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Economic feasibility of calcium looping under uncertainty

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HIGHLIGHTS

- Process and economic models often do not consider the uncertainty in the input variables.
- A stochastic approach was employed to assess economics of the calcium looping retrofit.
- Key economic performance indicators were highly affected by the input uncertainty.
- Outputs of the stochastic analysis were higher than these of the deterministic analysis.
- Stochastic approach is expected to yield more accurate and reliable results.

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ABSTRACT

An emerging calcium looping process has been shown to be a promising alternative to solvent scrubbing, which is regarded as the most mature CO_2 capture technology. Its retrofits to coal-fired power plants have the potential to reduce both energy and economic penalties associated with the mature CO_2 capture technologies. However, these conclusions have been made based on the deterministic outputs of the economic models that have not considered uncertainties in the model inputs. Therefore, this study incorporates a stochastic approach into the economic analysis of the retrofit of such emerging CO_2 capture technology to the coal-fired power plant. The stochastic analysis revealed that levelised cost of electricity (LCOE) and specific total capital requirement were highly affected by the uncertainty in the input variables to the process and economic models. The most probable values for these key economic performance indicators were shown to fall between 75 and 115 €/MW_{el}h, and 2100 and 2300 €/$kW_{el,gross}$, respectively. Interestingly, the most probable LCOE values for the coal-fired power plant will fall between 50 and 150 €/MW_{el}h. This indicated that the calcium looping retrofit scenario can become economically favoured, mainly due to the high economic penalties incurred by unabated coal-fired power plant associated with carbon tax. Importantly, the outputs of the stochastic economic assessment aligned well with the deterministic results reported in the literature. As the latter were generated using different sets of assumptions regarding the process and economic models, the stochastic approach to the economic assessment can minimise the impact of the model assumptions on estimates of the key economic parameters. Moreover, by indicating the probability of particular outputs, as well as ranking the model input variables according to their influence on the key economic performance, such analysis would allow making more insightful decisions regarding further funding and development of the calcium looping process. Finally, use of the stochastic approach in the economic feasibility assessment enables a more profound and reliable comparison of the different calcium looping retrofit configurations, as well as benchmarking different CO_2 capture technologies.

1. Introduction

To significantly reduce the risks and impacts associated with climate change, the 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]. Carbon capture and storage (CCS) technologies are expected to be essential for reducing the environmental impact of the power sector in the short- to mid-term [2], which is one of the major CO_2 emitters due to a large share of coal-fired power plants in the global power generation fleet [3–5]. CCS has been shown to be the least cost-intensive option for decarbonisation of the power sector that would enable achieving the desired emission reduction levels by 2050. This is primarily because of the high capital requirement of the alternative technologies, such as geothermal power plants and offshore wind farms [2,6]. Importantly, large-scale deployment of CCS is expected to reduce wholesale electricity prices in the UK by up to 15% by 2030

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Nomenclature

a	multi-variable polynomial parameter, -
a_1	Rodríguez et al. [43] model fitting parameter, -
a_2	Rodríguez et al. [43] model fitting parameter, -
b	Rodríguez et al. [43] model fitting parameter, -
b_i	multi-variable polynomial parameter,
C_0	reference capital cost of calcium looping process, €/kW_{el}
CF	capacity factor, -
c_i	multi-variable polynomial parameter,
e_{CO_2}	specific CO_2 emission, $gCO_2/kW_{el}h$
EP	net efficiency penalty, $\%_{HHV}$ points
f	neuron activation function
F_0	fresh-limestone make up rate, kmol/s
f_1	Rodríguez et al. [43] model fitting parameter, -
f_2	Rodríguez et al. [43] model fitting parameter, -
f_{calc}	calcination reaction extent, -
f_{carb}	carbonation reaction extent, -
FCF	fixed charge factor, -
FOM	fixed operating and maintenance cost, €
F_R	CaO looping rate, kmol/s
$\tilde{g}$	dependent variable, -
$LCOE$	levelised cost of electricity, €/$MW_{el}h$
	rate of CO_2 emission, kg/s
SCF	specific fuel cost, €/$MW_{ch}h$
SF,Q	scaling factor for reactor heat input, -
SF,V	scaling factor for reactor volume, -
TCR	total capital requirement, €
$Q_{0,calc}$	reference heat input to the calciner, MW_{th}
Q_{calc}	heat input to the calciner, MW_{th}
r_0	fraction of never-calcined limestone in the system, -
V	volume of reactors, m^3
V_0	reference volume of reactor, m^3
VOM	variable operating and maintenance cost, €/$MW_{el}h$
u_i	stochastic variable, -
w_k	artificial neural network node weight, -
$\dot{W}_{net}$	net power output of the integrated system, MW_{el}
X_{ave}	average sorbent conversion, -
y	artificial neural network output, -
α	fraction of the total cost of a circulating fluidised bed reactor associated with the heat transfer surfaces, -
η_{th}	net thermal efficiency, -
η_b	boiler thermal efficiency, -
θ	artificial neural network layer bias, -
φ	neuron output, -

Abbreviations

ANN	artificial neural network
CCS	carbon capture and storage
CCU	CO_2 compression unit
HP	high-pressure
IP	intermediate-pressure
LCOE	levelised cost of electricity
LP	low-pressure
MEA	monoethanolamine
MDEA	methyldiethanolamine
MVR	multi-variable polynomial
PZ	piperazine

compared to a no-CCS scenario [6]. Also, lack of CCS in the power sector will require 40% higher capital cost to achieve more than 50% reduction of the global energy-related CO_2 emissions by 2050 relative to 2009 (IEA 2 °C scenario) [2].

Post-combustion CO_2 capture technologies are regarded as the key class of CCS technologies for decarbonisation of the power sector, as they can be both easily retrofitted to the existing and integrated with the new-built coal-fired power plants [7,8]. Chemical solvent scrubbing using amine-based solvents, such as monoethanolamine (MEA), piperazine (PZ) or methyldiethanolamine (MDEA), is currently perceived as the most mature CO_2 capture technology that will probably be a first choice technology for decarbonisation of coal-fired power plants [9–11]. However, despite the recent developments in chemical solvent scrubbing [12], retrofits of such technologies are predicted to reduce the net thermal efficiency of the entire system by 7–13% points [10,13,14]. A calcium looping process, which is based on the reversible carbonation reaction of lime with CO_2, is considered as an emerging CO_2 capture technology [15] and has already been demonstrated at a scale of 1.9 MW_{th} [13]. Integration of this process to the coal-fired power plant has been shown to impose a net efficiency penalty of 5–8% points [13,16], which is lower compared to the figures reported for the mature CO_2 capture technologies. As a result, it has been estimated that the cost of CO_2 avoided corresponding to the calcium looping retrofits has a potential to be lower (7–87.5 €/tCO_2) [17–23] compared to that of the mature chemical solvent scrubbing (35–75 €/tCO_2) [24–27]. Therefore, calcium looping is perceived as an emerging CO_2 capture technology that could reduce both energy and economic penalties associated with the mature CO_2 capture technologies.

However, predictions of the economic performance indicators for retrofits of post-combustion CO_2 capture technologies to coal-fired power plants have been only obtained using deterministic models. Although such approach can provide the point estimates of the economic performance indicators under any set of assumptions, these models do not consider the uncertainty in the input variables and are highly sensitive to selection of the particular set of assumptions. As the initial values for inputs to economic models, such as capital costs, fuel prices, carbon tax, and cost of CO_2 transport and storage, can vary significantly depending on the considered economic environment [28], the deterministic nature of such model predictions does not provide a definitive representation of the actual system's economic performance. Importantly, around 40% of the mega-projects across different industries, which are usually defined as developments costing more than 1 billion USD, experience cost overruns [29]. This was also the case for the Kemper County and Boundary Dam projects that exceeded the initial cost estimation by a factor of 3 and 1.15, respectively [30,31]. Importantly, the costs of the former project may further increase, as the unit is not yet operational. For this reason, the credibility of economic model prediction can be improved by considering the effect of uncertainty in the model inputs to generate the best- and the worst-case scenario estimates, as well as the probabilistic distributions of the economic model outputs.

An application of stochastic analysis to techno-economic assessment of the engineering systems has been shown to provide a more profound insight into operation and techno-economic performance of these systems [32–38]. As indicated above, the economic performance of the calcium looping retrofits has been only assessed using a deterministic approach, which does not account for the uncertainties in the model inputs. For this reason, this study incorporates the stochastic approach into the economic analysis of the retrofit of such emerging CO_2 capture technology to the coal-fired power plant. This is achieved by combining a robust approximation model of the retrofitted system using a robust artificial neural network, which is developed from a finite number of deterministic simulations in Aspen Plus®, and the economic model with the Monte Carlo simulation. It is expected that by considering the effect of uncertainties on the prediction of the key economic performance indicators, such as levelised cost of electricity (LCOE) and specific total