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Economics of 1st, 2nd, and 3rd Gen CCS technologies

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Duncan Leeson, Jamie Fairclough, William Brown and Michael O'Connell did the actual work…

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Overview

Overview of talk

Introduction

Discussion of methodology

CCS on Power – LCOE

CCS on Industry – Cost of CO_2 avoided

Limitations of the study

Suggestions for necessary research

CCS proposed as one part of the solution

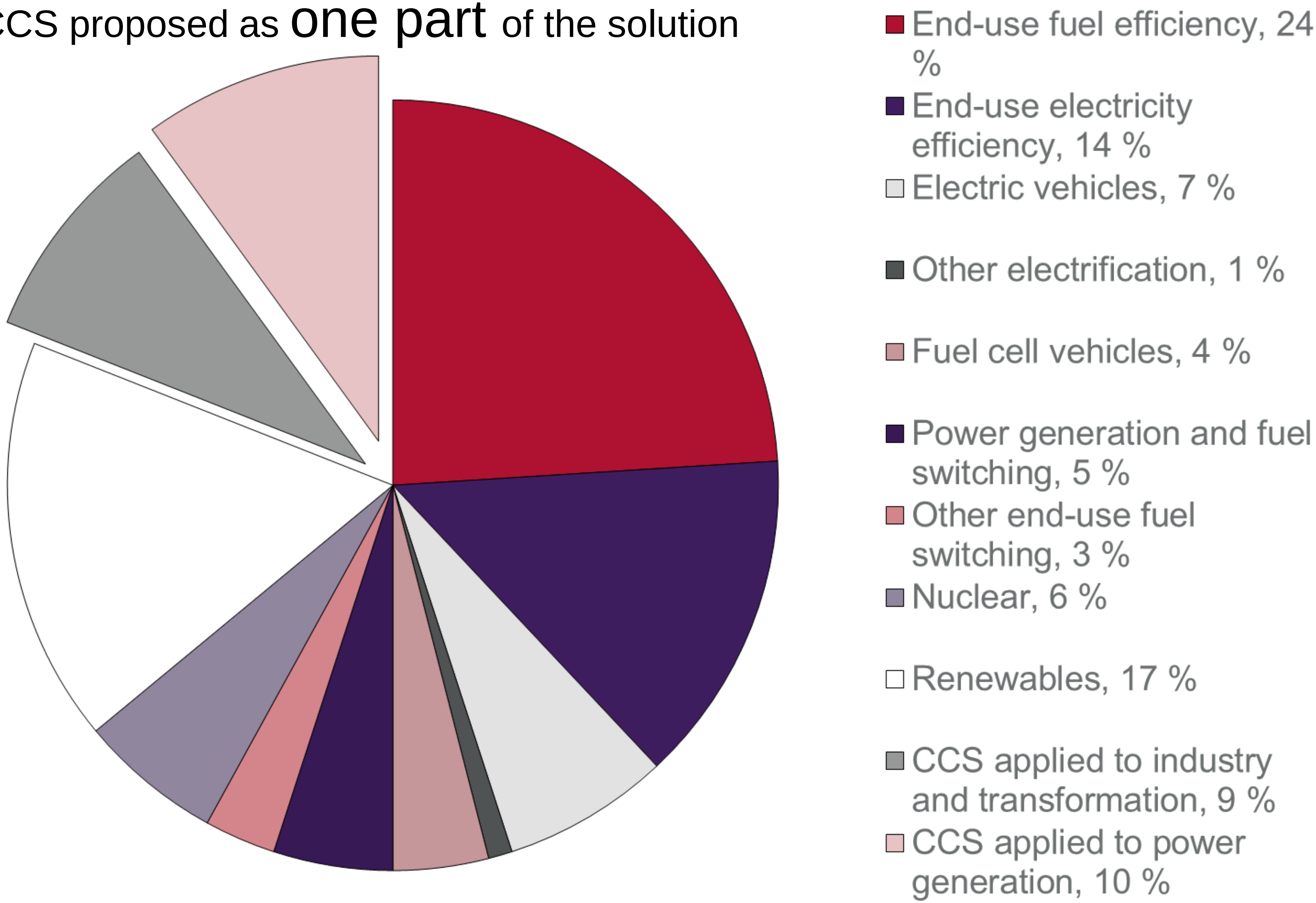

Figure. Total low-cost GHG reduction in 2050 (43 Gt) according to the IEA Energy Technology Perspectives

Definitions… It depends on who you ask

What is a 1st Generation Technology?
APGTF – Short term: 0 – 10 years away

MEA or Oxyfuel – IGCC?
CCS from concentrated industrial sources

What is a 2nd Generation Technology?
APGTF – Medium Term: 7 – 15 years

Improved solvents, Ca looping?

What is a 3rd Generation Technology?
APGTF – Long term: 10 – 20 years away

MOF, Chemical Looping, NOHMs

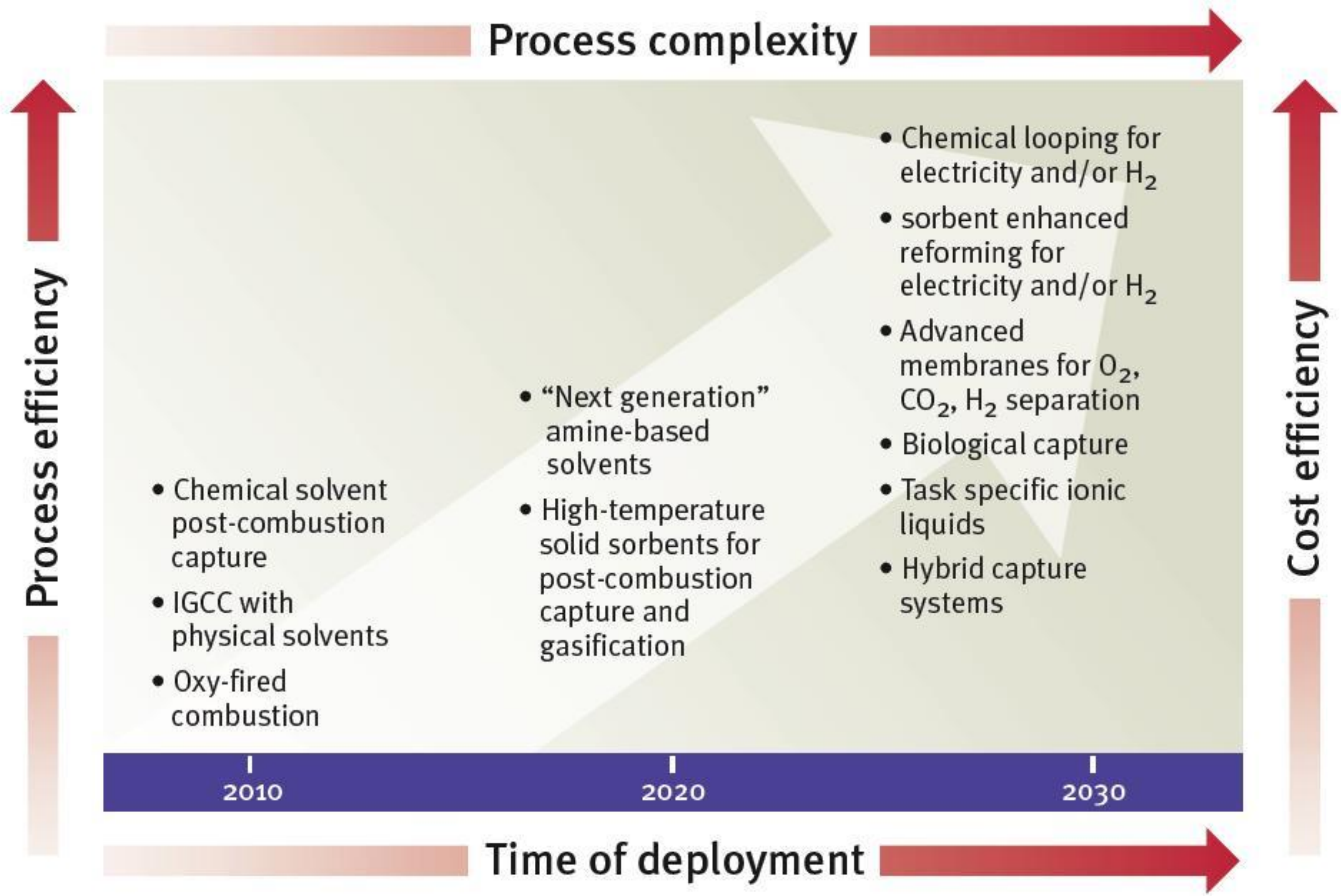

Figure. Likely technology adoption trajectory after Figueroa et al (2008)

Figueroa JD. Fout T. Plasynski S. McIlvried H. And Srivastava RD. Advances in CO2 capture technology–The U.S. Department of Energy's Carbon Sequestration Program International Journal of Greenhouse Gas Control 2 (2008) 9–20

Technology readiness levels

TRLs	Status
Applied and strategic research	
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof of concept
4	Technology / part of technology validation in a laboratory environment
Technology validation	
5	Technology / part of technology validation in a working environment
6	Technology model or prototype demonstration in a working environment
System validation	
7	Full-scale technology demonstration in working environment
8	Technology completed and ready for deployment through test and demonstration
9	Technology deployed

Developed by NASA and adapted by the UK Advanced Power Generation Technology Forum

Methodology

Systematic Review

- Define search term
- Refine search terms until a certain number of papers are included in the search (around 500)
- Read all abstracts and summarise potential relevance via a questionnaire – Rank as High/Medium/Low
- Full papers for all High relevance studies read
- Further key references (e.g. original papers where results are quoted in the paper read) are included
- Economic data is extracted, converted to USD at the prevailing exchange rate and a capital cost escalator used to bring all data to a common cost year (here 2013).

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Systematic Review

Advantages:

Removes Bias

A wide range of papers are included

Does not require an intimate knowledge of the field

Disadvantages:

A lot of work compared to traditional literature reviews

May miss key, well known references (but see “removes bias”)

Can miss non academic references

For the work presented here, over 1000 abstracts were read and categorised.

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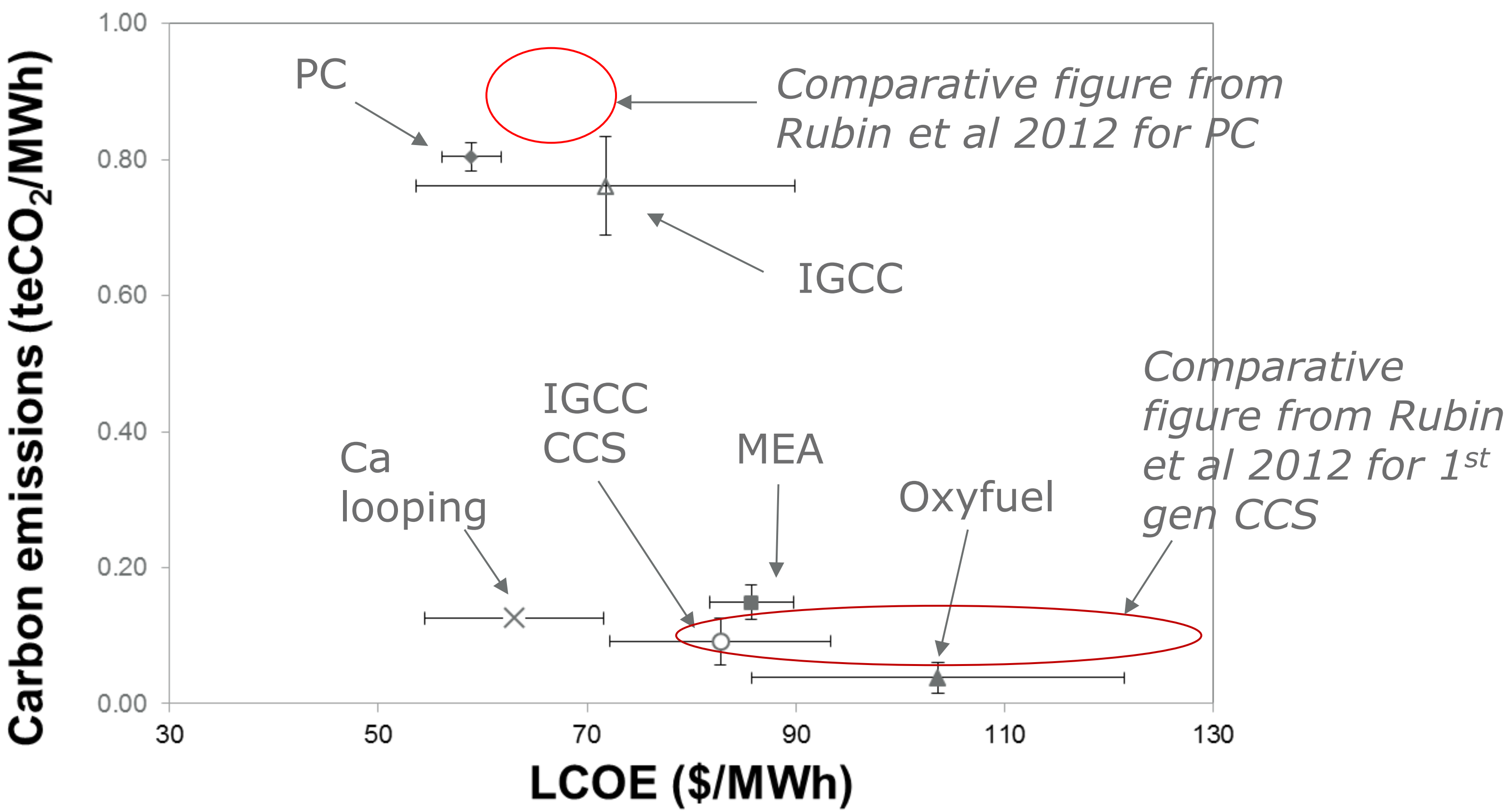
Systematic Review - Electricity

	Number of high relevance papers reviewed		Strength of Evidence		
Technology	Academic Database Searches	Reviewer additions	Technical	Economic	Policy
Amine	33	6	Strong	Strong	N/A
Oxy fuel	24	4	Strong	Strong	N/A
IGCC CCS	21	3	Strong	Strong	N/A
Calcium looping	13	2	Medium	Medium	N/A
Chemical looping	8	2	Medium	Weak	N/A
Policy	32	3	N/A	N/A	Strong

Search terms refined until 619 abstracts located. All abstracts read and categorised – 196 high relevance papers located, with 89 categorised as "highest" relevance (full paper read).

LCOE for a number of Technologies



Not including compression and transport costs
MEA error bars reflect better agreement – more industrial experience
Potentially, lower costs represent less fully developed knowledge

Major Findings

Costs were only included where a full CCS plant model was developed, integrated with a power plant.

Unsurprisingly, the largest number of studies investigated oxyfuel or amine scrubbing.

In general, oxyfuel had a LCOE slightly higher than MEA scrubbing, though the results had greater variability.

IGCC had huge variation in costs calculated – even when CCS was not applied.

Ca looping was the most studied of the 2^{nd} / 3^{rd} generation technologies, and generally had the lowest prices. However, many studies referred one or two initial studies for dual CFB costs; lack of independence in the field.

Owing to the huge variations in baseline cases, it was not possible to reliably convert the costs to a cost of CO_2 avoided.

Large effect of discount rate / financial assumptions noted.

Industrial CCS

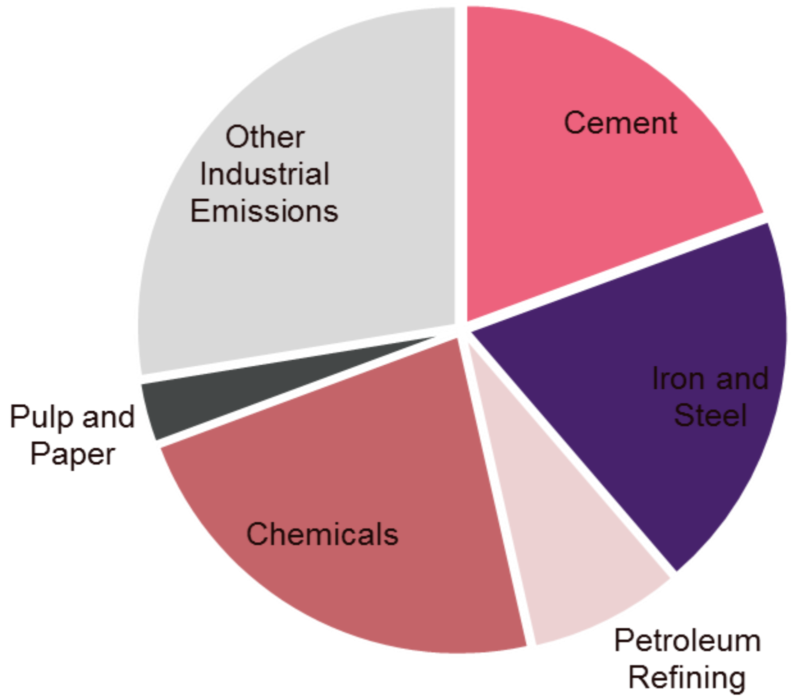
Comparison of Industrial Sectors

The four largest CO_2 emitting industrial sectors make up almost 75% of industrial emissions.

The sectors discussed in terms of industrial processes are iron and steel production, petroleum refining, chemical manufacturing, cement manufacture and pulp and paper production

- Chemical manufacture and petroleum refining were amalgamated in this study due to the similar nature of the boilers which CO_2 would be captured from.
- The pulp and paper industry was also investigated due to the large potential for carbon capture in this sector

Global Direct Industrial Emissions (Mt per annum)



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Systematic Review Process - Industrial

Search

- Initial search terms were drawn together to cover the major technological areas of CCS, policy and costs
- Search terms were entered into three academic databases
- Results were recorded, and search terms customised to return a selection of relevant papers; in this case, 525.

Summarise

- All abstracts were screened and non-relevant papers were discarded according to agreed criteria
- All 262 papers deemed relevant in the initial screening were read, summarized and prioritised
- A questionnaire was formulated to allow all relevant data from the papers to be classified

Analysis

- Papers were sorted by industry and information regarding technology, policy or cost noted in questionnaire and compared where applicable
- In order to directly compare capital costs and produce meaningful cost analysis, a cost escalator model was constructed to convert all costs to 2013 US Dollars

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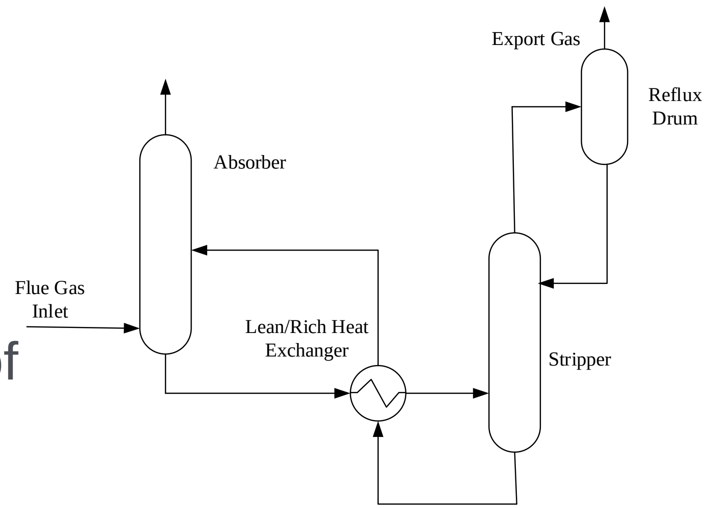
Main Technological Options for Industrial Carbon Capture

Post Combustion Capture through Amine Solvents

- Amine-based solvents such as MEA and MDEA can strip CO_2 from flue gases with capture efficiencies of >99%,
- This gives a waste gas stream of very high purity CO_2
- Can be easily retrofitted onto existing plants
- Generally high cost of regenerating the solvents, which are often toxic and corrosive



Main Technological Options for Industrial Carbon Capture

Chemical/Metal Looping Technologies

- Operate by repeated reaction and regeneration of a metal oxide or CaO.
- High temperatures are needed to regenerate the solid sorbent.
- Problems with solid transport and **attrition**, and loss of activity of sorbent over time

- Particular synergy where heat or steam is being produced using natural gas as a fuel, or (Ca-looping) in cement manufacture

Main Technological Options for Industrial Carbon Capture

Oxyfuel Combustion

- By burning fuels in pure oxygen (plus recycled CO_2) instead of air, the flue gas is almost pure CO_2.
- Can provide heat for boilers and furnaces, e.g. in iron and steel mills
- Using a smaller volume of oxygen then air means that process equipment can be smaller, so lower capital costs (oxyfuel in cement plant)
- Requires large, energy intensive air separation unit

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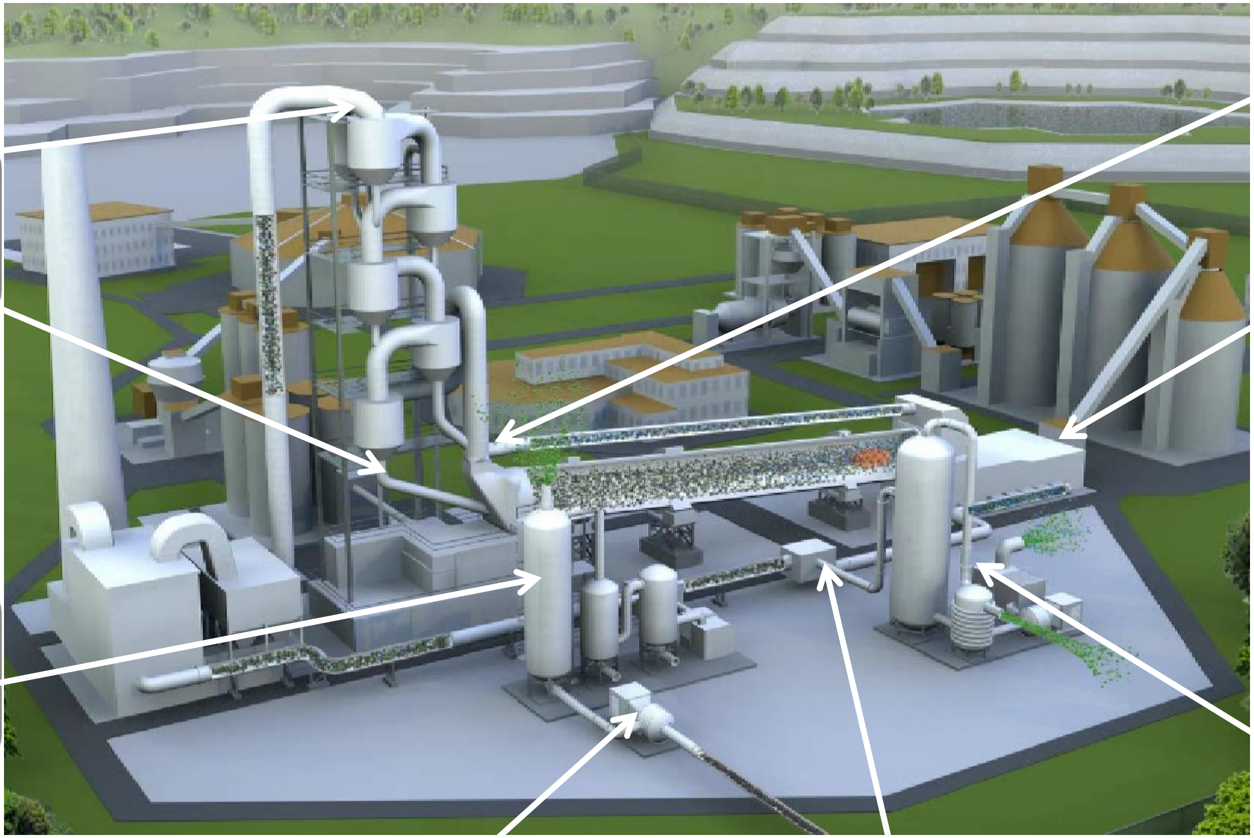
Oxy-fuel process in cement plant



http://www.ecra-online.org/

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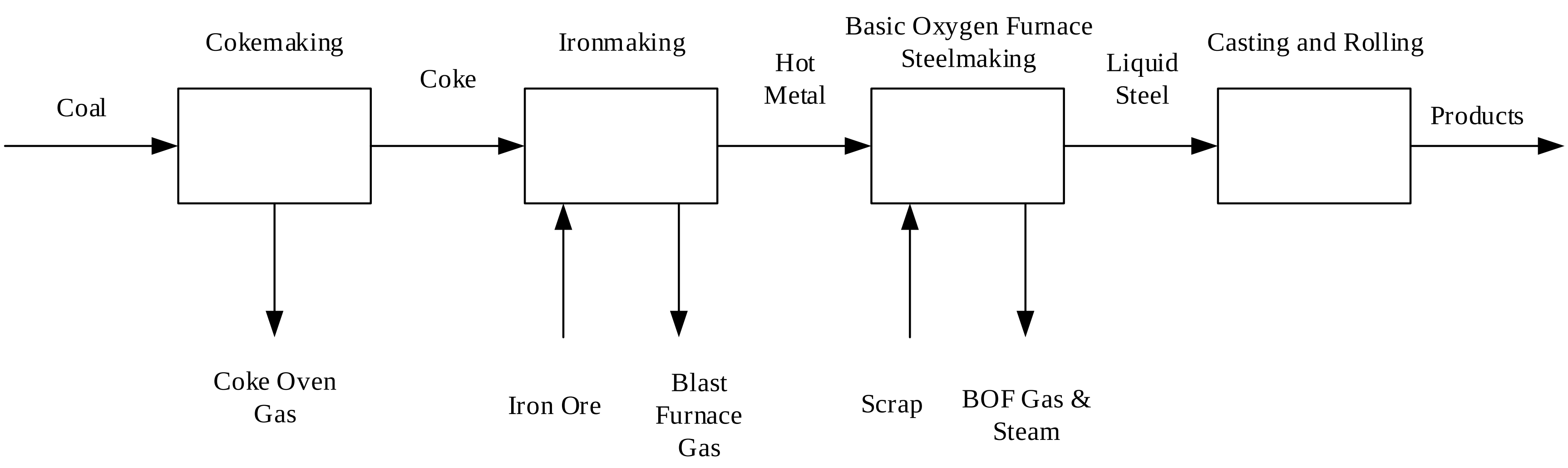
Main Technological Options for Industrial Carbon Capture

Other technologies

- Mineral carbonation of waste slags forms stable carbonates on reaction with CO_2, although a limited capture potential and low TRL
- Biological systems using bacteria or algae to capture CO_2 are still in early development
- Membranes to directly separate CO_2 from flue gases have been trialled, but little cost data for large scale use exists
- Formation of hydrate compounds on reaction with CO_2 which can be filtered out of flue streams

Carbon Capture on Iron & Steel Production Facilities

- Large point-sources of CO_2 mean that the iron and steel industries are comparatively well suited to having carbon capture implemented on them.
- Waste process heat can be used in regeneration of the amine sorbent, reducing the energy cost associated with post combustion capture technologies through heat integration



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Carbon Capture on Iron & Steel Production Facilities

- Vast majority of research regards using amine sorbents for post combustion capture
- Post combustion using MEA found to cost between $59-116/tCO_2$ on different plant items, such as the coke oven and blast furnace
- Using a shift reactor and a Selexol amine solvent, carbon capture reported to cost 24-27$ per tonne captured.
- Potential for use of steel waste slags for mineral carbonation, though large variations in reported costs and very low capture potential

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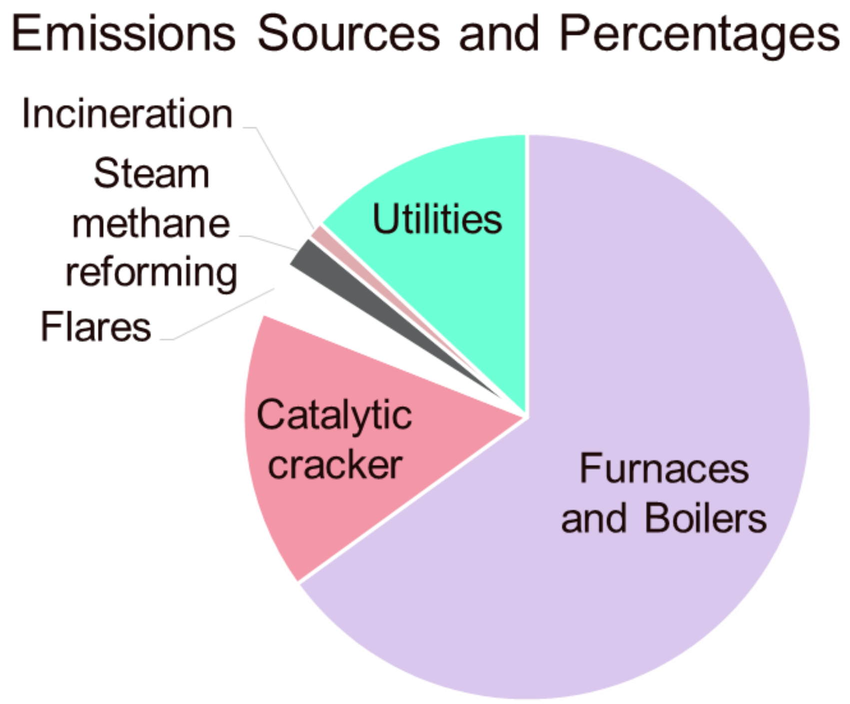
Carbon Capture on Petroleum Refineries and Chemical Manufacturing

- 60% of emissions from the industry come from various furnaces and boilers, with utilities making up about half of the remainder
- This means that CCS will struggle to reduce emissions greatly unless applied to multiple point sources at a vastly increased cost
- Nature of refineries as long serving process plants means that retrofit potential (as with amine scrubbing) is an important factor for plant owners



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Carbon Capture on Petroleum and Chemical Refineries

- Post combustion amine capture ranges in cost from $69 -123 depending on capture location and method, with the preferred location a combined stack able to mitigate about 50% of emissions

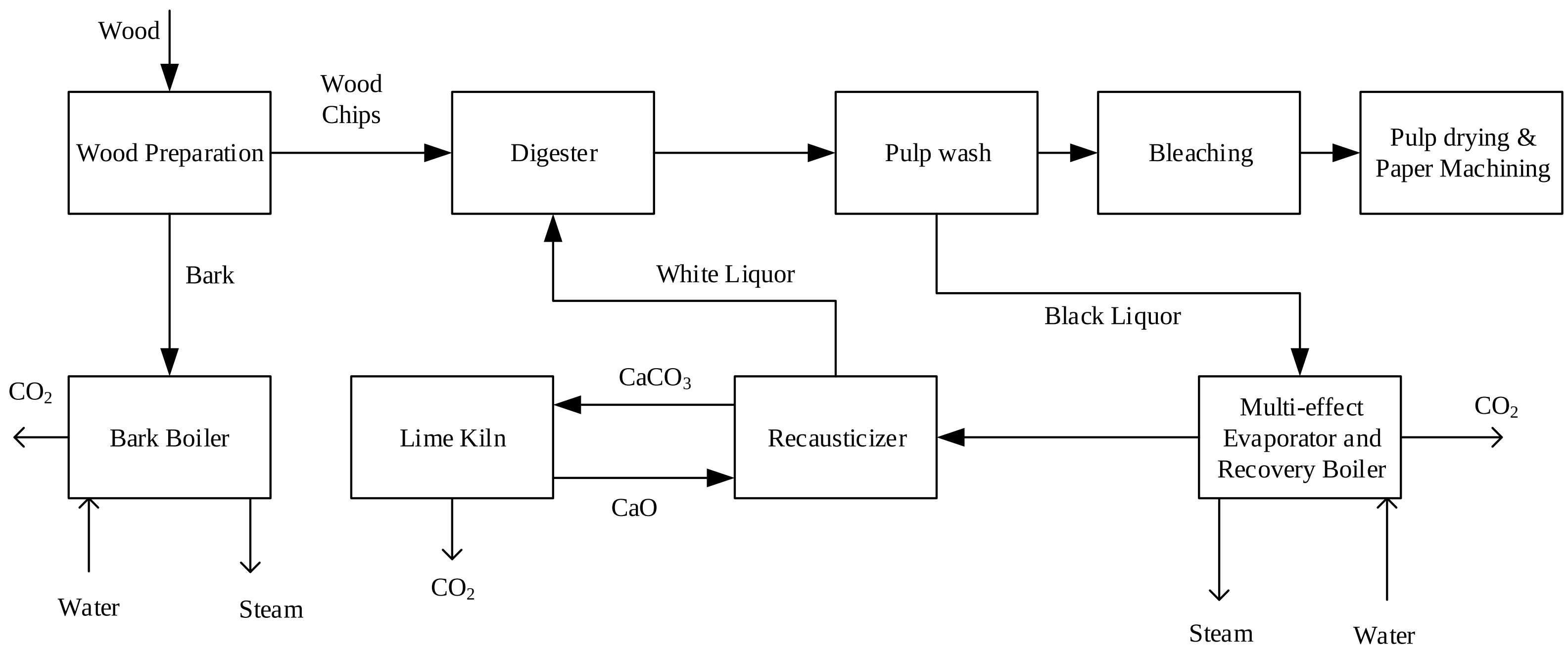
- When applied to a gasifier, post combustion capture can be effected for the lower cost of $41 per tonne, but with a capture potential limited to 15% of plant emissions.

- Oxyfuel combustion can capture a higher proportion of the CO_2 at a cost of $65/t$CO_2$ which can be used to mitigate emissions from various plant items at the same time

- Chemical looping can be applied to the refinery boilers at costs of $44-58 per tonne depending on the solid replacement rate active in the system

Carbon Capture on Pulp & Paper Production Facilities

- Research into retrofitting post-combustion CCS onto large boilers.
- New plants will utilise black-liquor gasification technologies to reduce emissions and can be combined with post-combustion capture
- Pulp and paper mills are often located away from other industries in sparsely populated countries, such as Sweden or Finland



Carbon Capture on Pulp & Paper Production Facilities

- Small volume of research available, with both papers that discuss costs considering post-combustion capture of boilers
- Boiler flue gas captured at cost of $15 per tonne on a standard plant for 62% of CO_2 captured
- Black liquor gasification process used followed by amine capture gives a higher cost of $34 but with a capture potential of over 90%.
- Potential for significantly higher transport costs due to isolated location not considered here but may make process economics significantly less favourable

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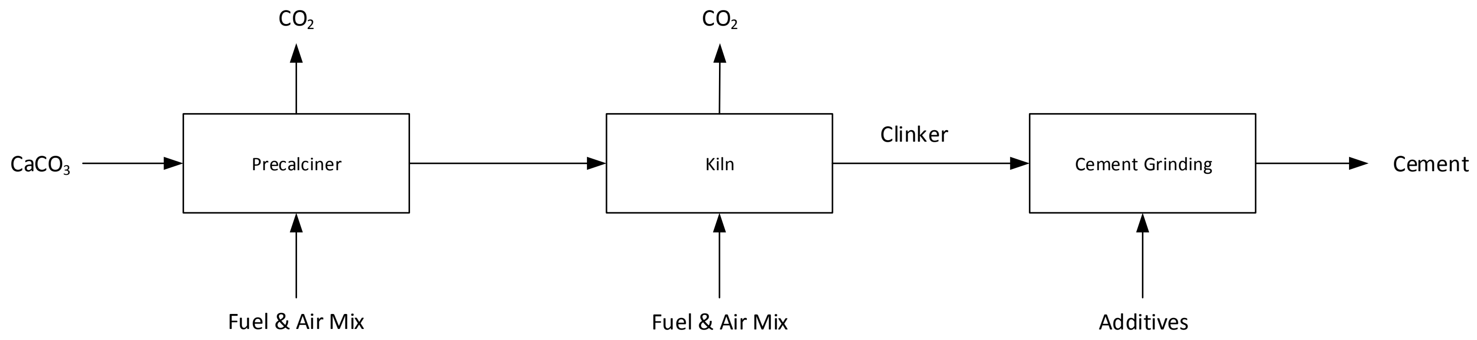
Carbon Capture on Cement Plants

- 5% of all global CO_2 emissions can be attributed to the cement manufacture process.
- Within the process, 60% of the emissions are due to the calcination reaction and the other 40% attributable to combustion for heat generation
- Hence pre-combustion can only capture a maximum of 60% of emissions, though with energy costs this is reduced to around 52%
- Impurities in the flue stream such as SO_2 and dust can cause amine scrubbing units to have high heat duties and necessitate a high degree of solvent regeneration due to side reactions

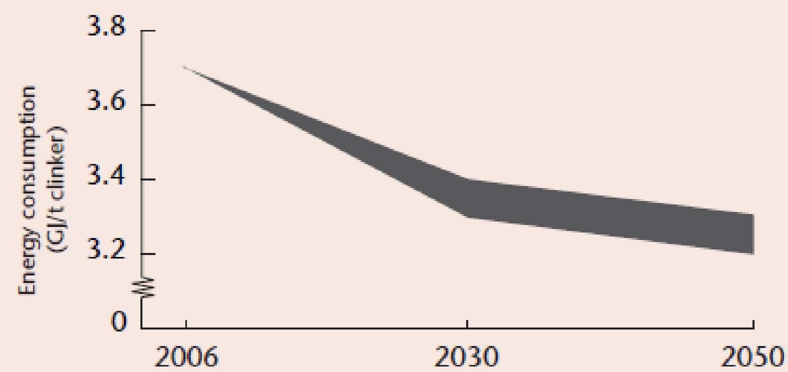


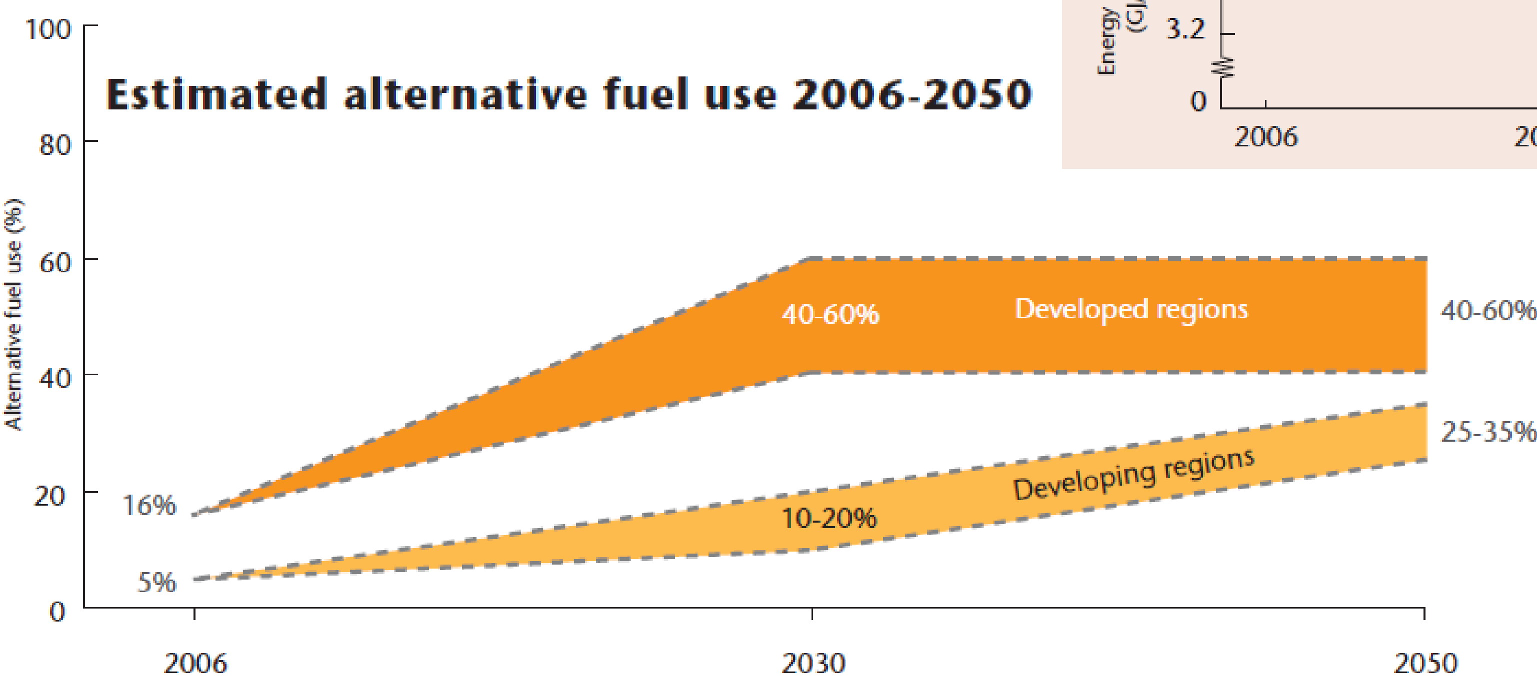
Potential mitigation options

Clinker content:
78% (2006) → 71% (2050)

Thermal efficiency

Thermal energy consumption for clinker manufacture in different years:





Source: WBCSD/IEA Cement Roadmap, 2011

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Carbon Capture on Cement Plants

- Two major technologies costed for cement plants – amine post-combustion capture and calcium looping
- Research near-evenly split between the two technologies
- Post combustion capture has an estimated capture cost of $106 per tonne for cement plants
- Calcium looping technologies average at $38 per tonne, though are less developed
- Oxy-combustion has been investigated and estimated at an average cost of $55 per tonne.

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Cost Comparisons for Industrial Processes

	Iron and Steel		Refineries		Pulp and Paper		Cement	
	Cost (USD 2013)	Number	Cost (USD 2013)	Number	Cost (USD 2013)	Number	Cost (USD 2013)	Number
Post-combustion	74.23	5	77.60	5	24.73	2	106.53	3
Oxy-combustion	N/A	0	65	1	N/A	0	59.46	1
Mineralisation	62.50	2	N/A	0	N/A	0	N/A	0
Calcium Looping	N/A	0	51	1	N/A	0	37.78	4

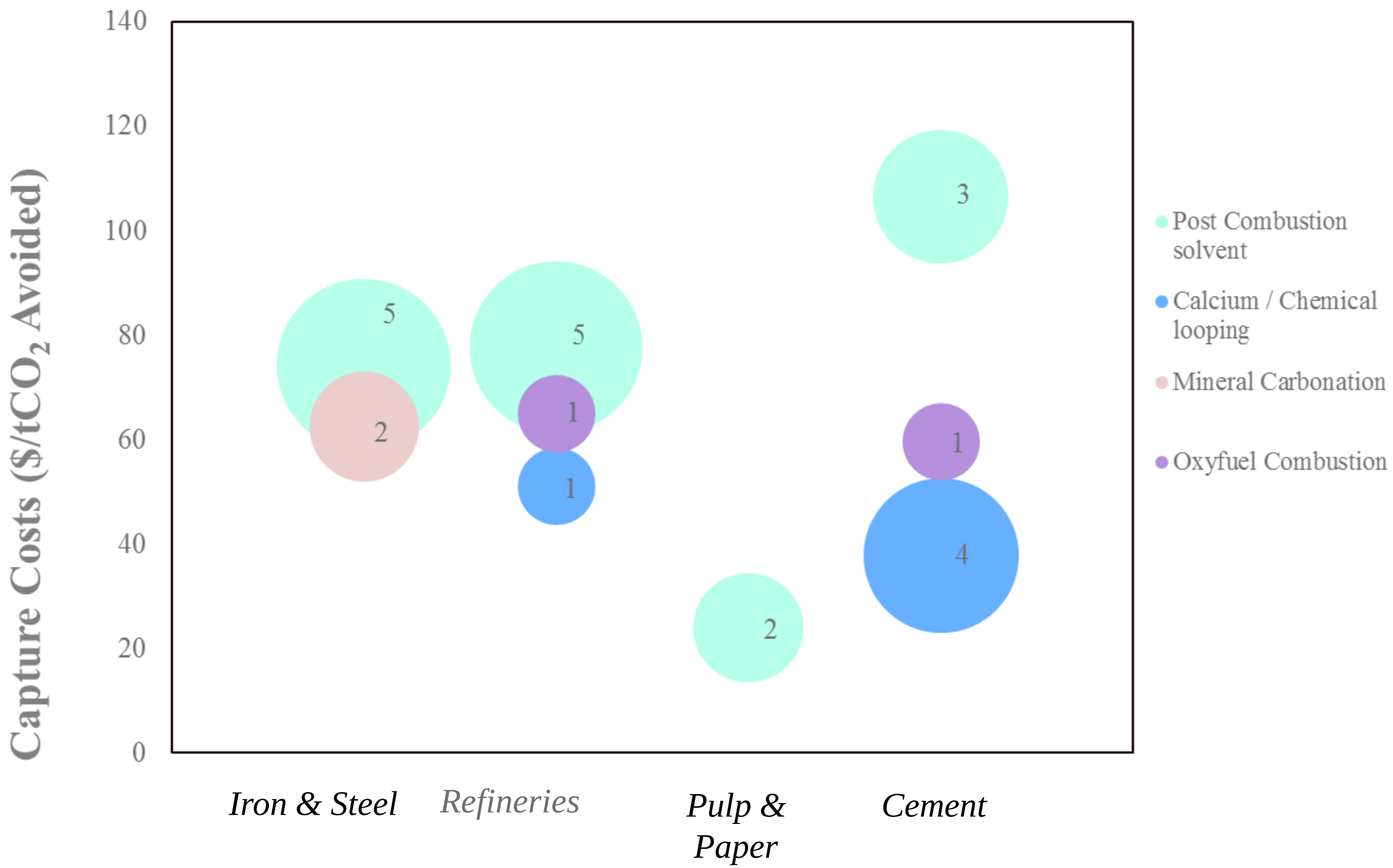
Figures from UNIDO 2011 (rebased)

	Iron and Steel		Refineries		Pulp and Paper		Cement	
	Low	High	Low	High			Low	High
	64.8	86.4	48.6	129.6			59.4	162

Unido includes transport and storage, and a wide range of future techs (HIsarna / Finex for iron making, etc).

Unido technology roadmap for industrial CCS 2007. United Nations Industrial Development organisation. http://www.unido.org/fileadmin/user_media/Services/Energy_and_Climate_Change/Energy_Efficiency/CCS/CCS_Industry_Roadmap_WEB.pdf

Relative Abundance of Cost Information for Industrial Carbon Capture



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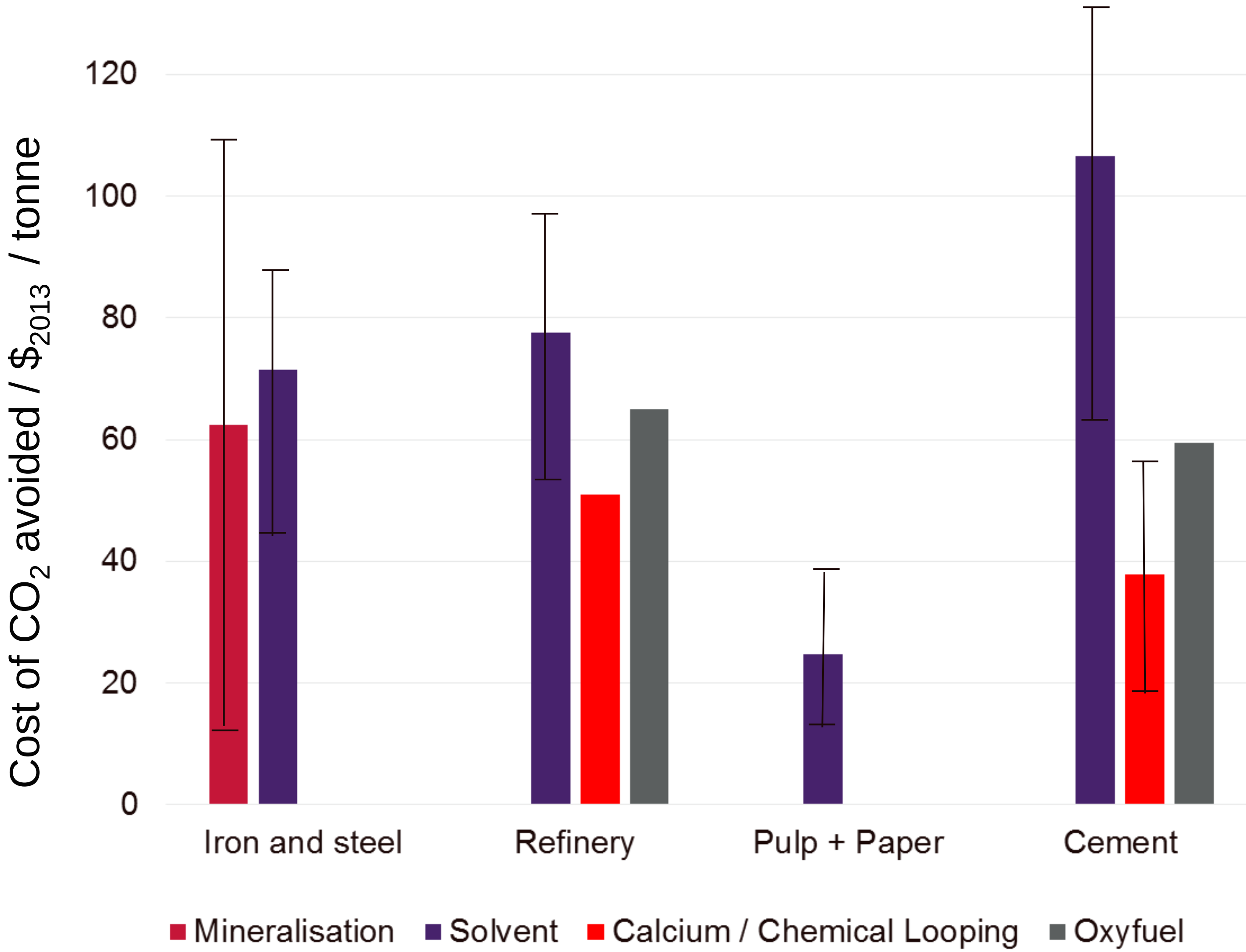
Cost Information for Industrial Carbon Capture (including Standard Deviation)



Error bars are not shown for single values

Note – huge error bars for mineralisation – factor of 10 difference between 2 studies

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Major Findings

Costs were only included where a full CCS plant model was developed, integrated with the industrial process of interest.

Post combustion solvent scrubbing was most prominent, but a large number of studies of cement with Ca looping

Solvent scrubbing frequently the most expensive option investigated – for cement, this is because there is insufficient low-grade heat available onsite – a CHP plant is necessary (though partial capture up to 50 % may be a cheaper, more viable option).

Where the aim is purely to produce heat, and gas is currently burned, chemical looping is an excellent choice. (unless pressurised, CLC with natural gas is a non-starter on the grounds of efficiency, for power generation).

But – don't forget that post-combustion capture using solvents has the big advantage of not having any potential adverse effects on the clinker.

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Comparison / Power and Industrial CCS

- Cost of Capital was one of the major determinants, for both power and industrial CCS, of profitability.

- Post combustion amine capture is comparatively cheaper for power production than when applied to industrial CCS (excepting pulp and paper – though limited number of studies).

- Calcium looping is low in cost for both sectors, with particular applicability to cement CCS.

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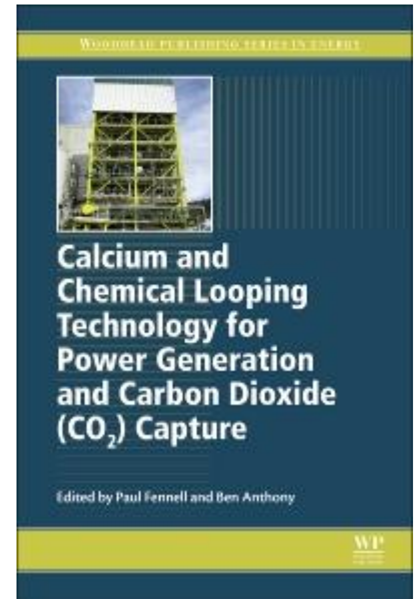
Non systematic – comparison between Ca looping and Chemical Looping

Chemical Looping

Authors	Cost / 2013 USD (low	high)	
Melein and Roijen (2009)	43.86		Refinery boiler (low replacement)
Melein and Roijen (2009)	56.97		Refinery boiler (high replacement)
Lyngfelt and Linderholm (2013)	15.42	33.74	Power station (extreme range)
Lyngfelt and Linderholm (2013)	24.10	25.06	Power station (likely range)
Morin et al (2006)	12.53	17.35	Power station
ZEP (2011)	24.77		Rebasing of Morin et al according to ZEP guidelines

Calcium Looping

Authors	Cost / 2013 USD (low	high)	
MacKenzie et al (2007)	30.43		Pressurised CFB
Cormos (2014)	33.10		Gasifier gas, precombustion
Cormos (2014)	36.80		Gasifier gas, post-combustion
Abanades et al (2007)	15.20		Power station
Romeo et al (2009)	17.76		Power station
Romeo et al (2011)	16.62		Power station + cement works
Rodriguez et al (2012)	21.93		Cement works



Shameless plug for new book

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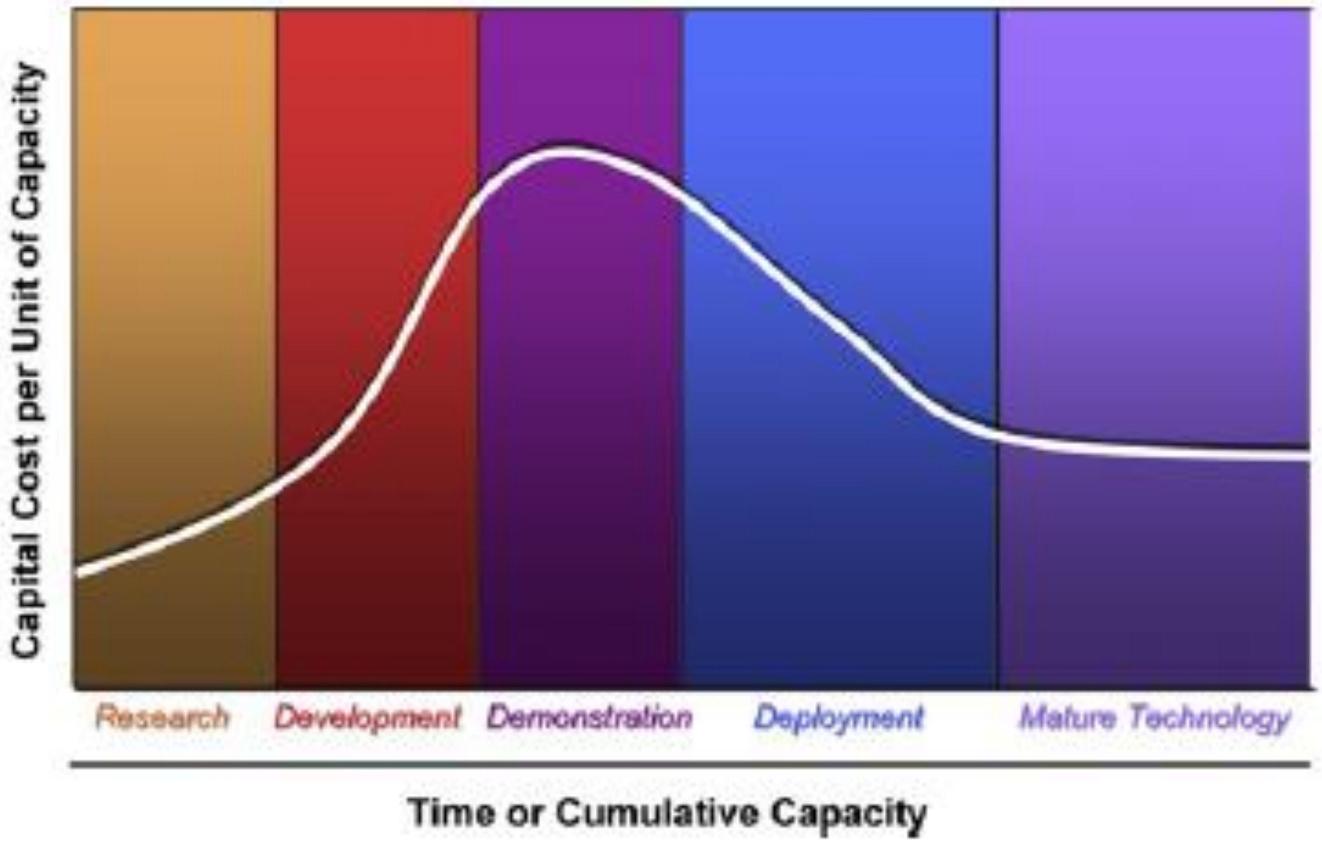
Issues with the studies / Future work needed

- A number of technologies are missing from the analysis, which now requires broadening to include them. In particular, low temperature solid sorbents need specifically investigating.
- CCS for natural gas sweetening has not been included.
- The methodology employed does not allow for significant improvements in technologies with time – though in many cases there are insufficient studies to allow comparison.
- One major finding is that there are simply not enough independent studies of different CCS technologies applied to industry, and not enough technoeconomic studies of new sorbents in realistic process models.
- **All work – must give both the unindexed costs, CAPEX / OPEX, etc and assumptions, etc plus any financial models. Too much variability in financial assumptions for cross-technology comparison, even before differences of baseline technological assumptions.**

Technological development pathway



(From Rubin et al 2012)

Rubin is pessimistic, and thinks that many novel processes will never get over the hump – they will be beaten by more mature technologies, even if sub-optimal. Personally, I think it all depends on a decent forward carbon price.

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Final word on Economics

Oil prices rise 6% as Saudi Arabia bombs Yemen rebels

2 hours ago | Business

The airstrikes came after Iran-backed rebel groups marched on the port city of Aden

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Future Work Required

Clearly set out techno-economic studies comparing a large number of different technologies, on different industries, with common cost assumptions.

The US is starting to do this, but progress in industrial CCS is very slow.

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UKCCSRC Phase 2 – Advanced Sorbents for CCS via Controlled Sintering

UKCCSRC Phase 2 – UK Demonstration of Enhanced Calcium Looping and First Global Demonstration of Advanced Doping Techniques

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EPSRC Engineering and Physical Sciences Research Council

UKCCS RESEARCH CENTRE

Research Councils UK Energy For a Low Carbon Future

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Further References

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