Evaluating technology options to mitigate greenhouse gas emissions

Cost of CO_2 Capture in the Industrial Sector: Cement and Iron and Steel Industries

IEAGHG Technical Review
2018-TR03
September 2018

IEA GREENHOUSE GAS R&D PROGRAMME

International Energy Agency

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 30 member countries and beyond. Within its mandate, the IEA created Technology Collaboration Programmes (TCPs) to further facilitate international collaboration on energy related topics. To date, there are 38 TCPs who carry out a wide range of activities on energy technology and related issues.

DISCLAIMER

The IEA GHG TCP, also known as the Technology Collaboration Programme on Greenhouse Gas R&D, constitutes an autonomous and independent framework within the International Energy Agency (IEA) network, and consists of one or more IEA member country. Views, findings and publications of the IEA GHG TCP do not necessarily represent the views or policies of the IEA Secretariat or all its individual member countries

This report was prepared as an account of the work sponsored by IEAGHG. The views and opinions of the authors expressed herein do not necessarily reflect those of the IEAGHG, its members, the organisations listed below, nor any employee or persons acting on behalf of any of them. In addition, none of these make any warranty, express or implied, assumes any liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product of process disclosed or represents that its use would not infringe privately owned rights, including any parties intellectual property rights. Reference herein to any commercial product, process, service or trade name, trade mark or manufacturer does not necessarily constitute or imply any endorsement, recommendation or any favouring of such products.

COPYRIGHT

Copyright © IEA Environmental Projects Ltd. (IEAGHG) 2018. All rights reserved.

ACKNOWLEDGEMENTS AND CITATIONS

This report was prepared as an account of the work sponsored by IEAGHG and IEA.

The report was prepared by:
- Monica Garcia (IEAGHG)
- Niels Berghout (IEA)
- Laura Herraiz (University of Edinburgh and IEA secondment)

To ensure the quality and technical integrity of the research undertaken by IEAGHG each study is managed by an appointed IEAGHG manager.

The IEAGHG manager for this report was:
- Monica Garcia

The reviewers for this report were:
- Araceli Fernandez Pales (IEA)
- Samantha McCulloch (IEA)
- Cecilia Tam (IEA)
- Keith Burnard (IEAGHG)
- Tim Dixon (IEAGHG)

The reviewers of the methodology developed within this report were:
- Niall Mac Dowell (Imperial College London)
- Andrea Ramirez (TU Delft)

The report should be cited in literature as follows:
'IEAGHG, "Cost of CO_2 Capture in the Industrial Sector: Cement and Iron and Steel Industries", 2018-TR03, September, 2018.'

Further information or copies of the report can be obtained by contacting IEAGHG at:

IEAGHG, Pure Offices, Cheltenham Office Park, Hatherley Lane, Cheltenham, GLOS., GL51 6SH, UK
Tel: +44 (0)1242 802911
E-mail: mail@ieaghg.org Internet: www.ieaghg.org

COST OF CO_2 CAPTURE IN THE INDUSTRIAL SECTOR: CEMENT AND IRON AND STEEL INDUSTRIES

Executive Summary

This study gives an overview of the cost estimates of implementing carbon capture technologies in the cement and iron and steel sectors based on a comprehensive review of available literature. Given the potential of carbon capture as a decarbonisation option in industry, the communication of techno-economical estimations of carbon capture systems is essential. This work has reviewed and discussed high quality studies. Findings show significant differences in the costing methods and heat integration frameworks used from one study to another and a new methodology to homogenise literature results is given. Those outputs can support policy makers, energy-economic models, and cement and iron and steel industries particularly. Additionally, it can inform future research on areas for improvement.

This work was divided in three phases. Firstly, a high-level screening process of publications coming from academia, industry and other organisations, was undertaken to determine the quality and origin of the data, depth of the technical and economic analysis and transparency on the assumptions and method used.

Secondly, key input parameters were standardized to represent a North West European context. Materials and energy flows were standardized for an average plant, built on similar plant size, capacity factor, grid CO_2 intensity, power equivalent factor and CO_2 compression outlet pressure. Economic parameters were standardized through a described new cost approach, which is based on an aggregation method, and supported on homogeneous energy/fuels price, labour costs, contingencies cost and plant economic lifetime. Capital costs (CAPEX) and operational costs (OPEX) are given as increase of those over a reference case (as ΔCAPEX, ΔOPEX). The cost metrics are CO_2 avoidance cost ($\$_{2016}$/ t CO_2 avoided), CO_2 capture cost ($\$_{2016}$/ t CO_2 captured) and increase of cost of products manufacturing ($\$_{2016}$/ t cement, $\$_{2016}$/ t steel).

And thirdly, due to the heterogeneity of reported waste heat available and potential for selling the energy surplus, several cases were re-assessed under two scenarios: absence of available waste heat and inability of exporting energy to the electricity grid.

For the iron and steel sector, our findings show a broad range of CO_2 avoidance costs across the different steel manufacturing routes as well as capture technologies and configurations. For the traditional production configuration, blast-furnace based process, CO_2 capture through vacuum pressure swing adsorption (VPSA) was found to be the most cost effective, with CO_2 avoidance cost of 52 $\$_{2016}$/t$CO_2$. An advanced configuration over the blast furnace-based process (BF) comprises recirculating the fluegas and operating under oxyfuel conditions, called top gas recycling oxygen blast furnace (TGROBF). Incorporating CO_2 capture to this advanced configuration has been considered as an hybrid system. In that case, adding VPSA is still the cheapest option at full capture rate, 52 $\$_{2016}$/t$CO_2$, compared to adding chemical absorption, (56-82 $\$_{2016}$/t$CO_2$). In the long run, advanced smelting reduction (HIsmelt) and COREX, in combination with VPSA, were found to be the most cost-effective solutions, 52 and 34 $\$_{2016}$/t$CO_2$ respectively. However, in practice, VPSA has not been tested at large scale and could present mechanical challenges offered by working under vacuum. While chemical absorption is the most advanced technology, it is not the cheapest for any of the steelmaking routes, at 56-93 $\$_{2016}$/t$CO_2$. However, the costs are predictively less uncertain. Additionally, in the long term, costs can be reduced by the use of advanced solvents, as calculated for the blast furnace configuration, 52-80 $\$_{2016}/tCO_2$.

For the cement industry, CO_2 avoidance cost figures fall within a smaller range than that in the steelmaking industry, with some solids-based arrangements offering more cost-effective routes, 38-86 $\$_{2016}/tCO_2$. Other promising solutions are oxyfuel (69-86 $\$_{2016}/tCO_2$) and membranes (69-78 $\$_{2016}/tCO_2$), although the former involves deeper modifications to the cement manufacturing process, whereas the latter shows limited emission reduction potential due to its inherent technological characteristics. As in the steelmaking process, chemical absorption is the most technology mature solution, although it shows high avoidance cost, 72-180 $\$_{2016}/tCO_2$. Using advanced solvents seems to offer significant potential for improvement at similar or lower costs than other capture alternatives, 61 $\$_{2016}/tCO_2$. In contrast, hybrid technologies (indirect calcination combined with chemical absorption) show high costs, 199 $\$_{2016}/tCO_2$ and potentially offer additional challenges arising from the individual capture technologies and operating them in combination.

The large overlap in CO_2 avoidance cost ranges observed between the various capture technology groups and configurations makes it difficult to determine the “best” technology for each sector. Large-scale projects are required not only to obtain more reliable and accurate data, but also to identify operational issues and inform R&D on possible avenues to improve the performance of capture technologies as well as their integration with the manufacturing process. This study identified differences on the level of cost details from one study to another, which is often a function of the maturity level of the technologies assessed. As a technology becomes more mature, and as more cost data becomes available, a higher cost is often reported, which is not observed in emerging technologies.

Summary of results obtained in this work

COST PARAMETER	**SCENARIO**	**Cement**						**Iron and Steel[g]**			
		Traditional chemical absorption	**Advanced chemical absorption**	**Membranes**	**Oxyfuel**	**Solids-based**	**Hybrid[d]**	**Traditional chemical absorption**	**Advanced chemical absorption**	**VPSA**	**Hybrid[e]**
CO_2 avoidance cost ($\$_{2016}$/ t CO_2 avoided)	**BASIS**	72-180	61	69-78	69-86	38-86	199	56-82	52-80	34-52	65-135
	No-heat-recovery	77-215	91	69-78[a]	69-86[a]	64-348	261	56-119	28-70	34-52[a]	81-135
	No electricity export	72-215	61	69-78[b]	69-86[b]	38-91	199[b]	69-93	12-37[f]	34-52[b]	52-90
CO_2 captured cost ($\$_{2016}$/ t CO_2 captured)	**BASIS**	34-79	45	51-57	50-63	11-63	146	16-21	7-16	11-14	23-66
	No-heat-recovery	34-93	59	51-57[a]	50-63[a]	21-68	171	17-30	7-18	11-14[a]	33-66
	No electricity export	36-101	45	51-57[b]	50-63[b]	20-67	146[b]	7-23[f]	3-9[f]	11-14[b]	33-44
Increase of manufacturing cost [c] ($\$_{2016}$/ t cement or steel)	**BASIS**	46-116	20	39	38-39	26-40	94	54-93	74-76	30-45	69-86
	No-heat-recovery	46-116	26	39[a]	38-39[a]	37-65	110	54-117	77-78	30-45[a]	69-86[a]
	No electricity export	49-116	20	39[b]	38-39[b]	40-74	94[b]	39-117[f]	36-37[f]	30-45[b]	69-86[b]

[a] Those cases do not include waste heat available to recover

[b] Those cases do not include revenue from electricity export

[c] At full CO_2 capture rate on the treated fluegas. To note that the increase of manufacturing cost ($\$_{2016}$/ t cement or steel) was calculated based on the reference without CO_2 capture included in each study.

[d] Indirect calcination combined with MEA-based chemical absorption

[e] Oxyfuel combined with traditional chemical absorption or VPSA

[f] Note that a lower cost is seen in the "no electricity export" scenario compared to the "basis" scenario. That is one of the limitations of the cost method. The energy cost is reported as increase of energy cost compared to a reference case. When there is not electricity export, the increase of energy cost becomes zero as the cost method does not reflect any difference between investing the energy on the capture system and having energy surplus that cannot be sold (reference).

[g] This economic review included several steelmaking configurations (Blast furnace, HIsmelt, Corex). This table is an overview and has not been divided by technology or by fluegas treated (BFG, BOFG, CHPG, COG, SGPG, LKPG, SRVG)

Glossary

BF	Blast furnace	**LKP(G)**	Lime Kiln Plant (gas)
BFG	Blast furnace gas	**LS**	Liquid steel
BFHS	Blast furnace hot stove	**MDEA**	Monodiethylethanolamine
BOF(G)	Basic oxygen furnace (gas)	**MEA**	Monoethylethanolamine
CCS	Carbon Capture and Storage	**PP(G)**	Power Plant (gas)
CEMCAP	Acronym of "CO_2 capture from cement production" project	**PZ**	Piperazine
CHP(G)	Combined Heat and Power unit gas	**SGP(G)**	Steam generation plant (gas)
CLEANKER	Acronym of "Clean Clinker production by Calcium looping process" project	**SRV(G)**	Smelt Reduction Vessel (gas)
CO(G)	Coke Oven (gas)	**STEPWISE**	Acronym of "SEWGS Technology Platform for cost effective CO_2 reduction in the Iron & Steel Industry"
CO2STCAP	Acronym of "Cutting the Cost of CO_2 Capture in Process Industry"	**TGROBF(G)**	Top Gas Recirculation Oxygen Blast Furnace (gas)
COG	Coke Oven Gas	**ULCOS**	Acronym of "Ultra- Low CO_2 Steelmaking"
COPP	Coke oven power plant	**VPSA**	Vacuum Pressure Swing Adsorption
LEILAC	Acronym of "Low Emissions Intensity Lime And Cement" project		

Contents

1. Introduction

1.1 Background

Manufacturing industry and refineries are major contributors to global CO_2 emissions. In 2014, those sectors were responsible for 24% (8.3 Gt) of direct CO_2 emissions, coming from both fuel combustion and industrial processes. Among the industrial subsectors, cement and iron and steel manufacturing are the largest emitters, accounting for 28% and 27% of the direct CO_2 emissions within both sectors, respectively (IEA, 2017a). In the absence of strong climate policies, the CO_2 emissions from those sectors are expected to rise over the coming decades (IEA, 2017a,b).

To limit average global temperature increase to well below 2°C above pre-industrial levels, as agreed in the UNFCCC's Paris Agreement, deep CO_2 emissions reductions across the industry sector are required (IEA, 2017a,b). Several carbon-intensive subsectors, like cement and iron and steel, show few alternatives to CCS for making significant emissions reductions. However, CO_2 mitigation options like energy and material efficiency, fuel switching, renewable energy are insufficient to reach the ambitious abatement goals. The IEA's beyond 2 degree Celsius scenario which explores least-cost decarbonisation pathways, shows that CCS accounts for around 40% (42 $GtCO_2$) and about 25% (26 $GtCO_2$) of the cumulative CO_2 emissions reductions projected in the cement and iron and steel sectors over the period 2014-2060 if future temperature increases are to be limited to 1.75 °C by 2100 (IEA, 2017a).

1.2 Overview of key literature and recent R&D projects (2013-2017)

Several studies on the technical and economic feasibility of carbon capture technologies in the cement and iron and steel sectors have been published. However, as highlighted in Leeson et al. (2017) and Kuramochi et al. (2012), while most of those are informative, do not contain detailed information on the cost methodology and or the data and assumptions underlying the analysis.

Table 1 and 2 contain the capital costs reported in the selected studies on CO_2 capture technologies in the cement and iron and steel sectors (see the methodology section for more information on the studies screening method). The reported costs range from 206 M$ $_{2010}$ to 5296 M€ $_{2013}$ for the iron and steel sector, and from 51 M€ $_{2014}$ to 595 M$ $_{2007}$ for the cement sector[1]. It should be noted that the results are based on different technical assumptions, currencies and geographical locations.

---

[1] Note that those studies include new construction and retrofitted cases, covering multiple plant sizes, locations, configurations, capture rate and source of fluegas to be treated.

Table 1 Systematic review of techno-economic studies on CO_2 capture applied to the Iron and Steel sector.

CO_2 capture technology	Details	Fluegas	Energy consumption (GJ/tCO_2)			Capture rate (%)	Capital Cost	Currency	Location	References
			Fuel	Steam	Electricity*					
Blast Furnace										
Chemical absorption (MEA)	New construction	BFHS, SGP	9.52	0	0	90	5036 (TCR)	M€ $_{2013}$	Europe (NL)	IEAGHG 2013 (a)
Chemical absorption (MEA)	New construction	COP, BFHS, LKP, SGP	9.58	0	0	90	5296 (TCR)	M€ $_{2013}$	Europe (NL)	IEAGHG 2013 (a)
Chemical absorption (MEA)	Retrofit	PP, BFHS	0	0	0.56-1.25	From 9 to 89	69.81-234.12 (TCR)	M€ $_{2012}$	Finland	Tsupari et al. (2015)
Chemical absorption (MEA)	Retrofit. Steam and electricity from a gas CHP plant with CCS	BF, PP	0	0	0.47	90	412.02	M$ $_{2010}$	Australia	Ho et al. (2013)
Chemical absorption (MDEA)	Retrofit	COP, BFHS, PP	4.03	0	0.54	95	699 (Total spent cost)	M$ $_{2011}$	USA	NETL (2014)
VPSA	Retrofit. Steam and electricity from a gas CHP plant with CCS	BF, PP	0	0	0.29	90	227	M$ $_{2010}$	Australia	Ho et al. (2013)
Top Gas Recycling Blast Furnace (TGRBF)										
Oxyfuel	Retrofit. NGCC power plant, including Steam Generation Plant (gas boiler)	OBF	9.8	0	0	90	4877 (TCR)	M€ $_{2013}$	Europe (NL)	IEAGHG (2013a)

0Oxyfuel+VPSA	Retrofit. Electricity from the grid	BF, OBF	1.63	0	1.4	74	370 (additional investment)	M€ $_{2013}$	Finland	Tsupari et al. (2015)
Oxyfuel	Retrofit. Steam and electricity from a gas CHP plant with CCS	TGRBF, OBF	0	0	0.62	90	298.9	M$ $_{2010}$	Australia	Ho et al. (2013)
Oxyfuel+VPSA	Retrofit. Steam and electricity from a gas CHP plant with CCS	TGRBF, PP	0	0	0.4	90	206	M$ $_{2010}$	Australia	Ho et al. (2013)
<u>Smelting Reduction</u>										
HIsarna										
Chemical absorption (MEA)	Retrofit. Steam and electricity from a gas CHP plant with CCS	RV, PP	0	0	0.66	90	502.15	M$ $_{2010}$	Australia	Ho et al. (2013)
VPSA	Retrofit. Steam and electricity from a gas CHP plant with CCS	RV, PP	0	0	0.46	90	350	M$ $_{2010}$	Australia	Ho et al. (2013)
COREX										
Chemical absorption (MEA)	Retrofit. Steam and electricity from a gas CHP plant with CCS	RV, PP	0	0	0.75	90	475	M$ $_{2010}$	Australia	Ho et al. (2013)
VPSA	Retrofit. Steam and electricity from a gas CHP plant with CCS	RV, PP	0	0	0.42	90	352	M$ $_{2010}$	Australia	Ho et al. (2013)

BF: Blast furnace; BOF: basic oxygen furnace; PP: power plant; TGRFB: Top gas recycling blast furnace; RV: vessel; COP: coke oven plant; BFHS; blast furnace hot stoves; SGP; steam generation plant;

Table 2 Systematic review of techno-economic studies on CO_2 capture applied to the Cement sector.

CO_2 capture technology	**Details**	**Energy consumption (GJ/tCO_2)**			**Capture rate (%)**	**Capital Cost**	**Currency**	**Location**	**References**
		Fuel	**Steam**	**Electricity***					
Chemical absorption									
MEA	Retrofit, new construction. Steam produced with CHP. 15% of required heat supplied with waste heat	7.61	0	-0.16	90	541-545 (TCR)	M€$_{2013}$	Europe (NL)	IEAGHG (2013b)
MEA	Retrofit, new construction. Steam produced with gas boiler. 15% of required heat supplied with waste heat	10.68	0	-1.73	90	440-443 (TCR)	M€$_{2013}$	Europe (NL)	IEAGHG (2013b)
MEA	Retrofit. Steam produced with gas boiler. Waste heat 6MW	3.1-3.3	6-9 *10E^{-5}	0.74-0.81	60-90	286-309 (TPC)	M€$_{2014}$	Norway	Anantharaman et al. (2016)
MDEA	Retrofit. With and without gas pre-treatment	4.44	0	0.49-0.52	95	209-288 (spent)	M\$$_{2011}$	USA	NETL (2014)
MEA	Retrofit. Heat recovery	3.13	0	-0.04	85	210 (TIC)	M\$$_{2012}$	China	Liang and Li (2012)
MEA	Retrofit. 31 MW from waste heat. Gas boiler for remaining heat	0	0	0.15-0.29	42-85	75-120 (Capex)	M€$_{2014}$	Norway	Jakobsen et al. (2017)
Advanced solvents	Retrofit. 31 MW from waste heat. Gas boiler for remaining heat	0	0	0.16	42	79	M€$_{2014}$	Norway	Jakobsen et al. (2017)
MEA	Retrofit. Gas boiler for steam production	2.94	0	0.15	90	270	M€$_{2014}$	Europe	Gerbelova et al. (2017)
MEA	CHP and electricity imported	14	0	-0.31	95	233	M€$_{2014}$	Europe	Ozcan (2014)
Hybrid system (MEA chemical absorption+ external combustor)	New constuction. CHP for steam production	6.4	0	0..79	85	338	M€$_{2014}$	Europe	Ozcan (2014)

Oxyfuel									
Oxyfuel calcinator	Retrofit, new construction. Electricity imported	3.95	0	1.18-1.33	65-90	275-300 (TCR)	M€ $_{2013}$	Europe (NL)	IEAGHG (2013b)
Oxyfuel calcinator	Retrofit. Electricity imported	0	0	0.59	87	217	M€ $_{2014}$	Europe	Gerbelova et al. (2017)
Solids-based									
Indirect calcination	Heat recovery	3.86-4.13	0	From -0.2 to 0.8	46-58	84-395	M$ $_{2007}$ **	Europe	Rodriguez et al. (2011), Diego et al. (2016) , Ozcan (2014)
Double calcium looping	Heat recovery	5.79	0	-0.6	94	595	M$ $_{2007}$ **	Europe	Diego et al (2016)
Calcium looping-oxy CFB Calciner	Heat recovery . New construction	4.84	0	0	89	294	M$ $_{2007}$ **	Europe	Rodriguez et al. (2011)
Calcium looping-oxy CFB calciner and CFB calcinator	Heat recovery. New construction	5.09	0	0	99	352	M$ $_{2007}$ **	Europe	Rodriguez et al. (2011)
Calcium looping (as post-combustion arrangement)	Heat recovery	8.43	0	-0.52	88	183	M€ $_{2014}$	Europe	Ozcan (2014)
Chemical looping	Heat recovery	8.85	0	-1	88	163	M€ $_{2014}$	Europe	Ozcan (2014)
Membrane									
Polaris polimeric	Retrofit. 31 MW from waste heat. Gas boiler for remaining heat	0	0	0.5	42	51 (investment cost)	M€ $_{2014}$	Norway	Jakobsen et al. (2017)
NTNU	Retrofit. 31 MW from waste heat. Gas boiler for remaining heat	0	0	0.45	42	61 (investment cost)	M€ $_{2014}$	Norway	Jakobsen et al. (2017)
Membrane	Electricity imported	4	0	1.27	90	112 (TPC)	M€ $_{2014}$	Europe	Ozcan (2014)

TPC: Total plant cost; TCR: Total capital requirement; TIC: Total investment cost

* Negative values on electricity consumption indicate that surplus energy is produced in an onsite energy plant, which is exported and sold to a third party.

**The currency was considered M$$_{2007}$, although it was based on assumption of equipment costs remaining similar over time

Previous literature collected information on CCS R&D projects 2013 (IEAGHG (2013a and 2013b), Kuramochi et al. (2012), Leeson et al. (2017)). Table 3 provides an overview of projects starting in 2013 and later. For the cement sector, most R&D activities focus on amine-based post-combustion capture, followed by solids-based looping systems. The LEILAC project (Low Emissions intensity Lime and Cement) aims to scale up the innovative Calix configuration based on direct separation. Although this process has been applied on magnesium production, there are still several challenges that need to be tackled when applying this technique to cement production. Similarly, the CLEANKER project aims to advance calcium looping to a higher technology readiness level (TRL) by testing a pilot plant in a cement plant in Vernasca, Italy. Membrane-based technologies are being explored in the CEMCAP and Norcem projects, where operability issues will be identified. Also within the framework of the CEMCAP project, several pilot plants (30-200 kW_{th}) have been successfully testing the Ca-looping technology as a PCC application under cement plant conditions (Arias et al. 2017; Hornberger et al. 2017). For the iron and steel sector, the STEPWISE project aims to demonstrate the feasibility of pre-combustion capture technology at the Swerea Mefos facilities in Luleå, Sweden, by incorporating new catalysts and a novel reactor configuration. Starting in the same year, 2015, the CO2STCAP project, explores several partial capture options for the cement and steelmaking sectors, including tests performed at the Swerea Mefos facilities. Other current and past initiatives were included in Wordsteel (2018), such as Baosteel programme, China Steel Corporation (CSC), Course50, POSCO CO_2 breakthrough framework, HIsarna ironmaking process, ULCOS, AISI and the Australian programme. Based on those schemes, it is expected to reach commercial-scale demonstration projects, such as new smelting reduction technology by Tata Steel, or the CO_2 capture system coupled with advanced low CO_2 emissions steel production by Course 50 in Japan in 2030.

Table 3 R&D projects on CO_2 capture in the cement and Iron and Steel sectors (started in 2013-2017)

<table>
<tr><td colspan="5">Cement sector</td></tr>
<tr><td>Project</td><td>Coordinator</td><td>Carbon Capture Technology</td><td colspan="2">Timeframe</td></tr>
<tr><td>LEILAC</td><td>CALIX</td><td>Direct Separation</td><td colspan="2">2016-2020</td></tr>
<tr><td rowspan="3">CEMCAP</td><td rowspan="3">SINTEF</td><td>Traditional and advanced amine based post-combustion</td><td colspan="2" rowspan="3">2016-2018</td></tr>
<tr><td>Oxycombustion</td></tr>
<tr><td>Membrane-based post-combustion</td></tr>
<tr><td>CLEANKER</td><td>LABORATORIO ENERGIA AMBIENTE PIACENZA</td><td>Calcium Looping</td><td colspan="2">2017-2021</td></tr>
<tr><td rowspan="3">CO2STCAP</td><td rowspan="3">TEL-TEK</td><td>Amine based post-combustion</td><td colspan="2" rowspan="3">2015-2018</td></tr>
<tr><td>Oxycombustion</td></tr>
<tr><td>Oxycombustion + Selexol</td></tr>
<tr><td rowspan="4">Norcem Brevik</td><td rowspan="4">NORCEM</td><td>Amine based post-combustion</td><td colspan="2" rowspan="4">2013-2017</td></tr>
<tr><td>Sorbent based post-combustion</td></tr>
<tr><td>Membrane based post-combustion</td></tr>
<tr><td>Calcium looping</td></tr>
<tr><td colspan="5">Iron and Steel sector</td></tr>
<tr><td>Project</td><td>Coordinator</td><td>Carbon Capture Technology</td><td>Fluegas</td><td>Timeframe</td></tr>
<tr><td>STEPWISE</td><td>ECN</td><td>Pre-combustion: Sorption Enhanced Water-Gas Shift (SEWGS)</td><td>BFG</td><td>2015-2019</td></tr>
<tr><td rowspan="4">CO2STCAP</td><td rowspan="4">TEL-TEK</td><td rowspan="2">Amine based post-combustion</td><td>COG+BFG+BOFG+ CHP</td><td rowspan="4">2015-2018</td></tr>
<tr><td>COG+BFG+BOFG</td></tr>
<tr><td rowspan="2">Pre-combustion</td><td>COG+BFG</td></tr>
<tr><td>BFG</td></tr>
</table>

BFG: Blast Furnace Gas; BOFG:Basic Oxygen Furnace Gas; CHP: Combined Heat and Power; COG: Coke Oven Gas

1.3 Rationale and objectives

The available literature contains several transparent cost assessments on carbon capture systems in the cement and steelmaking sectors. However, it has been identified that those are somehow incomplete or difficult to compare, either due to a limited number of capture technologies covered, or the use of different cost methods from one study to another.

Regarding the cement industry, from the studies selected based on their high transparency and level of detailed information, only few assessed multiple technologies. IEAGHG (2013b) evaluated amine based post-combustion capture, and oxyfuel systems operating at partial and full capture rate in both new construction and retrofitted cement plants. Jakobsen et al. (2017) compared two amine-based post-combustion processes, with MEA and advanced solvents, and two membrane-based post-combustion systems, using Polaris polymeric membranes or a fixed site carrier designed by NTNU (He et al., 2015). Ozcan (2014) assessed emerging technologies such as indirect calcination and hybrid systems, to compare those with calcium looping, chemical looping and MEA-based post-combustion, all of those at full capture rate for new construction. Also Diego et al. (2016) and Rodriguez et al. (2008, 2009, 2012) evaluated several solid-based technologies at partial and full capture rate for new construction (greenfield) cement plants. Although those reports have a well-described method, they are incomplete in one way or another. For example, none of them covered all the existing CO_2 capture technologies. Additionally, most studies neither investigate further on the assumptions and nor discuss the many aspects affecting the economic results, which makes it difficult to compare the findings of the different studies.

Other studies focused on the techno-economic assessments of specific technologies. NETL (2014), Gerbelova et al. (2017) and Liang and Li (2012) considered amine-based post-combustion capture for full capture in retrofitted facilities, using MDEA and MEA. For example, recently, the CEMCAP project (Anantharaman et al., 2016) assessed amine-based post-combustion for partial and full capture. Differences in the design of the CO_2 capture systems are observed. For example, in the case of MEA based post-combustion, the operation conditions such as solvent concentration or heat of absorption varies from one study to another. Moreover, the steam required for the MEA regeneration is produced in an on-site CHP or a gas boiler, as for example, in the case of IEAGHG (2013b), while CEMCAP (Anantharaman et al. 2016) assumes the required steam is imported from a gas boiler located externally. Consequently, IEAGHG included the CAPEX and OPEX costs of this additional equipment while CEMCAP considered a payment for steam supply. Additionally, further difference between literature studies is the assumption on the amount of waste heat available in the cement plant. For example, CEMCAP (Anantharaman et al., 2016) considered that there are 6.4 MW available while IEAGHG considered that 15% of the energy required for regeneration can be covered with the waste heat from the cement production process. Those decisions within the cost methodology directly impact on the cost figures and increase the difficulty of obtaining an homogeneous overview of the price of CO_2 capture systems.

Regarding the iron and steel industry, the complexity is greater than in the case of the cement production. There are several production processes and emission points. Consequently, studies differ not only by CO_2 capture technologies, but also by production technology and the point sources from which CO_2 is captured. Regarding the CO_2 capture technologies, only a few studies in the literature assessed the cost of CO_2 capture in the iron and steel industry, as included in Table *1*. IEAGHG (2013a) reviewed an amine-based post-combustion and a hybrid system (post-combustion and oxyfuel applied to different point sources) as full capture systems for new construction and retrofitted plants (also called greenfield and brownfield respectively). Tsupari et al. (2015) extended their review to cover amine-based, oxyfuel and hybrid systems (oxyfuel combined with VPSA) at several capture rates, ranging from 9% to 89%, for brownfield iron and steel facilities. Also, Ho et al. (2013) reviewed MEA-based post-combustion, VPSA and hybrid technologies (oxyfuel combined with MEA-based and with VPSA) at full capture rate for retrofitting cases. In one case, NETL considered the MDEA-based post-combustion at full capture. It should be noted that those iron and steel studies discussed above assessed different production methods and emissions points. Additionally, while none of the studies covered all the available technologies, each of them applied different CO_2 capture technology design with similar differences to those described for the cement case. Moreover, cost methodologies with different economic assumptions are used by each author.

As well as the two industrial sectors considered in the present work, Leeson et al. (2017) aimed to show a future scenario model and presented a systematic literature review of the cost of CO_2 capture in the petroleum refineries, and pulp and paper industries. Although the cost of CO_2 avoided from literature was updated for currency and year, the authors did not standardise key input parameters like energy prices in the studies reviewed. As studies differ regarding their costing methods and underlying assumptions, a wide cost range was found, with 17 to 164 \$/t CO_2 captured for the cement industry and 9.8 to 115.8 \$/t CO_2 captured for the iron and steel industry. Additionally, there are some uncertainties in the reported information.

Having a common method to evaluate the CO_2 capture technologies applied to the main industrial sectors is required. Without that, it is difficult to compare economic data from reports produced by different institutions. To this end, Kuramochi et al. (2012) made a consistent review of literature studies and standardised the techno-economic key parameters, such as: the capacity factor, energy prices, grid electricity, interest rate, economic plant lifetime, CO_2 compression pressure and grid electricity intensity. As this study was published in 2012, there is a need to update the analysis, especially due to the large number of studies published in the period 2012-2017, including recent data on novel capture technologies coming from R&D and testing campaigns.

As seen in the previous section, the studies selected from the literature differ with respect to their techno-economic assumptions. In addition, there is not one unique paper where all the CO_2 capture technologies were assessed. Consequently, it is difficult to compare the techno-economic performance between the capture technologies.

The objectives of this study are to: a) develop a method based on a bottom-up analysis which allows for a comparative assessment of CO_2 capture technologies in the industry sector; and b) conduct a consistent assessment of the techno-economic performance of carbon capture technologies applied to the cement and iron and steel industries. To enable a fair comparison among the studies, the performance indicators are the cost of manufacturing, CO_2 captured, and CO_2 avoided[2] (Table 10).

---

[2] The CO_2 avoidance rate is calculated based on the difference of CO_2 emissions in the carbon capture cases compared to the reference plant in each study. Direct emissions (CO_2 released within the manufacturing process boundaries) and indirect CO_2 emissions from the electricity grid (based on the emission factor) and power production are taken into account in the carbon balance to calculate the CO_2 avoidance rate. The CO_2 capture rate is calculated based on the fluegas treated.

2. Description of cement and iron and steel sectors

2.1 Iron and steel sector

The global iron and steel subsector accounts for 23% (35.6 EJ) of the total global industry final energy demand and 28% (2.3 Gt) of the industrial sector's total direct[3] CO_2 emissions in 2014 (IEA 2017). Currently, around 60% of the global crude steel production is made from pig iron in blast furnaces. Figure 1 shows a simplified process diagram of a conventional integrated iron and steelmaking process, comprising sinter and pelletisation plants, coke oven (CO), blast furnace (BF) and basic oxygen furnace (BOF) process. A detailed description of the energy and mass flows can be found in IEAGHG (2013a). The process involves five steps: coking, iron ore agglomeration, iron making in the blast furnace (BF), steel making in the basic oxygen furnace (BOF) and manufacturing of the final product (casting and rolling). Iron ore, steel scrap and metallurgical coal are the three main raw materials for steelmaking. In the first step, coke is produced by heating coal in the absence of air to remove volatile organic compounds (coke oven gas, COG), tar and sulphur compounds, while the iron ore fines are agglomerated in the sinter plant. The coke, pulverised coal and sintered iron ore are fed to the blast furnace to produce pig iron and blast furnace gas (BFG). This process involves several steps. First, the coke burns with oxygen to produce carbon dioxide, which is then reduced with coke to produce carbon monoxide (Equations 2-3). The reduction reaction between the iron ore and the carbon monoxide removes the oxygen from the mineral and produces high purity iron (Equation 4).

$$C + O_2 \rightarrow CO_2 \qquad (1)$$

$$CO_2 + C \rightarrow 2\,CO \qquad (2)$$

$$Fe_2O_3(s) + 3CO\,(g) \rightarrow 2Fe\,(l) + 3CO_2 \qquad (3)$$

In the blast oxygen furnace, steel and off-gas (BOFG) are produced by using a high-purity, high-temperature oxygen to remove the remaining carbon and other impurities present from the pig iron. Recycled iron scrap can be fed to the blast oxygen furnace as well. The various off-gases released throughout the production process (COG, BFG, BOFG) are partly recycled to recover some of the chemical energy through the displacement of fossil fuel by the support of CO and H_2 to the reduction reactions, while the remaining gas is used for power production. CO_2 emissions are mainly released in the blast furnace (BF) and the basic oxygen furnace (BOF). The BF is the principal source, accounting for 70% of the CO_2 emissions of the whole process, with a concentration of around 22%-vol, while the BOF gas (BOFG) has a concentration of approximately 14%-vol. Additional CO_2 is emitted in the coking oven and the CHP (combined heat and power) plant. The multiple point sources and varying volumetric CO_2 concentrations of the aforementioned streams make it challenging to capture all CO_2 emitted by the iron and steel plant, also because of space limitations and the physical distances between the point sources. Moreover, the implementation of the CO_2 capture systems on all emissions points would require the industrial plant to temporarily cease its production, resulting in the loss of economic revenues.An option is to implement independent CO_2 capture systems, one per CO_2 source, which could increase the total integration cost but would impact the production process to a lower extent than trying to use a single capture system. Accordingly, the most commonly investigated configuration captures the CO_2 emitted from the blast furnace flue gas or from a combined flux of COG, BFG and BOFG sent to the CHP, which has a volumetric CO_2 concentration of approximately 30%.

---

[3] Direct CO_2 emissions in iron and steelmaking include energy-related emissions and process CO_2 emissions generated from the use of lime in the BF and BOS.

The typical European plant description is included in IEAGHG (2013a). The greatest energy consuming component is the blast furnace, with approximately 18.67 GJ/tonne pig iron. Applying process-integrated measures can increase the energy efficiency and, consequently, save energy along the production process and reduce CO_2 emissions. Heat recovery in the sinter plant can reach 30% of the input heat. In the blast furnace, up to 30% of the gross energy consumption can be recovered as waste heat while other measures such as direct injection of reducing agents can save up to 3.6% of the energy consumption. Some of the heat in the pelletisation unit can be recovered, representing 4% of the energy consumption. Additionally, some energy can be recovered from the BOF gas. Most of the energy saving techniques are already implemented in the BAT (Best Available Techniques) model.

The alternative to steel production from pig iron is the DRI-EAF route, in which iron ore is reduced in solid state to DRI (Direct Reduced Iron) and then melted in an electric arc furnace (EAF). Natural gas is commonly used to produce syngas through SMR, to be used as reducing agent, instead of coke. Although generally more environmentally friendly than BF+BOF configuration, DRI-EAF only represents a small contribution of the total production of European steel, although more extended in other locations. In 2014, around 30% of the global crude steel production was made via the DRI-EAF route (IEA, 2017), a route that is commonly less carbon intensive than the BF+BOF route, although alternatives such as coal-based DRI through coal gasification are not more environmentally friendly than traditional arrangements. The use of EAFs allows steel to be made not only from DRI but also from steel scrap. In that case, steel scrap is melted to obtain new products. The main disadvantage is the high electricity consumption. However, that can be a good option in locations where renewable electricity is the main contribution in the electricity grid.

New steelmaking configurations have emerged with the aim to lower the energy and carbon intensity of the manufacturing process compared to the conventional BF+BOF arrangement. The most important initiatives in this regard are the ULCOS programme, COURSE 50 and advances done by Tata Steel. The most notable emerging manufacturing technologies are electrolysis based steelmaking, advanced DRI-EAF, TGRBF (topgas recirculated blast furnace), advanced smelting reduction (HIsarna, HIsmelt) and solid state reduction (Corex, currently at commercial stage). While the first one, the electrolysis based steelmaking process, has not progressed much over the past years, TGRBF, HIsmelt and Corex are at a more advanced technological stage. In the TGRBF arrangement, the off-gas from the BF is cleaned and reused in the production process, thereby decreasing CO_2 emissions with 15% compared to the BF+BOF configuration; this improvement is without CO_2 capture, although typically is operated under oxyfuel conditions (TGROBF). In the HIsmelt process, a reactor combines coal preheating and partial pyrolysis, a melting cyclone for ore melting and a smelter vessel for final ore reduction and iron production. This configuration avoids emissions from coking and sintering and requires a smaller area. In the HIsmelt process, coal and iron ore are injected in a molten iron bath at about 1450°C where the following reaction takes place:

$$3\,[C]_{iron} + Fe_2\,O_3 \rightarrow 2\,[Fe]_{iron} + 3\,CO \qquad (4)$$

The heat required to achieve the reaction is extracted from the carbon monoxide and hydrogen released by injecting a fraction of coal fines into the smelter offgas. Oxygen enriched air is injected into the smelter and, through the combustion, CO_2 and water are produced. HIsmelt emits 20% less CO_2 emissions compared to the conventional configuration, based on blast furnace and basic oxygen furnace arrangement. Around 10% of this reduction comes from fuel savings while the rest is due to the absence of the pre-treatment and coke oven plant.[4][5][6]

The Corex process uses two reactors, one for the reduction step and another one for the smelting step. Like the HIsmelt process, there is no need for a coking and sintering step, resulting in hot metal production cost savings of approximately 20% compared to the traditional BF+BOF process. Moreover, the gas pollutants and waste water emissions are much lower compared to the traditional BF+BOF process. Although the COREX configuration avoids CO_2 emissions from sintering and coking, the ratio of fuel/steel produced is higher. As in the BF+BOF process, CO_2 is emitted during the combustion of carbonic fuels, but there is a reduction of approximately 20% due to the higher process efficiency. (Kumar and Kumar, 2016)

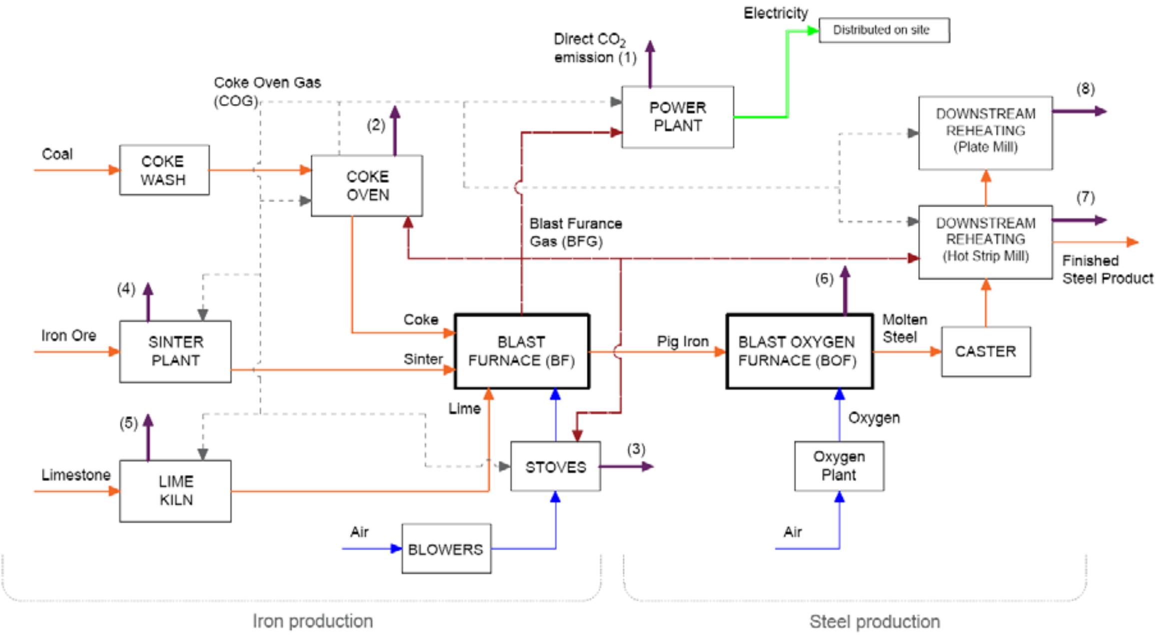

Figure 1 Configuration and CO_2 emissions points in the traditional steelmaking process (BF+BOF) Schematic diagram for a BF+BOF configuration for steel production (Ho et al. 2013)

---

[4] A Brief Overview of Low CO_2 Emission Technologies for Iron and Steel Making (Xu & Cang, 2010)

[5] Best Available Techniques (BAT) Reference Document for Iron and Steel Production, JRC Reference Report. Industrial Emissions directive 2010/75/EU, European Commission.

[6] Ironmaking process alternatives screening study. Volume I: Summary report, October 2000, DOE

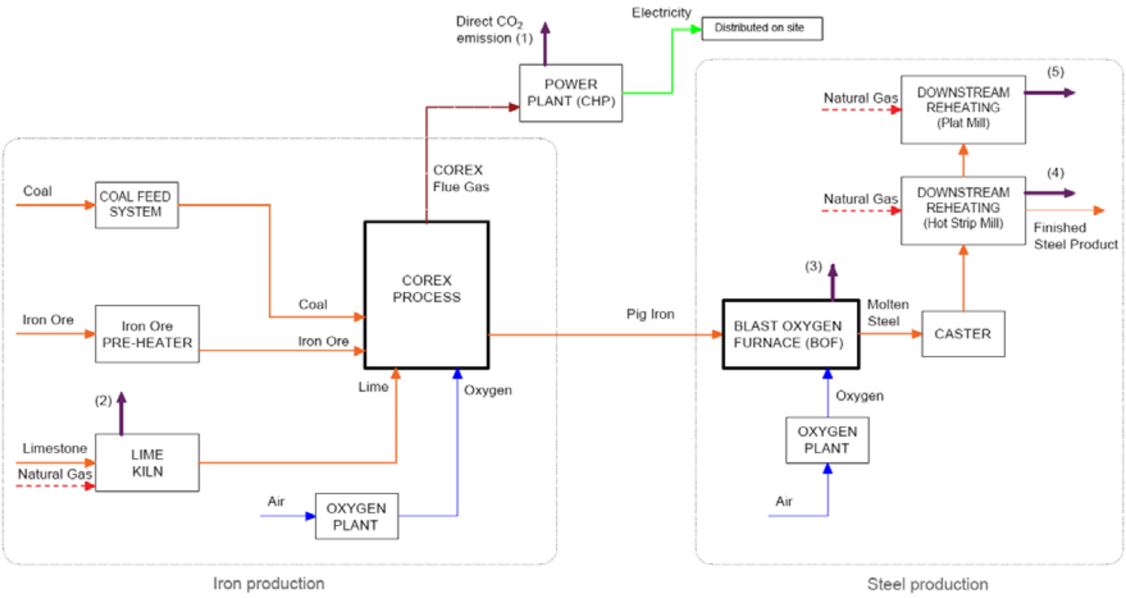

Figure 2 Schematic diagram for the integrated COREX steel mill, adapted from (Ho et al.2013)

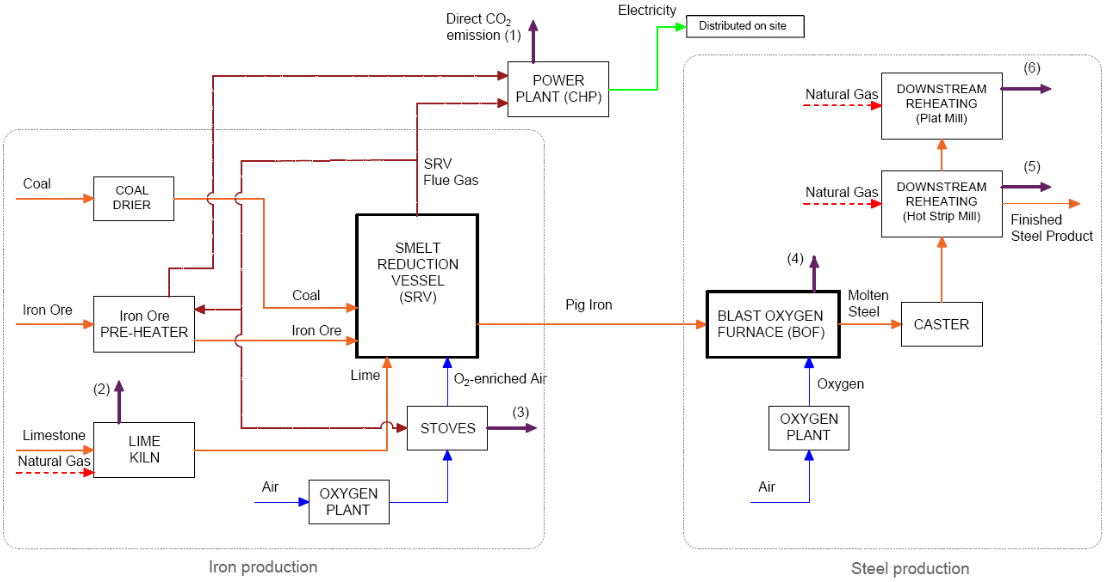

Figure 3 Schematic diagram for an integrated HIsmelt steel mill, adapted from (Ho et al. 2013)

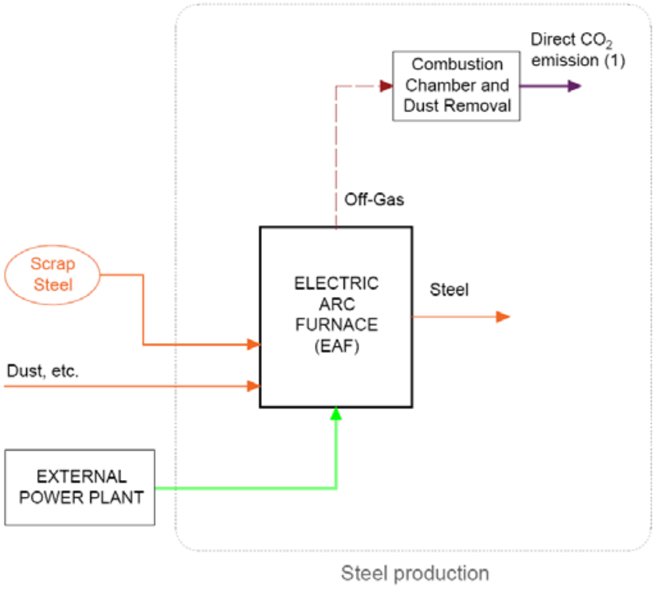

Figure 4 Schematic diagram for a mini mill using Electric Arc Furnace (EAF), adapted from (Ho et al. 2013)

2.2 Cement sector

Cement production is the second most CO_2 intensive industrial process, releasing approximately 2.2 Gt CO_2 per year in 2014, which corresponds with around 27% of total direct industrial CO_2 emissions and 5% of global anthropogenic carbon emissions (IEA, 2018). Specific CO_2 emissions have been reported to be in the order of 0.5-0.6 tCO_2/t cement in 2014, combining direct process and energy related CO_2 emissions (ECRA, 2017; IEA, 2018).

The most common configuration for cement production is based on the dry process. (Figure 5). In the cement manufacturing process, raw meal, consisting of limestone, silica, alumina, iron ore and other components, is fed to the preheater and pre-calciner centrifugal units where it mixes with hot flue gases from the kiln, which provides the heat for the calcination reaction to take place. Calcium carbonate ($CaCO_3$) is converted into calcium oxide (CaO) at approximately 900 ºC, releasing carbon dioxide (CO_2) which is carried to the stack by the upwards draught created in the centrifugal pre-heaters. This is followed by the clinkering process in which CaO reacts at a high temperature, typically 1400 – 1500 ºC, with silica, alumina and ferrous oxide to form the silicates, aluminates and ferrites of calcium which comprise the clinker. The clinker is then ground or milled together with gypsum and other additives to produce cement.

The CO_2 emissions from cement production are created during the process: around 50% of the emissions result from the calcination process in which limestone ($CaCO_3$) is converted into calcium oxide (CaO), over 40% of the emissions are generated during the fuel combustion in the kiln furnaces, and the remaining 10% corresponds to indirect emissions related to raw material transportation and electricity used in the manufacturing process (IEAGHG, 2013b). The fuel consumption is significant due to the highly endothermic calcination reaction and the high operation temperature, around 1450 ºC, in the rotary kiln. Approximately 60% of the fuel is used in the calciner and 40% in the kiln. The CO_2 concentration in the cement plant flue gas is typically 15-30%-vol, depending on the source.

CO_2 emissions from cement production can be partially reduced by increasing fuel efficiency, switching to alternative fuels including renewables and or waste residues, and mixing clinkers with mineral additives. Although these measures reduce energy-related CO_2 emissions, they do not tackle the CO_2 emissions originated in the calcination reaction. Therefore, it is essential to implement carbon capture technologies on cement processes to reduce CO_2 emissions by more than 90%.

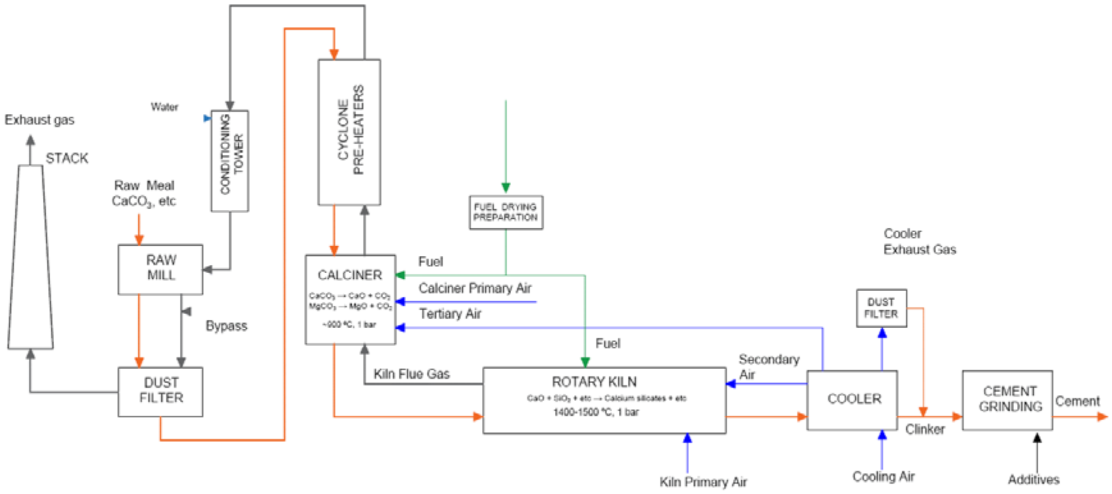

Figure 5 Schematic diagram of a dry cement production process (adapted from Anantharaman et al. 2016)

3. Method

3.1 Scope and system boundaries

This study covers CO_2 capture technologies that are in different stages of development today, being in the modelling, laboratory, pilot, demonstration or commercialization phase. For the cost assessment, it is assumed that the technologies are fully mature, i.e. Nth-of-a-kind. Costs of first-of-a-kind plants or expectations on the evolution of costs in coming years are, therefore, excluded. The analysis includes both new “greenfield” plants and retrofits of existing plants. The performance of an industrial plant with CO_2 capture is compared with an identical industrial plant without CO_2 capture (base case) with the same industrial production rate. The geographical location in this study is North-West Europe. [7]

The system boundaries are at the limits of the industrial plant (Figure 6). All onsite CO_2 emissions are taken into account, i.e. from the industrial process, onsite power and/or steam generation, CO_2 separation, purification and compression to a standardised pressure, as well as CO_2 emissions associated with the import/export of electricity, fuels and/or steam. Depending on the study, capture may also include the CO_2 coming from the onsite energy plant used to supply energy for the CO_2 capture process. Excess electricity produced by an onsite energy plant is assumed to replace grid electricity generated over the period 2020-2030. Changes in mass and energy flows resulting from industrial process modifications due to CO_2 capture are accounted for as well. For example, modifying cement or iron and steel processes to oxyfuel combustion may improve the energy efficiency, resulting in less raw material and/or fuel consumption (Kuramochi et al. 2012). As shown in Figure 6, CO_2 transport and storage are excluded from the analysis.

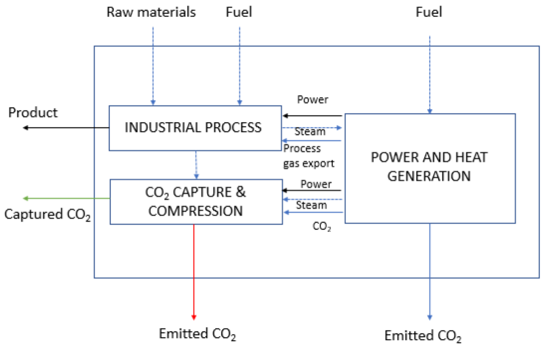

Figure 6 System boundaries of industrial processes considered in this study (based on Kuramochi et al. 2012)

3.2 Screening of literature

Publications and databases from academia, industry and other organisations presenting techno-economic cost data on CO_2 capture in the cement and iron and steel sectors were screened and considered for further analysis. The high-level screening process aimed to determine the scope and system boundaries of the studies, quality and origin of the data, depth of the technical and economic analysis and transparency on the assumptions and method used. The studies were assessed on their data quality and transparency by assigning scores (low, medium, high). In the selection process, preference was given to recent, detailed and transparent studies presenting

---

[7] This study has not standardized the materials and equipment costs given in the studies.

high quality techno-economic data, as those studies allow for a recalculation (i.e. standardisation) of the techno-economic parameters. Also, the origin of the data was considered. Some studies combine data from earlier studies in their analysis to determine the performance of CO_2 capture and were excluded

From now on, in this report, the following terminology will be used: the publications selected are called “studies”; the specific technologies together with the configurations assessed within those studies are called “cases”; and the group of assumptions under which the cases are re-evaluated are called “scenarios”.

3.3 Performance indicators

The performance indicators used to measure the performance of the CO_2 capture technologies are based on those presented by Kuramochi et al. (2012). The specific CO_2 emissions avoided $\Delta MCO_{2,spec}$ (t CO_2 avoided/t industrial product) is the main technical indicator used for CO_2 capture performance. It is assumed that there is only one output product, i.e. cement and steel; other output is considered to be by-product. Note that the import/export of steam is estimated as lost/gained electricity from a steam turbine power plant, using a power equivalent factor. The technical performance parameter is as follows:

$$\Delta M_{CO_2,spec} = \frac{M_{CO_2,cap} - [\Delta M_{CO_2,ind} + \{\Delta P_{ind} + \Delta H_{ind} \times f_{st,ind} + P_{cap} + \Delta H_{cap} \times f_{st,cap}\} \times EM_{sp,elec} + \Delta F \times EF_F]}{M_{ind}} \quad (5)$$

where $M_{CO2,cap}$ is the CO_2 capture rate (t CO_2 captured/s), $\Delta M_{CO2,ind}$ is the change of total carbon input in the industrial process due to CO_2 capture (tCO_2-eq/s), M_{ind} is the production rate of the industrial product (t/s), ΔP_{ind} is the change in the electricity import to the industrial process due to CO_2 capture (MW), P_{cap} is electricity import for CO_2 capture and compression (MW), ΔH_{ind} is the change in the steam import for the industrial process due to CO_2 capture (MW), H_{cap} is steam import for CO_2 capture and compression (MW), f_{St} is the power equivalent factor for steam (dimensionless), η is the efficiency of the steam plant (dimensionless), ΔF_{gas} is the change in the net process gas export from the industrial process due to CO_2 capture (MW), EF_F is the emission factor of the fuel and $EM_{sp,elec}$ is the CO_2 emission factor of grid electricity (tCO_2/MJ_e). Regarding the power equivalent factors, high-pressure steam is assumed for industrial process steam ($f_{St,Ind}$), while low-pressure steam is assumed for CO_2 capture steam ($f_{St,Cap}$) (e.g. chemical absorption).

The CO_2 avoidance cost C_{CO2} ($\$_{2016}/tCO_2$ avoided) is used as an economic performance indicator for CO_2 capture performance:

$$C_{CO_2\ avoid.} = \frac{\alpha \times TCR + \Delta C_{energy} + \Delta C_{FOM} + \Delta C_{materials}}{\Delta M_{CO_2,spec} \times M_{ind}} \quad (6)$$

where α is the annuity factor (yr^{-1}), TCR is the Total Capital Requirement ($), ΔC_{energy}, ΔC_{FOM} and $\Delta C_{materials}$ are the incremental annual costs for energy use ($/yr), fixed operation and maintenance (O&M) ($/yr), and material consumption ($/yr) due to CO_2 capture, respectively. $\Delta M_{CO2,spec}$ is the specific CO_2 emissions avoided (t CO_2 avoided/t product), and M_{ind} is the industrial production (t/yr).

The annuity factor is a function of the real interest rate r (%) and economic lifetime LT (years) of the technology (see Equation 7).

$$\alpha = \frac{r}{1-(1+r)^{-LT}} \qquad (7)$$

In both the cement and iron and steel sector, a number of manufacturing routes can be identified. To compare their performance, the cost of manufacture (C_{ind}) is calculated:

$$C_{ind} = \frac{C_{energy}+C_{FOM}+C_{materials}+\alpha\times TCR}{M_{ind}} \qquad (8)$$

where C_{ind} is the Total Capital Requirement ($/t product), C_{energy}, C_{FOM} and $C_{materials}$ are the total annual cost of energy use ($/yr), fixed operation and maintenance ($/yr), and material consumption ($/yr), respectively.

3.4 Standardisation of key parameters

To enable a fair comparison of the technologies, several underlying parameters are standardised. The procedure as proposed by Kuramochi et al. (2012) is discussed in the following subsections.

3.4.1 Normalisation of CO_2 compression pressure

Energy consumption for the CO_2 compression step makes up a major share in the total energy costs. Hence, it is important to standardise the CO_2 compression pressure using Equation 9. The compression outlet pressure used in this study is 110 bar.

$$E_{sp,comp} = \frac{ZRT_1}{M\eta_{is}\eta_m}\frac{N\gamma}{\gamma-1}\left\{\left(\frac{p_2}{p_1}\right)^{\gamma-1/N\gamma}-1\right\} \qquad (9)$$

where $E_{Sp,comp}$ is the specific electricity requirement (kJ/kgCO_2), Z is the CO_2 compressibility factor at 1.013 bar, 15°C (0.9942), R is the universal gas constant (8.3145 J/(mol K)), T_1 is the suction temperature (313.15 K), γ is the specific heat ratio (c_p/c_v) (1.294), M is the molar mass (44.01 g/mol for CO_2), η_{is} is the isentropic efficiency (80%), η_m is the mechanical efficiency (99%), p_1 is the suction pressure (kPa), p_2 is the discharge pressure (11,000 kPa), and N is the number of compressor stages (=4).

3.4.2 Indexation

All cost figures are converted to constant (real) 2016 US Dollars ($\$_{2016}$) using Equation 10. Costs reported in other currencies are first converted to US Dollars using year-average currency exchange rate data (CER_i) (OECD, 2017) for the year the cost data ($Cost_i$) are reported, and are then escalated to the year 2016 using the Chemical Engineering Plant Cost Index ($CEPCI$) (CEEI, 2017) (see ***Table 4***).

$$Cost_{2016} = Cost_i \times CER_i \times \frac{CEPCI_{2016}}{CEPCI_i}$$

Table 4 Chemical engineering plant cost index (CEEI, 2017).

Cost year reported	CEPCI	Cost year reported	CEPCI
2007	525.4	2012	584.6
2008	575.4	2013	567.3
2009	521.9	2014	580.2
2010	550.8	2015	537.0
2011	585.7	2016	541.7

3.4.3 Normalization of cost figures

Not all studies include the same cost components. Therefore, as recommended by Rubin et al. (2013), a common set of cost items, and a consistent method of aggregating these cost items, is used to obtain the total capital and operating cost.

Capital cost

The capital costs are computed using the cost structure and steps presented in Table 5.

The Bare Erected Cost (BEC) comprises cost for process equipment, supporting facilities and labour (direct and indirect). A standard plant size is determined based on the literature review. Capital costs are strongly influenced by geographical location and plant capacity. So-called material factors from the IEAGHG (2018) are suggested to correct for geographical differences in material costs. To convert the cost obtain the Northwest European cost, $C_{Ref,NW\ Europe}$ ($), Equation 11 is proposed.

$$C_{ref,NW\ Europe} = C_{ref,i} \times MF_i \tag{11}$$

where $C_{ref,i}$ ($) is the cost for process equipment in location i in the reference study and MF_i is the material factor for location i (USA: 0.94; Australia: 1.00; China: 0.77).

To correct for plant capacity, the process equipment cost (PEC) is standardised by applying a generic relation as presented in Equation 12. An average scaling factor of 0.67 is used, in line with guidelines of DOE/NETL (2013).

$$C_{PEC} = C_{ref,NW\ Europe} \times \left(\frac{Q}{Q_{ref}}\right)^{SF} \tag{12}$$

where C_{PEC} is the capital cost ($) of the process equipment in this study, Q is the equipment capacity (kt/yr) of the manufacturing plant in this study, Q_{ref} is the capacity (kt/yr) the manufacturing plant in the reference study, and SF is the economic scaling factor.

As in the IEAGHG cost method (IEAGHG, 2013c) a factor of 2.08 was used to account for supporting facilities and installation costs.

Total Plant Cost (TPC) comprises BEC, cost for engineering services and project contingencies. Project contingencies account for the costs of process equipment or other costs that would have been identified in more detailed designs of the project (Rubin et al. 2013, AACE (2011)). The factor used for project contingencies used in this study is consistent with the so-called cost class, which reflects the technical detail level of design of the study (see Table ***6***). Process contingencies are excluded in this work, as there is currently no consensus as to whether or not to include them to calculate the costs of a Nth-of-a-kind plant (van der Spek, 2017).

Total Capital Requirement (TCR) comprises TPC, owner's cost (incl. royalties, land cost, financing costs, inventory capital, pre-production costs, other miscellaneous costs) and interest and cost escalations during construction. The way owner's costs are structured differs among literature studies. As detailed information and cost breakdowns are often missing, a standardised factor (7% of TPC) was used instead to calculate the Total Overnight Cost (TOC), which comprise TPC and owner's costs (see Table 5). This approach is in line with the IEAGHG cost method (IEAGHG, 2013). Similarly, a fixed factor is used to account for interest during construction and cost escalation during the construction phase. The factor was taken from the NETL Power Systems Financial Model (NETL, 2011). Decommissioning costs at the end of the plant's life are ignored in this study.

Table 5 Composition of capital cost elements in this study based on the nomenclature proposed by Rubin et al. (2013). The last column shows how the different cost elements are obtained in this study.

Capital cost item	**Source / computation step**
Process Equipment Cost (PEC)	Data original study (standardised with Equations 14 + 15)
Supporting facilities	
Labour (direct + indirect)	208% of PEC
Bare Erected Cost (BEC)	
Engineering services	8% of BEC
Engineering, Procurement & Construction (EPC) Cost	
Contingencies:	
Process	Excluded from analysis
Project	7.5-40% of EPC (see Table ***6***)
Total Plant Costs (TPC)	
Owner's cost	7% of TPC, o*f which*:
(feasibility studies, surveys, land, permitting, finance transaction cost, pre-paid royalties, initial catalyst, other site-specific items)	
Inventory capital	0.5% of TPC (spare parts); other costs [a]
Pre-production (start-up)	2% of TPC to cover modifications to equipment; other costs [b]
Total Overnight Cost (TOC)	
Interest during construction (IDC)	
Cost escalations during construction	10.75% of TOC [c]
Total Capital Requirement (TCR)	

[a] Other costs for inventory capital include: 30 days of full load for chemicals, fuel and consumables.

[b] Other costs for pre-production (start-up) include: 3 months of maintenance and operating and support labour costs, 1 month of maintenance materials, 1 month of chemicals, consumables and waste disposal costs, and 1 month of fuel cost (25% of full load).

[c] The NETL Power Systems Financial Model shows cost factors in the range of 1.075 and 1.140, reflecting different construction periods and risk profiles of the plant being assessed. An average factor of 1.1075 (= 10.75% of TOC) was used in this study.

Table 6 Guidelines for project contingency costs, based on Rubin et al. (2013) and AACE (2011)

Estimate Class*	**Design effort**	**Project contingency cost (%-EPC)**	**Value used in this study**
Class I	Simplified	30-50	40
Class II	Preliminary	15-30	22.5
Class III	Detailed	10-20	15
Class IV	Finalised	5-10	7.5

* Estimate class are defined in AACE (2011) as function of maturity level of definition

Operation and maintenance (O&M) costs

The O&M costs are grouped into fixed O&M (C_{FOM}) and variable O&M costs (C_{VOM}) (see

Table 7).

Fixed O&M costs are commonly independent of plant utilisation; it comprises costs for labour, maintenance, taxes and insurances. Labour costs were standardised using an average European wage of 60 k€/person/yr, based on a system with 5 shifts and 320 days of operation per year (IEAGHG, 2013).

Variable O&M costs include cost items whose use is directly proportional to the amount of product manufactured or CO_2 captured. The cost items as proposed by Rubin et al. (2013) are grouped into costs for consumption of energy and of materials. Where literature reports the amount of energy and materials consumed, costs for energy (C_{energy}) and materials ($C_{materials}$) are normalised using standard energy and material prices (see Equations 17 and 18). Otherwise, costs are used as reported in the reviewed literature study. CO_2 transport and storage costs as well as CO_2 emission taxes/credits are excluded from the analysis.

$$C_{Energy} = \sum_i E_i \times P_i \qquad (13)$$

$$C_{Materials} = \sum_i M_j \times P_j \qquad (14)$$

where E_i is the annual energy consumption (or production in case of excess energy) of energy carrier i (GJ/yr), M_i is the annual consumption of material j (kg/yr). P_i and P_j are the prices of energy carrier i ($/GJ) and material j ($/kg), respectively.

Table 7 Composition of O&M cost elements in this study based on the nomenclature proposed by Rubin et al. (2013). The last column shows how the different cost elements are obtained in this study.

O&M cost element	Source / computation step
Labour	
Operating	= labour hours (hr/yr) x average wage (USD/FTE/yr)
Supervision	20% of operating labour
Maintenance	40% of total maintenance cost
Administrative & support	30% of operating + 12% of maintenance labour
Maintenance materials	Data from original study
Property taxes and insurance	1.5% of TPC per year
Fixed O&M costs (C_{FOM})	
Fuel	See Equation 13
Other consumables (e.g. catalyst, chemicals, water, solvents).	See Equation 14
Waste disposal (excl. CO_2)	Data from original study
CO_2 transport	Excluded from analysis
CO_2 storage	Excluded from analysis
By-product sales (credit)	See Equations 13 + 14
Emission tax (or credit)	Excluded from analysis
Variable O&M costs (C_{VOM})	

[a] Average European wage of 60 k€/fte/yr, 5 shifts, and additional 30% of operating labour for administrative/support labour. An increase of 25% over the number of workers needed for the facility without CO_2 capture is considered.

Table 8 gives an overview of the standardised input parameters common for both the iron and steel and cement industry investigated in this study. The energy prices and carbon intensity of the power system were based on the 2DS scenario in the Energy Technology Perspectives 2017 (IEA, 2017a) and apply to North-West Europe over the period 2020-2030. Other parameters that are specific for individual sectors are presented in later sections.

Table 8 - General input parameters used in this study.

Parameters	Unit	Base case	Reference
Capacity factor [a]			
Cement sector	%	80 [b]	IEAGHG (2013b)
Iron and Steel sector	%	80 [b]	IEAGHG (2013a)
Economic plant lifetime	yr	25 [b]	IEAGHG (2013b)
Real discount factor	%	8 [b]	IEAGHG (2013b)
Energy content of fuels (LHV)			
Steam coal	MJ_{LHV}/kg	24.1	IEA (2005)
Coking coal	MJ_{LHV}/kg	28.8	IEA (2005)
Natural gas	MJ_{LHV}/m^3	37.4	IEA (2005)
CO_2 emission factor			
Steam coal	$kgCO_2/GJ_{LHV}$	95	IEA (2005)
Coking coal	$kgCO_2/GJ_{LHV}$	115	IEA (2005)
Natural gas	$kgCO_2/GJ_{LHV}$	56	IEA (2005)
Grid electricity [c]	$kgCO_2/GJ_{LHV}$	47	IEA (2017a)
Energy prices [c]			
Steam coal	USD_{2016}/GJ_{LHV}	3.0	IEA (2017a)
Coking coal	USD_{2016}/GJ_{LHV}	4.5	Assumption
Natural gas	USD_{2016}/GJ_{LHV}	8.0	IEA (2017a)
Electricity	USD_{2016}/GJ_{LHV}	25	IEA (2017a)
Low pressure-temp. steam	USD_{2016}/GJ_{LHV}	7.5	Assumption
Power equivalent factor for steam			
High pressure-temp. steam ($f_{st,ind}$)	-	0.45	Kuramochi et al. (2012)
Low pressure-temp. steam ($f_{st,cap}$)	-	0.23	Kuramochi et al. (2012)

[a] The capacity factor is the ratio of the net output produced to the output that could have been generated at continuous full-load and full-capacity operation.

[b] Typical values found in literature.

[c] Nominal values used for the grid CO_2 emission factor and steam coal, natural gas and electricity prices are based on the 2DS scenario in the *Energy Technology Perspectives (ETP) 2017* for Western Europe over the period 2020-2030 (IEA, 2017a). The high-end and low-end values used for the sensitivity analysis reflect the ranges of the grid CO_2 emission factor and energy prices found across different scenarios in the ETP study. Similar value ranges are assumed for the coking coal and steam price.

[d] Similar to Kuramochi et al. (2013), the price of coking coal is assumed to be 50% higher than the price of steam coal.

3.4.4 Alternative techno-economic scenarios

The techno-economic performance of the industrial processes with CO_2 capture is strongly influenced by the input parameters. The impact of those values are generally assessed through a sensitivity analysis. Overall, the parameters included in sensitivity analysis are: energy prices, annualized capital cost, grid electricity CO_2 emission factor and power equivalent factors for steam (see Table 8). Moreover energy use for CO2 capture and annualised capital cost are both varied. The annualised capital cost reflects uncertainties in annual operation hours, economic plant lifetime, real interest rate and the capital cost estimation factors.

In previous reports (IEAGHG 2013a, 2013b), several sensitivity analyses were carried out to link the CO_2 avoidance cost to the selection of the key economic parameters. In this report, the assumptions on how to value the import/export of steam and electricity have been studied, as those have a large impact on the performance of the capture technologies. In this work, two alternative scenarios were devised to examine those parameters. *Scenario B* excludes revenues and CO_2 emissions reductions related to the export of excess electricity generated in an *onsite* gas turbine or CHP unit, which could significantly improve the performance of the capture technologies. To make the impact of this factor explicit, costs and emissions of fuel consumption related to the sale of excess electricity generation are also excluded. Lastly, studies make different assumptions on the availability of waste heat that can be used to produce steam for the CO_2 capture process. In practice, waste heat availability will differ according to the industrial plant type and level of heat integration. *Scenario C* examines the performance of CO_2 capture without the availability of waste heat. The corresponding steam (derived from the waste heat) is assumed to be produced in an onsite energy plant that was already used to partly supply the capture process with steam in the base case. In case all steam was produced from waste heat in the base case, a new natural gas-fired boiler was assumed to be built to supply this steam, with a CAPEX of 85€/KW and an additional 2% of such CAPEX as operational cost.

4. Limitations of this study

The reviewed studies were standardised using the method and data described in Section 3. However, the present study shows several limitations.

- The underlying data and process designs of the manufacturing and carbon capture systems differ between the reviewed studies, thus making a comparison between the cases more difficult. Equipment costs, materials and energy flows were extracted from the studies and were not modified but standardized. That implies some limitations based on different process designs selected by the authors of the studies. For example, the specific energy consumption for the CO_2 capture process varies from one study to another, as in the case of chemical absorption with MEA (reporting a heat of absorption between 3.2 and 4 MJ/tCO_2 captured). Operational conditions such as CO_2 loading or absorber temperature impact the heat of absorption and energy required for regeneration, which dominates the energy consumption.
- Several studies provided insufficient information required for the standardisation process. For example, Ho et al. (2013) did not specify whether the carbon capture equipment costs referred to bare equipment costs, total plant cost, or total overnight cost. In those cases, additional assumptions were made. Conversely, other studies included much more detailed cost information. It was observed that detailed cost estimations tend to present higher costs, whereas the opposite is seen with less detailed studies.
- Technological improvements in capture technologies that have taken place over recent years are not necessarily reflected in the quantitative results as some studies date back to 2012 and costs included in those could be even older. This is especially the case for chemical absorption and solids-based technologies, which have shown advances in configuration and equipment materials over recent years.

- The energy or steam production technologies differ among studies, affecting the CAPEX and fixed OPEX. Commonly, energy-rich gas streams coming from the production process are fed to a CHP plant to generate electricity and steam. Additional steam required for the capture system, as is the case of chemical absorption process, is produced through the existing boiler. The extra energy required is produced either in a newly constructed NGCC/ coal CHP unit (e.g. IEAGHG, 2013a; Ho et al., 2013), a gas boiler (NETL,2014), or imported from the grid (e.g. Tsupari et al., 2013). Additionally, the heat recovered from the production facility changes from one study to another. The differences among studies increase the range of avoidance cost per technology, which potentially offers the opportunity to analyse the impact of the heat and energy integration on the final costs.
- In the case of chemical absorption, most of the studies calculated economic impacts based on energy calculations. That means that for advanced solvents, the cost impact is only reflected on the energy used for regeneration during the desorption step. However, other aspects should be considered as well, such as absorption and desorption temperature, solvent flowrate, hydrodynamics, physical properties such as density and viscosity (which impact on the pumping and heat transfer), or variations on the absorber size due to different kinetic performance. Consequently, less accurate designs and estimated cost figures are introduced.
- In the cases of steelmaking, the blast furnace and basic oxygen furnace route (w/o CO_2 capture) was used as the reference case against the costs of all other cases, including configurations with advanced steelmaking processes, such as smelting reduction. A similar approach was used in the reviewed studies. However, as a result, in some cases part of the CO_2 avoided and cost differences were due to the application of the advanced production method rather than solely because of the CO_2 capture technology. (e.g. Corex, HIsmelt or TGROBF). Only one study (Ho et al. 2013) included cost information about the Corex and HIsmelt manufacturing processes with carbon capture. Consequently, the cost figures are not compared against another study and its validation remains undefined.
- Lastly, the techno-economic performance was calculated for North-West Europe. As reported recently by IEAGHG (2018), the cost of CO_2 capture systems are very dependent on location. The results should be corrected using location cost factors, as presented in IEAGHG (2018), to determine the techno-economic performance for specific locations.

5. Assessment of CO_2 capture technologies

5.1 Iron and steel sector

5.1.1 Overview of capture technologies

Technology advances required to achieve a low carbon scenario are commonly centred on changes in the production process, as discussed earlier, through modifications to the conventional configurations BF+BOF. Based on the multiple point sources of CO_2 in the production of iron and steel, this sector offers flexibility for a wide variety of capture configurations as reflected on the literature. For any specific technology, published economic analysis can vary on the implementation pathway and most of the studies are generally considered partial capture systems, even though the system itself is considered full capture on the treated flue gas.

In principle, all the available CO_2 capture routes are suitable for retrofitting iron and steel production plants. Chemical absorption is more favourable to reduce emissions in fluegas with a low CO_2 content, such as in BF+BOF and COREX configurations, while physical separation principles would be more suited to cases with a high partial pressure of CO_2 in the fluegas, as in adsorption-based systems such as PSA or VPSA (pressure swing adsorption or vacuum pressure swing adsorption), and WGS or SEWGS (water-gas shift or sorption enhanced water-gas shift reactions) (IEAGHG 2014).

The capture routes for the iron and steel sector are compared for a plant size of 4.0 Mt/yr steel production (3.9 Mt/yr iron production) and a capacity factor of 80%, based on the standard steelmaking process (Table 4). The CO_2 capture technologies evaluated include post-combustion (chemical absorption with amines, MEA and MDEA, and VPSA) and hybrid technologies (TGROBF+chemical absorption with amines, MEA and PZ+MDEA and TGROBF+VPSA). Capture rates vary between 9 and 95%.

Table 9 General technical information of the standard steelmaking process

	Value	Unit	Reference
Standardized plant size - Steel or Hot Rolled Coil	4	Mt/yr steel	IEAGHG (2013a)
Standardized plant size - Iron or Hot Metal	3.9	Mt/yr iron	IEAGHG (2013a)
CO_2 emitted (w/o capture)	3.4-9.4	Mt/year	Average

An overview of the standardised CO_2 avoidance costs and avoidance rates for iron and steel manufacturing with CO_2 capture is presented in Figure 7. The additional steel manufacturing costs due to CO_2 capture are presented in Figure 8. The discussion below is focused on the CO_2 avoidance cost, noting that, generally, the steel manufacturing cost follows a similar trend. However, there are individual cases where this is not the case, for example the cases of partial capture rate, which show a relatively low relative increase in manufacturing cost compared to the reference case, and cases with a notable difference on CO_2 emissions[8].

BF+BOF configuration: added CO_2 capture with no further modification

Of the iron and steel production processes, BF+BOF is the most used configuration globally but also the most emissions intensive. Two main post-combustion capture (PCC) categories were identified in literature, namely amine- based chemical absorption (MEA, MDEA, MDEA+PZ, or advanced solvents[9]), and VPSA (vacuum pressure swing adsorption). Note that the costs of the cases with advanced solvents is less accurate than the costs of the other PCC

---

[8] CO_2 emissions were standardized by plant size and production capacity but not by an homogeneous emissions factor (tonne CO2 emitted/tonne steel produced) due to assumptions and configurations in the different cases. Consequently, there are differences on CO_2 emissions which impact on the CO_2 avoided and CO_2 avoidance cost.

[9] The cases of chemical absorption with advanced solvents are from Tsupari et al. (2013). In this reference, those are called “advanced solvent” (amino-acid based solvent from Siemens (2011)) and “Low temperature solvent” (solvent able to regenerate at low temperature, presented in Zhang et al. (2010)). In both cases, it is not specified how the solvent make-up consumption (0.2 and 1.5 Kg/ t CO_2 respectively) and solvent make-up cost (0.75 and 1 €/Kg respectively) are calculated, compared to the MEA (1 €/Kg for make up cost and 1.5 Kg/ t CO_2 captured for make-up consumption). Solvent regeneration energy is specified as 2.7 and 3.0 MJ/Kg CO_2 captured for the “advanced” and “Low temperature” solvents , compared to 3.4 MJ/Kg CO_2 captured reported for MEA.

cases due to higher uncertainties related to the process performance, design and assumptions on prices.

Several authors have evaluated the cost of the MEA-based chemical absorption process. Although a wide cost range was observed for the selected studies, the range became much smaller (64-93 $\$_{2016}$/ton CO_2 avoided) after the standardisation step. The difference in costs are mostly due to the absence of homogeneity on the production process configuration such as energy production source, point sources from which CO_2 is captured, capture rate, new built vs retrofit, and assumptions on the process design. Surprisingly, the lowest capture rate cases reported by Tsupari et al. (2015) were the cheapest cases, perhaps based on low capital cost compared to that from other studies such as IEAGHG (2013a). The MDEA cases do not show lower CO_2 avoidance cost (80 $\$_{2016}$/ton CO_2 avoided). As seen in Figure 7, the cost of CO_2 avoided does not depend strongly on the origin of the steam production or treated flue gas stream (from BF and onsite power plant (PPS) (Tsupari et al. 2013, IEAGHG 2013a and Ho et al. 2013), or from the coke oven plant (COP), BF and PPS (IEAGHG, NETL)). Although more expensive, MEA-based PCC is nowadays the most reliable system due to the extensive experience using that technology at industrial scale.

Advanced solvent-based PCC systems show significantly lower avoidance costs and higher CO_2 avoidance rates (see Figure 8)[10], becoming the cheapest processes of the group studied in this work. The main advantages of the advanced solvent are the lower solvent make-up rate, lower solvent cost and lower energy requirements compared to the traditional MEA-based solution. Using advanced solvents, the CO_2 avoidance cost is reduced from 21 to 73% for original capture rates between 9 and 84% (17-90% by the use of those advanced solvents).

Apart from solvents-based post-combustion, VPSA (vapour pressure swing absorption) has been studied. VPSA technology exhibits lower CO_2 avoidance rate than the MEA-based PCC, at capture rates between 74% and 90%.

Smelting reduction: added CO_2 capture with no further modification

The HIsmelt configuration without CO_2 capture exhibits lower steel production costs compared to the BF arrangement (Kuramochi et al. 2012). CO_2 capture can be implemented in the smelting reduction step, where the CO_2 concentration is higher (25-30% CO_2). Those are the cases of the HIsmelt and COREX processes, where the implementation of post-combustion technologies (chemical absorption and VPSA) have been assessed in the literature (Table 1). The PC CO_2 capture systems studied in the selected reports are: VPSA and MEA-chemical absorption. By adding CO_2 capture systems, the cost of the HIsmelt configuration is still lower than that in BF+BOF or TPGRBF when comparing for a similar CO_2 avoidance rate. However, CO_2 capture in the COREX process could be even cheaper than that in HIsmelt, at similar production price but with lower CO_2 avoidance rate (Figure 8). For the COREX process, only post-combustion technologies, VPSA and MEA-based chemical absorption have been assessed (Ho et al. 2013). Compared to the MEA case, the CO_2 avoidance cost and additional manufacturing cost of steel of VPSA are 50% and 55% lower respectively. This is mainly due to the lower energy and material costs for the capture process using VPSA.

Applying VPSA to the COREX process shows the lowest CO_2 avoidance cost, with 34 $\$_{2016}$/t CO_2 and for a capture rate of 87%, mainly due to the low energy requirement. At this capture

---

[10] For the calculation of the advance solvent cases, the specific capital cost was assumed to be similar to those of the MEA cases, due to missing data in the underlying study. Assumptions on cost of solvents, make-up rate and energy requirements are extracted from the referenced studies.

rate and with similar specified CO_2 avoided, MEA-based PCC, has a CO_2 avoided cost of approximately 65% higher than the VPSA system.

At similar CO_2 avoidance rate (0.58-0.64 tCO_2/t steel), we can compare VPSA, MEA-based post-combustion applied to the COREX process (Ho et al. 2013) and advanced solvent based post-combustion applied to the BF+BOF configuration (Tsupari et al. 2013). The standardized results from Ho et al. (2013) exhibits a CO_2 avoidance cost of 85 $\$_{2016}$/t CO_2 compared to the 64 $\$_{2016}$/t CO_2 showed in Tsupari et al. (2015), influenced by higher material and energy costs. The use of the advance solvent decreases that cost to 23 $\$_{2016}$/t CO_2 although still less accurate[9].

As seen in Figure 8, there is a clear relation between manufacturing cost and the amount of CO_2 avoided. As expected, the raise of capture rate and its consequent increase of process complexity due to a more sophisticated configuration to treat multiple flue gas result in higher capital cost and/or energy cost, depending on the energy supply. The cost per tonne of steel is still lower in facilities implementing VPSA systems compared to amine-based capture systems.

Hybrid capture: process-integrated CO_2 capture (oxyfuel as TGROBF) with add-on CO_2 capture

In the TGROBF (pure oxygen top gas recirculation in the blast furnace) configuration, the carburant (air) in the blast furnace is substituted by oxygen. The result is that the fluegas is more concentrated in CO_2 and can be easily separated and compressed in an oxyfuel arrangement. After capturing the CO_2, the CO_2 can be recirculated and used as reducing agent, where the consumption of coke will be reduced depending on the recirculation ratio. Hybrid technologies combining TGROBF with VPSA or chemical absorption have been reported in the literature. However, each of the assessments considered different flue gas sources as seen in Table 1, and it is not clear if the implementation of the hybrid configuration offers economic advantages over the oxyfuel arrangement (TGROBF).

In the present paper, three TGROBF studies were reviewed (Tsupari et al. 2015, IEAGHG 2013a and Ho et al. 2013), covering hybrid technologies of oxyfuel combustion plus chemical absorption (with MEA and MDEA+PZ as solvents), and oxyfuel combustion plus VPSA; all are applied to capture CO_2 from the TRG and OBF off-gases. Another promising configuration involving cryogenic separation added to an advanced TGROBF-BOF arrangement is currently being tested in the framework of the ULCOS consortium, but was excluded from this review due to insufficient performance data being available.

The lowest CO_2 avoidance cost is shown by the TGROBF+VPSA configuration (52 $\$_{2016}$/$tCO_2$), at 90% of CO_2 capture rate and electricity produced in an on-site natural gas CHP. If electricity is imported, the CO_2 avoidance cost increases greatly (90 $\$_{2016}$/$tCO_2$), although compared with a case capturing the 74% of CO_2 instead of 90%. At the same CO_2 avoided (ton CO_2/ton steel) and CO_2 capture rate (90%) as TGROBF+VPSA, we find the TGROBF+ chemical absorption with MEA to be slightly costlier (65 $\$_{2016}$/$tCO_2$). All cost concepts (energy cost, OPEX, CAPEX and material costs) are increased in the TGROBF+ chemical absorption with MEA compared to TGROBF+VPSA. As seen in Figure 8, using another solvent, MDEA+PZ instead of MEA, but including the steam production onsite by a gas boiler increases the CO_2 avoidance cost (up to 95 $\$_{2016}$/$tCO_2$) due to a greater CAPEX and OPEX, mainly due to the additional equipment and running costs associated with the added gas boiler.

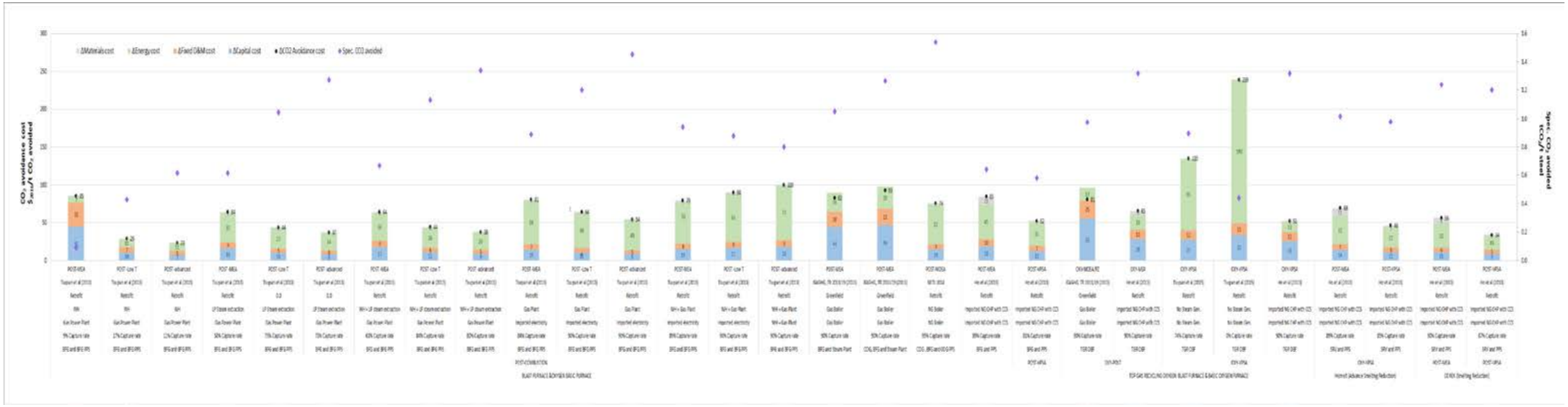

Figure 7 CO_2 avoidance cost ($$_{2016}$/ t CO_2 avoided) and specific tonne of CO_2 avoided per tonne of Steel. CO_2 price is not considered in the calculations. CR stands for capture rate

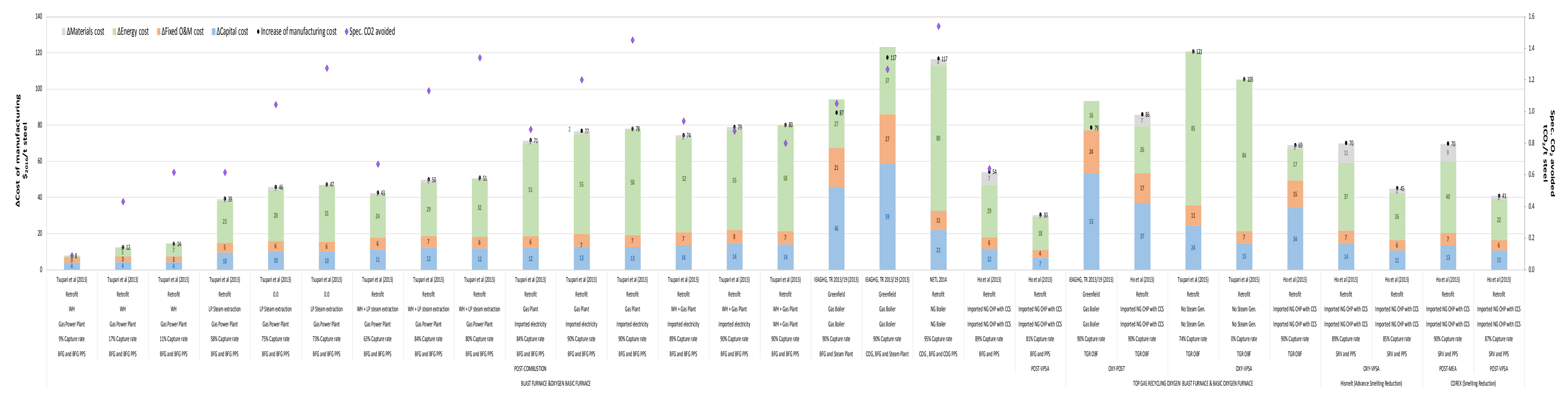

Figure 8 Additional production costs ($_{2016}$/ t steel) due to CO_2 capture and specific tonne of CO_2 avoided per tonne of Steel. CO_2 price is not considered. CR stands for capture rate

5.1.2 Alternative scenarios: Absence of waste heat and inability of exporting electricity to the electricity grid

Heat integration is a crucial factor when designing carbon capture systems to fit within a production process environment. Power plants have generally access to LP steam for solvent-based CO_2 capture. However, in iron and steel production, an external supply of steam is needed for the integration of a CO_2 capture system. As pointed out in Husebye et al. (2012), the source of steam supply has a considerable impact on the cost of CO_2 capture. In their study, the lower costs were showed in the cases where it is possible to use waste heat from the process, followed by using steam extracted from the low pressure steam circuit (LP)[11] and steam production through gas boilers. The most expensive pathway to produce steam for the solvent regeneration would be through electric boilers, although that is unlikely. Additionally, as commented in Tsupari et al. (2013), the cost of CCS in industrial facilities is highly dependent on the chosen system boundaries and assumptions.

During the steelmaking process, steam is generated to achieve the adequate moisture level in the hot blast air (IEAGHG, 2013a). In the conventional iron and steel manufacturing process, BF+BOF, steam is generally produced through the recovery of waste heat in boilers in the basic oxygen furnace (BOF), which covers the steam demand for the steelmaking process. The addition of a solvent-based CO_2 capture system increases the steam demand, as requirement for the solvent regeneration step. As peculiarity in the iron and steel manufacturing process, some of that required steam can be supplied from the intermediate steam from the turbine without further investments in heat recovery (Tsupari et al. 2013). Due to advances in industrial environment, motivated by new climate change policies and potential cost savings, the objective however is to obtain more efficient systems, which will make less waste heat available over time. Consequently, a potential approach is to reach a better heat integration within the steelmaking process without losses or waste heat being available for CO_2 capture systems.

We explored the scenario of absence of waste heat and/or its recovery. In addition to the benefit of exploring the hypothetical case of more efficient plants, that scenario without heat recovery for steam production helps to standardise the results from the literature, as only few considered this waste heat availability[12]. For example, IEAGHG (2013) considered that some steam produced for the steelmaking process was available for the regeneration of the solvent (MEA or MDEA+PZ), representing only 0.29-0.36% of the steam required for stripping. As in the previous analysis, the comparison of the studies is still limited by the steam supply source.

Moreover, industries could be located in regions where there would not be access to inject electricity on the grid. That scenario has been explored, considering that there is not revenue from selling the energy surplus produced in the manufacturing plant.

---

[11] Low pressure steam circuit within an onsite power plant

[12] For calculation of the scenario without heat recovery, this steam demand has been supplied by a gas boiler installed onsite (see methodology). The cases explored in Tsupari et al. (2013) are based on capture rates depending on the heat recovered from the extra steam produced in the BOF boilers and from the LP circuit before the turbine. In the scenario without heat recovery, those cases have been assessed fixing the capture rate. In the studies of NETL, Tsupari et al. (2015) and Ho et al. (2012), there is not recovery of heat and those were not been modified. As in the previous analysis, the comparison of the studies is still limited by the steam supply source.

Scenario B: Exclusion of energy export to the electricity grid

Scenario B excludes revenues and CO_2 emissions reductions related to the export of excess electricity generated in an onsite gas turbine or CHP unit. The credits related to electricity export could significantly improve the performance of the capture technologies. However, there is some debate on the real potential of being able to inject electricity on the grid from an industrial source. Moreover, it can be questioned if accounting for these credits could artificially change the performance of the capture technology and show a slightly distorted picture of the costs, also dependent on the power/steam production system and manufacturing plant. The three capture cases with electricity export are all from the study from Tsupari et al. (2013) and related to post-combustion capture using MEA, low-T solvent and advanced solvents.

Comparing both figures (7 and 9) it can be seen that the increase of cost of energy in the capture cases is considerably reduced when excluding credits for electricity sale. The reason is that, following the present method, the cases with CO_2 capture are compared to a reference case. While all those cases have a revenue based on electricity export, the decrease of electricity export is translated as a cost of electricity. Making this revenue null, there is no difference on energy cost between the reference and the CO_2 capture cases. Under those premises, MEA-based post-combustion installed on the blast furnace configuration becomes more competitive, cheaper than VPSA (as post-combustion arrangement) on the blast furnace, HIsmelt and COREX configurations. As seen before, the CO_2 avoidance cost of post-combustion is even lower if advanced solvents are used.

In this scenario, the CO_2 avoidance cost is 69-93 $\$_{2016}/tCO_2$ for traditional chemical absorption; 12-37 $\$_{2016}/tCO_2$ for advanced chemical absorption; 34-52 $\$_{2016}/tCO_2$ for VPSA; and 52-90 $\$_{2016}/tCO_2$ for hybrid technologies.

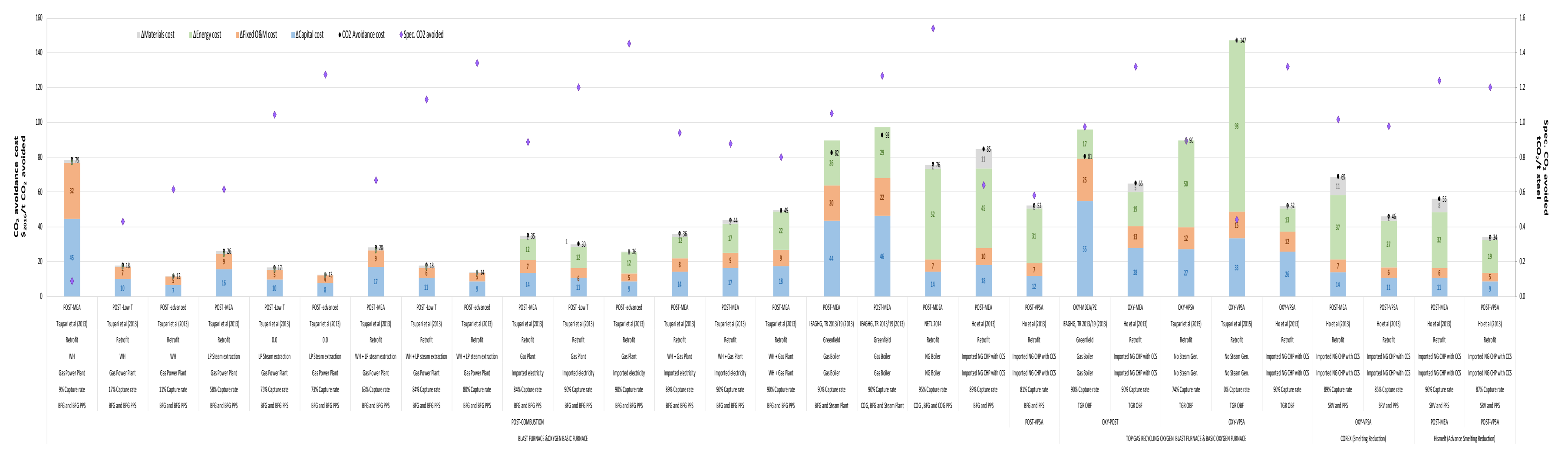

Figure 9 CO$_2$ avoidance cost (\$$_{2016}$/ t CO$_2$ avoided) and specific tonne of CO$_2$ avoided per tonne of Steel. CO$_2$ price is not considered in the calculations. There is not emissions or cost revenue due to electricity export. CR stands for capture rate

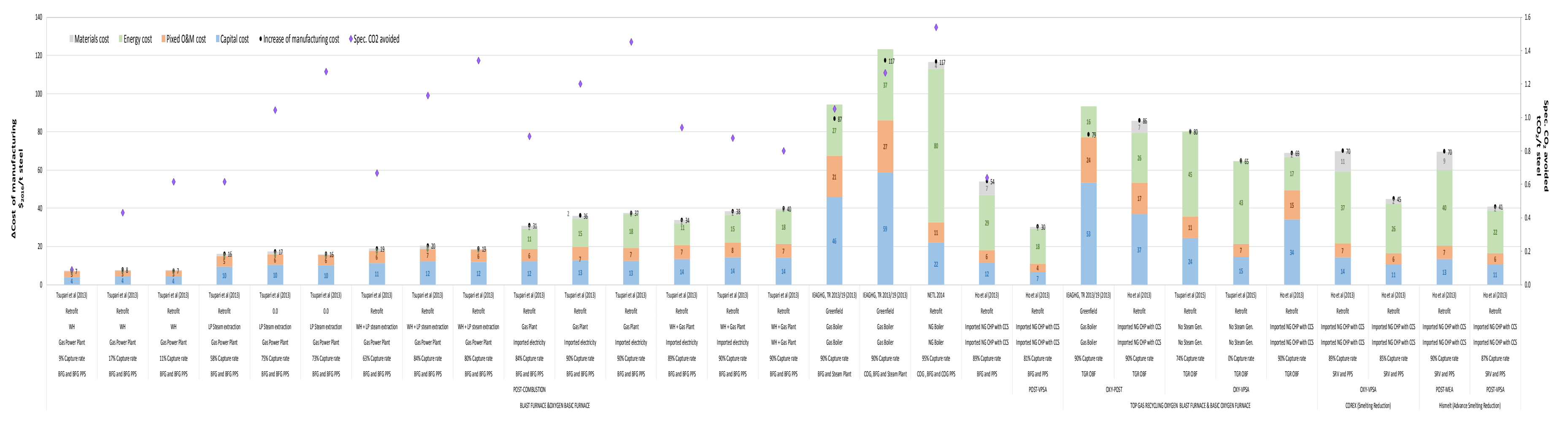

Figure 10 Additional production costs ($\$_{2016}$/ t steel) due to CO_2 capture and specific tonne of CO_2 avoided per tonne of Steel. CO_2 price is not considered. There is not emissions or cost revenue due to electricity export. CR stands for capture rate

Scenario C: Absence of waste heat recovery

Two underlying studies assumed a certain level of waste heat, available for the capture process. Scenario C examines the impact of the waste heat availability on the techno-economic performance of these capture cases (see Figure 11).

The cases explored in IEAGHG (2013a) included waste heat recovery from the boilers, quantified as 28GJ/year (5-6% of the total energy requirement for steam production for the CO_2 capture process). Tsupari et al. (2013) included three carbon capture cases, where the capture rate depends on the waste heat recovered. In those premises, 3 solvents were considered (MEA, low T solvent and advanced solvent). In the first case, the waste heat is quantified as 269 GW/year, while in the second one that is 1795 GW/year and recover the low TP steam cycle. The second case sums up both previous waste heat sources, from the manufacturing process and from the low TP steam cycle. Finally, the last case also recovers the waste heat from the manufacturing. Then, the waste heat recovered covers from 10 to 100% of the heat requirement for solvent regeneration.

For homogenisation of results, those eleven cases, two from IEAGHG (2013a) and nine from Tsupari et al. (2013) (3 waste heat recovery cases using the three proposed solvents in each), were assessed without considering heat recovery but an onsite gas boiler to supply steam. Additionally, in Tsupari et al. (2013) the waste recovery required the installation of an advanced heat exchange system (€23MM) which was removed in the scenario C. All those cases are applied to the traditional blast furnace configuration.

Under this scenario, the relative order of technologies per avoidance cost is not modified from the basis scenario, and VPSA is the cheaper capture technology for the steelmaking process considered in this work (COREX, HIsmelt, TGROBF or BF+BOF). In this scenario, the avoidance cost is not altered in the cases from the IEAGHG study due to the low waste heat assumed in the original study. However, in this scenario, the avoidance cost is significantly higher on the cases of Tsupari et al. (2013) (28-119 $\$_{2016}$/t CO_2, meaning a relative increase of 4-56%) due to the nature of their study, where the capture rate depends on the waste heat available[13].

---

[13] In this re-assessment, the capture rate was kept as the original study.

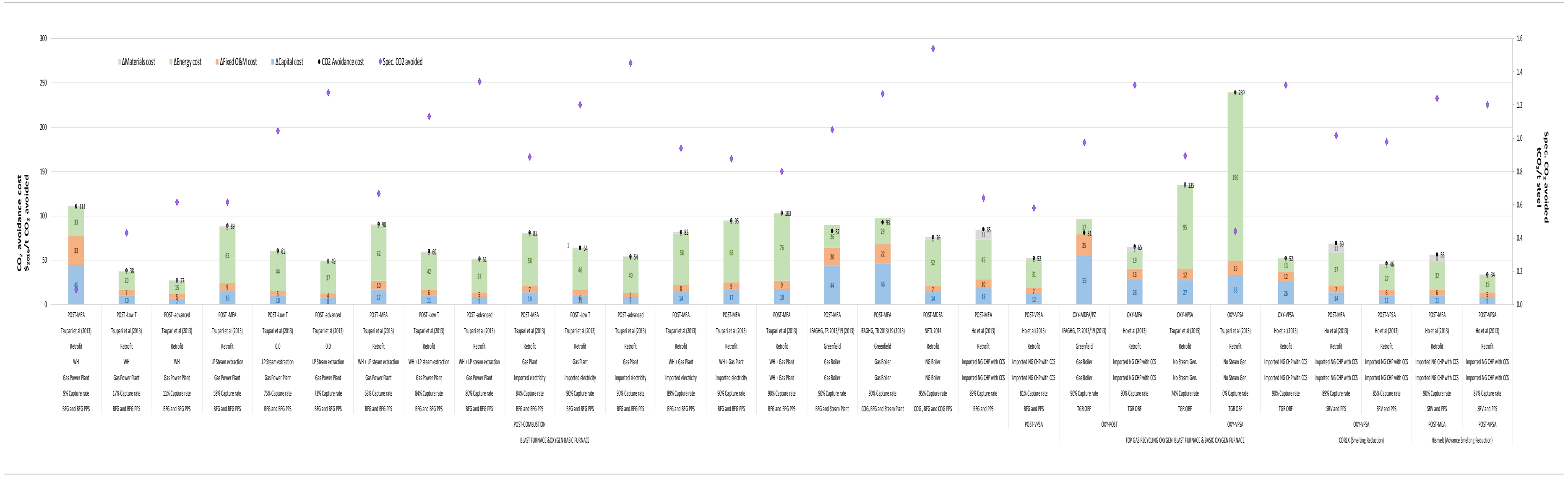

Figure 11 CO₂ avoidance cost ($$_{2016}$/ t CO₂ avoided) and specific tonne of CO₂ avoided per tonne of Steel. CO₂ price is not considered in the calculations. There is not weast heat available to invest in the CO₂ capture process. CR stands for capture rate

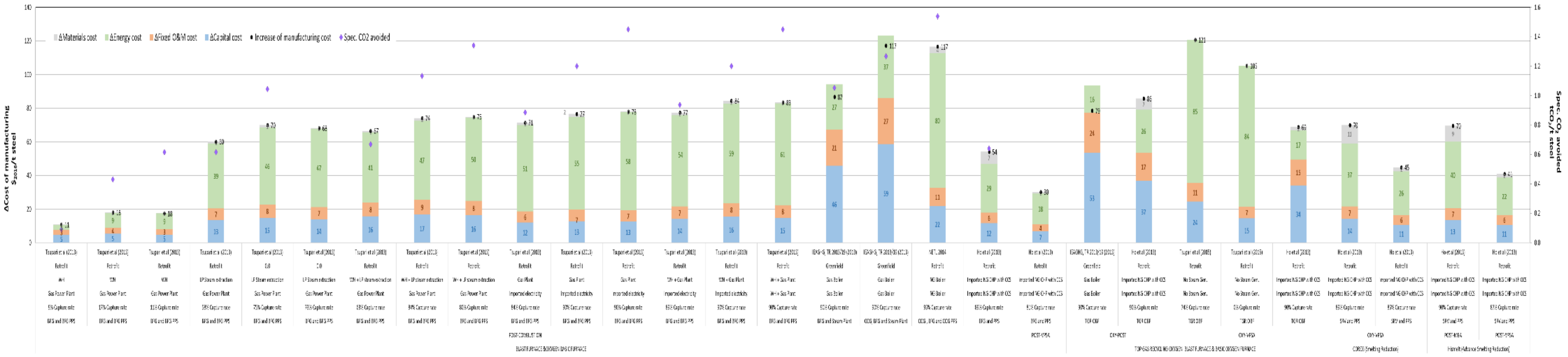

Figure 12 Additional production costs ($\$_{2016}$/ t steel) due to CO_2 capture and specific tonne of CO_2 avoided per tonne of Steel. CO_2 price is not considered. There is not waste heat available to use in the CO_2 capture process. CR stands for capture rate

5.2 Cement sector

5.2.1 Overview of capture technologies

In this section, the main CO_2 capture technologies for the cement process are described. The capture routes for the cement sector are compared based on a plant size of 1.36 Mt/yr cement production and a capacity factor of 85%. The figures were adjusted using a fixed clinker/cement ratio of 1.36. All reviewed studies assume a roughly similar reference cement plant, with a calciner, dry kiln process and a 5-stage cyclone preheater. However, the CO_2 intensity of cement production varies considerably per study, from 0.59 to 1.17 tCO_2/t Portland cement, which is most likely due to differences in feedstock, fuel and energy efficiency.

An overview of the standardised CO_2 avoidance costs and avoidance rates for cement manufacturing with CO_2 capture is presented in Figure 18. The additional cement manufacturing costs due to CO_2 capture are presented in Figure 19. Discussions below are focused in the CO_2 avoidance cost, and to note that, generally, the cement manufacturing cost follows a similar trend. However, there is one individual case where that is not correct. This the case of NETL (2014), where a high rate of CO_2 emissions from the production was included.

Post-combustion capture

Two main post-combustion capture (PCC) categories were identified in literature, namely chemical absorption and membranes. The former category seems to be the only realistic option for the short term, given its low technical risk dur to his higher TRL. Both types of technologies can be retrofitted to existing cement plants (Ozcan 2014). Most reviewed studies investigated the MEA-based absorption process, either in combination with a new-build or retrofitted cement plant. These studies may provide rather pessimistic cost figures, compared to the rapid development in energy efficient solvents over the last decade (Idem et al., 2015). Two publications examined other amine solvents, using advanced amines (Jakobsen et al. 2017) and methyldiethanolamine with piperazine (MDEA/PZ) (NETL, 2014).

Three of the reviewed studies looked into membrane CO_2 separation. Membranes are typically suited for CO_2 separation from concentrated gas streams, such as cement flue gas. However, achieving high capture rates is often not possible, so multiple stages and/or stream recycling is necessary, resulting in increased complexity, energy consumption and costs. Most membrane types are still in an early stage of development, but significant performance improvement is expected in the future (IEAGHG, 2014). Membrane CO_2 separation is driven by the partial CO_2 pressure difference between the two membranes sides (feed and permeate), which is often created by using a compressor on the feed side or vacuum-pump on the permeate side. Several membrane configurations have been proposed for CO_2 capture in the cement industry. Merkel et al. (2012) developed a multi-stage polymeric membrane configuration for retrofit applications. This high permeable membrane type (PolarisTM) is at an advanced stage of development and testing. Jakobsen et al. (2017) and Ozcan et al. (2014) investigated the performance of this membrane for the cement industry. A multi-stage fixed site carrier (FSC) membrane configuration was developed by NTNU and has been tested at the Norcem Brevik cement plant (Hägg 2015).

Figure 18 shows a wide range in CO_2 avoidance costs (72-199 $\$_{2016}$/t CO_2) for the amine-based PCC options. This is mainly due to differences in capture process design and varying assumptions on: (i) thermal energy requirements for MEA/amine regeneration, (ii) the amount of waste heat coming from the cement plant that is available to produce low-temperature steam for solvent regeneration, and (iii) the origin of the energy required for the CO_2 capture process. Also, detailed studies, like those from the IEAGHG and CEMCAP, may display higher CO_2 avoidance costs than most other studies, as detailed cost estimates tend to result in higher cost estimates. Only four out of eight studies reported assumptions on thermal energy requirements for MEA regeneration. Values vary widely per study, ranging from 2.8 GJ/tCO_2 captured (IEAGHG 2013b) to 4.1 GJ/tCO_2 captured (Gerbelová et al. 2017). A lower specific steam consumption is reported for advanced amines by Jakobsen et al. (2017) (2.1 GJ/tCO_2 captured). Not enough details are provided in the NETL (2014) study to evaluate the benefit of using MDEA/PZ compared to the use of MEA. With regard to the availability of waste heat coming from the cement process and/or CO_2 compression section, Jakobsen et al. (2017) assumed that 33% of the required solvent regeneration steam can be generated using waste heat, while other studies assumed lower percentages (e.g. IEAGHG: 15%, CEMCAP: 7%) or no waste heat availability at all (e.g. Gerbelová et al. 2017, NETL 2014). These different assumptions are reflected in the high standardised energy costs for, e.g., Gerbelová et al. 2017 and Anantharaman et al. (2016), whereas the opposite is true for, e.g., IEAGHG (2013b) and Jakobsen et al. (2017) (see Figure 18).

The wide range in CO_2 avoidance rates (0.30-1.09 tCO_2/t cement) for the amine-based cases is due to the same factors causing the variability in the CO_2 avoidance costs, but also because of varying capture rates and different specific CO_2 emissions per tonne of produced cement in the reference cement plants. The high CO_2 avoidance rates for NETL and Liang and Li are caused by the high specific CO_2 emissions of the cement production, whereas the high avoidance rate of Jakobsen is a direct result of the high waste heat available.

The energy and CO_2 avoidance costs of configurations with a CHP unit are typically lower than that for similar configurations with a boiler, because of the higher overall energy generation efficiencies and revenues coming from the export of excess electricity. However, the capital costs of configurations with a CHP unit are typically higher. The IEAGHG (2013b) study shows that the cases with a natural gas-based CHP unit have lower CO_2 avoidance costs than the cases with a coal-based CHP unit.

For similar MEA capture configurations, retrofit applications show slightly lower CO_2 avoidance costs than new-build configurations, although the difference is very small (see e.g. IEAGHG 2013b study). Likewise, the capture rate seems to have only a minor impact on the avoidance cost (see studies from Anantharaman et al. 2016, and Jakobsen et al. 2017).

The membrane cases show a rather small spread in CO_2 avoidance cost (69-78 $\$_{2016}$/t CO_2), regardless of the differences in the studied membrane types, configurations (retrofit vs. greenfield) and capture rates.

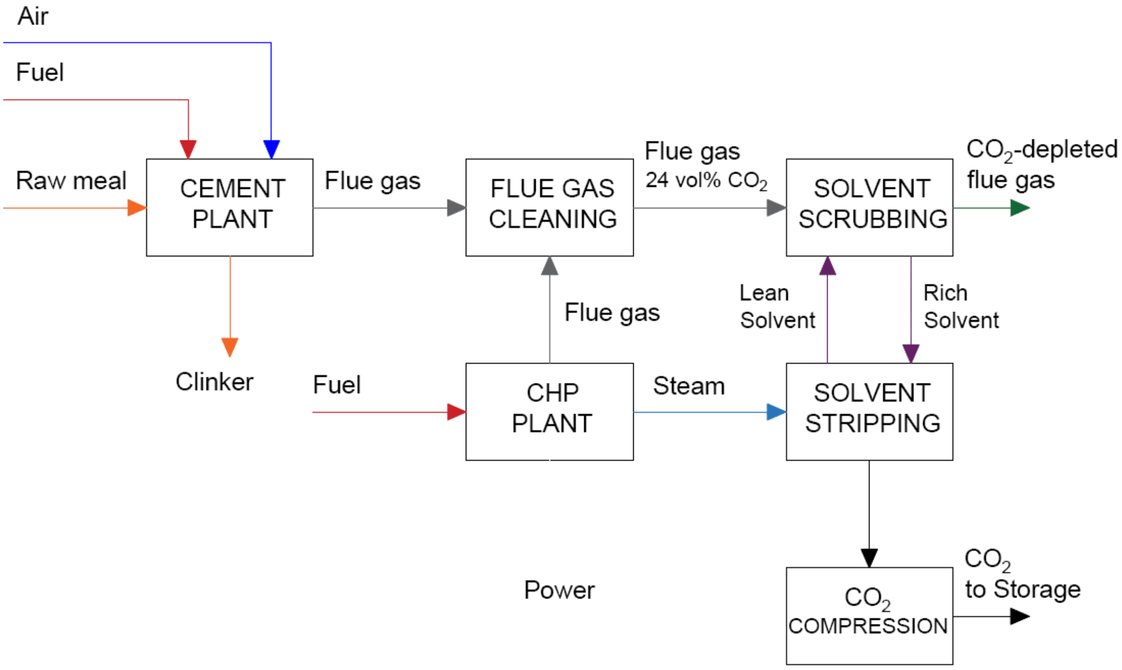

Figure 13 Schematic configuration of a cement plant with chemical absorption system to capture the CO_2 from the CHP and cement plant

Oxyfuel combustion with CO_2 capture

The oxyfuel combustion technology relies on the combustion of fuel with pure oxygen mixed with recirculated flue gas instead of air to obtain a high CO_2 concentration flue gas, which allows for a relatively easy purification by liquefaction. The partial oxyfuel concept concentrates the oxyfuel combustion only on the calciner, which is responsible for around 60% of the plant's CO_2 emissions. As the other sections of the plant (raw mill, cooler, kiln) are separated from the calciner, this option allows these other installations to operate conventionally. A variant of this concept is to replace the conventional air-fired calciner with a circulating fluidised bed (CFB) oxyfuel combustion calciner (Rodríguez et al. 2012). The limited impact on the plant's operation makes the partial oxyfuel concept a low-risk option and suitable for retrofitting (IEAGHG 2013b). In the full oxyfuel concept, the whole plant is operated under oxyfuel conditions, which influences the heat transfer in almost all sections of the plant due to changes in the gas atmosphere. The full oxyfuel concept is currently in the modelling and laboratory phase, and is more challenging than the partial oxyfuel option. Oxyfuel combustion can be retrofitted to existing kilns, but most of the core components would have to be replaced (IEA GHG, 2013). Literature seems to agree that an optimised oxyfuel technology could significantly improve the thermal energy efficiency of the cement plant compared to post-combustion technology (IEAGHG, 2008). Yet, technical difficulties may arise as well. Small-scale experiments show that the CO_2-rich atmosphere could potentially impair the calcination of limestone, but can be avoided by keeping the calciner temperature kept above a minimum threshold temperature (Zeman 2009). Other issues that still need to be solved are burner and cooler design as well as air-in leakage in the raw mill and kiln.

Figure 18 shows that the spread in CO_2 avoidance cost in the group of oxyfuel cases (37-86 $\$_{2016}/tCO_2$) and avoidance rate (0.40-0.66 tCO_2/t cement) is considerably smaller than that for post-combustion capture, partly because fewer studies were considered. Furthermore, only two energy options were examined, namely electricity import for the conventional oxyfuel combustion configuration and onsite electricity generation using a steam cycle, partly using waste heat from the cement process, for the CFB oxyfuel calciner configuration. The full oxyfuel combustion cases with electricity import show lower avoidance costs (69-80 $\$_{2016}$/t$CO_2$) than the partial oxyfuel combustion cases (82-86 $\$_{2016}$/t$CO_2$), mainly due to economies of scale related to the ASU. The CFB calciner configuration shows similar specific capital and fixed O&M cost as the full oxyfuel combustion cases with electricity import. However, the CO_2 avoidance costs (37 $\$_{2016}$/t$CO_2$) are much lower, because of onsite electricity generation and waste heat utilisation, resulting in negative energy cost. Similar for post-combustion capture, the cost differences between the retrofit and greenfield cases are minor.

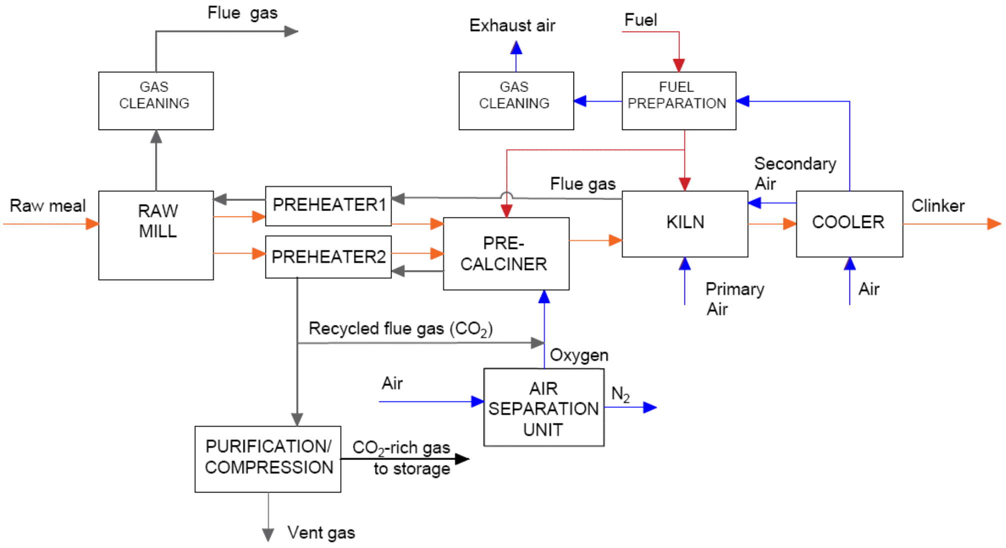

Figure 14 Schematic configuration of a cement plant with partial oxyfuel CO_2 capture

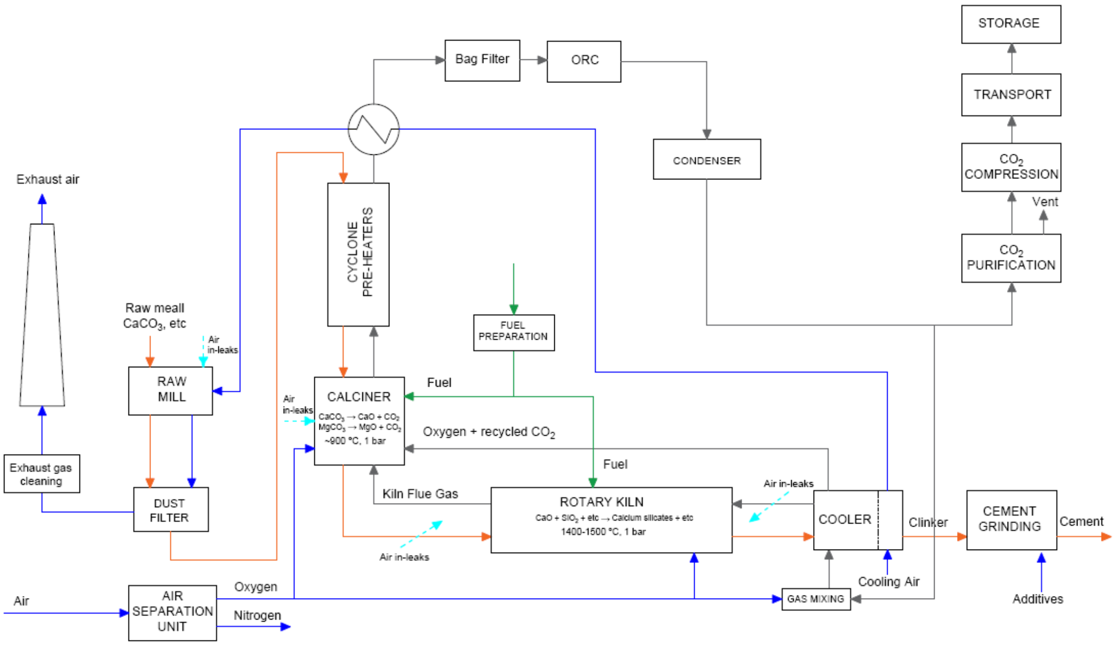

Figure 15 Schematic configuration of a cement plant with a integrated full oxyfuel combustion capture system (adapted from ECRA, 2012)

Solid looping systems

Another advanced CO_2 capture technology category is solid looping systems, in which CO_2 is captured at high temperature in cyclical processes using fluidised or fixed bed reactors. In the process, a solid carrier is used to transfer either CO_2 or O_2 from one reactor to another. The main advantage of solid looping systems is the energy and mass synergies that can be achieved by integrating these technologies into the cement process. Solid looping systems have been extensively reported in literature through several configurations. Indirect calcination is the simplest among them. In this process, the fuel combustion and limestone calcination are separated into distinct chambers. Hot calcium oxide (CaO) is circulated between both chambers for heat transfer. This configuration allows for separation of CO_2 from limestone calcination in a concentrated form, but has a relatively low maximum carbon capture rate since only CO_2 generated in the calciner is captured. The energy penalty can be minimised by integrating the process with a heat recovery steam cycle. A hybrid configuration, combining indirect calcination with MEA-based chemical absorption, was proposed by Ozcan (2014). In this arrangement, the MEA process removes the remaining CO_2 related to the clinkering occurring in the kiln and fuel combustion for the indirect calcination process.

Calcium looping (Ca-looping) involves chemical reactions between CaO and CO_2 through sequential carbonation-calcination cycles. Part of the CaO from the calciner is sent to a high-temperature carbonator where is it used to absorb CO_2 contained in flue gas to form $CaCO_3$. The generated $CaCO_3$ is circulated back to the calciner where it is decomposed into CaO and a high-concentration stream of CO_2. After several cycles, the CaO loses its sorbent reactivity and is fed to the kiln for cement production. Ca-looping systems can be deployed as a post-combustion application added to a conventional cement production process, or be integrated in the cement plant by replacing a conventional air-fired calciner with a CFB oxyfuel combustion calciner and a carbonator to capture CO_2 from the kiln flue gas (see Figure 16). The use of oxygen in the calciner chamber results in a high-concentration stream of CO_2 coming from both the decomposition of $CaCO_3$ and indirectly from the kiln flue gas. Retrofitting Ca-looping to cement plants should be possible by replacing the existing calciner with an oxy-calciner (Ozdic, 2014). Considerable amounts of waste heat can be recovered from the high-temperature flue gas leaving the carbonator.

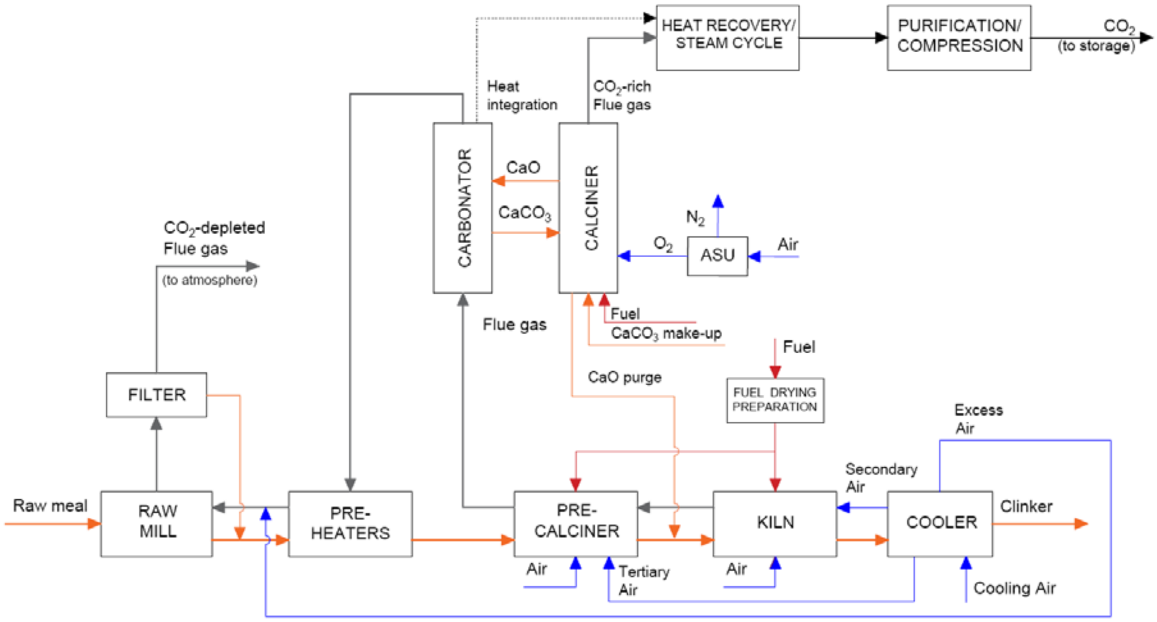

Figure 16 Schematic diagram of cement plant with a calcium looping system.

Another possibility is the *double Ca-looping* configuration, which combines indirect calcination (first CaO loop) with Ca-looping (second CaO loop). Unlike the oxyfuel Ca-looping configuration, this concept does not need oxy-fired combustion, which significantly reduces the electricity consumption for oxygen combustion in the calciner. Yet, the thermal input for the overall plant is higher.

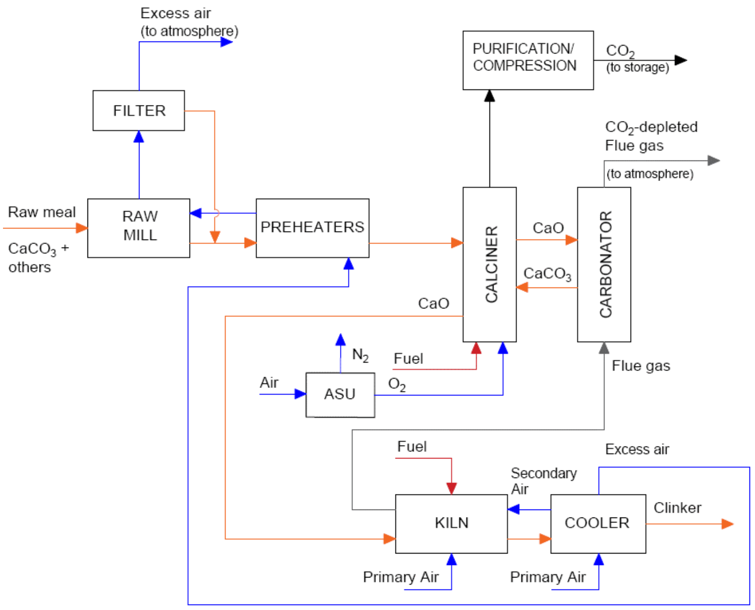

Figure 17 Schematic diagram of cement plant with an oxy-fired circulating fluidized oxyfuel calciner in a calcium-looping system.

The last configuration involves coupling of a chemical looping combustion (CLC) cycle with a Ca-looping process. This configuration comprises an air reactor and a fuel reactor and uses a metal oxide as an oxygen carrier. The exothermic reduction of the metal oxide in the fuel reactor provides heat to the calciner. The CLC cycle substitutes the energy intensive ASU that is used in most Ca-looping processes.

The economic performance of the solid looping systems varies considerably, not only between the capture configurations but also between studies examining the same configuration (see Figure 18). Indirect calcination shows a relatively wide spread in avoidance cost (36-86 $\$_{2016}$/t CO_2) and avoidance rate (0.18-0.37 tCO_2/t cement), which is mainly due to varying assumptions on the origin of the energy (steam cycle or electricity import), the amount of waste heat available, and electricity export. Combining indirect calcination with MEA-based post-combustion capture appears to be much costlier (199 $\$_{2016}$/t CO_2) than the other solid looping options. Both studies that investigated Ca-looping (Ozcan and Rodriguez) show higher avoidances rates (0.49-0.76 tCO_2/t cement) than the indirect calcination cases, while the avoidance costs (53-71 $\$_{2016}$/t CO_2) are rather similar between both technologies. The difference between Ozcan (2014) and Rodriguez et al. (2012) in terms of costs and avoidance rate is a result of different capture rates and the high electricity export in the study of Ozcan (2014). The avoidance cost (81 $\$_{2016}$/t CO_2) of the double Ca-looping concept was found to be higher than those for the other configurations, as the higher capital expenses do not appear to offset the lower energy costs. Chemical looping shows CO_2 avoidance cost (52 $\$_{2016}$/t CO_2) which are at the lower end of the range observed for the other Ca-looping configurations (53-71 $\$_{2016}$/t CO_2), but this is partly due to high credits for electricity sale and waste heat utilisation.

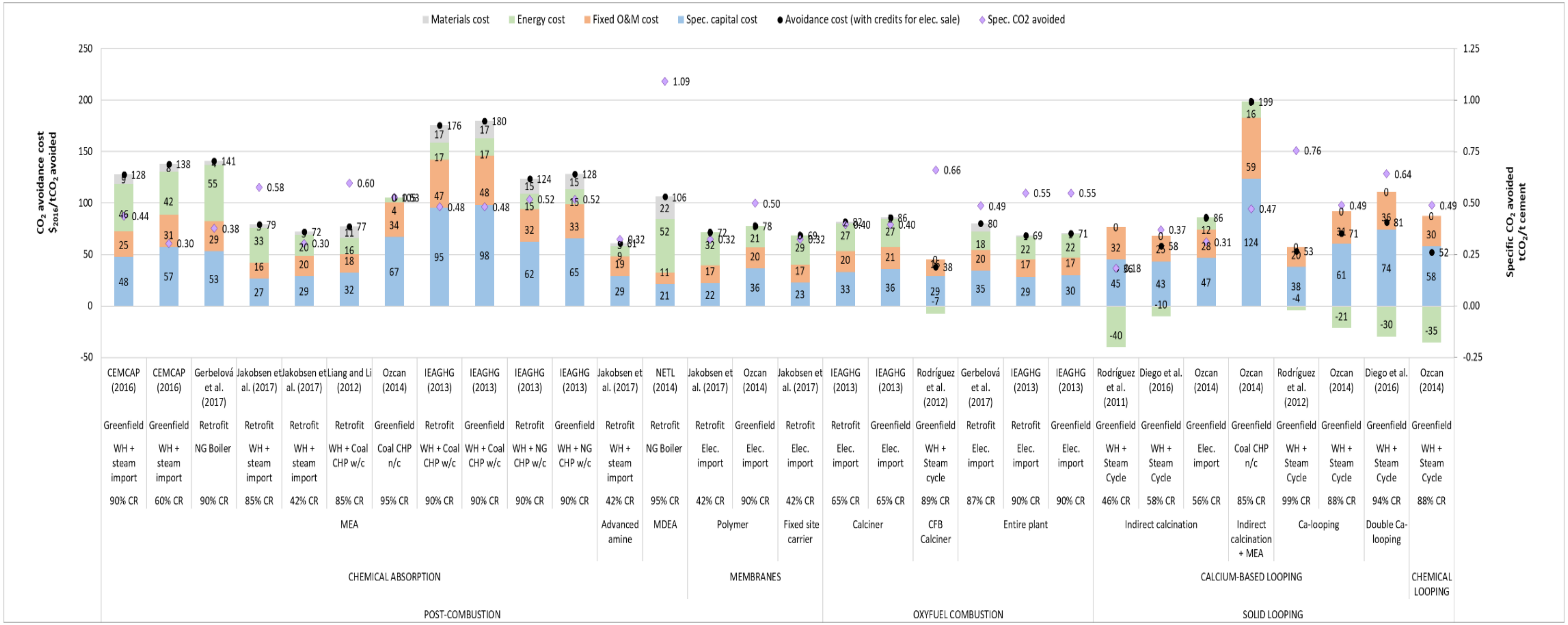

Figure 18 Overview of standardised CO_2 avoidance costs and avoidance rates for cement production with CO_2 capture. The configurations with a CHP unit include credits for the export of excess electricity. CR stands for capture rate.

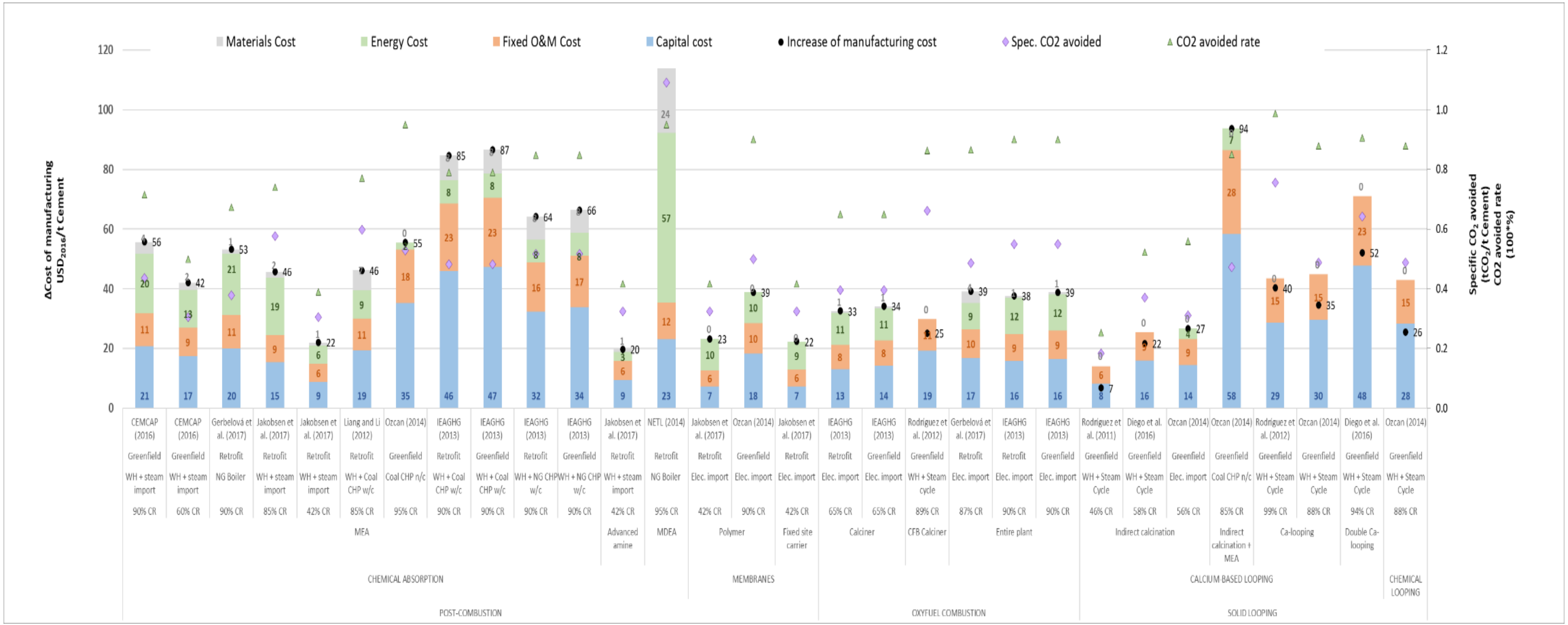

Figure 19 Overview of standardised cement manufacturing costs and avoidance rates for cement production with CO₂ capture. CR stands for capture rate

5.2.2 Alternative scenarios: Absence of waste heat and inability of exporting electricity to the electricity grid

As in the case of the steelmaking sector, heat integration is crucial for the implementation of CO_2 capture systems in the cement industry. The studies in the literature frequently include waste heat available to produce the required steam or energy in the CO_2 capture system. However, that assumption can be controversial for two reasons: first, switching to more efficient manufacturing process will reduce or eliminate this waste heat availability; and secondly, the waste heat can be reused in other sections of the manufacturing process, such as raw materials drying. In this report, the scenario of absence of waste heat has been explored, which homogenised the waste heat assumptions made along the studies.

Moreover, as for the steelmaking sector, inability of injecting the surplus energy on the electricity grid has been explored through an additional scenario. Equal to the previous scenario, that homogenised assumptions on economic and environmental revenues and offered a more complete overview of the integration of the cement industry in the electricity grid.

Scenario B: Inability of exporting energy to the electricity grid

Surplus of energy has been reported along several cases collected in the underlying studies of CCS in the cement industry included in this work. Furthermore, all those studies assumed that electricity can be exported to the grid, except in CEMCAP (Anantharaman et al. 2016) which considered that export to be unrealistic for many cement plants. In total, 10 cases were re-assessed by excluding economic and emission credits for electricity export. Figure 20 shows that the cost especially grows in some cases of chemical absorption, where the CO_2 avoidance cost increases from 72-180 to 72-215 \$/t CO_2.

In this scenario, generally, the capture technologies with the lower CO_2 avoidance cost are oxyfuel combustion (69-86 \$/t CO_2) and the membrane-based capture options (69-78 $\$_{2016}$/t CO_2). The most expensive option is still the hybrid technology. To note that the CO_2 avoidance costs of those capture technologies remains the same than in the basis case, as those cases do not include revenue from electricity export. The cost of cement manufacturing under this scenario is shown in Figure 21

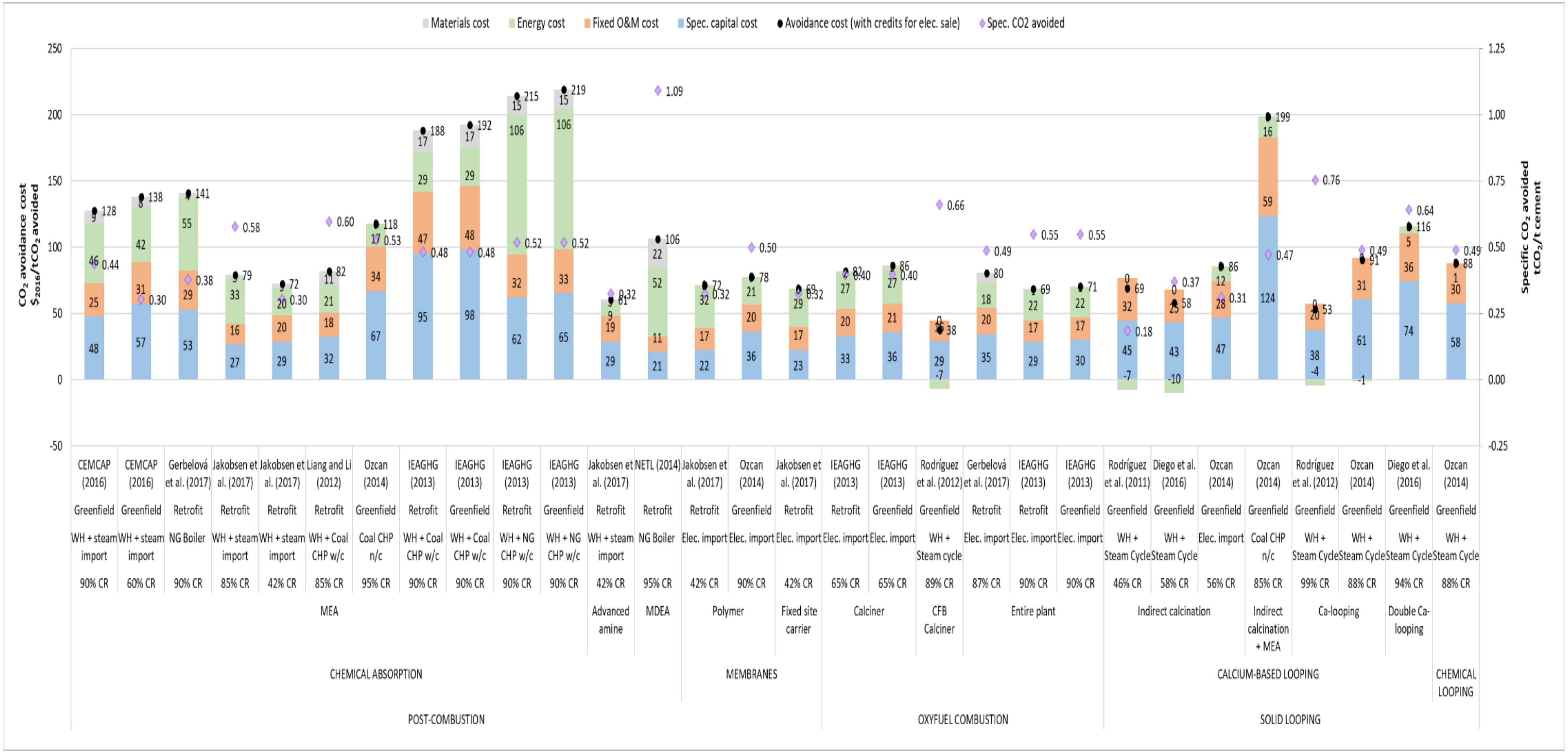

Figure 20 Overview of standardised CO_2 avoidance costs and avoidance rates for cement production with CO_2 capture in absence of revenue from electricity export. CR stands for capture rate

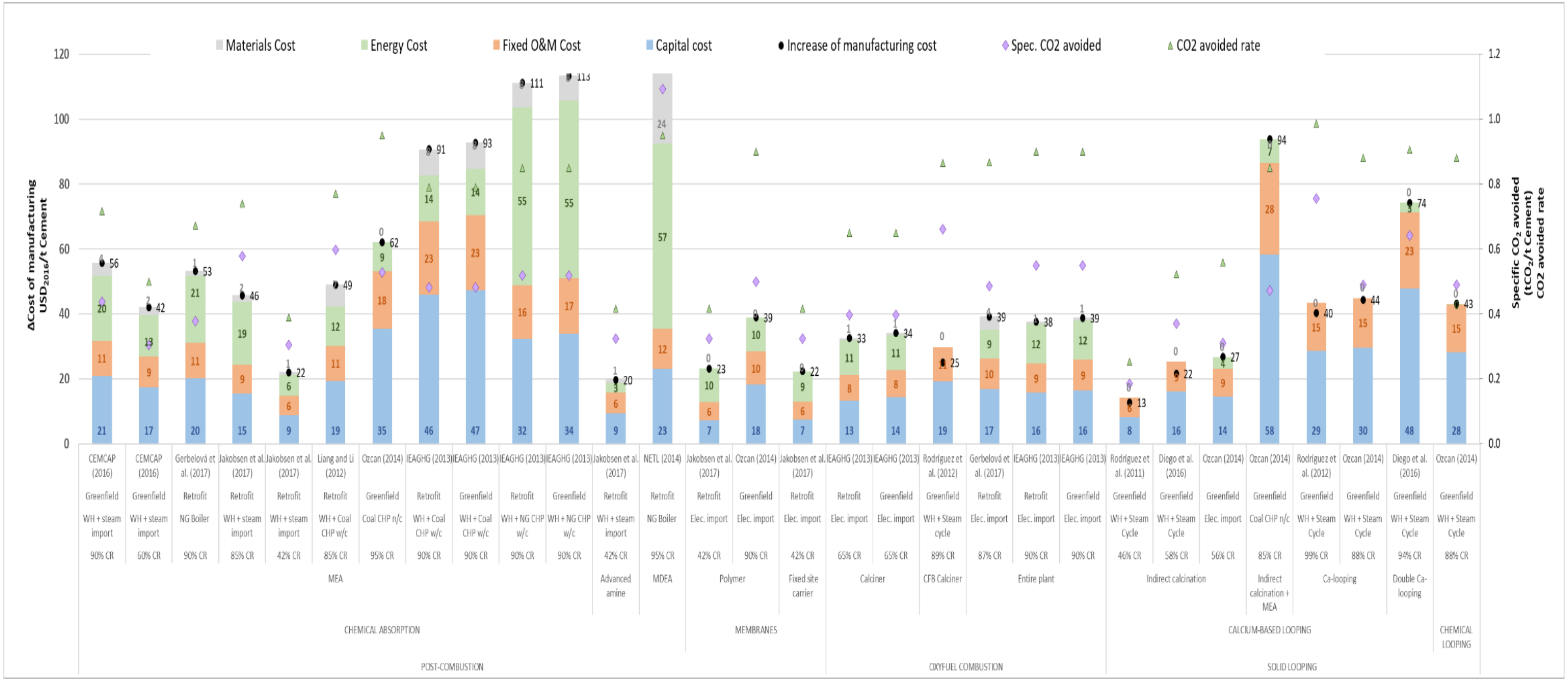

Figure 21 Overview of standardised cement manufacturing costs and avoidance rates for cement production with CO_2 capturein absence of revenue from electricity export. CR stands for capture rate

Scenario C: Absence of waste heat recovery

Several studies assumed that waste heat from the cement process is available and can be used for the CO_2 capture process. However, differences can be observed within the assumptions from one study to another. IEAGHG (2013) considered that 15% of the energy required for solvent regeneration within the MEA-based post-combustion configuration (representing 24-33 MW), was covered by the waste heat from the cement production process. For the same technology, CEMCAP (Anantharaman et al. 2016) assumed a fixed waste heat available (6MW) to invest on the steam production for the solvent regeneration. The studies on solids-based technologies – i.e. Rodriguez et al. (2012, 2011), Diego et al. (2016) and Ozcan (2014) – assumed substantial amounts of waste heat (up to 240 MW) to be available. In this work, a total of 12 cases were re-assessed by excluding waste heat recovery (see Figure 26). As seen in the graph, the CO_2 avoidance cost increases substantially, 64-348 $\$_{2016}$/t CO_2, for the solids-based cases, with a relative growth of 38- 90% over the basis scenario. The reason for that increase is the high heat integration of those capture systems in the manufacturing process, as reported in the original studies. Heat recovery is essential in amine-based systems, as the energy and cost penalty are intimately related to the steam production for solvent regeneration. A good heat integration would be translated in large savings. However, the literature studies covering amine-based capture did not assume large amounts of waste heat to be available, compared to the studies on solids-based technologies. Consequently, the relative increase in avoidance cost for the amine-based capture studies is smaller (5-46%), with a CO_2 avoidance cost of 77-215 $\$_{2016}$/t CO_2. Oxyfuel and membrane-based systems are cheaper options, 69-86 and 69-78 $\$_{2016}$/t CO_2 respectively, due to the absence of dependency of those technologies on steam production.

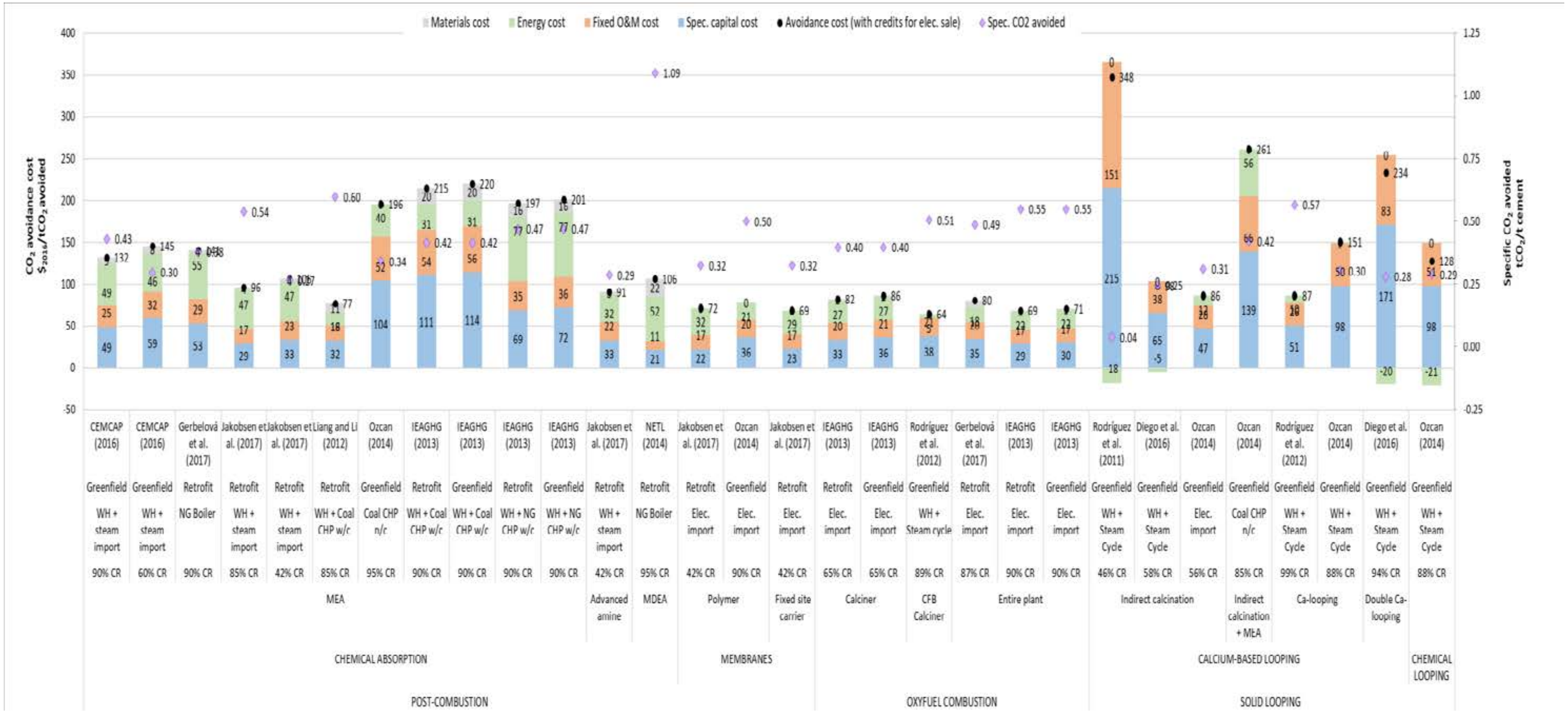

Figure 22 Overview of standardised CO_2 avoidance costs and avoidance rates for cement production with CO_2 capture in absence of waste heat recovery. CR stands for capture rate

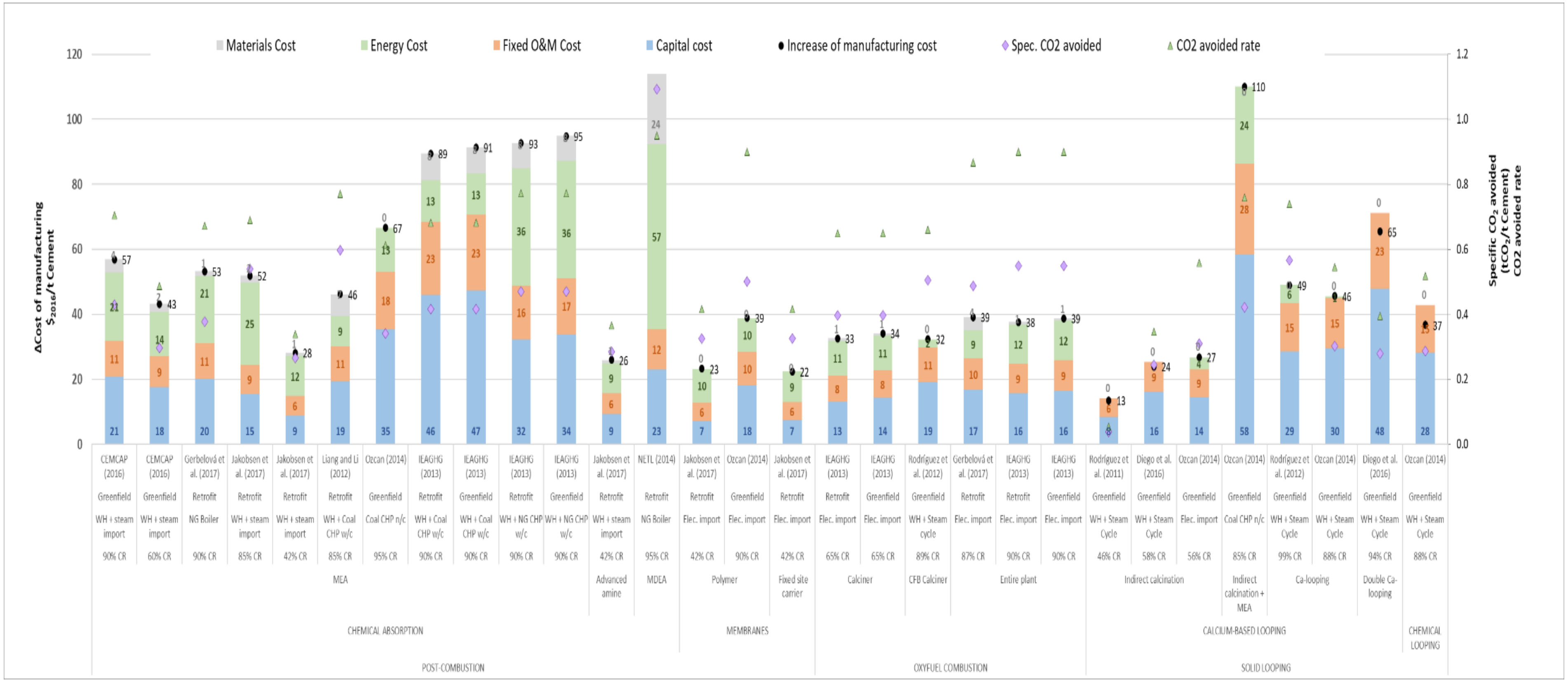

Figure 23 Overview of standardised cement manufacturing costs and avoidance rates for cement production with CO_2 capture, in absence of waste heat recovery. CR stands for capture rate

6. Summary

In this work, a techno-economic review of CO_2 capture technologies for the cement and iron and steel sectors has been done. Results from the literature have been standardized for a number of key technical and economic parameters using a set of input values applying to North-West Europe. Cost of the implementation of CO_2 capture technologies in the cement and iron and steel sectors are presented in Table 10, based on three scenarios: basis scenario, taking into consideration environmental and economic revenue from export of surplus energy produced on the industrial site, and the available waste heat reported in the reference studies; no-waste-heat-recovery, under the premise of absence of available waste heat to use for CO_2 capture; and no-export-revenue, considering that the energy surplus cannot be exported and there are no economic or environmental revenues.

For the iron and steel sector, CO_2 reductions can be achieved by implementing new production routes over the traditional blast furnace with basic oxygen furnace (BF+BOF), such as top gas recirculation on the blast furnace (TGRBF) operating under oxyfuel combustion (TGROBF) and advanced smelting processes (for example, HIsmelt, Corex). In this work, 29 cases were assessed. CO_2 capture technologies have been evaluated separately on the different steelmaking processes and with a full or partial capture rate. The technologies included in this review are: post-combustion (chemical absorption with MEA, MDEA and advanced solvents, and vapour swing adsorption (VPSA)) and hybrid systems (oxyfuel combined with chemical absorption and oxyfuel combined with VPSA). The flue gas treated, at partial or full capture rate, are the combined gas output streams from the BF and the onsite power plant, or from the coke oven plant (COP), BF and power plant. Results show a CO_2 avoidance cost range of 56-82 $\$_{2016}/tCO_2$ for chemical absorption with traditional amines[14], 52-80 $\$_{2016}/tCO_2$ chemical absorption using advanced amines[15], 34-52 $\$_{2016}/tCO_2$ for VPSA; and 65-135 $\$_{2016}/tCO_2$ avoided for hybrid technologies (oxyfuel combined with chemical absorption or VPSA). The most cost-effective production route seems to be the Corex process, which is still in an early stage of development. Note that those figures are estimates under the assumptions made on the cost method and considering that the technologies assessed in this work are still at an early development stage. Consequently, actual costs remain uncertain. Regarding the HIsmelt and Corex configurations, only one study included cost estimations (Ho et al. 2013), so the figures are not validated against another study.

For the cement sector, 32 cases were assessed. The technologies included in this review are post-combustion (chemical absorption with traditional and advanced solvents, and membranes), oxyfuel, solids-based (calcium looping, chemical looping, double calcium looping, and indirect calcination) and hybrid technologies (indirect calcination with chemical absorption with MEA). The evaluated systems cover partial and full capture rate, new construction and retrofitting. Post-combustion has the highest TRL and consequently, the cost figures seem to be less uncertain as it has been tested at larger scale and economic evaluations include less estimations. Results show a CO_2 avoidance cost range of 79-180 $\$_{2016}/tCO_2$ for chemical absorption using traditional amines. The large cost range is due to differences on configurations and assumptions. Using and advanced solvent reduced the CO_2 avoidance cost to 61 $\$_{2016}/tCO_2$; 69-78 $\$_{2016}/tCO_2$ for membranes; 69-86 $\$_{2016}/tCO_2$ for oxyfuel technologies;

---

[14] In this study, MEA, MDEA, PZ are considered traditional amines

38-86 $\$_{2016}/tCO_2$ for solids-based technologies; and 199 $\$_{2016}/tCO_2$ for the hybrid arrangement (indirect calcination combined with MEA-based chemical absorption).

The present study shows that the techno-economic competitiveness of the capture technologies is considerably affected by several key factors, including the availability of waste heat, the origin of the steam and electricity used for the carbon capture process, and the possibility to sell surplus energy to third parties. This shows that the heat integration is a key factor in the implementation of CO_2 capture systems.

From an economical point of view, those scenarios are essential to homogenise the assumptions in the literature, which shows a wide range of waste heat available and surplus of produced energy. From the perspective of future improvements in the manufacturing processes, energy efficiency might be higher, and the waste heat might be limited or not available at all. Under those scenarios, technologies non-dependent on steam demand, such as membranes, solids-based, VPSA or advanced chemical absorption[11] are economically more favourable.

Table 10 Summary of results obtained in this work

COST PARAMETER	**SCENARIO**	**Cement**						**Iron and Steel**[g]			
		Traditional chemical absorption	**Advanced chemical absorption**	**Membranes**	**Oxyfuel**	**Solids-based**	**Hybrid**[d]	**Traditional chemical absorption**	**Advanced chemical absorption**	**VPSA**	**Hybrid**[e]
CO_2 avoidance cost ($\$_{2016}$/ t CO_2 avoided)	**BASIS**	72-180	61	69-78	69-86	38-86	199	56-82	52-80	34-52	65-135
	No-heat-recovery	77-215	91	69-78[a]	69-86[a]	64-348	261	56-119	28-70	34-52[a]	81-135
	No electricity export	72-215	61	69-78[b]	69-86[b]	38-91	199[b]	69-93	12-37[f]	34-52[b]	52-90
CO_2 captured cost ($\$_{2016}$/ t CO_2 captured)	**BASIS**	34-79	45	51-57	50-63	11-63	146	16-21	7-16	11-14	23-66
	No-heat-recovery	34-93	59	51-57[a]	50-63[a]	21-68	171	17-30	7-18	11-14[a]	33-66
	No electricity export	36-101	45	51-57[b]	50-63[b]	20-67	146[b]	7-23[f]	3-9[f]	11-14[b]	33-44
Increase of manufacturing cost[c] **(**$\$_{2016}$/ t cement or steel)	**BASIS**	46-116	20	39	38-39	26-40	94	54-93	74-76	30-45	69-86
	No-heat-recovery	46-116	26	39[a]	38-39[a]	37-65	110	54-117	77-78	30-45[a]	69-86[a]
	No electricity export	49-116	20	39[b]	38-39[b]	40-74	94[b]	39-117[f]	36-37[f]	30-45[b]	69-86[b]

[a] Those cases do not include waste heat available to recover

[b] Those cases do not include revenue from electricity export

[c] At full CO_2 capture rate on the treated fluegas. To note that the increase of manufacturing cost ($\$_{2016}$/ t cement or steel) was calculated based on the reference without CO_2 capture included in each study.

[d] Indirect calcination combined with MEA-based chemical absorption

[e] Oxyfuel combined with traditional chemical absorption or VPSA

[f] Note that a lower cost is seen in the “no electricity export” scenario compared to the “basis” scenario. That is one of the limitations of the cost method. The energy cost is reported as increase of energy cost compared to a reference case. When there is not electricity export, the increase of energy cost becomes zero as the cost method does not reflect any difference between investing the energy on the capture system and having energy surplus that cannot be sold (reference). (See section 4 for a list of the limitations)

[g] This economic review included several steelmaking configurations (Blast furnace, HIsmelt, Corex). This table is an overview and has not been divided by technology or by fluegas treated (BFG, BOFG, CHPG, COG, SGPG, LKPG, SRVG)

7. Final remarks

This study gives an overview of the cost estimates of implementing carbon capture technologies in the cement and iron and steel sectors based on a comprehensive review of available literature. Given the potential of carbon capture as a decarbonisation option in industry, the communication of techno-economical estimations of carbon capture systems is essential. This paper has reviewed and discussed high quality studies. Findings show significant differences in the costing methods and heat integration frameworks used from one study to another. In this work, a new methodology to homogenise literature results is given. Those outputs can support policy makers, energy-economic models, and cement and iron and steel industries particularly. Additionally, it can inform future research on areas for improvement.

Nevertheless, the results should be taken with discretion since these are limited by energy and materials flows, and materials and equipment costs given in the particular studies, and by additional assumptions described within the text. However, the present work aims to show these limitations in a transparent way (See Section 4). Firstly, it must be remembered that no one has yet built or operated a full-scale carbon capture system on a cement or iron and steel plant. Consequently, the results presented here concern technologies at TRL lower than 9. Note that the capture technology itself can be at advanced stage (meaning higher TRL) in the power sector but not in an industrial environment. Secondly, the design of the carbon capture system might change from one case to another case, which increases the cost range shown per technology.

It cannot be assumed that favourable technologies in the cement sector will be so in the iron and steel sector due to the heterogeneity of flue gas, CO_2 emissions points, operation conditions, etc. Moreover, the installation and integration of carbon capture technologies are site-specific due to individualities of each manufacturing process. Further considerations that would influence the uptake of carbon capture at individual plants would include whether the integration of the carbon capture technology would mean stopping the production for a long period of time, as well as other technical and operational concerns that are not covered in this review – for example the potential for specific traces in the fluegas within the individual productions to be accumulated in the carbon capture system; there could be mechanical challenges associated with VPSA systems; and the potential for effective heat integration can change from one facility to another one.

8. References

AACE (2011). Cost Estimate Classification system- As applied in engineering, procurement, and construction for the process industries., AACE International Recommended Practice No. 18R-97 (Rev. November 29,2011). AACE International, Morgantown, WV.

Anantharaman, R., Fu, C., Roussanaly, S., & Voldsund, M. (2016). D4.2 Design and performance of CEMCAP cement plant with MEA post combustion capture, 35. Retrieved from https://www.sintef.no/globalassets/sintef-energi/cemcap/d4.2-design-and-performance-of-cemcap-cement-plant-with-mea-post-combustion-capture_rev1~1.pdf

Arias, B., Alonso, M., Abanades, C., 2017. CO_2 Capture by Calcium Looping at Relevant Conditions for Cement Plants: Experimental Testing in a 30 kWth Pilot Plant. DOI:10.1021/acs.iecr.6b04617 Ind. Eng. Chem. Res. 2017, 56, 2634−2640.

CEEI, 2017. Chemical Engineering, Economic Indicators: Chemical Engineering Plant Cost Index (CEPCI).

Consonni, S., 2016. CO_2 capture and reuse in the cement industry “From the lab to the plant” - Integration of Ca-Looping System. Presentation. University of Mons -9 November 2016.

Diego, M. E., Arias, B., & Abanades, J. C. (2016). Analysis of a double calcium loop process configuration for CO2capture in cement plants. Journal of Cleaner Production, 117, 110–121. https://doi.org/10.1016/j.jclepro.2016.01.027

DOE/NETL. (2011). Power Systems Financial Model Version 6.6 User’s Guide. Doe/Netl-2011/1492, 1.

ECRA, Technical Report TR-ECRA-119/2012, ECR CCS Project- Report on Phase III

ECRA (2017). Development of State of the Art Techniques in Cement Manufacturing: Trying to Look Ahead. European Cement Research Academy (ECRA) and Cement Sustainability Initiative (CSI) (eds.) ECRA, Düsseldorf and Geneva, www.wbcsdcement.org/technology.

European Commission, JRC (2009), Summary on Energy Efficiency issues in the BREF Series

Gerbelová, H., van der Spek, M., & Schakel, W. (2017). Feasibility Assessment of CO_2 Capture Retrofitted to an Existing Cement Plant: Post-combustion vs. Oxy-fuel Combustion Technology. Energy Procedia, 114(November 2016), 6141–6149. https://doi.org/10.1016/j.egypro.2017.03.1751

Hägg M-B. CO2 capture using a membrane pilot process at cement factory, in Brevik Norway - lessons learnt. Trondheim Carbon Capture and Storage conference 8, 17-18 June 2015. Trondheim, Norway 2015.

He, X., Fu, C., Hagg, M.B., 2015. Membrane system design and process feasibility analysis for CO2 capture from flue gas with a fixed-site-carrier membrane. Chem. Eng. J. 268, 1-9.

Ho, M. T., Bustamante, A., & Wiley, D. E. (2013). Comparison of CO2 capture economics for iron and steel mills. International Journal of Greenhouse Gas Control, 19, 145–159. https://doi.org/10.1016/j.ijggc.2013.08.003

Hornberger, M., Spoerl, R., Scheffknecht, G., 2017. Calcium looping for CO_2 capture in cement plants – pilot scale test. Energy Procedia 114 (2017) 6171 – 6174.

Husebye, J., Brunsvold, A. L., Roussanaly, S., & Zhang, X. (2012). Techno economic evaluation of amine based CO_2 capture: Impact of CO_2 concentration and steam supply. Energy Procedia, 23(1876), 381–390. https://doi.org/10.1016/j.egypro.2012.06.053

IEA/OECD, 2005. Energy Statistics Manual. Paris (France).

IEA (2017a) Energy Technologies Perspectives - Catalysing Energy Technology Transformations. International Energy Agency, Paris (France).

IEA (2017b). World Energy Outlook 2017. International Energy Agency, Paris (France).

IEA (2018). Technology Roadmap. Low-carbon transition in the cement industry. International Energy Agency, Paris (France).

IEAGHG (2008) CO2 Capture in the Cement Industry, 2008/03, July 2008

IEA Greenhouse Gas R&D Programme (IEA GHG) (2013a). Iron and Steel CCS study (Techno-economics integrated steel mill).

IEAGHG. (2013b). Deployment of CCS in the Cement Industry, 2013/19, December 2013

IEAGHG (2013c) Toward a common method of cost estimation for CO_2 capture and storage at fossil fuel power plants, Report 2013/TR2

IEAGHG (2014) Assessment of emerging CO_2 capture technologies and their potential to reduce costs (2014/TR4)

IEAGHG (2018). Effects of plant location on costs of CO_2 capture, 2018-04, April 2018

Jakobsen, J., Roussanaly, S., & Anantharaman, R. (2017). A techno-economic case study of CO2 capture, transport and storage chain from a cement plant in Norway. Journal of Cleaner Production, 144, 523–539. https://doi.org/10.1016/j.jclepro.2016.12.120

Kumar, D., & Kumar, D. (2016). Latest Developments in the Iron and Steel Industry. Management of Coking Coal Resources. https://doi.org/10.1016/B978-0-12-803160-5.00002-2

Kuramochi, T., Ramírez, A., Turkenburg, W., & Faaij, A. (2012). Comparative assessment of CO2capture technologies for carbon-intensive industrial processes. Progress in Energy and Combustion Science, 38(1), 87–112. https://doi.org/10.1016/j.pecs.2011.05.001

Leeson, D., Mac Dowell, N., Shah, N., Petit, C., & Fennell, P. S. (2017). A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. International Journal of Greenhouse Gas Control, 61, 71–84. https://doi.org/10.1016/j.ijggc.2017.03.020

Liang, X., & Li, J. (2012). Assessing the value of retrofitting cement plants for carbon capture: A case study of a cement plant in Guangdong, China. Energy Conversion and Management, 64, 454–465. https://doi.org/10.1016/j.enconman.2012.04.012

NETL (2014), Cost of Capturing CO_2 from Industrial Sources, DOE/NETL-2013/1602, https://www.netl.doe.gov/energy-analyses/temp/CostofCapturingCO2fromIndustrialSources_011014.pdf

OECD, 2017. URL: https://data.oecd.org/conversion/exchange-rates.htm (Visited: 03/08/2017).

Ozcan, D. C. (2014). Techno-Economic Study for the Calcium Looping Process for CO_2 Capture from Cement and Biomass Power Plants. PhD Thesis, School of Engineering, The University of Edinburgh, (November 2014). https://doi.org/10.1016/j.enconman.2015.01.060

Rodríguez, N., Alonso, M., Grasa, G., & Abanades, J. C. (2008). Process for capturing CO_2 arising from the calcination of the CaCO3 used in cement manufacture. Environmental Science and Technology, 42(18), 6980–6984. https://doi.org/10.1021/es800507c

Rodriguez, N., Alonso, M., Abanades, J. C., Grasa, G., & Murillo, R. (2009). Analysis of a process to capture the CO2resulting from the pre-calcination of the limestone feed to a cement plant. Energy Procedia, 1(1), 141–148. https://doi.org/10.1016/j.egypro.2009.01.021

Rodríguez, N., Murillo, R., & Abanades, J. C. (2012). CO_2 capture from cement plants using oxyfired precalcination and/ or calcium looping. Environmental Science and Technology, 46(4), 2460–2466. https://doi.org/10.1021/es2030593

Rubin, E. S., Mantripragada, H., Marks, A., Versteeg, P., & Kitchin, J. (2012). The outlook for improved carbon capture technology. Progress in Energy and Combustion Science, 38(5), 630–671. https://doi.org/10.1016/j.pecs.2012.03.003

Rubin, E. S., Short, C., Booras, G., Davison, J., Ekstrom C., Matuszewski M., McCoy S. (2013). A proposed methodology for CO_2 capture and storage estimates. International Journal of Greenhouse Gas Control, 17(2013) 488-503. http://dx.doi.org/10.1016/j.ijggc.2013.06.004

Tsupari, E., Kärki, J., Arasto, A., Lilja, J., Kinnunen, K., & Sihvonen, M. (2015). Oxygen blast furnace with CO_2 capture and storage at an integrated steel mill - Part II: Economic feasibility in comparison with conventional blast furnace highlighting sensitivities. International Journal of Greenhouse Gas Control, 32, 189–196. https://doi.org/10.1016/j.ijggc.2014.11.007

van der Spek, M., Ramirez, A., & Faaij, A. (2017). Challenges and uncertainties of ex ante techno-economic analysis of low TRL CO_2 capture technology: Lessons from a case study of an NGCC with exhaust gas recycle and electric swing adsorption. Applied Energy, 208(June), 920–934. https://doi.org/10.1016/j.apenergy.2017.09.058

Wordsteel (2018). Facsheet: Climate change mitigation by technology, innovation and best practice transfer. www.wordsteel.org

Xu C.C., Cang D. (2010). A brief Overview of low CO_2 emission technologies for iron and steel making. International Journal of Iron and Steel Research, 17(3) (March) 1-7. https://doi.org/10.1016/S1006-706X(10)60064-7

Zeman F. Oxygen combustion in cement production. In: 9th International Conference on greenhouse gas control technologies. Washington D.C., USA; 2009.

Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

Pure Offices, Cheltenham Office Park, Hatherley Lane,
Cheltenham, Glos. GL51 6SH, UK

Tel: +44 1242 802911
mail@ieaghg.org
www.ieaghg.org