European Symposium on Computer Aided Process Engineering – 15
L. Puigjaner and A. Espuña (Editors)

Techno-Economic Modelling and Cost Functions of CO_2 Capture Processes

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Abstract

The paper contributes to techno-economic modelling of CO_2 capture process in coal-fired power plants. Technological options of CO_2 capture have been chosen and cost estimation relationships (CERs) for the chosen options provided. The CERs are being fitted into a developed overall model of carbon capture and sequestration. Functions relating capital costs, operation and maintenance costs and total annualised costs to plant electricity output and amount of CO_2 avoided have been developed. The influence of interest rates and plant life has also been analysed.

Keywords: CO_2, capture, cost functions, techno-economic modelling

1. Introduction

The environmental concerns are translated by national and international regulations into research and development of new technologies of carbon capture and sequestration. "An integrated assessment of geological carbon sequestration in the UK" project aims to enable a comprehensive evaluation of carbon storage options. It addresses techno-economic, geological, environmental, socio-political and legal dimensions of carbon storage. The cost estimation relationships were developed and are being incorporated in an overall model.

2. Background and work description

The objective is the development and calculation of cost functions for carbon capture processes on the basis of a literature review.

2.1 Literature data

Cost estimates vary significantly in the literature, which is quite natural as different authors consider different technologies, scenarios, reference cases, etc.
Hendriks et al. (2000) estimate costs for CO_2 removal projects in the Netherlands under various scenarios. For a range of fuel prices and discount rates they estimate the following capture costs: Natural gas combined cycle USD 41-66 and furnace/combined heat and power up to USD 45.

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Anderson and Newell (2003) review the technical and economic feasibility of a range of carbon capture and storage options. Their cost of carbon capture for new and retrofitted plants is USD 45 – 58 per t of CO_2 captured. They forecast that in the near future, with the technology improvements, the cost reduction up to USD 34 – 42.
Johnson and Keith (2004) look at under what assumptions and with what carbon prices, carbon capture and storage can be competitive (the assumed technology of around 2015). They found that CCS can contribute significantly to carbon reductions when carbon prices are below USD 27 per t CO_2. New coal-fired power plants with carbon capture become competitive when carbon prices are around USD 20. Retrofitting existing power plants is not competitive below USD 82. Gas-fired power plants with carbon capture become competitive only at a much higher carbon price of USD 48.
Kallbekken and Torvanger (2004) consider different scenarios for carbon capture and sequestration technologies and conclude that the cost ranges might be USD 7-21 (low cost estimate), USD 40-50 (medium cost estimate) or USD 75-95 (high cost estimate).
DTI UK (2003) gives the overall cost of carbon capture and sequestration obtained through a range of case studies. The results show the overall cost of CCS to be of the order of GBP 28-35/t CO_2 for EOR and GBP 22-27/t CO_2 for storage in depleted gas reservoirs with ±30% uncertainty. The report also provides cost estimates for some of the items like new IGCC (GBP 13-34 ≈ 24-63 USD) or new GTCC (GBP 21 ≈ 39 USD)
Holt et al (2000) estimate the total CCS cost to lie in the range USD 29-45.
Li and Klemeš (2003) and Li, Klemeš and Shackley (2003) presented preliminary results dealing with the choice of the technology and cost model – an optimised operation of an amine system and integrated framework aimed at cutting down the CO_2 avoidance costs.
Comparison of the literature data (eg Rao and Rubin, 2002) brings to conclusion that *today, amine-based scrubbing process is considered the best technology available for post-combustion CO_2 capture*. The O_2/CO_2 recycling process, which involves burning the coal with O_2 in an atmosphere of recycled flue gas, has also gained much interest. One of the most comprehensive works on this topic, (Singh et al, 2000), compares these two technologies and concludes that the *capital and operating cost in terms of USD/t of CO_2 avoided were similar for both cases*. The data on other existing processes necessary for development of cost functions is rather scarce and unfit for the cost function development. On this base it was decided to analyse the amine scrubbing process in this work.

2.2 Software and methodology used

To obtain accurate cost estimation of CO_2 capture process it is necessary to include a detailed simulation of CO_2 capture processes, for which there have been some works done by worldwide groups. A group in Carnegie Mellon University working on "Assessment of Amine-Based CO_2 Capture Technology for Power Plant Greenhouse Gas Control" is one of the leading research centres in this field. They considered a detailed amine scrubbing plant performance model (Fig. 1) implemented in IECM software. Based on the simulation results of the performance model, the capital costs as well as the operating & maintenance costs for the amine scrubbing process can be estimated. The facilities that are accounted for the capital cost include: flue gas blower, absorber, regenerator, solvent processing area, MEA reclaimer, steam extractor, heat exchanger, pumps, CO_2 compressor. The sum of these is the total process facilities cost (PFC). Then engineering and home office cost, general facilities, project and process contingencies are considered with assigned ratio to the total process facilities cost. The sum of above costs is the total capital requirement (TCR).

The fixed operating & maintenance costs (Fixed O&M) include: total maintenance cost (2.5 % TPC), maintenance cost allocated to labour (40 % of total maintenance cost), administration & support labour cost (30 % of total labour cost) and operating labour (2 jobs/shift).

The varied operating & maintenance costs (Variable O&M) include: reagent (MEA), water cost, CO_2 transport cost, CO_2 storage/disposal cost and solid waste disposal cost.

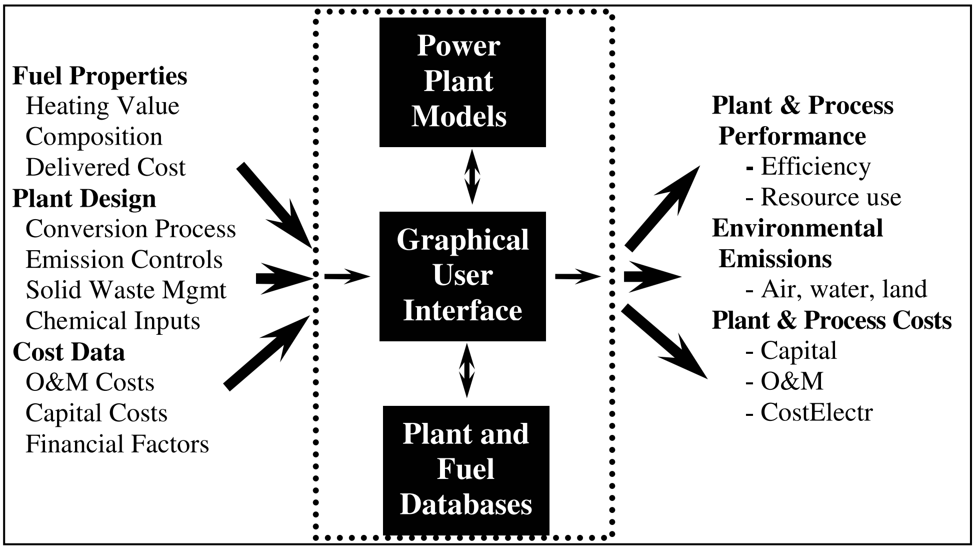

Figure 1 Amine scrubbing plant performance model implemented in IECM (version 3.5.5) software, Center for Energy and Environmental Studies (2004)

3. Cost Estimation Relationships

The Cost Estimation Relationships (CERs) have been defined at three CO_2 removal efficiencies: 90 %, 85 % and 90 % with plants range being 300 to 2000MW.

3.1 Cost Estimation Relationships against Plant Size (Eq 1, Tab 1)

$$Cost = A + B \cdot Plant\ Size \qquad (1)$$

Table 1 CER Coefficients for capital costs, O&M costs and Total Annualised Costs

Rem. Effic.	Coef.	PFC	TCR	Ann. TCR	Var O&M	Fix. O&M	Tot. O&M	Sorb.	Steam	Elec.	Tot. Ann. Cost
90%	A	9.4351	14.680	1.5180	5.5448	1.0085	6.5650	0.0010	3.0525	2.4855	8.4130
	B	0.2582	0.3965	0.0410	0.1107	0.0099	0.1200	0.0231	0.0215	0.0200	0.1614
85%	A	9.5321	14.641	1.5139	5.3107	1.0122	6.3230	0.0225	0.0204	0.0170	7.8369
	B	0.2471	0.3795	0.0392	0.1060	0.0094	0.1155	0.0017	2.8858	2.4054	0.1547
95%	A	9.6090	14.759	1.5261	5.1791	0.9858	6.1649	0.0000	3.2222	2.5490	7.6910
	B	50.721	77.907	8.0556	21.824	1.9490	23.773	4.4890	4.2994	3.4055	31.820

3.2 Costs of Avoided CO_2 against Plant Size (Eq 2, Tab 2)

$$Cost\ of\ CO_2\ Avoided = A \cdot ((PZ/100)-2)^2 - B \cdot ((PZ/100)-2) + C \qquad (2)$$

where PZ – Plant Size

Table 2 Coefficients for Cost of CO_2 Avoided against Plant Size CERs

Removal Effic.	Coefficient	Value of Coefficient
	A	0.1098
90 %	B	3.4086
	C	56.533
	A	0.1175
85 %	B	3.6693
	C	59.736
	A	0.1005
95 %	B	3.1301
	C	53.596

3.3 Costs Estimation Relationships against Amount of CO_2 Avoided (Eq 1, Tab 3)

$$Cost = A + B \cdot Amount\ of\ CO_2\ Avoided \qquad (3)$$

Table 3 CER Coefficients for capital costs, O&M costs and Total Annualised Costs

Rem. Effic.	Coef.	PFC	TCR	Ann. TCR	Var O&M	Fix. O&M	Tot. O&M	Sorb.	Steam	Elec.	Tot. Ann. Cost
90%	A	9.3908	14.613	1.5109	5.5257	1.0068	6.5442	0.000	3.0488	2.4824	8.3837
	B	51.338	78.8200	8.1500	22.019	1.9690	23.983	4.6091	4.2924	3.4900	32.089
85%	A	9.5210	14.6240	1.5121	5.3062	1.0118	6.3181	0.0008	2.8850	2.4047	32.566
	B	52.005	79.8800	8.2596	22.3110	1.9950	24.306	4.7427	4.2982	3.5820	7.8302
95%	A	9.6090	14.7590	1.5261	5.1791	0.9858	6.1649	0.000	3.2222	2.5490	7.6910
	B	50.7210	77.9070	8.0556	21.824	1.9490	23.773	4.4890	4.2994	3.4055	31.820

3.4 Costs of Avoided CO_2 against Amount of CO_2 Avoided (Eq 4, Tab 4)

$$Cost\ of\ CO_2\ Avoided = A \cdot ((CAV/0.503)-2)^2 - B \cdot ((CAV/0.503)-2) + C \qquad (4)$$

where CAV = Amount of CO_2 avoided

Table 4 Coefficients for Cost of CO_2 Avoided against Amount of CO_2 Avoided CERs

Removal Effic.	Coefficient	Value of Coefficient
	A	0.1098
90 %	B	3.4086
	C	56.533
	A	0.1175
85 %	B	3.6693
	C	59.736
	A	0.1005
95 %	B	3.1301
	C	53.596

3.5 Influence of Plant Life (Eq 5, Tab 5)

The base case plant output was 1000 MW with removal efficiency 95 %

$$Parameter = A + B \cdot Plant\ Life \qquad (5)$$

Table 5. Plant Life CER coefficients for capital costs, O&M costs and Total Annualised Costs

Coef.	PFC	TCR	Ann. TCR	Var O&M	Fixed O&M	Total O&M	Sorb	Steam	Elect.	Tot. Ann. Cost	Cost of CO2 avoided
A	281.4	433.7	87.33	140.0	11.44	151.5	23.84	36.51	28.91	238.8	72.34
B	0	-0.05	-1.48	-0.632	0	-0.636	0	-0.35	-0.28	-2.114	-1.29

3.6 Influence of Bond Interest Rate (Eq 6, Tab 6)
The base case plant output was 1000 MW with removal efficiency 95 %

$$Parameter = A + B \cdot Bond\ Interest\ Rate \qquad (6)$$

Table 6. Bond Interest Rate CER coefficients for capital costs, O&M costs and Total Annualised Costs

Coef.	PFC	TCR	Ann. TCR	Var O&M	Fixed O&M	Total O&M	Sorb	Steam	Elect.	Tot. Ann. Cost	Cost of CO2 avoided
A	281.4	422.5	35.96	117.5	11.44	129.0	23.84	23.97	18.98	164.9	26.77
B	0.000	2.124	1.940	0.944	0.000	0.936	0.000	0.524	0.415	2.884	1.822

4. Conclusions

- *Simple and reliable relationships* have been developed from a very detailed model (IECM-CS) which was impractical for application directly in this project due to large amount of its input and output parameters. They relate capital expenses, operating costs, sorbent cost, steam cost electricity cost and cost of CO_2 avoided to plant size and to amount of CO_2 avoided for three CO_2 removing efficiencies of 85%, 90% and 95 %.
- To compare the obtained data and putting them into the perspective, the literature cost estimations are given below and the figures from this study are provided (Tab 7). The table is modified to make the comparison as much correct as possible. For that purpose, the prices are all given in late 2004 USD and the technologies are limited to coal-fired plant, IGCC, GTCC and amine scrubbing technology.
- The future work will be focused on fitting and testing the developed CERs with the overall CCS model developed by our project partners.
- Presented cost functions can be applied for both grassroots design problems and for the retrofit though for the latter, cost adjustments will need to be taken into account which consider the cost of retrofitted capital equipment relative to similar equipment installed in a new plant. These factors affect the capital costs directly and the operating and maintenance costs indirectly.

Table 7 Comparison of cost figures

Source	Current cost 11/2004 USD/t
Cost figures obtained in this study: **Coal-fired plant - 300 - 2000 MW range - MEA technology**	**30 - 65**
Anderson and Newell (2003) - Coal/gas power plant, MEA technology - Integrated gasification combined-cycle	 45.7 - 59 28.5
Hustad (Kallbekken S. and Torvanger, 2004) Coal power plant	25.3
Dijkstra and Jansen (2004)- Combined cycle, MEA technology	59 – 71.5
DTI, UK, (2003) - with Enhanced Oil Recovery - with storage in depleted gas reservoirs - New IGCC - New GTCC - Coal PF Retrofit	 52-65 41-50 24-63 39 35

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Acknowledgements

The financial and informational support from the Tyndall Centre for Climate Change Research project T2.21 "Assessing the Potential for Geological Carbon Sequestration in the UK" is gratefully acknowledged. The authors would also like to acknowledge the support of Carnegie Mellon University who provided the ICEM-CS (version 3.5.5) software for the testing purposes and technical support.