



# High-efficiency negative-carbon emission power generation from integrated solid-oxide fuel cell and calciner



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## HIGHLIGHTS

- A process for high-efficiency negative-carbon emission power generation is proposed.
- Process utilises residual heat from SOFC to calcine a carbonate material.
- Net thermal efficiency was found to be between 43.7 and 47.7%<sub>LHV</sub>.
- CO<sub>2</sub> removal rate from air of 463.5–882.3 gCO<sub>2</sub>/kW<sub>el</sub>h can be achieved.
- Minimum cost of electricity and CO<sub>2</sub> capture of 69.1 £/MW<sub>el</sub>h and 129.1 £/tCO<sub>2</sub> was reached.

## ARTICLE INFO

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## ABSTRACT

Direct air capture of CO<sub>2</sub> has the potential to help meet the ambitious environmental targets established by the Paris Agreement. This study assessed the techno-economic feasibility of a process for simultaneous power generation and CO<sub>2</sub> removal from the air using solid sorbents. The process uses a solid-oxide fuel cell to convert the chemical energy of fuel to electricity and high-grade heat, the latter of which can be utilised to calcine a carbonate material that, in turn, can remove CO<sub>2</sub> from the air. The proposed process was shown to operate with a net thermal efficiency of 43.7–47.7%<sub>LHV</sub> and to have the potential to remove 463.5–882.3 gCO<sub>2</sub>/kW<sub>el</sub>h, depending on the fresh material used in the calciner. Importantly, the estimated capital cost of the proposed process (1397.9–1740.5 £/kW<sub>el,gross</sub>) was found to be lower than that for other low-carbon emission power generation systems using fossil fuels. The proposed process was also shown to achieve a levelised cost of electricity of 50 £/MW<sub>el</sub>h, which is competitive with other low-carbon power generation technologies, for a carbon tax varying between 39.2 and 74.9 £/tCO<sub>2</sub>. Such figure associated with the levelised cost of CO<sub>2</sub> capture from air is lower than for other direct air concepts.

## 1. Introduction

The Paris Agreement, reached at the 21<sup>st</sup> Conference of the Parties, has suggested that to significantly reduce the risks and impacts of climate change, the global mean temperature increase needs to be held well below 2 °C and efforts to limit it to 1.5 °C above pre-industrial levels need to be pursued [1]. To achieve this ambitious goal, the recent scenarios imply that negative emissions technologies, such as bioenergy with carbon capture and storage, direct air capture (DAC), and enhanced weathering of minerals, need to be widely deployed, although they are only in the early development phase [2–6].

The concept of DAC, which was initially proposed by Lackner et al. [7], has some distinctive features that make it viable for wide

deployment. Primarily, as DAC does not need to be located at the emission source, it has potential to address emissions from point and distributed sources, including emissions from agriculture, buildings and transportation sectors that account roughly for half of the annual anthropogenic CO<sub>2</sub> emissions [8,9]. Furthermore, the gas to be treated in DAC – ambient air – contains low amounts of SO<sub>x</sub> and NO<sub>x</sub>, which implies lower degradation of the sorbent compared to CO<sub>2</sub> capture from combustion flue gases [8,10,11]. The main disadvantage of DAC is, however, an extremely low concentration of CO<sub>2</sub> in the ambient air of about 400 ppm, which is about 350 times lower than the CO<sub>2</sub> concentration in the flue gas from the combustion of coal [8]. For this reason, the cost of removing CO<sub>2</sub> from ambient air was estimated to range between 400 £/tCO<sub>2</sub> [12] and 800 £/tCO<sub>2</sub> [13], which is an order

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**Nomenclature**

$AC_k$	cross-section area of heat exchanger $k$ [m <sup>2</sup> ]
$C_j$	capital cost of equipment $j$ [£]
$CF$	capacity factor [–]
$e$	number of electrons produced per mole of H <sub>2</sub> [–]
$e_{CO_2}$	specific negative CO <sub>2</sub> emission [gCO <sub>2</sub> /kW <sub>el</sub> h]
$F$	Faraday constant [C/kmol]
$FCF$	fixed charge factor [–]
$FOM$	fixed operating and maintenance cost [£]
$I_c$	current density [mA/cm <sup>2</sup> ]
$I_{SOFC}$	solid-oxide fuel cell current [A]
$LCOA$	levelised cost of CO <sub>2</sub> capture from air [£/tCO <sub>2</sub> ]
$LCOE$	levelised cost of electricity [£/MW <sub>el</sub> h]
$LHV$	lower heating value of fuel [kJ/kg]
$\dot{m}_{calc}$	calcined material production rate [kg/s]
$\dot{m}_{CO_2}$	rate of CO <sub>2</sub> removal from air [kg/s]
$\dot{m}_{fuel}$	fuel consumption rate [kg/s]
$\dot{m}_{O_2}$	O <sub>2</sub> production rate in the air separation unit [kg/s]
$\dot{n}_{H_2,eq}$	equivalent H <sub>2</sub> molar flow rate [kmol/s]
$\dot{n}_{i,in}$	inlet molar flow rate of component $i$ in the fresh fuel [kmol/s]
$\dot{n}_{O_2,eq}$	amount of O <sub>2</sub> consumed in the anode [kmol/s]
$P_{fuel}$	fuel inlet pressure [bar]
$P_i$	partial pressure of component $i$ in the gas mixture [bar]
$P_{i,ref}$	reference partial pressure of component $i$ in the gas mixture [bar]
$P_{ref}$	reference solid-oxide fuel cell operating pressure [bar]
$P_{SOFC}$	solid-oxide fuel cell operating pressure [bar]
$S/C$	steam-to-carbon ratio [–]
$SCF$	specific fuel cost [£/MW <sub>el</sub> h]
$T_{ref}$	reference solid-oxide fuel cell operating temperature [°C]
$T_{SOFC}$	solid-oxide fuel cell operating temperature [°C]

$TCR$	total capital requirement [£]
$\dot{Q}_k$	heat transferred in heat exchanger $k$ [kW <sub>th</sub> ]
$U_a$	air utilisation factor [–]
$U_f$	fuel utilisation factor [–]
$V_{ref}$	reference voltage [V]
$V_{SOFC}$	actual voltage of solid-oxide fuel cell [V]
$VOM$	variable operating and maintenance cost [£/MW <sub>el</sub> h]
$\dot{W}_{j,BRK}$	break power output/requirement of equipment $j$ [kW <sub>el</sub> ]
$\dot{W}_{net}$	net power output of the entire system [kW <sub>el</sub> ]
$\dot{W}_{SOFC,AC}$	solid-oxide fuel cell AC power output [kW <sub>el</sub> ]
$\dot{W}_{SOFC,DC}$	solid-oxide fuel cell DC power output [kW <sub>el</sub> ]
$\Delta T_{LMTD,k}$	log mean temperature difference in heat exchanger $k$ [K]
$\Delta V_{anode}$	reference voltage correction due to variation in the fuel composition [V]
$\Delta V_{cathode}$	reference voltage correction due to variation in the oxidant composition [V]
$\Delta V_p$	reference voltage correction due to variation in the actual pressure [V]
$\Delta V_T$	reference voltage correction due to variation in the actual temperature and current density [V]
$\eta_{BFP}$	isentropic efficiency of boiler feedwater pump [–]
$\eta_{Sc/AC}$	DC-to-AC inverter efficiency [–]
$\eta_{th}$	net thermal efficiency [–]

**Abbreviations**

ASU	air separation unit
CCU	CO <sub>2</sub> compression unit
DAC	direct air capture
LCOA	levelised cost of CO <sub>2</sub> capture from air
LCOE	levelised cost of electricity
PR-BM	Peng-Robinson-Boston-Mathias
SOFC	solid-oxide fuel cell

of magnitude higher than figures reported for CO<sub>2</sub> capture from combustion processes [14]. Nevertheless, DAC is regarded as potentially important in alleviating the effects of anthropogenic CO<sub>2</sub> emissions in the long term, should the direct removal of CO<sub>2</sub> from air be required to stabilise the CO<sub>2</sub> concentration at a desired level [13,15,16]. Importantly, DAC is not currently an economically feasible technology and is expected to be deployed only after 2050, by which time the centralised CO<sub>2</sub> emitters will have been completely decarbonised [17,18].

A number of DAC concepts employing natural inorganic materials, including regenerative processes using strong bases such as NaOH in Na/Ca, KOH in K/Ca, and Ca(OH)<sub>2</sub> in CaO/Ca(OH)<sub>2</sub>/CaCO<sub>3</sub> cycles [11,19,20], have been evaluated and found to be effective in scrubbing CO<sub>2</sub> from the ambient air. However, these processes are energy intensive and require very high regeneration temperatures [11]. This is because the sorbent regeneration is conducted via calcination of the CaCO<sub>3</sub> that takes place at temperatures above 700 °C, usually 800–950 °C depending on the CO<sub>2</sub> partial pressure in the gas stream leaving the calciner [21]. To maintain a high purity of the concentrated CO<sub>2</sub> stream, the calcination process is usually driven by the direct oxy-combustion of fuel in the calciner [8,11]. This introduces the main source of the parasitic load in the process, as O<sub>2</sub> production is usually conducted in a cryogenic air separation unit that is characterised with a specific power requirement of 184–230 kW<sub>el</sub>/tO<sub>2</sub> [22–24]. The main alternative options to drive the calcination process include chemical looping [25–28], which uses oxygen carriers to transfer oxygen from air to the fuel, and indirect heat transfer from a combustor via solid heat carriers [29,30], heat transfer wall [30,31] or heat pipes [32,33].

This study proposes to utilise the high-grade heat from a solid-oxide fuel cell (SOFC) to drive the calcination process in a once-through DAC concept. In contrast to the other high-temperature DAC concepts, the

proposed process will generate electricity at a high efficiency, in addition to capturing CO<sub>2</sub> from the ambient air and producing a concentrated CO<sub>2</sub> stream. As a result, the proposed process is expected to be more economically viable compared to the DAC concepts reported in the literature. Importantly, such process will be incorporated in the Balanced Energy Network (BEN) project that aims to demonstrate a heating, cooling and electricity network that minimises the cost and CO<sub>2</sub> emissions by balancing the delivery of these energy vectors. Therefore, to assess the process feasibility, a techno-economic analysis and parametric studies on the key design parameters are performed in this study. Furthermore, the effect of the sorbent composition on the techno-economic performance is assessed for a range of natural materials.

**2. Model development****2.1. Process description**

The process for simultaneous power generation and CO<sub>2</sub> removal from the air (Fig. 1) comprises four distinct sub-systems: fresh material calciner, heat recovery system including a simple steam cycle, CO<sub>2</sub> compression unit (CCU), and SOFC. The main principle behind the proposed process is to use the SOFC to generate electricity with a high efficiency and produce heat for calcination of the fresh material. The calcined material can then be used for direct air capture, which is expected to take place in the open environment, enabling negative CO<sub>2</sub> emissions.

The core of the process is the flash calciner, where the fresh material is decomposed upon heating. The temperature at which the calcination takes place depends on the type of fresh material (Table 1) fed to the

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