower regeneration energy [20,22,24]. The last quality makes these materials attractive for CO_2 capture from

Abbreviations: CCS, Carbon capture and storage; MEA, Monoethanolamine; MIP, Molecularly imprinted polymer

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Nomenclature

Parameters

AC	Cost of CO_2 avoided (£/tCO_2)
a	Turbine design parameter (–)
CF	Capacity factor (–)
e_{CO_2}	Specific CO_2 emission (g CO_2/kW_{el}h)
FC	Fuel cost (£)
FCF	Fixed charge factor (–)
FOM	Fixed operating and maintenance cost (£)
$LCOE$	Levelised cost of electricity (£/MW_{el}h)
$\dot{m}$	Mass flow rate (kg/s)
n	Adiabatic index (–)
p	Steam pressure (bar)
$\dot{Q}_{fuel}$	Heat input from fuel combustion (MW_{th})
SCF	Specific fuel cost (£/MW_{el}h)
TCR	Total capital requirement (£)
VOM	Variable operating and maintenance cost (£/MW_{el}h)
$\dot{W}_{net}$	Net power output (MW_{el})
v	Velocity (m/s)
ρ	Density (kg/m^3)
η_i	Isentropic efficiency (–)
η_{th}	Net thermal efficiency (–)

Superscripts

0	Parameter at design conditions

Subscripts

capture	Corresponds to coal-fired power plant with CO_2 capture
in	Stream parameter at inlet to the unit operation
out	Stream parameter at outlet from the unit operation
ref	Corresponds to reference coal-fired power plant

coal-fired power plants, as they have the potential to reduce the energy-intensity associated with CO_2 capture.

Integration of the vacuum-swing adsorption process (adsorption at 2 bar, regeneration at 0.1 bar) using Zeolite 13X, which is the most popular adsorbent [20], as the post-combustion CO_2 capture plant to an ultra-supercritical coal-fired power plant was found to impose a net thermal efficiency penalty of 10.3% points [25]. This was found to be 0.6% lower than for chemical solvent scrubbing using mono-ethanolamine (MEA). A similar conclusion can be drawn when analysing performance of the temperature-swing adsorption process using dry sodium carbonate, in which CO_2 was adsorbed at about 55 °C and regenerated at about 140 °C. Namely, the net efficiency penalty of such process on integration to a supercritical coal-fired power plant was found to be 7.1–9.9% points, which was 1.9–4.5% points lower compared to chemical solvent scrubbing using MEA [26]. Furthermore, the use of metal oxides, such as calcium oxide, in high-temperature solid looping temperature cycles is regarded as an emerging CO_2 capture technology suitable for decarbonisation of coal-fired power plants [12,20,27]. In this temperature-swing adsorption process, CO_2 is adsorbed by the sorbent at 600–650 °C and reclaimed through sorbent regeneration at temperatures higher than 900 °C. It has been reported that depending on the operating conditions and the steam conditions in the reference coal-fired power plant, the net efficiency penalty associated with this technology is expected to be between 3 and 8% points [28–35]. Finally, retrofit of the temperature-swing adsorption system using novel materials, such as amine-based sorbent or metal organic frameworks, was shown to impose net efficiency penalties of 10% points and 7% points, respectively [36]. This performance was found to be competitive compared to the advanced chemical solvent scrubbing (Econamine FG +) process, for which the efficiency penalty was estimated to be 11% points.

Although the adsorption processes using solid sorbents were shown to impose lower net efficiency penalties on retrofit to coal-fired power plants, there are several issues that may degrade their performance. Namely, the presence of moisture and impurities, such as NO_x and SO_x, in flue gas can dramatically degrade the capture capacity of zeolites and metal organic frameworks [13,37,38]. Also, calcium-based sorbents are prone to react with SO_x [39,40] and their cyclic performance needs to be improved prior to large-scale deployment [20,40]. Carbonaceous materials are characterised by low sensitivity to moisture and flue gas impurities [19], but their CO_2 adsorption capacity is affected by low CO_2 partial pressure in the flue gas [19,41]. On the other hand, polymer-based materials, such as acrylamide-based molecularly imprinted polymer (MIP) particles, porous aromatic frameworks, hypercrosslinked polymers, and covalent organic polymers, have been shown to have high selectivity and CO_2 uptake, as well as high hydrothermal stability [22,23,42–44]. The MIP particles, which are polymers with template-shaped cavities within their matrix to enable molecular recognition towards specific target molecule [23,45], were also shown to be insensitive to moisture, SO_x, NO_x and O_2 present in the flue gas [46,47]. As the MIP sorbent was shown to be a suitable material for fixed and fluidised bed systems [23,48], this study is conducted to assess the techno-economic feasibility of a CO_2 capture system using MIP sorbent in a 580 MW_{el} coal-fired power plant retrofit scenario.

2. Model development

2.1. Supercritical coal-fired power plant

The 580 MW_{el} supercritical coal-fired power plant was used in this study as a reference system. The process model of this unit, which has previously been developed in Aspen Plus® [49,50] based on the revised NETL report [51], comprises three sub-models: supercritical boiler, flue gas treatment train (NO_x, SO_x and fly ash), both modelled using the Peng-Robinson-Boston-Mathias equation of state, and steam cycle represented by STEAMNBS steam tables. The boiler heat exchange sections, which include the primary, secondary, and reheat superheaters, as well as the economiser, were modelled using pressure drops and temperature levels set based on the revised NETL report [51]. Both the live (242.3 bar) and reheat steam generated in these sections were assumed to leave the boiler at the temperature of 593.3 °C. Steam turbines were modelled as individual turbine sections, hence the high-, intermediate-, and low-pressure cylinders were further divided into the required steam turbine sections. The condenser was assumed to operate at a fixed pressure of 0.069 bar, which corresponds to a condensation temperature of 38.7 °C. The feedwater heating train comprised five LP feedwater heaters including the deaerator, and three surface HP feedwater heaters. At design conditions, the feedwater heaters were characterised by the terminal temperature difference of 2.78 °C and the minimal temperature difference between subcooled condensate and inlet feedwater of 5.56 °C. The key performance parameters of the model are provided in Table 1. The prediction accuracy of this model was compared with data from a revised NETL report [51] and was shown to closely represent both the process stream data (temperature, pressure, mass flow rate) and the thermodynamic performance (gross power output, net thermal efficiency) of the coal-fired power plant [49,50].

The MIP sorbent needs to be preheated to 80 °C to reclaim CO_2. The configuration investigated in this study assumes that the heat for sorbent regeneration is provided by direct contact with steam extracted

Table 1
Supercritical coal-fired power plant key performance parameters.

Parameter	Value
Gross power output (MW_{el})	580.4
Net power output (MW_{el})	552.7
Net thermal efficiency ($\%_{HHV}$)	38.5
Flue gas stream (kg/s)	617.2
CO_2 content in flue gas ($\%_{vol}$)	15.2
Coal consumption rate (kg/s)	53.8
Air consumption rate (kg/s)	526.5
Live steam generation rate (kg/s)	462.3
Excess air ratio ($\%_{vol}$)	20.0
Live steam pressure (bar)	242.3
Reheated steam pressure (bar)	45.2
Intermediate-/low-pressure crossover pipe pressure (bar)	9.3
Condenser pressure (bar)	0.069
Live and reheated steam temperature (°C)	593.3
Mechanical efficiency of the rotational machinery (%)	99.0

from the steam cycle. This is because extraction of steam was found to be the most efficient option for providing heat for solvent regeneration in mature chemical solvent scrubbing systems [44]. Moreover, the process configuration based on a dual intermediate/low-pressure crossover pressure system with heat integration [50] is adopted in this study, as it allows reducing the steam pressure and temperature to the values required for MIP sorbent regeneration while reducing the impact of steam extraction on the coal-fired power plant performance (Fig. 1).

As reported for the chemical solvent scrubbing retrofit scenarios [50,52], extraction of steam from the steam cycle results in off-design operation of the low-pressure turbine. This results in the loss of power output not only as a result of reduced low-pressure turbine throughput, but also due to a loss in the inlet pressure to this turbine cylinder. As the condenser pressure is assumed to be fixed at 0.069 bar, pressure gradients across a turbine section are determined using Stodola's ellipse law presented in Eq. (1) [45–47] to determine the inlet pressure in a back-to-front manner.

$$\frac{\dot{m}_{in}}{\dot{m}^0_{in}} = \frac{p_{in}}{p^0_{in}} \cdot \sqrt{\frac{p^0_{in} \cdot \rho_{in}}{p_{in} \cdot \rho^0_{in}}} \cdot \sqrt{\frac{1-\left(\frac{p_{out}}{p_{in}}\right)^{\frac{n+1}{n}}}{1-\left(\frac{p^0_{out}}{p^0_{in}}\right)^{\frac{n+1}{n}}}} \tag{1}$$

Importantly, a drop in the steam pressure downstream of the extraction point causes an increase in the steam velocity. As a result, the kinetic energy at the inlet to the low-pressure turbine increases. With further increase in the steam kinetic energy on expansion in the low-pressure turbine stages, the turbine discharge loss is expected to increase compared to the figure under design conditions. This, in turn, would affect the isentropic efficiency of the low-pressure turbine and could cause operational issues, such as vibration of the last stage moving blades [48]. Therefore, the isentropic efficiency is updated using Eq. (2), which is based on the approach used by Salisbury [49] and Knopf [46] assuming that each turbine section reaches its optimal performance at design conditions and comprises 50% reaction blading (a = 0.7071).

$$\frac{\eta_i}{\eta^0_i} \cong 2\frac{a}{\frac{V^0_{in}}{V_{in}}} \cdot \left[\left(a - \frac{a}{\frac{V^0_{in}}{V_{in}}}\right) + \sqrt{\left(a - \frac{a}{\frac{V^0_{in}}{V_{in}}}\right)^2 + 1 - a^2}\right] \tag{2}$$

2.2. CO_2 capture system using molecularly imprinted polymer sorbent

The process considered in this study utilises MIP sorbent as a CO_2 capture sorbent (Fig. 2), the characteristics of which are listed in Table 2, and comprises two interconnected fluidised beds with assumed pressure drop of 200 mbar. To ensure favourable operating conditions in the adsorber, which is modelled as a conversion reactor, flue gas from the coal-fired power plant is cooled in the direct contact cooler to 40 °C. The flash calculations are performed using the Rachford-Rice equation [53] and the process streams are characterised using the Peng Robinson equation of state.

Conversion of the MIP sorbent in the adsorber is determined using its nominal capacity and the assumed adsorption extent of 70%, which

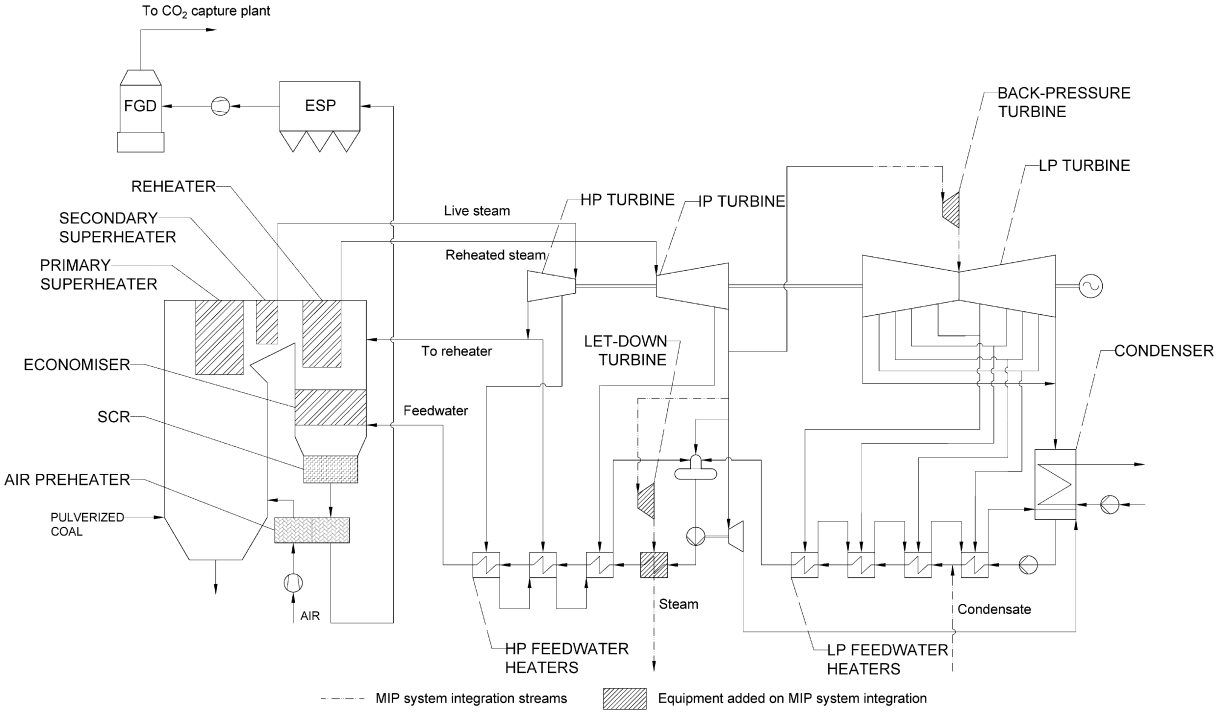


Fig. 1. Process flow diagram of reference supercritical coal-fired power plant.

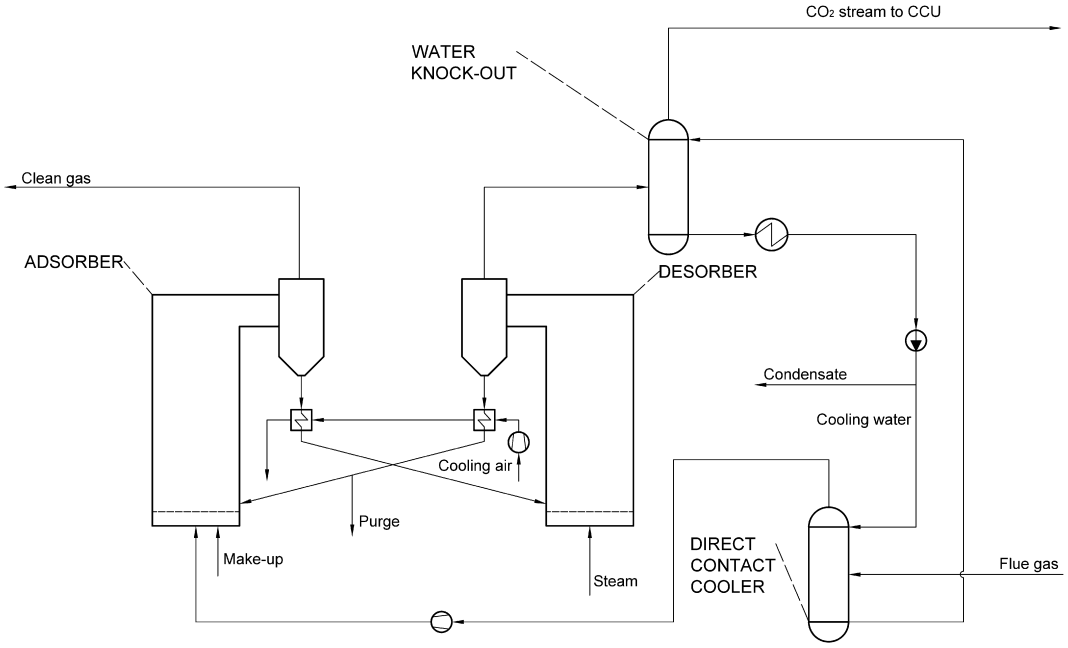


Fig. 2. Process flow diagram of the CO_2 capture system using acrylamide-based molecularly imprinted polymer sorbent.

Table 2
Properties of acrylamide-based molecularly imprinted polymer sorbent.[1]

Property	Value
Heat of adsorption (kJ/mol CO_2)	31.2
Sorbent capacity (mmol CO_2/g)	0.56
Sorbent heat capacity (kJ/kg K)	0.95–1.53[2]

[1] The properties of acrylamide-based molecularly imprinted polymer material were provided by the CoERcE project partner and are not yet available in the open literature.

[2] The heat capacity of the MIP sorbent is given by $Cp = 94.437 \times (T - 273.15)^{0.5882}$ within the temperature range of 50–120 °C.

is commonly made for other CO_2 capture systems comprising fluidised beds, such as calcium looping [12,54]. In addition, the amount of the sorbent fed to the adsorber is determined to ensure a CO_2 capture level of 90%. The CO_2-rich sorbent is then heated using air preheated by the lean sorbent leaving the desorber. This aims at reduction of the heat requirements of the process by minimising the amount of waste heat in the CO_2 capture plant. CO_2 is then reclaimed from the preheated CO_2-rich sorbent on its further heating to 80 °C in the desorber, which is also modelled as a conversion reactor with the assumption that the conversion of sorbent is complete. The heat requirement for the sorbent regeneration is met by direct contact of CO_2-rich MIP sorbent and steam extracted from the steam cycle. CO_2 is then separated from water vapour on cooling in the water knock-out tower, which is modelled using the same approach as a direct contact cooler, and sent to the CO_2 compression unit. Part of the condensed water is returned to the steam cycle to balance the amount of steam extracted from the intermediate/low-pressure crossover pipe. The CO_2 compression unit comprises nine intercooled compression stages, each of which was modelled as a polytropic compression stage with a stage efficiency of 78–80% [7,55], and the pressure ratio and polytropic head not exceeding 3 and 3050 m, respectively [56]. It is assumed that the CO_2 delivery pressure of 110 bar [57] is achieved by a CO_2 pump, which is characterised with an isentropic efficiency of 80%.

3. Process performance evaluation

3.1. Considerations

Having linked the coal-fired power plant and the CO_2 capture system using MIP sorbent (MIP retrofit scenario), the thermodynamic performance is evaluated using the system's net power output ($\dot{W}_{net}$) and net thermal efficiency (η_{th}), which is defined in Eq. (3) as the ratio of the net power output and the heat input from fuel combustion ($\dot{Q}_{fuel}$). In addition, environmental performance of the MIP retrofit scenario is represented in Eq. (4) as the specific CO_2 emissions (e_{CO2}), defined as the ratio of CO_2 emission rate ($\dot{m}_{CO2}$) and the net power output. This parameter is commonly used to characterise the environmental performance of the fossil fuel power generation systems [58–62].

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{fuel}} \tag{3}$$

$$e_{CO_2} = \frac{\dot{m}_{CO_2}}{\dot{W}_{net}} \tag{4}$$

The economic performance of the proposed system is compared with the reference coal-fired power plant without CO_2 capture using the levelised cost of electricity (*LCOE*) and the cost of CO_2 avoided (*AC*) that are calculated according to Eq. (5) and Eq. (6) [32,63,64], respectively.

$$LCOE = \frac{TCR \times FCF + FOM}{\dot{W}_{net} \times CF \times 8760} + VOM + \frac{SFC}{\eta_{th}} \tag{5}$$

$$AC = \frac{LCOE_{capture} - LCOE_{ref}}{e_{CO_2,ref} - e_{CO_2,capture}} \tag{6}$$

These parameters correlate thermodynamic performance indicators, such as net power output, net thermal efficiency (η_{th}), capacity factor (*CF*) and specific emissions (e_{CO2}), with economic performance, such as total capital requirement (*TCR*), variable (*VOM*) and fixed (*FOM*) operating and maintenance costs, specific fuel cost (*SFC*), and the fixed charge factor (*FCF*), which considers the system's lifetime and project interest rate.

The capital cost of the coal-fired power plant and the key equipment in the CO_2 capture system, such as direct contact cooler and water

Table 3
Key economic model assumptions.

Parameter	Value
Variable cost as a fraction of total capital cost (%) [32,67]	2.0
Fixed cost as a fraction of total capital cost (%) [32,67]	1.0
CO_2 transport and storage cost (£/tCO_2) [68]	7.0
Coal price (£/t) [67,69]	1.5
Expected lifetime (years) [32,67]	25
Project interest rate (%) [32,67]	8.78
Capacity factor (%) [32,67]	80
Tax, freight, insurance cost (% of free-on-board supplier cost) [66]	20
Offsites, indirect costs for home office and field expenses (% of labour and material cost including free-on-board supplier cost, freight, delivery, duties and instruments) [66]	30
Contractors fees (% of bare module cost) [66]	4
Project contingency (% of bare module cost) [66]	15
Design contingency (% of bare module cost) [66]	20

knock-out, pumps and fans, adsorber, desorber, heat exchangers and CO_2 compression unit, are determined using the exponential method function [65] with economic data gathered from NETL [51] and Woods [66]. Moreover, fixed and variable operating and maintenance costs are calculated as a fraction of total capital cost, while operating costs associated with fuel consumption, and CO_2 storage, transport and emission are determined based on process simulation outputs using economic data from Table 3.

The techno-economic assessment of the MIP retrofit scenario is first evaluated under the initial design basis using the sorbent characteristics presented in Table 2 and with the assumption that there is no sorbent degradation over multiple cycles; hence no purge is considered in the initial assessment. Moreover, due to lack of information on the MIP sorbent cost, which is, however, widely referred to as being lower compared to other adsorbents for other applications [70], the initial cost of sorbent is assumed to be 100 £/t. This is of the same order of magnitude as synthetic calcium-based sorbents [71]. Nevertheless, considering the uncertainty of the sorbent characteristics, the sensitivity of the key techno-economic performance indicators to variation in the sorbent cyclic performance, adsorption capacity, and specific cost is assessed by varying the MIP sorbent:

- make-up rate between 0 and 1.5%;
- adsorption capacity between 0.2 and 1 mmol CO_2/g;
- specific cost between 50 and 5000 £/t.

3.2. Techno-economic performance evaluation

Retrofit of the CO_2 capture system using MIP sorbent to the 580 MW_{el} coal-fired power plant was found to impose a net efficiency penalty of 5.3%$_{HHV}$ points and to result in an energy penalty of 14.1% (Table 4). In addition, the specific coal consumption was found to increase by 16.4%. Such thermodynamic performance is comparable to the performance of calcium looping with a supercritical CO_2 cycle retrofitted to the same reference coal-fired power plant, which resulted in a net efficiency penalty of 5.8%$_{HHV}$ points and 17.1% increase in the specific coal consumption [35]. Yet, reduction in the net power output in the MIP retrofit scenario can be expected to result in lower revenue from the electricity sales compared to the calcium looping retrofit scenario, which resulted in an increase of the system's net power output by about 45% [35]. Nevertheless, the performance of the MIP retrofit scenario compares favourably with the CO_2 capture systems using chemical solvents, such as MEA or chilled ammonia scrubbing. Retrofits of these systems to the same reference coal-fired power plant resulted in net efficiency penalties of 9.5 and 9% points, and energy penalties of 24.7 and 23.3%, respectively [34,50]. The specific coal consumption increased in these retrofit scenarios by 32.8 and 30.3%, respectively.

Table 4
Summary of techno-economic performance indicators.

Parameter	Reference coal-fired power plant	MIP retrofit scenario
Thermodynamic performance indicators		
Heat input from coal combustion (MW_{th})	1452.6	1452.6
Gross power output (MW_{el})	580.4	545.5
Auxiliary power requirement (MW_{el})	27.7	70.7
Net power output (MW_{el})	552.7	474.8
Gross thermal efficiency (%$_{HHV}$)	40.4	37.6
Net thermal efficiency (%$_{HHV}$)	38.0	32.7
Specific coal consumption (g/kW_{el}h)	350.3	407.7
Specific CO_2 emission (g/kW_{el}h)	786.8	92.2
Net energy penalty (%)	–	14.1
Net efficiency penalty (%$_{HHV}$ points)	–	5.3
Increase in specific coal consumption (%)	–	16.4
Economic performance indicators		
Specific capital cost (£/$kW_{el,gross}$)	1161.3	1648.1
Levelised cost of electricity (£/MW_{el}h)	36.9	57.5
CO_2 avoided cost (£/tCO_2)	–	29.3

Therefore, the MIP retrofit scenario has the potential to significantly reduce the impact of the CO_2 capture system on the performance of coal-fired power plants.

The analysis of the energy requirement of the CO_2 capture system using MIP sorbent revealed that the parasitic load arises primarily from the CO_2 compression unit (Fig. 3). This is because the heat requirement for MIP sorbent regeneration (226.7 MW_{th}) was found to be only 44% of the heat requirement in the amine scrubbing system (513.6 MW_{th}). Such reduction in the heat requirement can be associated with 1.15–3 times lower heat of adsorption of the MIP sorbent compared to the heat of absorption of the MEA solvent within the same operating temperature envelope (40–80 °C) [72]. Moreover, this is reflected in the specific heat requirement of the MIP sorbent (2.0 MJ_{th}/kg CO_2 at a sorbent capacity of 0.56 mmol CO_2/g) that was found to be comparable to the specific heat requirement reported for the following solvents: Cansolv (2.33 MJ_{th}/kg CO_2), K_2CO_3 (2–2.5 MJ_{th}/kg CO_2), Econamine FG+ (3.12 MJ_{th}/kg CO_2), and MDEA-PZ (2.52 MJ_{th}/kg CO_2) [73]. As a result, the steam extraction accounted only for 33% of the parasitic load in the MIP retrofit scenario (Fig. 3), as opposed to about 60% in the chemical solvent scrubbing retrofit scenarios [34].

The economic assessment (Table 4) revealed that retrofit of the CO_2 capture system using MIP sorbent will result in an increase of the specific capital cost of the entire system by 41.9% (486.8 £/$kW_{el,gross}$) compared to the specific capital cost of the reference coal-fired power plant. Such an increase in the specific capital cost, along with reduction in the net thermal efficiency, resulted in 55.8% increase in the levelised cost of electricity (LCOE) from 36.9 to 57.5 £/MW_{el}h. This corresponds to the cost of CO_2 avoided (AC) of 29.3 £/tCO_2. Importantly, the key economic indicators for the MIP retrofit scenario fall within the ranges reported previously for coal-fired power plants retrofitted with CO_2 capture systems using chemical solvents (LCOE = 55–60 £/MW_{el}h; AC = 30–75 £/tCO_2 [74–77]) and with calcium looping (LCOE = 25.8–116.7 £/MW_{el}h, AC = 7–87.5 £/tCO_2 [28,32,63,69,78–80]). Therefore, considering lower impact on the thermodynamic performance of the reference coal-fired power plant, the MIP retrofit scenario can be expected to bring higher profit from the electricity sales compared to the chemical solvent scrubbing retrofit scenarios.

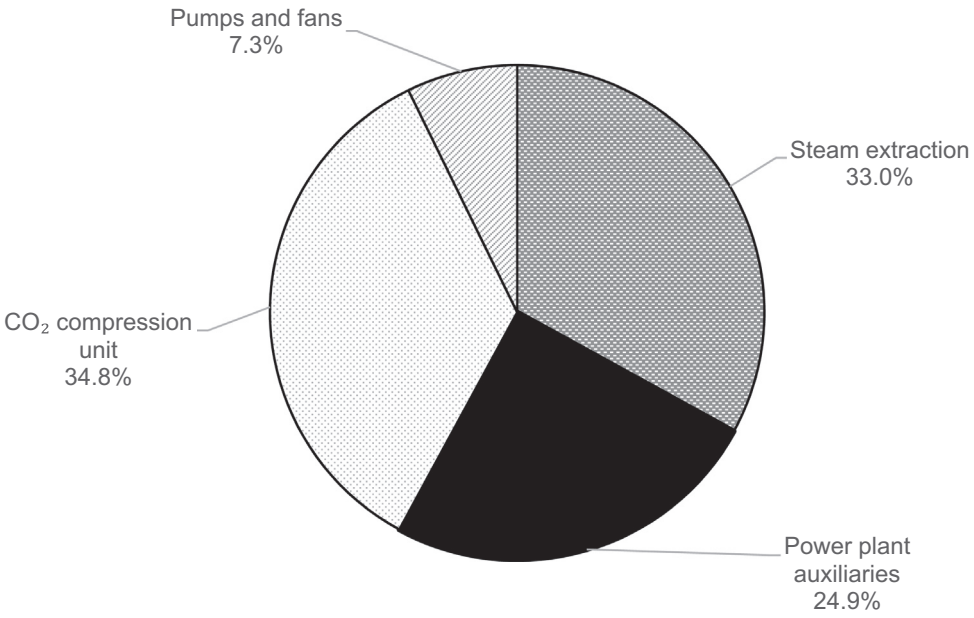


Fig. 3. Distribution of the parasitic load in the MIP retrofit scenario.

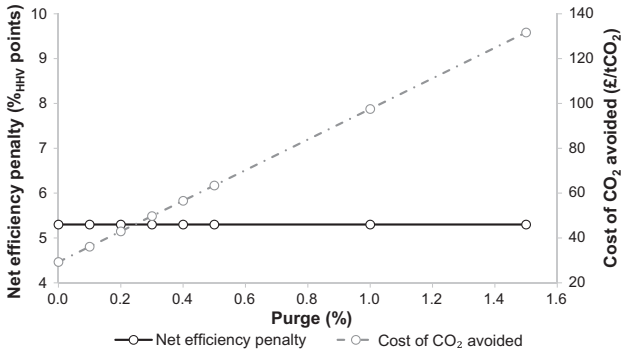


Fig. 4. Effect of MIP sorbent make-up rate on the key techno-economic performance indicators.

3.3. Parametric study

Further to evaluating performance of the MIP retrofit scenario under the initial design basis, it is important to assess the effects of uncertainty in the sorbent characteristics on the system's performance. As shown in Fig. 4, increasing the amount of fresh MIP sorbent fed to the system did not have an effect on the net efficiency penalty of the retrofitted system. The main reason behind such performance is the low temperature difference between the MIP sorbent purged from (40 °C), and the fresh MIP sorbent fed to (25 °C), the system that results in a very small increase (0.025%) of the steam requirement in the desorber.

Nevertheless, increasing the MIP sorbent make-up rate was found to deteriorate the economic performance of the retrofitted system. Namely, the cost of CO_2 avoided would increase linearly with increasing MIP sorbent make-up at a rate of 6.8 £/tCO_2 per 0.1% of sorbent make-up[1] (Fig. 4). This implies that the CO_2 avoided cost would increase to 36.1 £/tCO_2 and 63.4 £/tCO_2 for MIP sorbent make-up rates of 0.1% and 0.5%, respectively, which is comparable to the figures reported for coal-fired power plant retrofits with CO_2 capture systems using chemical solvents [74–77] and calcium looping [28,32,63,69,78–80] (Fig. 5a). Thus for higher values of MIP sorbent make up rate, the MIP retrofit scenario would become less economically favoured over mature CO_2 capture technologies.

Conversely to the make-up rate, the adsorption capacity of the MIP sorbent has a significant effect on both thermodynamic and economic performance of the MIP retrofit scenario. Fig. 6 shows that the net efficiency penalty could be reduced to 4.4%$_{HHV}$ points, if the sorbent capacity increased to 1 mmol CO_2/g. Interestingly, such sorbent capacity corresponds to the theoretical lime conversion in the calcium looping process of 5.6%, which is slightly below the residual value of the limestone sorbent (7–12%) [81]. On the other hand, for a sorbent capacity of 0.2 mmol CO_2/g, the net efficiency penalty increases sharply to 8.9%$_{HHV}$ points, which is comparable to the figures reported for other CO_2 capture technologies (Fig. 5b). This is due to the higher amount of sorbent that needs to be circulated in the system to achieve the desired CO_2 capture level of 90%, and thus increased heat requirement associated with the sensible heat of the sorbent entering the desorber. Importantly, the contribution of the sensible heat to the total heat requirement for MIP sorbent regeneration was found to reduce from 87% to 67% on increase of the sorbent capacity from 0.2 to 1 mmol CO_2/g. Nevertheless, increase in the net efficiency penalty for lower sorbent capacities was found to bring a subsequent increase in the cost of CO_2 avoided, which was estimated to be 50 £/tCO_2 for a sorbent capacity of 0.2 mmol CO_2/g and sorbent cost of 100 £/t. Upon increasing the sorbent capacity to 1 mmol CO_2/g, the cost of CO_2 avoided was found to reduce only by 3.7 £/tCO_2 compared to the value estimated under the initial design basis. Importantly, the economic performance of the MIP retrofit scenario was found to be linearly dependent upon the specific cost of the MIP sorbent. The cost of CO_2 avoided was found to be only marginally affected if the MIP sorbent cost is below 500 £/t, as its variation is not higher than 5% with respect to the values estimated using the initial sorbent cost of 100 £/t (Fig. 6). However, if the MIP sorbent cost increases to 5000 £/t, the cost of CO_2 avoided would increase by 40–65%, from 29.3 to 42–69.3 £/tCO_2, depending on the sorbent capacity. For this reason, the MIP sorbent needs to be further tested in order to quantify its cyclic performance, adsorption capacity under different operating conditions and sorbent cost. Moreover, the potential correlation between sorbent cost and adsorption capacity needs to be assessed.

4. Conclusions

This study assessed the techno-economic feasibility of the CO_2 capture system using MIP sorbent in a 580 MW_{el} supercritical coal-fired

[1] The percent of MIP material make-up is defined as the mass flow rate ratio of the MIP material make-up and the MIP material directed from the desorber to the adsorber.

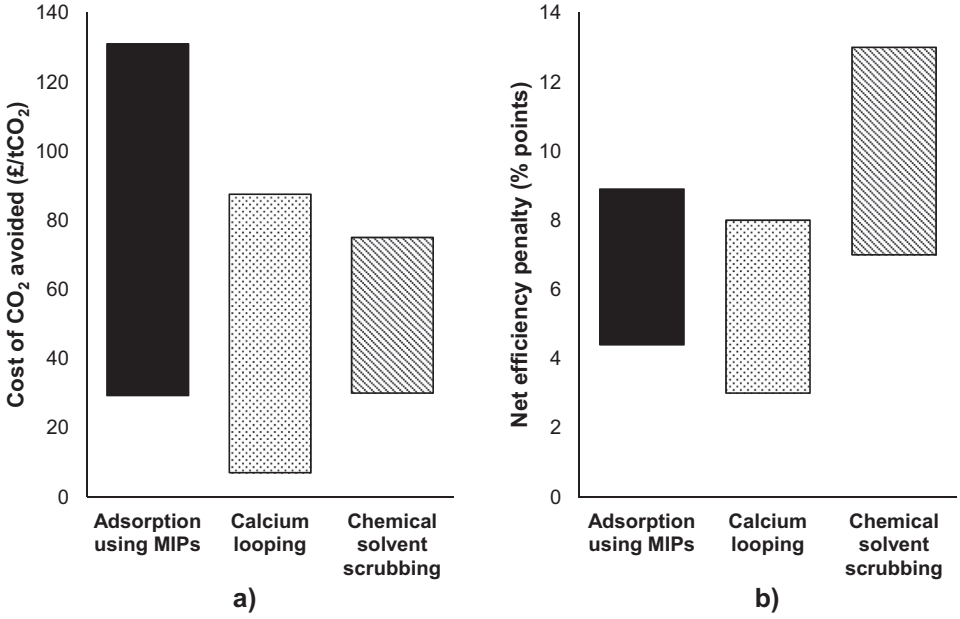


Fig. 5. Comparison of a) economic and b) thermodynamic performance of MIP retrofit scenario with calcium looping and chemical solvent scrubbing retrofits.

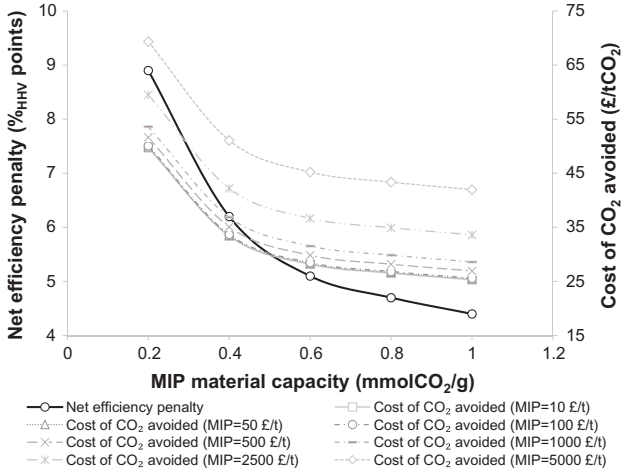


Fig. 6. Effect of MIP sorbent capacity and sorbent cost on the key techno-economic performance indicators.

power plant retrofit scenario. Under the initial design basis, the net efficiency penalty and the energy penalty of the MIP retrofit scenario were estimated to be 5.3%$_{HHV}$ points and 14.1%, respectively. Such thermodynamic performance was found to be superior to CO_2 capture systems using chemical solvents, such as MEA or chilled ammonia, retrofitted to the same reference coal-fired power plant. The specific heat requirement of the MIP sorbent (2.0 MJ_{th}/kg CO_2 at a sorbent capacity of 0.56 mmol CO_2/g) was found to be comparable to advanced CO_2 capture materials. Furthermore, the cost of CO_2 avoided for the MIP retrofit scenario was estimated to be 29.3 £/tCO_2, and fell within the lower end of the range reported for coal-fired power plants retrofitted with CO_2 capture systems using chemical solvents. To account for the uncertainty in the MIP sorbent characteristics, a parametric study was conducted. It was found that the thermodynamic performance of the MIP retrofit scenario is mainly affected by the sorbent capacity, as the net efficiency penalty was found to increase from 4.4 to 8.9%$_{HHV}$ points on reduction of the sorbent capacity from 1 to 0.2 mmol CO_2/g. Moreover, the economic performance was shown to be not only dependent upon sorbent capacity, but primarily on the cyclic performance of the MIP sorbent. This study revealed that the cost of CO_2 avoided would increase linearly with increasing MIP sorbent make-up at a rate of 6.8 £/tCO_2 per 0.1% of sorbent make-up. To reduce the uncertainty associated with this material, the MIP sorbent needs to be further tested in order to quantify its cyclic performance, adsorption capacity under different operating conditions and sorbent cost. Moreover, the potential correlation between sorbent cost and adsorption capacity needs to be assessed.

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References

[1] IEA. Carbon capture and storage: the solution for deep emissions reductions. Paris, France: IEA Publications; 2015.
[2] IEA. Energy technology perspectives 2015. Paris, France: IEA Publications; 2015.
[3] IEA. Energy technology perspectives 2010: scenarios & strategies to 2050. Paris, France: IEA Publications; 2010.
[4] Stéphenne K. Start-up of world's first commercial post-combustion coal fired CCS project: contribution of Shell Cansolv to Saskpower Boundary Dam ICCS project. Energy Procedia 2014;63:6106–10. http://dx.doi.org/10.1016/j.egypro.2014.11.642.
[5] Rackley SA. Carbon capture and storage. Burlington, USA: Elsevier; 2010.
[6] Oexmann J, Kather A, Linnenberg S, Liebenthal U. Post-combustion CO_2 capture: chemical absorption processes in coal-fired steam power plants. Greenhouse Gases Sci Technol 2012;2:80–98. http://dx.doi.org/10.1002/ghg.1273.
[7] Pfaff I, Oexmann J, Kather A. Optimised integration of post-combustion CO_2 capture process in greenfield power plants. Energy 2010;35:4030–41. doi:j.energy.2010.06.004.
[8] Strube R, Manfrida G. CO_2 capture in coal-fired power plants – impact on plant performance. Int J Greenhouse Gas Control 2011;5:710–26. http://dx.doi.org/10.1016/j.ijggc.2011.01.008.
[9] Mac Dowell N, Florin N, Buchard A, Hallett J, Galindo A, Jackson G, et al. An overview of CO_2 capture technologies. Energy Environ Sci 2010;3:1645. http://dx.doi.org/10.1039/c004106h.
[10] Blamey J, Anthony EJ, Wang J, Fennell PS. The calcium looping cycle for large-scale CO_2 capture. Prog Energy Combust Sci 2010;36:260–79. http://dx.doi.org/10.1016/j.pecs.2009.10.001.
[11] Oexmann J, Hensel C, Kather A. Post-combustion CO_2 capture from coal-fired power plants: preliminary evaluation of an integrated chemical absorption process with piperazine-promoted potassium carbonate. Int J Greenhouse Gas Control

2008;2:539–52. http://dx.doi.org/10.1016/j.ijggc.2008.04.002.
[12] Hanak DP, Anthony EJ, Manovic V. A review of developments in pilot plant testing and modelling of calcium looping process for CO_2 capture from power generation systems. Energy Environ Sci 2015;8:2199–249. http://dx.doi.org/10.1039/C5EE01228G.
[13] Boot-Handford ME, Abanades JC, Anthony EJ, Blunt MJ, Brandani S, Mac Dowell N, et al. Carbon capture and storage update. Energy Environ Sci 2014;7:130–89. http://dx.doi.org/10.1039/C3EE42350F.
[14] Bhown AS, Freeman BC. Analysis and status of post-combustion carbon dioxide capture technologies. Environ Sci Technol 2011;45:8624–32. http://dx.doi.org/10.1021/es104291d.
[15] Kheshgi HS, Thomann H, Bhore NA, Hirsch RB, Parker ME, Teletzke GF. Perspectives on CCS cost and economics. SPE Econ Manag 2012;4:24–31. http://dx.doi.org/10.2118/139716-PA.
[16] Renner M. Carbon prices and CCS investment: a comparative study between the European Union and China. Energy Policy 2014;75:327–40. http://dx.doi.org/10.1016/j.enpol.2014.09.026.
[17] CSIRO. Assessing post-combustion capture for coal-fired power stations in Asia-Pacific partnership countries. EP116217. Newcastle, NW, USA: CSIRO Advanced Coal Technology; 2012.
[18] Hanak DP, Biliyok C, Yeung H, Białecki R. Heat integration and energy analysis for a supercritical high-ash coal-fired power plant integrated with a post-combustion carbon capture process. Fuel 2014;134:126–39. http://dx.doi.org/10.1016/j.fuel.2014.05.036.
[19] Kenarsari SD, Yang D, Jiang G, Zhang S, Wang J, Russell AG, et al. Review of recent advances in carbon dioxide separation and capture. RSC Adv 2013;3:22739–73. http://dx.doi.org/10.1039/C3RA43965H.
[20] D'Alessandro DM, Smit B, Long JR. Carbon dioxide capture: prospects for new materials. Angew Chem Int Ed 2010;49:6058–82.
[21] Leung DYC, Caramanna G, Maroto-Valer MM. An overview of current status of carbon dioxide capture and storage technologies. Renewable Sustainable Energy Rev 2014;39:426–43. http://dx.doi.org/10.1016/j.rser.2014.07.093.
[22] Nabavi SA, Vladisavljević GT, Wicaksono A, Georgiadou S, Manović V. Production of molecularly imprinted polymer particles with amide-decorated cavities for CO_2 capture using membrane emulsification/suspension polymerisation. Colloids Surf., A 2017;521:231–8. http://dx.doi.org/10.1016/j.colsurfa.2016.05.033.
[23] Nabavi SA, Vladisavljević GT, Eguagie EM, Li B, Georgiadou S, Manović V. Production of spherical mesoporous molecularly imprinted polymer particles containing tunable amine decorated nanocavities with CO_2 molecule recognition properties. Chem Eng J 2016;306:214–25. http://dx.doi.org/10.1016/j.cej.2016.07.054.
[24] McDonald TM, Lee WR, Mason JA, Wiers BM, Hong CS, Long JR. Capture of carbon dioxide from air and flue gas in the alkylamine-appended metal-organic framework mmen-Mg 2(dobpdc). J Am Chem Soc 2012;134:7056–65. http://dx.doi.org/10.1021/ja300034j.
[25] Riboldi L, Bolland O. Evaluating pressure swing adsorption as a CO_2 separation technique in coal-fired power plants. Int J Greenhouse Gas Control 2015;39:1–16. http://dx.doi.org/10.1016/j.ijggc.2015.02.001.
[26] Nelson TO, Green DA, Box P, Gupta RP, Henningsen G, Turk BS. Carbon dioxide capture from flue gas using dry regenerable sorbents. Durham, NC, USA: RTI International; 2009.
[27] Abanades JC, Arias B, Lyngfelt A, Mattisson T, Wiley DE, Li H, et al. Emerging CO_2 capture systems. Int J Greenhouse Gas Control 2015;40:126–66. http://dx.doi.org/10.1016/j.ijggc.2015.04.018.
[28] Romeo LM, Abanades JC, Escosa JM, Paño J, Giménez A, Sánchez-Biezma A, et al. Oxyfuel carbonation/calcination cycle for low cost CO_2 capture in existing power plants. Energy Convers Manag 2008;49:2809–14. http://dx.doi.org/10.1016/j.enconman.2008.03.022.
[29] Martínez I, Murillo R, Grasa G, Carlos Abanades J. Integration of a Ca looping system for CO_2 capture in existing power plants. AIChE J 2011;57:2599–607. http://dx.doi.org/10.1002/aic.12461.
[30] Abanades JC, Anthony EJ, Wang J, Oakey JE. Fluidized bed combustion systems integrating CO_2 capture with CaO. Environ Sci Technol 2005;39:2861–6. http://dx.doi.org/10.1021/es0496221.
[31] Vorrias I, Atsonios K, Nikolopoulos A, Nikolopoulos N, Grammelis P, Kakaras E. Calcium looping for CO_2 capture from a lignite fired power plant. Fuel 2013;113:826–36. http://dx.doi.org/10.1016/j.fuel.2012.12.087.
[32] Yang Y, Zhai R, Duan L, Kavosh M, Patchigolla K, Oakey J. Integration and evaluation of a power plant with a CaO-based CO_2 capture system. Int J Greenhouse Gas Control 2010;4:603–12. http://dx.doi.org/10.1016/j.ijggc.2010.01.004.
[33] Ströhle J, Lasheras A, Galloy A, Epple B. Simulation of the carbonate looping process for post-combustion CO_2 capture from a coal-fired power plant. Chem Eng Technol 2009;32:435–42. http://dx.doi.org/10.1002/ceat.200800569.
[34] Hanak DP, Biliyok C, Anthony EJ, Manovic V. Modelling and comparison of calcium looping and chemical solvent scrubbing retrofits for CO_2 capture from coal-fired power plant. Int J Greenhouse Gas Control 2015;42:226–36. http://dx.doi.org/10.1016/j.ijggc.2015.08.003.
[35] Hanak DP, Manovic V. Calcium looping with supercritical CO_2 cycle for decarbonisation of coal-fired power plant. Energy 2016;102:343–53. http://dx.doi.org/10.1016/j.energy.2016.02.079.
[36] Glier JC, Rubin ES. Assessment of solid sorbents as a competitive post-combustion CO_2 capture technology. Energy Procedia 2013;37:65–72. http://dx.doi.org/10.1016/j.egypro.2013.05.086.
[37] Sumida K, Rogow DL, Mason JA, McDonald TM, Bloch ED, Herm ZR, et al. Carbon dioxide capture in metal-organic frameworks. Chem Rev 2012;112:724–81. http://dx.doi.org/10.1021/cr2003272.
[38] Li G, Xiao P, Webley P, Zhang J, Singh R, Marshall M. Capture of CO_2 from high humidity flue gas by vacuum swing adsorption with zeolite 13X. Adsorption 2008;14:415–22. http://dx.doi.org/10.1007/s10450-007-9100-y.
[39] Stanmore BR, Gilot P. Review—calcination and carbonation of limestone during thermal cycling for CO_2 sequestration. Fuel Process Technol 2005;86:1707–43. http://dx.doi.org/10.1016/j.fuproc.2005.01.023.
[40] Dean CC, Blamey J, Florin NH, Al-Jeboori MJ, Fennell PS. The calcium looping cycle for CO_2 capture from power generation, cement manufacture and hydrogen production. Chem Eng Res Des 2011;89:836–55. http://dx.doi.org/10.1016/j.cherd.2010.10.013.
[41] Wang J, Huang L, Yang R, Zhang Z, Wu J, Gao Y, et al. Recent advances in solid sorbents for CO_2 capture and new development trends. Energy Environ Sci 2014;7:3478–518. http://dx.doi.org/10.1039/C4EE01647E.
[42] Ben T, Pei C, Zhang D, Xu J, Deng F, Jing X, et al. Gas storage in porous aromatic frameworks (PAFs). Energy Environ Sci 2011;4:3991–9. http://dx.doi.org/10.1039/c1ee01222c.
[43] Martín CF, Stöckel E, Clowes R, Adams DJ, Cooper AI, Pis JJ, et al. Hypercrosslinked organic polymer networks as potential adsorbents for pre-combustion CO_2 capture. J Mater Chem 2011;21:5475. http://dx.doi.org/10.1039/c0jm03534c.
[44] Xiang Z, Zhou X, Zhou C, Zhong S, He X, Qin C, et al. Covalent-organic polymers for carbon dioxide capture. J Mater Chem 2012;22:22663. http://dx.doi.org/10.1039/c2jm35446b.
[45] Chen L, Xu S, Li J. Recent advances in molecular imprinting technology: current status, challenges and highlighted applications. Chem Soc Rev 2011;40. http://dx.doi.org/10.1039/c0cs00084a.
[46] Zhao Y, Shen Y, Bai L, Hao R, Dong L. Synthesis and CO_2 adsorption properties of molecularly imprinted adsorbents. Environ Sci Technol 2012;46:1789–95. http://dx.doi.org/10.1021/es203580b.
[47] Zhao Y, Shen Y, Ma G, Hao R. Adsorption separation of carbon dioxide from flue gas by a molecularly imprinted adsorbent. Environ Sci Technol 2014;48:1601–8. http://dx.doi.org/10.1021/es403871w.
[48] Nabavi SA, Vladisavljević GT, Zhu Y, Manović V. Synthesis of size-tunable CO_2-philic imprinted polymeric particles (MIPs) for low-pressure CO_2 capture using oil-in-oil suspension polymerization. Environ Sci Technol 2017;51. http://dx.doi.org/10.1021/acs.est.7b03259.
[49] Hanak DP, Biliyok C, Manovic V. Rate-based model development, validation and analysis of chilled ammonia process as an alternative CO_2 capture technology for coal-fired power plants. Int J Greenhouse Gas Control 2015;34:52–62. http://dx.doi.org/10.1016/j.ijggc.2014.12.013.
[50] Hanak DP, Biliyok C, Manovic V. Efficiency improvements for the coal-fired power plant retrofit with CO_2 capture plant using chilled ammonia process. Appl Energy 2015;151:258–72. http://dx.doi.org/10.1016/j.apenergy.2015.04.059.
[51] Black J. Cost and performance baseline for fossil energy plants volume 1: Bituminous coal and natural gas to electricity. Pittsburgh, PA, USA: National Energy Technology Laboratory; 2013.
[52] Hanak DP, Biliyok C, Manovic V. Evaluation and modeling of part-load performance of coal-fired power plant with postcombustion CO_2 capture. Energy Fuels 2015;29:3833–44. http://dx.doi.org/10.1021/acs.energyfuels.5b00591.
[53] Rachford HH, Rice JD. Procedure for use of electrical digital computers in calculating flash vaporization hydrocarbon equilibrium. J Pet Technol 1952;4:327–8. http://dx.doi.org/10.2118/952327-G.
[54] Berstad D, Anantharaman R, Jordal K. Post-combustion CO_2 capture from a natural gas combined cycle by CaO/$CaCO_3$ looping. Int J Greenhouse Gas Control 2012;11:25–33. http://dx.doi.org/10.1016/j.ijggc.2012.07.021.
[55] Posch S, Haider M. Optimization of CO_2 compression and purification units (CO_2CPU) for CCS power plants. Fuel 2012;101:254–63. http://dx.doi.org/10.1016/j.fuel.2011.07.039.
[56] Sanpasertparnich T, Idem R, Bolea I, de Montigny D, Tontiwachwuthikul P. Integration of post-combustion capture and storage into a pulverized coal-fired power plant. Int J Greenhouse Gas Control 2010;4:499–510.
[57] Metz B, Davidson O, de Coninck H, Loos M, Meyer L. IPCC special report on carbon dioxide capture and storage. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2005.
[58] IEA. CO_2 emissions from fuel combustion highlights. Paris, France: IEA Publications; 2016.
[59] Hanak DP, Manovic V. Calcium looping combustion for high-efficiency low-emission power generation. J Clean Prod 2017;161:245–55. http://dx.doi.org/10.1016/j.jclepro.2017.05.080.
[60] Committee on Climate Change. Meeting carbon budgets – progress in reducing the UK's emissions London, UK 2015.
[61] Miller BG. Clean coal engineering technology. Boston, UK: Butterworth-Heinemannt; 2011.
[62] IEA. Power generation from coal. Ongoing developments and outlook. Paris, France: IEA Publications; 2011.
[63] Abanades JC, Grasa G, Alonso M, Rodriguez N, Anthony EJ, Romeo LM. Cost structure of a postcombustion CO_2 capture system using CaO. Environ Sci Technol 2007;41:5523–7. http://dx.doi.org/10.1021/es070099a.
[64] Zhao M, Minett AI, Harris AT. A review of techno-economic models for the retrofitting of conventional pulverised-coal power plants for post-combustion capture (PCC) of CO_2. Energy Environ Sci 2013;6:25–40. http://dx.doi.org/10.1039/c2ee22890d.
[65] Perry RH, Green DW, Maloney JO. Perry's chemical engineers' handbook. New York, NY, USA: McGraw-Hill; 2007.
[66] Woods DR. Rules of thumb in engineering practice. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA; 2007.

[67] Hanak DP, Manovic V. Economic feasibility of calcium looping under uncertainty. Appl Energy 2017;208:691–702. http://dx.doi.org/10.1016/j.apenergy.2017.09.078.
[68] Romano MC, Martínez I, Murillo R, Arstad B, Blom R, Ozcan DC, et al. Process simulation of Ca-looping processes: review and guidelines. Energy Procedia 2013;37:142–50. http://dx.doi.org/10.1016/j.egypro.2014.11.239.
[69] Mantripragada HC, Rubin ES. Calcium looping cycle for CO_2 capture – performance, cost and feasibility analysis. Energy Procedia 2013;63:2199–206.
[70] Whitcombe MJ, Chianella I, Larcombe L, Piletsky SA, Noble J, Porter R, et al. The rational development of molecularly imprinted polymer-based sensors for protein detection. Chem Soc Rev 2011;40:1547–71. http://dx.doi.org/10.1039/c0cs00049c.
[71] Lisbona P, Martínez A, Lara Y, Romeo LM. Integration of carbonate CO_2 capture cycle and coal-fired power plants. a comparative study for different sorbents. Energy Fuels 2010;24:728–36. http://dx.doi.org/10.1021/ef900740p.
[72] Kim I, Svendsen HF. Heat of absorption of carbon dioxide (CO_2) in mono-ethanolamine (MEA) and 2-(aminoethyl)ethanolamine (AEEA) solutions. Ind Eng Chem Res 2007;46:5803–9. http://dx.doi.org/10.1021/ie0616489.
[73] Goto K, Yogo K, Higashii T. A review of efficiency penalty in a coal-fired power plant with post-combustion CO_2 capture. Appl Energy 2013;111:710–20. http://dx.doi.org/10.1016/j.apenergy.2013.05.020.
[74] ZEP. The costs of CO_2 capture, transport and storage. European Technology Platform for Zero Emission Fossil Fuel Power Plants. 2011.
[75] Versteeg P, Rubin ES. A technical and economic assessment of ammonia-based post-combustion CO_2 capture at coal-fired power plants. Int J Greenhouse Gas Control 2011;5:1596–605. http://dx.doi.org/10.1016/j.ijggc.2011.09.006.
[76] Mac Dowell N, Shah N. The multi-period optimisation of an amine-based CO_2 capture process integrated with a super-critical coal-fired power station for flexible operation. Comput Chem Eng 2015;74:169–83. http://dx.doi.org/10.1016/j.compchemeng.2015.01.006.
[77] Rubin ES, Davison JE, Herzog HJ. The cost of CO_2 capture and storage. Int J Greenhouse Gas Control 2015;40:378–400. http://dx.doi.org/10.1016/j.ijggc.2015.05.018.
[78] Romano MC, Spinelli M, Campanari S, Consonni S, Cinti G, Marchi M, et al. The calcium looping process for low CO_2 emission cement and power. Energy Procedia 2013;37:7091–9. http://dx.doi.org/10.1016/j.egypro.2013.06.645.
[79] Hanak DP, Biliyok C, Manovic V. Calcium looping with inherent energy storage for decarbonisation of coal-fired power plant. Energy Environ Sci 2016;9:971–83. http://dx.doi.org/10.1039/C5EE02950C.
[80] Cormos C-C. Economic evaluations of coal-based combustion and gasification power plants with post-combustion CO_2 capture using calcium looping cycle. Energy 2014;78:665–73. http://dx.doi.org/10.1016/j.energy.2014.10.054.
[81] Alonso M, Rodríguez N, González B, Grasa G, Murillo R, Abanades JC. Carbon dioxide capture from combustion flue gases with a calcium oxide chemical loop. Experimental results and process development. Int J Greenhouse Gas Control 2010;4:167–73. http://dx.doi.org/10.1016/j.ijggc.2009.10.004.



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