TECHNOLOGY FACTSHEET

TNO

CARBON CAPTURE RETROFIT TO REF BASIC OXYGEN FURNACE STEELMAKING ON COKE OVENS, HOT STOVES, LIME KILNS AND STEAM GENERATION UNITS (60% AVOIDED EMISSIONS)

Date of factsheet	7-9-2020
Author	Kira West
Sector	Industry: Iron and steel
	All
ETS / Non-ETS	ETS
Type of Technology	Emission reduction
Description	The most common steelmaking route is called blast furnace-basic oxygen furnace (BF-BOF) steelmaking, which was invented in 1948 and now accounts for about 70% of global crude steel output (World Steel 2019). This process is also called basic oxygen steelmaking (BOS) or oxygen converter steelmaking (OCS). In the blast furnace, iron ore (in the form of sinter, pellets, and lump ore) and coal (in the form of coke and pulverized coal), and flux (alkaline or "basic" materials, typically burnt lime or dolomite, which react with impurities to form slag that can be separated) are injected into the top of the blast furnace, flowing downward into contact with upward-moving, hot, CO-rich gases at about 900 to 1300 degrees C. Through this process, the iron ore (Fe2O3) is reduced into elemental iron, and the iron is mixed with carbon monoxide (CO) from the flue gas. Carbon (supplied by coal and coke) acts as a reducing agent. The molten, carbon-rich (4-5%) pig iron (also referred to as hot metal) that is produced in the blast furnace is then oxidized in a basic oxygen furnace, in an exothermic oxidation reaction as pure, hot oxygen is blown over the metal, to reduce the carbon content to below 2% (often less than 1%, depending on final product specifications). Liquid crude steel is then tapped from the furnace, and slag (a byproduct, a mixture of metal oxides) removed. Coke (a high carbon content fuel, with most impurities present in coal removed) can be made onsite by heating coal in a coke oven to a high temperature (typically around 1000 degC) in vacuum conditions, or can be purchased from an offsite coke oven. In this configuration, CO2 is captured from the flue gases of heaters for coke oven batteries, hot stoves, lime kilns, and steam generation units, using post-combustion (end-of-pipe) capture technology, reaching about a 60% reduction in CO2 emissions compared to the baseline case. For the purposes of this factsheet, chemical absorption using MEA solvent has been considered as the capture technology. Off-gases from the blast furnace and basic oxygen furnace are assumed to be used (as is current practice) for energy purposes on-site, either through reinjection into the coke oven, pellet plant, or blast furnace, or by combustion to produce heat and power. CO2 capture at those utilities is also technically feasible, but is not covered in this factsheet. Post-combustion capture does not require any major modifications to the steelmaking process; MEA amine stripping technology is simply added to the plant to capture CO2 from existing flue gas streams. The modifications required for CO2 capture are cleaner flue gas (additional NOx and SOx scrubbing equipment); a CO2 capture unit (absorber and stripper columns, heat exchangers, condensers, and a reboiler); and a CO2 compression and dehydration unit. As the capture process requires electricity (notably for compression) and steam (mainly for solvent recovery), additional investments may also be required to expand the site's utilities. This factsheet does not specify the utility configuration, but provides additional electricity and steam demand for CCS. The cleaned flue gas enters the absorber and is brought into contact with the MEA amine solution. About 90% of the CO2 is absorbed into the amine solution (now together referred to as a rich loading solution), and is then pumped to the stripper. In the stripper column, the rich loading solvent is heated with steam from the reboiler (which uses a heat exchanger to transfer heat from external steam to a heat transfer fluid), breaking the chemical bonds between the amine solvent and the CO2, and causing it to release CO2, creating a relatively pure CO2 stream. The CO2 continues to the compressor, which compresses the gas to about 110 bar/11 MPa for transport and storage. The remaining solution (called a lean loading solution), now at a temperature of about 120 degrees C, is pumped back to the absorber to begin the cycle again, first passing through a heat exchanger to preheat the rich loading solution.
TRL level 2020	TRL 7
	Post-combustion CO2 capture technology has been demonstrated in a number of projects globally, including one project in the iron & steel sector. The only operating carbon capture project in the steel sector is in Abu Dhabi at Emirates Steel's natural gas-fired DRI plant. It uses MEA amine absorption to separate CO2 from the flue gases. However, CO2 capture has not yet been commercialized in a conventional BF-BOF plant.

TECHNICAL DIMENSIONS

	Functional Unit		Value and Range								
Capacity	Mton crude steel		-								
			Min			-			Max		
Potential	NL	Mton crude steel	Current			2030			2050		
			6.81			-			-		
			6.81	–	6.81	Min	–	Max	Min	–	Max
Market share		%	-			-			-		
			Min	–	Max	Min	–	Max	Min	–	Max

Capacity utlization factor		0.87
Full-load running hours per year		
Unit of Activity	Mton steel/year	
Technical lifetime (years)		25.00
Progress ratio		
Hourly profile		
Explanation	Potential has been given as the current total production of crude steel in the Netherlands in 2018. Because this is an end-of-pipe technology, it would be technically feasible to retrofit the entire capacity of Dutch steel production (which could evolve over time as well). Some operational parameters, such as full-load hours and hourly profile, have not been included because insufficient data is available. For post-combustion CO2 capture, capacity can be adapted to fit the plant, so no typical capacity is given. Capacity utilization factor is derived from 2018 data for conventional BF-BOF steelmaking in the Netherlands (without carbon capture). It is assumed that the addition of post-combustion carbon capture would not affect the utilization rate.	

COSTS

Year of Euro	2015

	Euro per Functional Unit	Current			2030			2050		
Investment costs	mln. € / Mton crude steel	233.39			-			-		
		76.96	–	233.39	Min	–	Max	Min	–	Max
Other costs per year	mln. € / Mton crude steel	-			-			-		
		Min	–	Max	Min	–	Max	Min	–	Max
Fixed operational costs per year (excl. fuel costs)	mln. € / Mton crude steel	25.17			-			-		
		25.17	–	25.17	Min	–	Max	Min	–	Max
Variable costs per year	mln. € / Mton crude steel	1.87			-			-		
		1.87	–	1.87	Min	–	Max	Min	–	Max

Costs explanation	Costs are for a retrofit of CO2 capture and compression equipment and associated utilities (including the cost of separation and compression of CO2, but not transport and storage). This factsheet considers a retrofit, end-of-pipe addition to a steelmaking process, and thus the costs are given per Mt crude steel output from the main process equipment. Though at the high end of the range, the IEAGHG 2013 study has the most detailed technical assessment of the equipment and operations, and is therefore chosen as the main source for cost data. Operating and variable costs include only direct labour costs and annual fixed maintenance costs for the carbon capture facilities. Fixed O&M for the full steelmaking process after retrofit would be about €105 million per year. Fixed OPEX is given as mln € per Mt/yr steel capacity. Variable costs shown above are for MEA sludge disposal costs. Variable costs for the full retrofitted plant (including water, refractories, electrodes, casting powder, and sludge/slag disposal fees) would be about €10.5 million/Mton crude steel. Variable costs exclude purchased scrap, ferroalloys, fluxes, and solvent (this can be calculated from the material flows below (assumed costs are provided in comments)). Fuel costs, including those for on-site oxygen production, are also excluded.

ENERGY IN- AND OUTPUTS

	Energy carrier	Unit	Current			2030			2050		
Energy carriers (per unit of main output)	*Main output:* Electricity	PJ	-			-			-		
			Min	–	*Max*	*Min*	–	*Max*	*Min*	–	*Max*
	Steam	PJ	4.25			-			-		
			4.25	–	5.43	*Min*	–	*Max*	*Min*	–	*Max*
	0	PJ	-			-			-		
			Min	–	*Max*	*Min*	–	*Max*	*Min*	–	*Max*
	0	PJ	-			-			-		
			Min	–	*Max*	*Min*	–	*Max*	*Min*	–	*Max*
Energy in- and Outputs explanation	In and outputs are given only for additional steam and electricity demand needed for the CO2 capture plant (absorption, compression, and solvent regeneration). This factsheet considers a retrofit, end-of-pipe addition to a steelmaking process, and thus the energy flows are given per Mt crude steel output from the main process equipment.All units are given as PJ/Mton crude steel. Saturated steam at 9 bar is assumed (IEAGHG 2013). For steam demand calculations, 1.39 t CO2 is assumed to be captured per tonne of crude steel. Zhang et al give a range of 3.3-3.9 GJ/t CO2 captured for regeneration of MEA solvent.										

MATERIAL FLOWS (OPTIONAL)

	Material	Unit	Current			2030			2050		
Material flows	Crude steel	Mton steel	-1.00			-			-		
			-1.00	–	-1.00	*Min*	–	*Max*	*Min*	–	*Max*
	MEA solvent	Mton	0.00			-			-		
			0.00	–	0.00	*Min*	–	*Max*	*Min*	–	*Max*
Material flows explanation	While most of the MEA solvent is recovered and reused, the small amount that is lost in the process must be replaced; this is what is shown here (and also included in the variable costs of the process). Assumed costs: MEA solvent (make-up) EUR 1638/t (IEAGHG 2013).This factsheet considers a retrofit, end-of-pipe addition to a steelmaking process, and thus the material flows are given per Mt crude steel output from the main process equipment.										

EMISSIONS (Non-fuel/energy-related emissions or emissions reductions (e.g. CCS)

	Substance	Unit	Current			2030			2050		
Emissions	CO2 captured	Mton CO2-eq	-1.39			-			-		
			-1.39	–	-1.39	*Min*	–	*Max*	*Min*	–	*Max*
	CO2 (process)	Mton CO2-eq	0.52			-			-		
			0.52	–	0.52	*Min*	–	*Max*	*Min*	–	*Max*
			-			-			-		
			Min	–	*Max*	*Min*	–	*Max*	*Min*	–	*Max*
			-			-			-		
			Min	–	*Max*	*Min*	–	*Max*	*Min*	–	*Max*
Emissions explanation	About 65% of the total CO2 from the plant is captured by capturing 90% of CO2 from flue gases from the coke oven, hot stoves, lime production and on-site power plant. This results in about a 60% avoided emissions compared to the base case (without CO2 capture). The negative emissions here represent captured CO2 from the coke oven, hot stove, lime production, and on-site power plant. About 0.76 tCO2/t crude steel are emitted after CO2 capture, of which about 0.56 tCO2/t crude steel are from chemical reactions in the process (and the remainder from fuel combustion). Insufficient data was available to determine the impact of the retrofit on NOx, SO2 and PM emissions.										

OTHER

Parameter	Unit	Current			2030			2050		
0	0	-			-			-		
		Min	–	*Max*	*Min*	–	*Max*	*Min*	–	*Max*
0	0	-			-			-		
		Min	–	*Max*	*Min*	–	*Max*	*Min*	–	*Max*
0	0	-			-			-		
		Min	–	*Max*	*Min*	–	*Max*	*Min*	–	*Max*
0	0	-			-			-		
		Min	–	*Max*	*Min*	–	*Max*	*Min*	–	*Max*
Explanation	0									

REFERENCES AND SOURCES

IEAGHG (2013), "Iron and Steel CCS Study (Techno-economics Integrated Steel Mill)," https://ieaghg.org/docs/General_Docs/Reports/2013-04.pdf.

CBS (2019), "Energiebalans; aanbod en verbruik, sector", https://opendata.cbs.nl/statline/portal.html?_catalog=CBS&_la=nl&tableId=83989NED&_theme=119.

European Commission (2016), "Iron production by electrochemical reduction of its oxide for high CO2 mitigation (IERO)."

Netherlands Environmental Assessment Agency (2009), "Greenhouse Gas Emissions in the Netherlands 1990-2007." http://www.emissieregistratie.nl/erpubliek/documenten/Algemeen%20(General)/Emissierapportages%20(Emission%20reports)/NIR%20Greenhouse%20Gas%20Emissions%20in%20the%20Netherlands/NIR2009.pdf, p 78.

Wang et al. (2017), "A Review of Post-combustion CO2 Capture Technologies from Coal-fired Power Plants," 13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland.

A. Carpenter (2012), "CO2 abatement in the iron and steel industry", IEA Clean Coal Centre, https://www.usea.org/sites/default/files/012012_CO2%20abatement%20in%20the%20iron%20and%20steel%20industry_ccc193.pdf.

Ho, M., Bustamante, A., and Wiley, D. (2013). "Comparison of CO2 Capture Economics for Iron and Steel Mills." International Journal of Greenhouse Gas Control.

A. Keys, M. van Hout, and B. Daniëls (2019), "Decarbonisation Options for the Dutch Steel Industry," MIDDEN report, https://www.pbl.nl/sites/default/files/downloads/pbl-2019-decarbonisation-options-for-the-dutch-steel-industry_3723.pdf.

Xue B., Yu, Y., Chen, J. et al. (2017). "A comparative study of MEA and DEA for post-combustion CO2 capture with different process configurations. International Journal of Coal Science & Technology.

Zhang, W., et al. (2016). "Parametric study on the regeneration heat requirement of an amine-based solid adsorbent process for post-combustion carbon capture." Applied Energy 168: 394-405.

World Steel (2019), "Steel Statistical Yearbook 2019 Concise version", downloaded from: https://www.worldsteel.org/en/dam/jcr:7aa2a95d-448d-4c56-b62b-b2457f067cd9/SSY19%2520concise%2520version.pdf.