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Flexible operation strategies for coal- and gas-CCS power stations under the UK and USA markets

Evgenia Mechleri[a,b], Paul S. Fennell[c], Niall Mac Dowell[a,b]

[a]*Centre for Process Systems Engineering, Imperial College London, South Kensington, London SW7 2AZ UK*
[b]*Centre for Environmental Policy, Imperial College London, South Kensington, London SW7 1NA UK*
[c]*Department of Chemical Engineering, Imperial College London, South Kensington, UK*

Abstract

The increased penetration of the intermittent renewable energy has increased the demand for flexible electricity supply. In this work, we evaluate four distinct strategies for flexible operation of CCS power plants: load following, solvent storage, exhaust gas by-pass and variable solvent regeneration (VSR) for coal- and gas-CCS power stations. With the aim to decoupling the power and capture plants in order to maximize profits, a multi-period dynamic optimisation problem was formulated and solved in the context of UK- and US-type markets. It was found that whilst the flexible operation strategies are strongly affected by the different markets, in all cases the variable solvent regeneration strategy was found to be the most profitable.

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Keywords: Flexible CCS; multi-period design; market sensitivities

1. Introduction and scope

Carbon capture and storage (CCS) has been proposed as a means to enable a least-cost transition to a low carbon energy system and is also important for decarbonizing the industrial sector [1]. Given the increasing penetration of intermittent renewable electricity generation and the inflexible nature of traditional nuclear power generation, decarbonised power plants need to be designed for flexible operation in order to be able to promptly respond to variation in electricity demand [2] and to exploit the associated variation of electricity prices, while maintaining the carbon intensity of the plant at low levels [3]. Flexible capture can be achieved in a range of ways. At the level of an

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individual power plant, flexible operation can be achieved using measures such as adding a solvent storage tank, bypassing the capture facility for certain time periods or operating the capture facility at different capture rates according to electricity output requirements (time varying solvent regeneration). To the best of our knowledge, the concept of flexible operation, was first introduced by Gibbins and Crane [4] in 2004, noting that this study makes reference to private communication with Prof Rochelle[1] on this subject in 2002. In the 2004 study, the concepts of solvent storage and exhaust gas venting (or capture bypass) were first introduced. Subsequently, several contributions focused on flexible operation of the capture process as a way to improve the economics of CCS power plants either by reducing the capture level through exhaust gas venting, by storing the solvent using rich and lean amine storage tanks or by varying the degree of solvent regeneration [3, 5-12]. In the solvent storage strategy, two solvent storage tanks are added between the absorber and the stripper. If solvent storage is available then a portion of the rich solvent can temporarily be stored, rather than being sent to the desorber for immediate regeneration. This stored rich solvent can then be subsequently regenerated by adding it to rich solvent generated by ongoing operations during a period of relatively low electricity prices. Previously-stored lean solvent from another tank is used to allow capture to continue. With the exhaust gas venting option, the power plant operates at times with partial or no capture of the CO_2. Under this strategy, the energy required for solvent regeneration is anticipated to be reduced or eliminated by venting a portion of the exhaust gas directly to atmosphere. Thus, the steam that would have been used for solvent regeneration is instead not extracted, resulting in increased net power output. In the time varying solvent regeneration strategy, we use the working solvent as means to provide flexibility to the power plant. This is achieved by allowing CO_2 to accumulate in the solvent during hours of peak electricity prices and regenerating the solvent during off-peak periods.

An important aspect that is analysed in this work is how the several flexible operation strategies differ in diverse markets. Traditionally, the main factors that affect the profits accrued by a power plant are the revenue from the increased power production during peak hours, the cost related to the carbon price and the fuel price. The increased deployment of intermittent renewable energy has two principle effects: to increase the volatility of electricity market and to reduce the important of fossil fuel prices in setting wholesale electricity prices. As has already been observed in Europe, a high penetration of intermittent renewable energy has the potential to produce negative electricity prices in addition to very high electricity prices [13]. Each year, long-term projections of the wholesale prices for oil, gas and coal for the UK under different strategies (low, central, high) are produced [14]. Carbon prices will also vary based on short-term traded carbon values for UK for central, low and high strategies. It is therefore essential to explore the profit sensitivity to these price oscillations. Moreover, it is interesting to examine the flexible operation strategies applied in different regions, UK vs USA, with high and low fuel prices, respectively and observe the profits of the decarbonised coal and gas power plants. In the remainder of this paper, using a load-following plant as the base case strategy, we apply a multi-period optimisation concept to compare three options for flexible operation of both coal- and gas-fired power plants: exhaust gas venting, solvent storage and time-varying solvent regeneration, under different electricity, carbon and fuel prices. We consider that the decarbonised power plants will be required to operate in a load following manner [3, 12, 15] as presented in Fig.1.

[1] Prof G. T. Rochell, U. Texas at Austin.

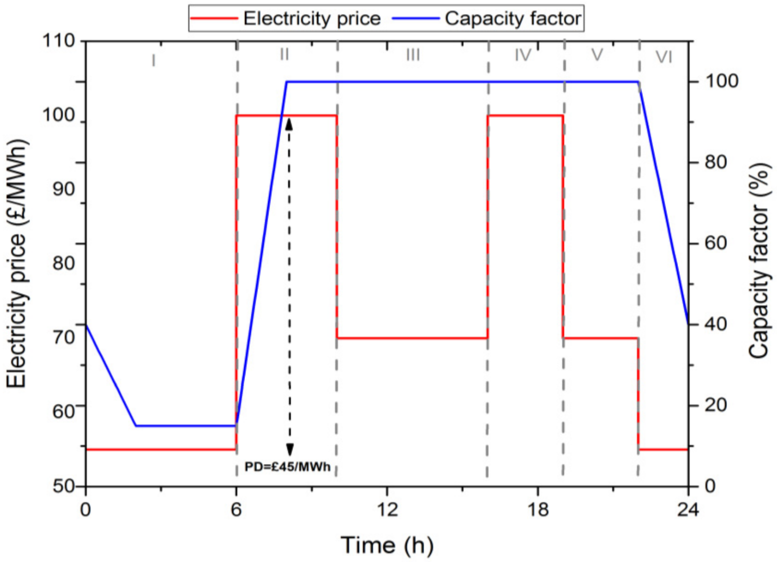

Fig. 1. Illustration of the multi-period concept. In this graph the red line represents the electricity price for the base case. The dashed lines are the price differential (PD) between "peak" and baseline electricity prices for the two cases. From this it can be observed that there are 6 distinct periods of operation denoted by the change of electricity prices within the 24h period. The blue line represents the power plant capacity factor illustrating the load following profile of the power plant. The question we are addressing here is what the optimal operation of the capture plant is in order to maximise the profit during these periods.

The dashed line in Fig.1 is the price differential between "peak" and baseline electricity prices within the 24h period. For example for the base case strategy as presented in this figure, the highest electricity price is £100/MWh and the lowest is £55/MWh, so the price differential is £45/MWh. In the sensitivity analyses, we increase or decrease the highest electricity price so as to increase or decrease the PD accordingly.

2. Model development

2.1. Supercritical pulverised coal-fired power plant (SCPC)

A model of a supercritical pulverised coal power plant (SCPC) was developed using the SCPC model provided by the gCCS toolkit [16]. The inputs of the model are the nominal power output, inlet and outlet steam conditions of the LP turbine, and flowrate of steam extracted as a function of the CO_2 captured. Steam is extracted at the inlet of the LP turbine. The electricity output of the standalone power plant model is 500 MWe, while integrated with capture is 440 MWe. The efficiency of the standalone SCPC model is 44%, while integrated with the capture plant is 38%. The nominal power output along with the temperature and pressure of the steam at the extraction point is specified (T=506 K, P=3.9 bar), while the flowrate of the required steam is calculated by the capture plant by setting a value at the capture rate, taken to be 90% as a base case in this work.

2.2. Combined cycle gas-fired power plant (CCGT)

A model of a Combined Cycle Gas Turbine plant was developed in order to specify the flowrate and composition of the flue gas stream supplied to the capture plant as well as the flowrate and thermodynamic state of the steam provided for the regeneration of the solvent. This model is based on the CCGT model provided by the gCCS toolkit

[16]. For the CCGT model, we have used the Siemens SGT5-4000F with the usual configuration of one gas turbine and three steam turbines. The electricity output of the standalone power plant model is 421 MWe, while integrated with capture is 395 MWe; 73% of the total power comes from the gas turbine while the remainder is provided by the steam turbines. The efficiency of the standalone CCGT model is 59%, based on the Siemens SGT5-4000F gas turbine [17], while integrated with the capture plant is 53%.

2.3. Capture plant model

The post-combustion CO_2 process has been modelled using the gCCS toolkit [17]. The specifications for this model are the gas outlet temperatures for the heat balance and the CO_2 capture rate which is set at 90%. We have chosen a 30% wt MEA solvent with 0.23 lean loading and 0.5 rich loading. These specifications are in turn used to determine the required solvent flowrate.

2.4. Formulation of the optimisation problem

The design and multi-period operation of the decarbonised power plant can be represented by the system of mixed differential and algebraic equations of the form:

$$f\big(x(t), y(t), u(t), v, \dot{x}(t)\big) = 0 \quad \forall t \in \big[0, t_f\big] \tag{1}$$

Where x (t) and y (t) are the differential and algebraic variables in the model, while $\dot{x}(t)$ are the time derivatives of the x (t). The control variables, u (t), and the time invariant variables, v, are to be determined by the optimisation. In this study, the control variables u(t) include the bypass fraction to storage for the solvent storage strategy, the bypass fraction and the lean solvent flowrate for the exhaust bypass strategy and the lean solvent loading for the time varying solvent regeneration strategy.

In some applications it is necessary to impose certain conditions that the system must satisfy at the end of the operation, i.e. the end-point constraints. These can be equality or inequality end point constraints of type:

$$w\big(t_f\big) = w^*, \qquad w^{min} \le w(t_f) \le w^{max} \tag{2}$$

where w is one of the system variables (x or y).

In our case, the end-point constraints were that the degree of capture at the end of the optimisation horizon would be in the range 89.9-90%, that there is no CO_2 accumulation at the end of the optimisation period for the solvent storage strategy and that the lean loading is at the same value at the end of the optimisation period as that at the beginning for the variable solvent regeneration strategy.

Our problem is also subject to path constraints in the case of the solvent storage and exhaust gas venting strategies

$$w^{min} \le w(t) \le w^{max} \qquad \forall t \in \big[0, t_f\big] \tag{3}$$

In the solvent storage strategy, the bypass fraction to storage should be between -1 and 1, the exhaust gas by pass fraction between 0 and 1, the lean solvent flowrate between 0 and 1000 kg/sec (704 kg/sec are required for 90% capture at full plant capacity) and the degree of capture to be in the range of 0-100%.

The dynamic optimisation seeks to determine the time variation of the control variables u (t) over the time horizon $t \in [0, tf]$ so as to maximise the final value of a single variable z subject to constraints (1)-(3):

$$max_{u(t)}, t \in \big[0, t_f\big] z(t_f) \tag{4}$$

where z(tf) is the short-run marginal cost (SRMC) profit of the plant as described in Eq.5.

$$\frac{£^{SRMC}}{MWh} = \frac{£^{MWhr}_{Fuel}}{n_{plant}} + \left(£^{CO_2}_{Tonne} \cdot CI^{TonnesCO_2}_{MWhr}\right) + £^{Var}_{O\&M} + £^{CO_2}_{T\&S} \quad (5)$$

where $£^{SRMC}$ is the SRMC of the electricity generated by a given plant. In this calculation the variable operating and maintenance costs ($£^{Var}_{O\&M}$) and fixed cost($£^{CO_2}_{T\&S}$) for transport and storage are also considered. The data for this equation were obtained from the Department of Energy and Climate Change (DECC) [14] for the fossil fuel prices and carbon prices and by the Joint Research Centre of the European Commission [18] for the efficiencies and carbon intensities. These values are presented in Table 1.

Table 1: Values from DECC and the JRC for use in evaluating Equation 1. The values reported here are for the central scenario by DECC. The efficiency values reported here are for plants with no CCS. In Equation 1, we impose an 8-10% penalty on the power plant. The carbon intensity is for a capture plant operating at 90% capture for SCPC and CCGT while the OCGT operates in an unabated fashion.

		Fuel price (£/MWh)	n_{plant}	CO_2 price (£/tonneCO_2)	CI (tonneCO_2/MWh)	VarO&M (£/tonneCO_2)	T&S (£/tonneCO_2)	Electricity price (£/MWh)
Central scenario	SCPC	9.86	55	70	0.07	4.38	19.60	42.40
	CCGT	24.53	60	70	0.04	3.06	19.60	62.62
	OCGT	24.53	42	70	0.49	1.53	19.60	99.94
High scenario	SCPC	13.89	55	105	0.07	4.72	32.20	61.30
	CCGT	35.04	60	105	0.04	3.86	32.20	90.40
	OCGT	35.04	42	105	0.49	1.93	32.20	144.95
Low scenario	SCPC	7.17	55	35	0.07	4.02	8.20	27.15
	CCGT	14.02	60	35	0.04	2.46	8.20	35.40
	OCGT	14.02	42	35	0.49	1.23	8.20	55.04

3. Evaluation of flexible operation strategies

In this section we present the results of our study. We start with the SCPC, comparing the different strategies for the central strategy and then we perform a sensitivity analysis based on different carbon and electricity price differentials for the UK and USA markets (high and low markets, respectively). The USA prices of coal and gas are lower than the prices in the UK, in large part due to lower taxes applied. In the UK 80% of the cost is taxes. Moreover, the USA the 'shale gas revolution' cut the price of gas by more than half. We then present the results for the same strategies for the CCGT model.

3.1. SCPC power plant

In Table 2, we present the profit for the baseline case for SCPC and CCGT plants for the UK and USA markets.

Table 2. Total profit for the three options for flexible operation of both coal- and gas-fired power plants: exhaust gas venting, solvent storage and time-varying solvent regeneration for the baseline case (PD= £45/MWh, CO_2 price =£70/tonCO_2, coal price=£7.7/MWh (UK) and 3.5£/MWh (USA) and gas price=£24.53/MWh (UK) and £14.02/MWh (USA)).

	Profit (k£)			
Flexibility scenarios	SCPC-UK	SCPC-US	CCGT-UK	CCGT-US
Load following	450	533	213	435
Exhaust gas venting	471	557	230	470
Time varying solvent regeneration	503	597	245	500
Solvent storage	465	550	232	474

In Fig.2, we present the cumulative profit for a sensitivity analysis on the carbon prices and electricity price differentials for the UK (fuel price of £7.7/MWh) for the different flexible strategies. In this analysis, we have included negative values of electricity price differential to include the possibility of price dips / negative prices.

From Fig.2, we can observe that for a price differential between the baseline and "peak" prices within a 24 hr period of up to £25/MWh, and regardless of the carbon price, there is a reduction in profit compared to the base strategy (PD= £45/MWh and CO_2 price =£70/ton). As the electricity price differential increases, we then observe an increase in profit which increases monotonically with the increase at the electricity price differential and baseline carbon price. However, beyond a certain level of PD, that even if the carbon price affects the same amount the profitability, it gets dominated by the revenue and therefore this influence becomes less apparent. This trend is similar for all strategies considered. We can also observe that the position of the "star", which represents the base case can show the % difference in profit between the different strategies (4.5%, 3.4% and 10.5% for the exhaust gas venting, solvent storage and time varying solvent regeneration strategy, respectively). Moreover, for high electricity price differential, the increase in profit for the different strategies becomes more obvious. The time varying solvent regeneration strategy is the most profitable option for providing additional flexibility to the coal-fired power plant.

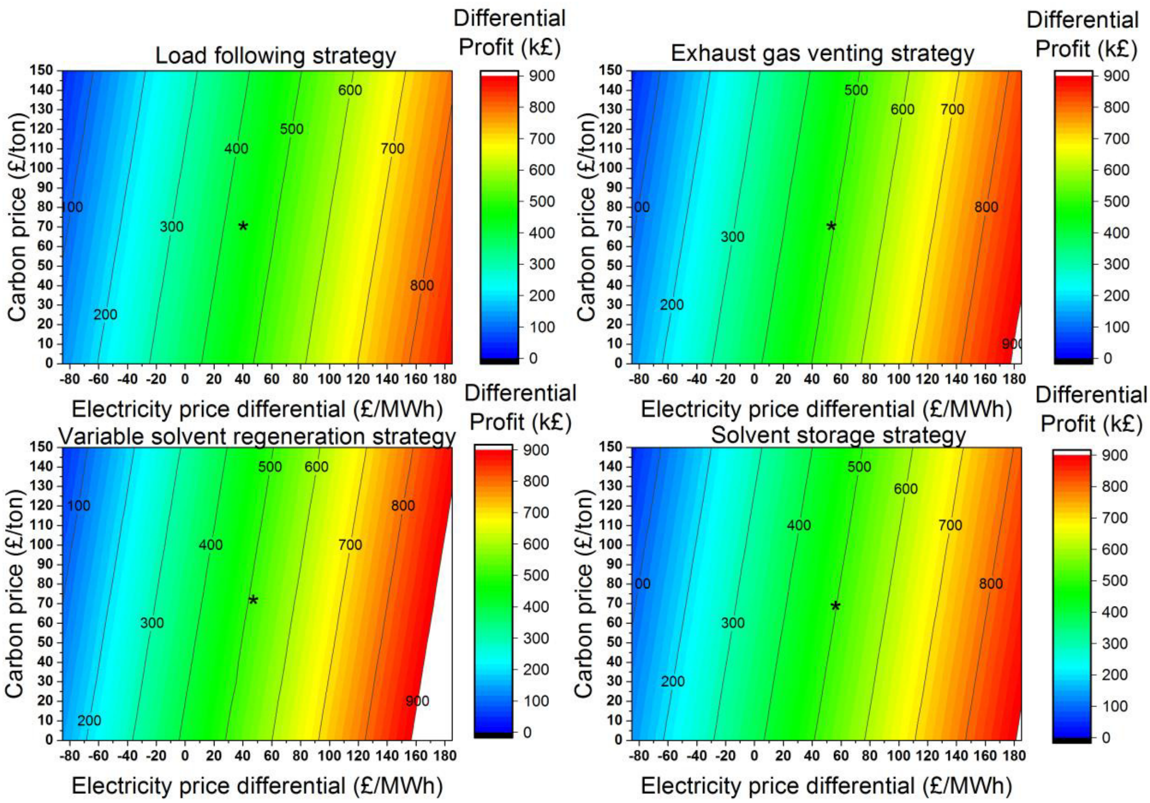

Fig.2. Sensitivity analysis for the UK strategy with fuel price of £7.7/MWh. In this Figure we illustrate the variation of CO_2 prices and electricity price differential (PD) (difference between baseline and "peak" electricity prices) as a function of the cumulative profit (k£) compared to the central strategy (PD= £45/MWh and CO_2 price =£70/ton_{CO2}). As the price differential increases then the gain increases and for high PD can reach more than £900k for the most profitable VSR strategy. The "star" represents the base case with CO_2 price=£70 ton_{CO2} and PD= £45/MWh.

As can be observed from Fig.3, as the fuel price decreases (USA), the profit associated with the decarbonised coal fired power plant increases by 16% exhibiting a profit of £533k in comparison to £450k for the UK in the reference strategy. Similar trends are observed for all strategies. When comparing the figures for UK and USA, the main conclusion is that lower fuel prices provide extra profitability for the different flexible strategies, with the most profitable option remaining the time varying solvent regeneration operating strategy.

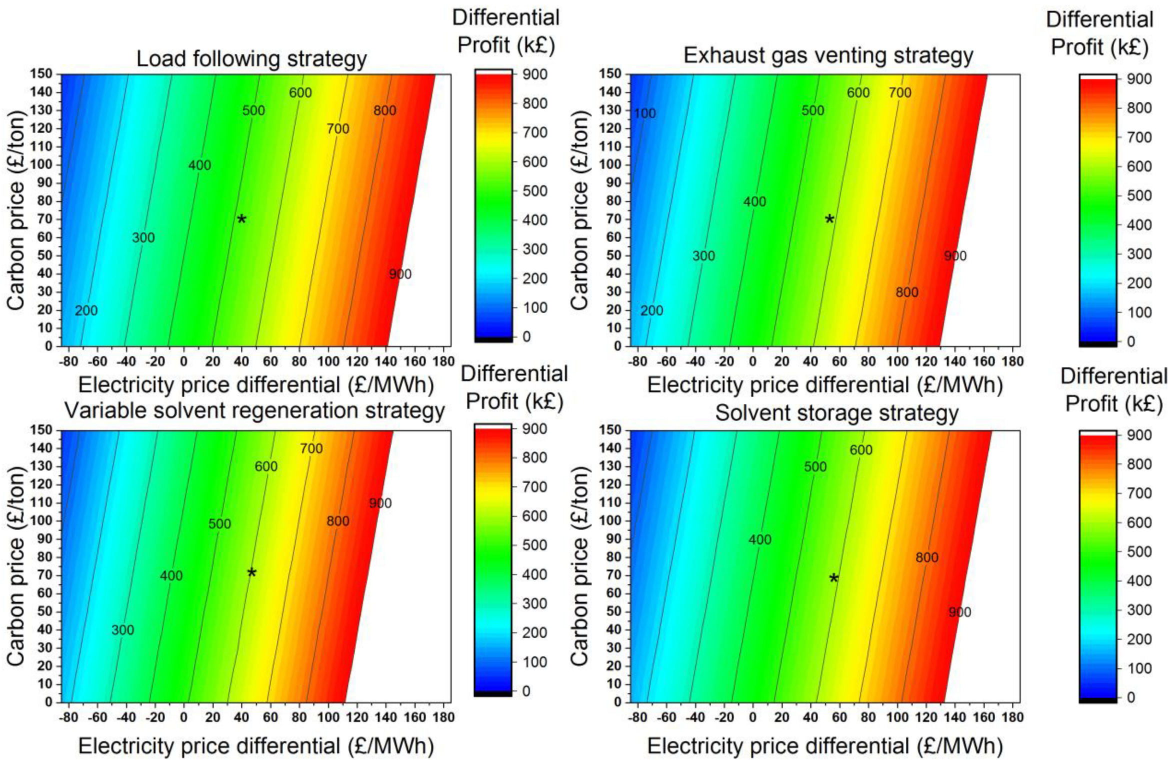

Fig.3. Sensitivity analysis for the US strategy with fuel price of £3.5/MWh. In this Figure we illustrate the variation of CO_2 prices and electricity price differential (PD) (difference between baseline and "peak" electricity prices) as a function of the cumulative profit (k£) compared to the central strategy (PD= £45/MWh and CO2 price =£70/ton$_{CO2}$). The "star" represents the base case with CO_2 price=£70 ton$_{CO2}$ and PD= £45/MWh.

2.2 CCGT power plant

Similar analysis has been performed for the CCGT plant for the UK and US markets. The trends observed were similar to the SCPC, while the cumulative profit was less than the SCPC due to the higher price of gas compared to coal. In Fig. 4, we observe the cumulative profits for the four different strategies for the central strategy (PD= £45/MWh and CO_2 price =£70/ton$_{CO2}$) for the SCPC and CCGT plant for the UK and US. For the UK the low coal price compared to the higher gas price (£7.7 £/MWh vs £24.53 £/MWh) leads the SCPC plant to exhibit higher profits for the various flexible operation strategies compared to the CCGT plant. However, when considering the flexible plants in the USA market, with coal price of £3.5 £/MWh and gas price of £7.17 £/MWh, we observe that the profit gap between the two plants is closing with the CCGT plants becoming more competitive.

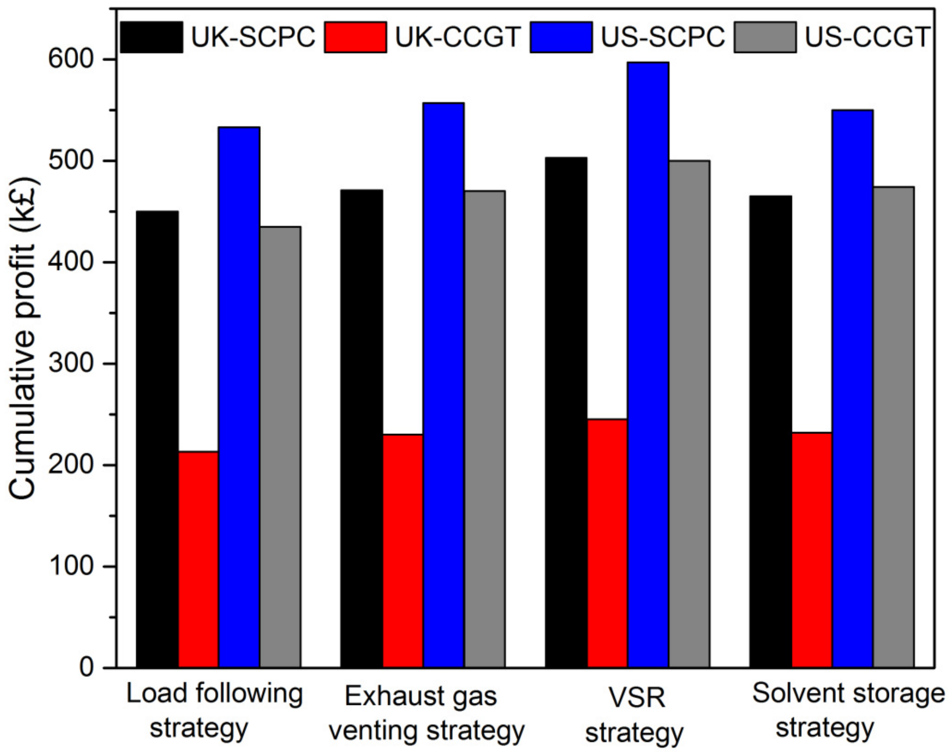

Fig.4. In this Figure we illustrate the cumulative profit (k£) for the CCGT and SCPC plants for the UK and USA markets for the central strategy (PD= £45/MWh and CO2 price =£70/ton$_{CO2}$). The CCGT plants for the USA market become more competitive compared to the SCPC plants.

In all cases, the variable solvent regeneration strategy was found to be the most profitable option. This conclusion appears robust to assumptions on fuel, carbon or electricity prices.

Conclusions

In this work we have formulated a multi-period optimisation problem in order to examine the various flexible operational strategies for coal- and gas- CCS power stations in the UK and USA markets. Four distinct strategies have been evaluated: load following, solvent storage, exhaust gas by-pass and variable solvent regeneration (VSR). Sensitivity analyses showed that, for all strategies, the flexibility benefit declined with reduced carbon and fuel prices, while a “peakier” electricity market, characteristic of one with significant quantities of intermittent renewables deployment, more significantly rewarded flexible operation. Comparing the SCPC and CCGT plants for the UK and USA markets, the CCGT plant becomes more competitive for the USA market.

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