

Combined heat and power generation with lime production for direct air capture

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ABSTRACT

Carbon capture and storage (CCS) has been shown to be the least cost-intensive option for decarbonisation of the power, heat, and industrial sectors. Importantly, negative-emission technologies, including direct air capture (DAC), may still be required after near-complete decarbonisation of the stationary emission sources. This study evaluates the feasibility of a novel polygeneration process for combined heat and power using a solid-oxide fuel cell, and lime production for DAC (CHP-DAC) that could contribute towards decarbonisation of the power, heat, and industrial sectors. Evaluation of the thermodynamic performance indicated that such process can achieve the total efficiency and effective electric efficiency of 65%_{LHV} and 60%_{LHV}, respectively, while removing CO₂ from the air at a rate of 88.6 gCO₂/kW_{ch}h. With the total expenditure spread over a number of revenue streams, the product prices required for the CHP-DAC process to break even were found to be competitive compared to figures for the existing standalone technologies, even if there was no revenue from CO₂ capture from the air. Moreover, the considered process was shown to be economically feasible, even under uncertainty. Hence, it can be considered as the carbon-neutral polygeneration process for sustainable and affordable production of heat, power, and lime that is negative-emission ready.

1. Introduction

Decarbonisation of the energy and industrial sectors is key to meeting the Paris Agreement that recommended keeping the global mean temperature well below 2 °C and undertaking efforts to limit it to 1.5 °C above pre-industrial levels to significantly reduce the risks and impacts of climate change [1]. The power sector can be primarily decarbonised via deployment of carbon capture and storage (CCS), switching from fossil fuels to biomass, and wide deployment of renewable energy sources [2]. It has been reported, however, that decarbonisation of the power sector without CCS will be significantly more expensive and the additional investment associated with higher share of renewables may reach at least £3.5 billion by 2050 [3]. Similarly, a reduction of CO₂ emissions in the heat sector is heavily dependent on the large-scale deployment of CCS. This is because the electrification of heating in buildings will be achieved primarily by wide deployment of heat pumps or direct electric heaters, and large-scale implementation of low-carbon district heating systems, which are expected to be key measures to meet the emission reduction target by 2050 [4]. Importantly, a combination of CCS with hydrogen production [5] and combined heat and power (CHP) generation [6,7] is predicted to play a pivotal role in decarbonisation of process heating in the industrial

sector. The industrial processes are also highly energy intensive, and their decarbonisation is even more challenging than decarbonisation of the power and heat sectors. This is because CO₂ emissions not only stem from fossil fuel combustion, but in many cases also from the chemical process itself. Decarbonisation of the lime industry is of particular interest, as lime has multiple applications in other industries and sectors, such as in environmental protection (flue gas treatment, water purification), agriculture (fertiliser production, soil and wastewater treatment), chemical production (calcium carbide production) and manufacturing (high-performance materials production). Therefore, to achieve near-complete decarbonisation of this industry, CCS is required to avoid the CO₂ emissions from both the fuel combustion and the process itself [8]. Importantly, use of lime as a sorbent for CO₂ capture from fossil fuel power plants [9,10] and industrial processes [11,12] has been recently regarded as a feasible option to reduce the energy and economic penalties associated with mature CCS technologies, such as chemical solvent scrubbing or oxy-fuel combustion. Therefore, the potential exists for synergy between the power and heat sectors, and the lime industry that would lead to reduced environmental burden associated with these processes, while ensuring that the product costs are affordable.

The near-complete decarbonisation of the power, heat and

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Nomenclature

AC_k	cross-section area of heat exchanger k or solid-oxide fuel cell, m^2
C_j	capital cost of equipment j , £
CT	corporate tax, £
D	depreciation rate, £
$e_{CO_2,air}$	specific negative CO_2 emission, gCO_2/kW_{chh}
$e_{CO_2,seq}$	specific CO_2 sequestered, gCO_2/kW_{chh}
E	total expenditure, £
IRR	Internal rate of return
L_I	loan interest, £
L_P	loan principal, £
LHV	lower heating value of fuel, kJ/kg
m_{calc}	calcined material production rate, kg/s
$m_{CO_2,air}$	rate of CO_2 removal from air, kg/s
$m_{CO_2,seq}$	rate of CO_2 sequestered, kg/s
m_{fuel}	fuel consumption rate, kg/s
m_{O_2}	O_2 production rate in the air separation unit, kg/s
CF	net cash flow, £
NPV	net present value, £
PI	Profitability index
q	corporate tax rate, –
R	total revenue, £
SV	salvage value, £

T_{SOFC}	solid-oxide fuel cell operating temperature, $^{\circ}C$
TCI	total capital investment, £
TCR	total capital requirement, £
Q_{DH}	heat output to district heating network, kW_{th}
$W_{j,BRK}$	brake power output/requirement of equipment j , kW_{el}
W_{net}	net power output of the entire system, kW_{el}
$W_{SOFC,DC}$	solid-oxide fuel cell DC power output, kW_{el}
η_b	thermal efficiency of conventional natural gas-fired boiler, –
η_{el}	effective electrical efficiency, –
η_{tot}	total system efficiency, –

Abbreviations

ASU	Air separation unit
CHP	Combined heat and power
CHP-DAC	Combined heat and power, and lime production for direct air capture
CCS	Carbon capture and storage
CCU	CO_2 compression unit
DAC	Direct air capture
NGCC	Natural gas combined cycle power plant
NPV	Net present value
SOFC	Solid-oxide fuel cell

industrial sectors may not be sufficient to meet the CO_2 emission reduction targets, and negative-emission technologies that remove CO_2 directly from the atmosphere may be required [13,14]. Direct air capture (DAC) can address emissions from both point and distributed sources, including emissions from agriculture, buildings and transportation sectors that account roughly for half the annual anthropogenic CO_2 emissions [15,16]. However, due to extremely low concentrations of CO_2 in the ambient air, the cost of CO_2 capture from the air has been estimated to fall between 400 £/t CO_2 and 800 £/t CO_2 [15], which is an order of magnitude higher than those reported for CO_2 capture from combustion processes [17]. Use of lime as a sorbent in DAC concepts has been found to be effective in removing CO_2 from the air. Lackner et al. [18] was the first to propose the concept of using calcium hydroxide for DAC. Although such concept was found to capture CO_2 from

air efficiently, it was deemed unfeasible due to high regeneration energy of the calcium hydroxide. Zeman and Lackner [19] proposed an alternative DAC concept based on the Kraft process, in which sodium hydroxide is used instead of calcium hydroxide for CO_2 capture, while the latter is used for regeneration of the sodium hydroxide from sodium carbonate. Yet, such concept was also shown to require a similar amount of energy for regeneration of sorbent. Finally, Nikulshina et al. [20] proposed using lime as a solid sorbent for DAC in a fluidised bed. The heat required for sorbent regeneration was provided by solar energy. Such DAC concept was shown to achieve a higher CO_2 capture level compared to the one using Na-based sorbents, but required the air to enter the reactor at an elevated temperature (375 $^{\circ}C$). As a result, the heat requirement for such concept was shown to be higher than that with alkali metal hydroxide solutions. Interestingly, the concepts

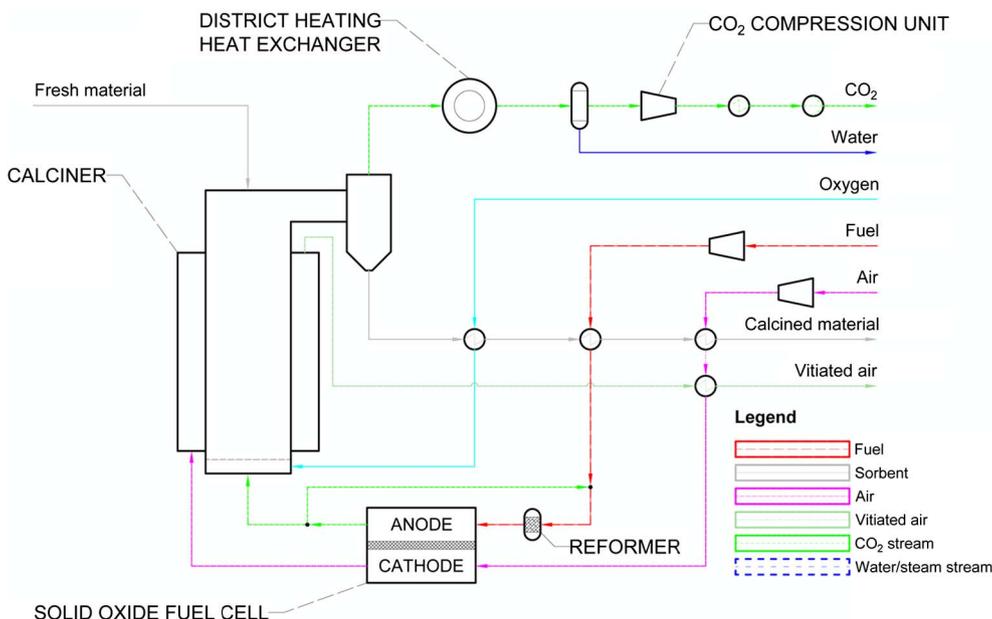


Fig. 1. Process flow diagram of system for combined heat and power generation, and lime production for direct CO_2 removal from the air.

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