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Evaluation of five alternative CO_2 capture technologies with insights to inform further development

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Abstract

The high cost of CO_2 capture using amine solvents from combustion sources such as natural gas-fired power plants remains a barrier to the adoption of CO_2 Capture and Storage (CCS) as a climate change mitigation measure. The objective of the work reported in this paper was to carry out a preliminary assessment of the potential of five alternative technologies suitable for post-combustion CO_2 capture from natural gas derived exhaust gases:

- CO_2 permeable membranes
- Molten Carbonate Fuel Cells
- High-pressure solvent absorption from high-pressure exhaust gas from pressurised combustion / power generation
- High-pressure solvent absorption supported by exhaust gas compression
- Supersonic flow driven CO_2 deposition

The results of the performance and cost evaluation for each technology are explained and the prospects for significant cost reduction compared to a state-of-the-art CO_2 capture process are discussed. Recommendations for further technology development activity are summarised in the conclusion of the paper.

Peer-review under responsibility of the organizing committee of GHGT-13.

Keywords: Carbon dioxide; CO_2 capture; molten carbonate fuel cells; CO_2 membranes; natural gas combined cycle.

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1. Introduction

The high cost of CO_2 capture using amine solvents from combustion sources such as natural gas-fired power plants remains a barrier to the adoption of CO_2 Capture and Storage (CCS) as a climate change mitigation measure. Whilst successful demonstration of CO_2 capture by amine solvents at large-scale has been invaluable in showing the readiness level of this technology, the results have also highlighted the opportunity for innovative approaches to improve performance and reduce cost. Many new and emerging technologies are under active development and have been reported in published literature. The majority of these have been focussed on CO_2 capture from coal-fired power generation. The work reported in this paper, funded by the CO_2 Capture Project (CCP), was performed by a collaborative project team of technology experts from both academe and the CCP industry members. The objective of the work was to carry out a preliminary assessment of five alternative technologies applied to post-combustion CO_2 capture from natural gas derived exhaust gases. Modern natural gas-fired power plant which use gas turbines in combined cycle produce an exhaust gas which is lower in CO_2 concentration and higher in oxygen concentration than is typical when compared to coal-fired plant. These factors lead to a large energy penalty and large equipment sizes which result in a high cost. This evaluation used information from published literature sources to make a high-level but systematic assessment of the integration possibilities for the alternative technologies with the base-line power generation process and created models of performance and estimates of the capital cost. The output from these models and cost estimates was then used to compute a figure for the specific cost of CO_2 avoided for each technology. Whilst no definitive conclusions should be drawn from such high-level evaluation the results are used to inform recommendations on areas for future work concerning further development of the alternative technologies and their integration with natural gas-fired power plant.

Nomenclature

CCP	CO_2 Capture Project
CCS	Carbon Capture and Sequestration
CO_2	Carbon Dioxide
EBTF	European Benchmarking Task Force
HRSC	Heat Recovery Steam Cycle (includes steam generator and steam turbine)
HRSG	Heat Recovery Steam Generator
LHV	Lower Heating Value
MCFC	Molten Carbonate Fuel Cells
MEA	Mono Ethanol Amine
NGCC	Natural Gas Combined Cycle

2. Evaluation base-line

The large-capacity, high efficiency gas turbine based combined cycle described in the CCS European Benchmarking Task Force report [1] (EBTF) was used as the basis of the reference for the work reported in this paper. This comprised two “F class” gas turbines paired with two multi-pressure Heat Recovery Steam Generators (HRSGs) and a single steam turbine. A base case was created by adding CO_2 capture by 30% Mono Ethanol Amine (MEA) solvent absorption. The steam used to drive the CO_2 desorption from the loaded solvent solution was taken from the steam turbine between the intermediate and low pressure sections. The major equipment line-up was completed by an electric-drive compressor to deliver CO_2 at high pressure ready for pipelining and geo-storage. The cost estimate was produced using industry-standard tools and well-established scaling factors. The key assumptions for this base-line can be seen in Table 1. The target purity specification for the CO_2 stream was based on a CO_2 enhanced oil recovery specification [2] and can be seen in Table 2.

The performance and cost estimates did not include any particular set-up or first-of-class costs or exceptional-case risk premiums or contingencies that might be needed for demonstration or first commercial CCS projects.

As would be expected the performance modelling results showed the significant reduction in power output from the base case compared to the reference plant.

- The reference plant is the natural gas combined cycle (NGCC) without capture
- The base plant is the NGCC with MEA-based capture

The consequence of steam extracted from the steam turbine is a 77 MW reduction in gross power generated by the steam turbine and the net power is further reduced by 43 MW which is required for CO_2 capture including the CO_2 compressor. The combined effect is to reduce the net output of the base case by 120 MW compared to the reference plant and the overall impact on the net efficiency of the plant is a substantial reduction from 58% to 50% on a Lower Heating Value (LHV) basis. This is summarised in Table 3. The capital cost and operating costs of the reference and base case were estimated. The capital cost increase from the reference to the base case was substantial at just over 75%, and the specific cost of CO_2 avoided was calculated to be around 75 $/t at a CO_2 capture rate of 90%. These results are comparable with the results of similar well-respected studies published by the United States Department of Energy National Energy Technology Laboratory [3] and the International Energy Agency Greenhouse Gas Research and Development programme [4].

Table 1 - Key Assumptions for basis of study

Assumption	Units	Value
Cost and financial		
Location basis		Northern Europe
Cost year basis		2014
Base currency used	€	Euros
Average exchange rate (2014)	$ / €	1.33
Time horizon	years	25
Inflation rate	%	2
Discount rate	%	10
Levelisation factor	-	0.856
First year capital charge factor	%	9.43
Fuel cost	$/GJ (2014)	4.5
Operating hours	hours / year	7880
Air supply		
Temperature	°C	15
Pressure	Pa	101,325
Relative humidity	%	60
Fuel supply		
Temperature	°C	10
Pressure	Pa	7,000,000
Gas turbine details		
Two F class machines @50Hz		
Pressure ratio		18.1
Turbine inlet temperature	°C	1360
Efficiency	% LHV	38.25
Natural gas preheat	°C	160
Heat recovery steam cycle details		
Three pressure levels	bar	130 / 35 / 4
Superheat level	°C	565
Condensing pressure	bar	0.048
Cooling water temperature	°C	18.2

Table 2 - Target purity specification for CO_2 product stream

Component	Unit	Value	limit
Carbon dioxide	% mol	95%	minimum
Nitrogen	% mol	4%	max
Hydrocarbons	% mol	5%	max
Water	mg / m³	480	max
Oxygen	ppm	10	max
Hydrogen Sulphide	ppm	10 - 200	max
Glycol	ml / m³	0.04	max
Temperature	°C	65	
Pressure	barg	150	

3. Alternative CO_2 capture technologies

We evaluated five different alternative CO_2 capture technologies:

- CO_2 permeable membranes
- Molten Carbonate Fuel Cells (MCFC)
- High-pressure solvent absorption from high-pressure exhaust gas from pressurised combustion / power generation
- High-pressure solvent absorption supported by exhaust gas compression
- Supersonic flow driven CO_2 deposition

In each case we used information describing the technology from published literature. It was necessary to try to normalise and align the performance and cost of each technology to a common basis to facilitate comparison with our base-line. In each case this required development of a process model to simulate performance and evaluate adjustments to the flow-sheet to integrate the technology with the power plant and to try to achieve the target CO_2 capture rate, at the CO_2 target purity and at the lowest specific cost of CO_2 avoided.

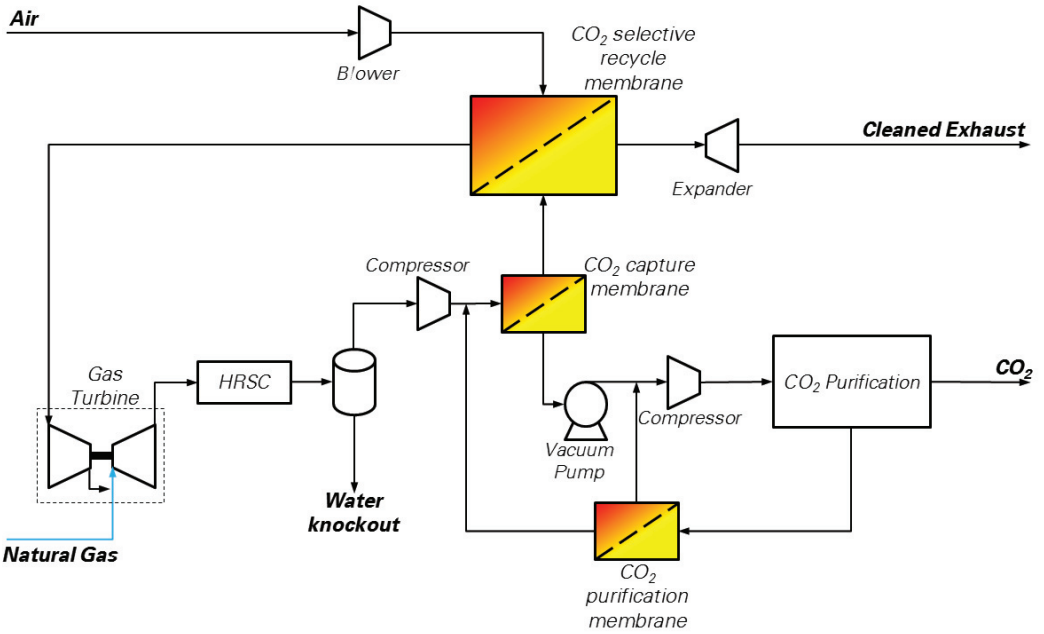

Figure 1 - CO_2 capture scheme using CO_2 permeable membranes

In this paper we report just a high level summary of the key results of the study. Further details, including performance and economic assumptions, techno-economic constraints of each technology, equipment models and process alternatives, will be published in a scientific publication under preparation by Forsyth et al.

3.1. CO_2 permeable membranes

Polymeric membrane technology has been successfully commercialised for CO_2 separation from natural gas. Such membranes have typically been used where the natural gas contains greater than 10% CO_2 and the feed gas is introduced to the membrane separation module(s) at high pressure. In such circumstances the performance and cost of the technology can be more attractive than amine or other types of solvent. However post-combustion CO_2 capture represents a significantly more challenging set of process conditions.

As a starting point we used the scheme described by Merkel et al [5], Figure 1. CO_2 permeable membranes are used in the flow sheet in three ways: To provide selective recirculation of CO_2 to the gas turbine inlet, to separate CO_2 from the CO_2-enriched exhaust gas and finally to help separate CO_2 from the incondensable gas stream in the final CO_2 purification section.

3.2. Molten carbonate fuel cells

Like other types of fuel cells MCFCs convert fuel into electricity. They also have the useful attribute that they transport CO_2 across the cell from one electrode to the other. This can be used to separate CO_2 from a dilute gas stream and produce a more concentrated CO_2 stream so it can form the basis of a CO_2 capture system. We were able to build on previous published work in this field [6,7, 8,9,10].

Unconverted fuel and hydrogen is carried in the CO_2 rich stream exhausted from the MCFC anode. Heat is recovered from this stream before the CO_2 is separated by condensation and the unconverted fuel and hydrogen is recycled to the MCFC anode. Details of the scheme are shown in Figure 2 and Figure 3.

3.3. High-pressure solvent absorption from high-pressure exhaust gas from pressurized combustion / power generation

An approach to tackling the low partial pressure of CO_2 in gas turbine exhaust gas is to feed the absorber with exhaust gas from the gas turbine combustor where it is at high pressure. Such a system [11] reported in Figure 4, offered by Sargas was used as the starting point for process modelling and cost estimating in this case. The GE-LMS100 intercooled gas turbine was used as a basis of design and a hot potassium carbonate process used as the capture technology [12,13]. The gas turbine is split so that one section comprising the compressor, high-pressure and intermediate-pressure expander stages provides pressurized hot exhaust gases to the HRSG. The exhaust gases, still at a pressure of around 8 bar, are decarbonised in the hot potassium carbonate process located downstream of the heat recovery section. Finally, the decarbonised exhaust gases are re-heated in the heat recovery section before passing to the second section of the gas turbine, where the gases are expanded in a low pressure turbine.

3.4. High-pressure solvent absorption supported by exhaust gas compression

Compressing exhaust gas to increase the partial pressure of CO_2 and help solvent absorption has been proposed as a way to improving the performance and economics of post-combustion CO_2 capture. A particular example proposed by Partnering in Innovation[14,15,16,17] uses the physical solvent properties of pure water to absorb CO_2 from exhaust gas which has been compressed to 60 barg. Due to the absorber height and structural requirements, it is placed in a 600 m deep water-filled well. This process exploits the hydrostatic pressure of the absorber and the gas-lift pumping technique to circulate the water. The CO_2-lean exhaust gas is heated and expanded in order to recover mechanical power. Different integration options of such a capture technology with the combined cycle power plant were assessed with the aim of maximizing the energy recovery while limiting CO_2 emissions. One option is shown in Figure 5.

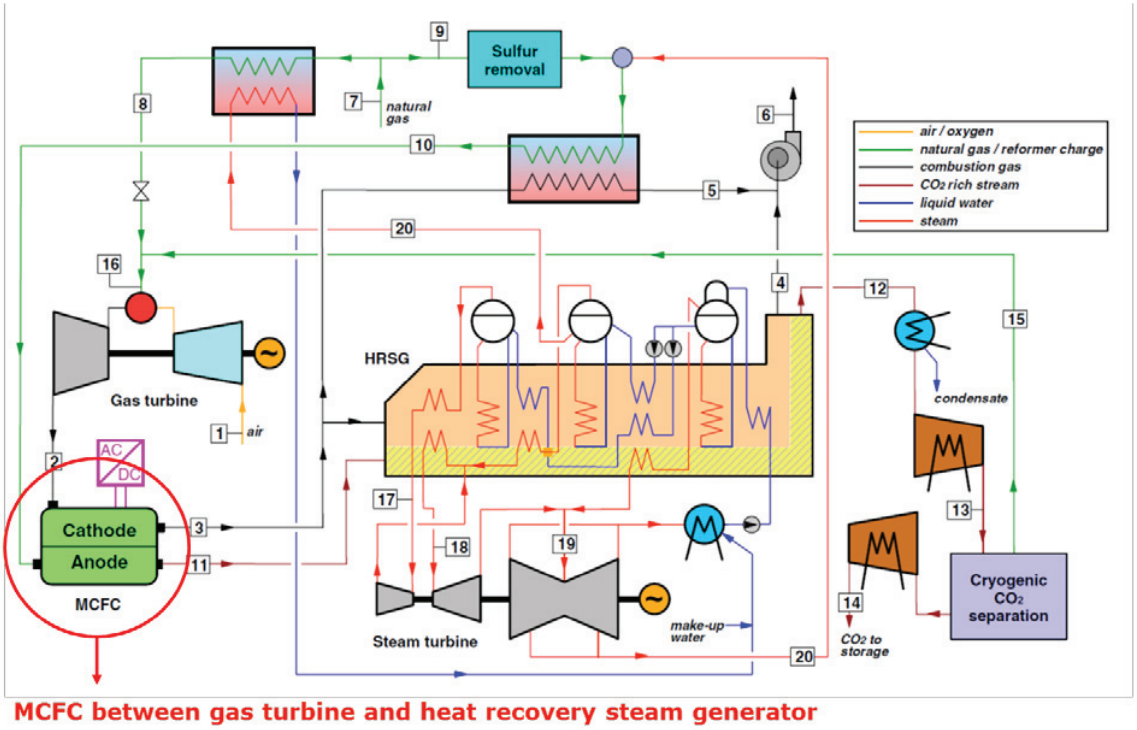

Figure 2 - Capture scheme using molten carbonate fuel cells, details of integration.

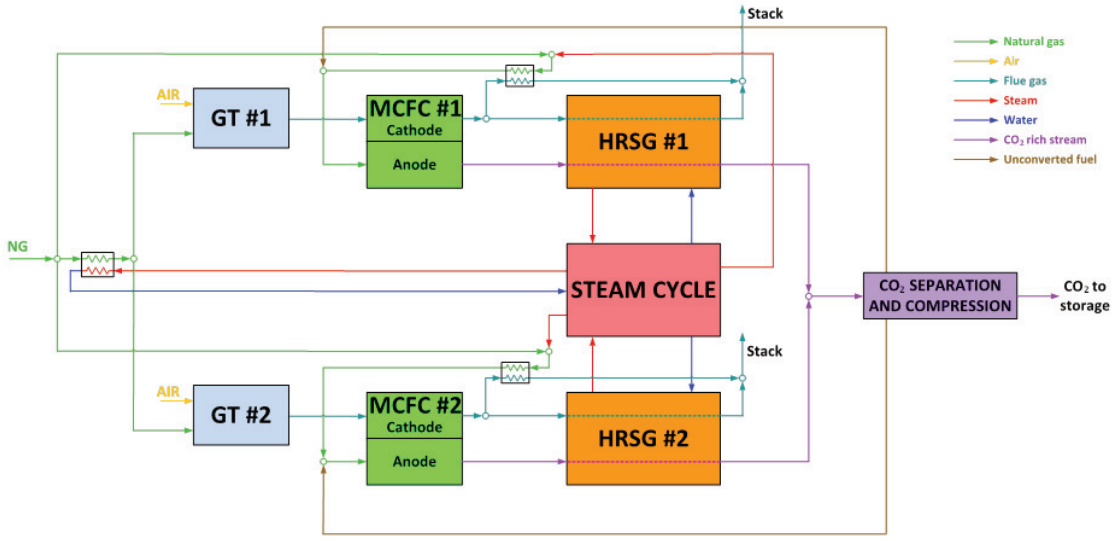

Figure 3 - Capture scheme using molten carbonate fuel cells, overall process with the combined cycle

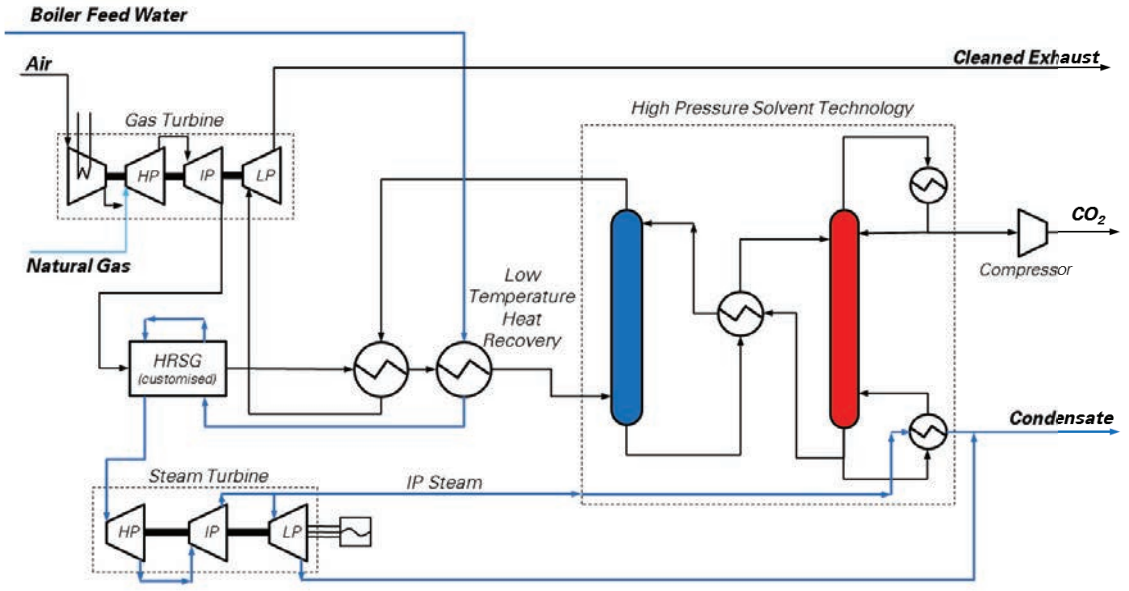

Figure 4 - High-pressure solvent absorption integrated with high pressure combustion.

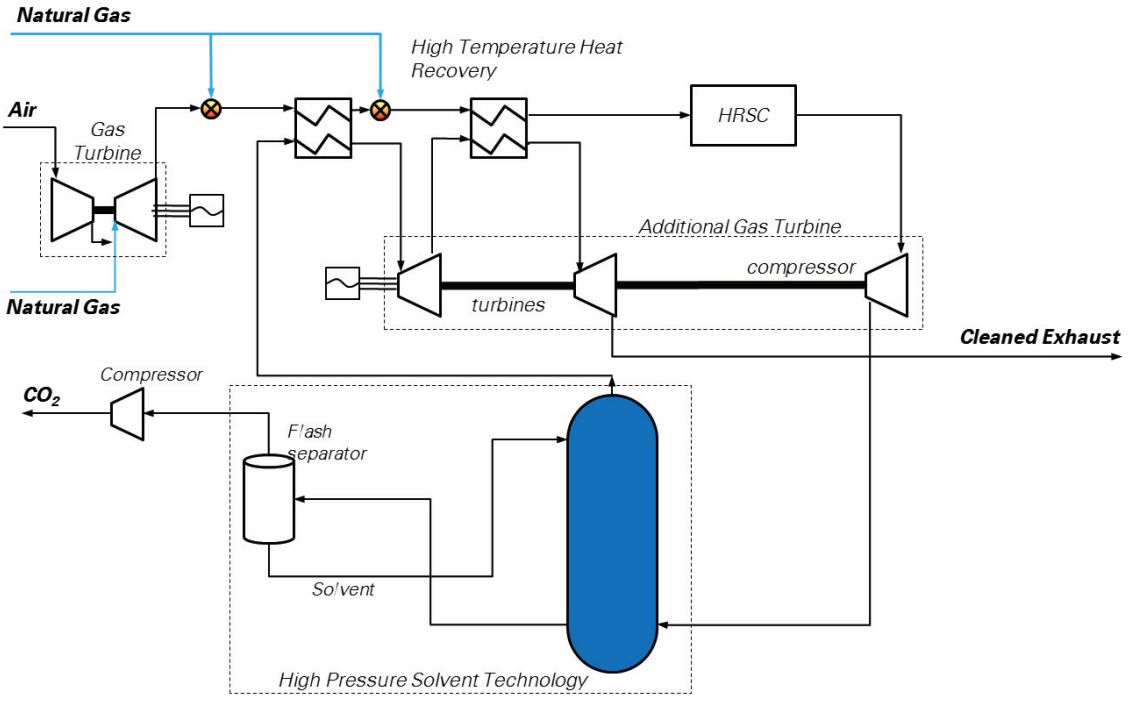

Figure 5 - High-pressure solvent absorption supported by exhaust gas compression

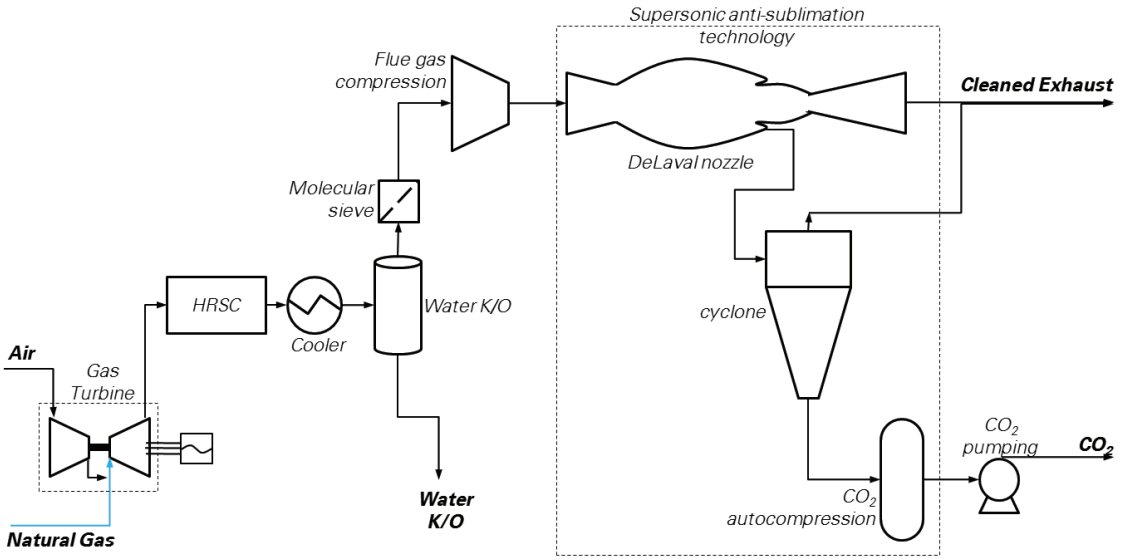

Figure 6 - CO2 capture by supersonic flow-driven deposition

3.5. Supersonic flow-driven CO_2 deposition

A distinctively different approach to CO_2 capture is depicted in Figure 6 and offered by Orbital ATK and Acent Laboratories [18,19,20,21,22,23]. Compressed exhaust gas is accelerated through a convergent/divergent nozzle to supersonic speed. The acceleration decreases the flow temperature causing the deposition of the CO_2 which is collected by inertial separation. Integration of this concept with the combined cycle power plant was modelled and costs estimated. This technology is at a lower technology readiness level compared to other cases reported in this paper. Given the significant uncertainty which still affects the assumptions on performance and costs, the outcome of this assessment should be treated just as an indication of the potential of this technology.

4. Results and Discussion

The results of the integration and performance modeling for the best cases for each of the technologies are summarised for comparison in Table 3.

The MCFC case is the only one which is able to show an efficiency improvement compared to the base case.

The MCFC case shows the increased fuel consumption and the additional power generated directly by the MCFC and also in the steam turbine from steam produced by heat recovery from the MCFC exhaust. Whilst the capture rate is somewhat less than the base case, the net electrical efficiency is considerably better at 57% LHV. The high electrical efficiency of the MCFC coupled with what is in effect a substantially lower energy requirement to separate the CO_2 from the exhaust gas stream compared to the amine solvent in the base case combine together to produce a net efficiency which is very close to the reference plant.

The Supersonic Flow-Driven CO_2 Deposition case and the CO_2 Selective Membrane case are similar in terms of overall energy penalty and net electrical efficiency around 49% LHV. Both cases are fundamentally electrically-powered CO_2 separation processes which require similar driving force. It is likely that both processes would perform better and consume less energy if either the concentration of CO_2 in the exhaust gas was greater or if a lower CO_2 capture rate was targeted.

Table 3 - Novel capture technology energy comparison

Case name	Gross power generated		CO_2 capture power & auxiliaries			Net power output	Fuel use (LHV)	CO_2 avoided	Net electric efficiency (LHV)
	Gas turbine	Steam turbine	CO_2 comp'r power	Other users	Power generation				
	MW_e	MW_e	MW_e	MW_e	MW_e	MW_e	MW_{th}	%	%LHV
NGCC (no capture)	544	293	0	7	0	830	1423		58 %
NGCC + Amine	544	216	23	28	0	710	1423	90 %	50 %
CO_2 permeable membranes	543	341	25	132	0	728	1518	88 %	48 %
Molten carbonate fuel cell	543	323	26	38	179	981	1710	79 %	57 %
High-pressure combustion with solvent capture	0	385	21	17	84	430	1087	85 %	40 %
High-pressure solvent with exhaust gas compression	544	293	78	719	939	979	2575	85 %	38 %
Supersonic deposition technology	544	293	1	144	0	692	1423	88 %	49 %

In this evaluation exercise the high pressure solvent cases both have similar net electrical efficiency around 40% LHV which is not competitive with the base case at 50% LHV.

The results of the capital cost estimation for each of the technologies are summarised for comparison in Table 4.

The cost estimate is broken into three categories. The power island and CO_2 removal section all feature conventional equipment. In each case the new technology section includes the characteristic new equipment and the cost estimate for that section was heavily dependent on the literature references which were simply scaled-into the estimate without specific contingencies.

Table 4 - Novel capture technology equipment cost comparison

Case Name	Total Plant Costs				
	Power Section	CO_2 Removal Section	New Technology Section (low certainty)	Total	Total Specific Plant Costs
	M$ (2014)	M$ (2014)	M$ (2014)	M$ (2014)	$ / kW (2014)
NGCC + Amine	854	694	0	1548	2181
CO_2 permeable membranes	1033	466	198	1697	2332
Molten carbonate fuel cell	915	426	488	1803	1839
High-pressure combustion with solvent capture	544	101	115	760	1767
High-pressure solvent with exhaust gas compression	879	217	1501	2597	2652
Supersonic deposition technology	879	239	493	1611	2329

Of all the alternative technology cases the High Pressure Combustion with Solvent Capture case has the lowest amount of novel technology and the specific capital cost is the lowest. This reflects the nature of the technology which is new integration of units which are fundamentally known and mostly proven.

The MCFC case also has a lower specific capital cost than the base case, though it should be noted that the new technology section accounts for more than 25% of the total capital cost.

The remaining three cases all have specific capital costs which exceed the base case.

The results of the specific cost of CO_2 avoided for each of the technologies are summarised for comparison in Table 5.

Table 5 - Novel Capture technology summary table

Case Name	Net electric efficiency % (LHV)	Total Specific cost 2014$ /kW	Avoided Cost $ / T $CO_{2\ avoided}$	Advantages	Disadvantages
NGCC (no capture)	58	1059	-		
NGCC + Amine	50	2181	75		
CO_2 permeable membranes	48	2332	86	Modular	High Capital costs
Molten carbonate fuel cell	57	1839	55	High efficiency, modular	Integration with NGCC
High-pressure combustion with solvent capture	40	1767	87	Mostly proven components, low capital cost,	Low efficiency, not retrofittable
High-pressure solvent with exhaust gas compression	38	2652	127	No integration risks with combined cycle plant,	Low efficiency, high capital cost
Supersonic deposition technology	49	2329	82	No integration risks with combined cycle plant	Low TRL

The MCFC case has the lowest specific cost of CO_2 avoided which is 25% lower than the base case. The other alternative technology cases all come in with avoided costs which exceed the base case due to the combination of lower efficiency and mostly higher capital costs.

5. Conclusions

CO_2 capture from natural gas-fired power generation presents challenges due to the low pressure and concentration of CO_2 in the exhaust gas. Five alternative technologies to amine solvent absorption have been evaluated and the possible advantages and disadvantages of each are discussed. Insights to guide further development may be summarised as follows:

5.1. CO_2 permeable membranes

Analysis of the results shows that the membrane material needs improvement particularly in terms of permeability to allow CO_2 capture with lower energy penalty and membrane area. The membrane module cost used in the capital cost estimation is much lower than current cost and is based upon future mass production of the material and module packaging. The operating costs assume that the membrane material is durable and capable of long service life. Analysis suggests that the minimum avoided cost for this technology may be found at a substantially lower capture rate than the 90% which was targeted in this assessment. The technology could be particularly suited to smaller scale applications where solvent systems may be less cost-effective. Further study of

this technology could investigate performance at lower capture rates, and study the optimum conditions needed by the membrane material.

5.2. Molten carbonate fuel cells

In this evaluation this technology was shown to be a strong performer in terms of efficiency and capital cost, however a large proportion of the capital cost estimate is dependent on the new technology, where there is low certainty on the figures. The MCFC cost used in the capital cost estimation is much lower than current costs and is based upon future mass-production of the stack components and packaging. The operating costs assume that the electrodes and electrolyte are resistant to degradation and capable of long service life. The MCFC integration with the combined cycle needs development and demonstration.

5.3. High-pressure combustion with solvent capture

This technology for the most part relies on the integration of fundamentally proven CO_2 capture processes and power plant components, though nevertheless development and demonstration are still required. The low capital cost and low efficiency could make the technology favoured in circumstances where fuel prices are lower.

5.4. High-pressure solvent capture with exhaust gas compression

This technology has challenges in this application from the low partial pressure of CO_2 in the exhaust gas. It appears that CO_2 may not have particularly good selectivity or solubility in water at the absorber conditions and therefore costly and energy intensive compression equipment used to overcome these deficiencies significantly limit the economic potential.

5.5. Supersonic flow-driven CO_2 deposition

This technology has challenges in this application from the low partial pressure of CO_2 in the exhaust gas. Physical property verification may be required to support the development of design and to improve the confidence in process modelling and to support advancing the readiness level of this technology, which is currently low for this application.

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