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Techno-economic assessment and comparison of CO_2 capture technologies for industrial processes: preliminary results for the iron and steel sector

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Abstract

This paper presents the methodology and the preliminary results of a techno-economic assessment of CCS implementation on the iron and steel sector. The results show that for the short-mid term, a CO_2 avoidance cost of less than 50 €/tonne at a CO_2 avoidance rate of around 50% are possible by converting the conventional blast furnace (BF) to Top Gas Recycling Blast Furnace (TGRBF). However, large additional power consumption for CO_2 removal and oxygen generation, and reduction in BF gas export, makes the economic performance of the technology very sensitive to energy prices. Add-on CO_2 capture for conventional BF may achieve similar costs (40 – 50 €/tCO_2 avoided), but the CO_2 avoidance rate will be only about 15% of the specific CO_2 emissions. For the long term future, although there are large uncertainties, advanced CO_2 capture technologies do not seem to have significant economic advantages over conventional technologies. The results also indicate that in a carbon-constrained society, when considering new plants, smelting reduction technologies such as the COREX process, may become a strong competitor to conventional blast furnace based steel making process when equipped with CO_2 capture. Although conventional iron and steel making using BF is expected to dominate the market in the long term, strong need for drastic CO_2 emissions reduction may drive the sector towards large scale implementation of advanced smelting reduction technologies.

Keywords: CO_2 capture; industry; techno-economic; iron and steel

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1. Introduction

Industry and petroleum refineries are among the largest contributors to anthropogenic CO_2 emissions. In 2006 these sectors together emitted more than 11Gt of CO_2 directly and indirectly[2], accounting for nearly 40% of total global CO_2 emissions [1-3]. CO_2 capture and storage (CCS) is considered a promising option to achieve significant reduction in CO_2 emissions from industry and petroleum refineries, not only because of their total CO_2 emissions

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[2] Industry accounted for 10.6Gt of direct and indirect emissions, and petroleum refineries accounted for 0.8Gt of direct emissions.

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but also because there are many industrial processes that generate gas streams rich in CO_2, or in some cases pure CO_2, which may enable CCS at low energy penalty and economic costs.

There are a number of literature reviews on the CO_2 capture technologies for industrial processes are available in the open literature, e.g. [2, 4-6]. These literature reviews, however, are incomplete in one way or another. Firstly, some reviews only cover a limited number of publications [4, 6]. Secondly, these reports do not look into the assumptions behind the CO_2 capture performance calculations of each publication. For economic performance assessments, assumptions on system boundaries, fuel price, capital cost estimation, interest rate, and economic lifetime, have a large impact on the results. Without standardizing key parameters, a fair comparison of economic performance of CO_2 capture published in the literature is not possible. The objective of this paper is to assess and compare the technical and economic performance of CO_2 capture from industrial processes on a consistent basis.

This research project investigates the following industrial sectors: cement, iron and steel, chemicals and petrochemicals, and petroleum refining. The first three sectors account for nearly three-fourths of global total industrial CO_2 emissions [2]. Petroleum refineries account for an additional 0.8Gt of CO_2 per year. Industrial processes that generate pure CO_2 streams, e.g. ammonia production and gasification, are not investigated as CO_2 capture is already practiced in an economical manner.

In this paper the methodology and preliminary results for one of the sectors (iron and steel) are presented. The complete assessment for all sectors will be presented in a research paper which is under preparation.

2. Methodology

2.1. Timeframe

The focus in this research is on the implementation of CO_2 capture in the short-mid term future (5 – 15 years) and in the long-term future (20 years or more). Short-mid term technologies are defined here as those that are either in pilot plant, demonstration or commercialization phase today [7]. Technologies are also categorized to be short-mid term technologies when all equipment required is commercially available today, even if the process as a whole has not yet been tested or demonstrated. All other technologies, either in proof-of-concept or laboratory phase today, are considered to be long-term future options [7].

2.2. System boundaries and performance indicators

Figure 1 shows the system boundaries of an industrial process as defined for this study. Besides direct emissions from the industrial process, the CO_2 emissions accountable for the import/export of process gas, electricity and steam are also taken into account. This approach enables to incorporate the effect of changes in material and energy flows of the industrial process due to process modification as a result of CO_2 capture.

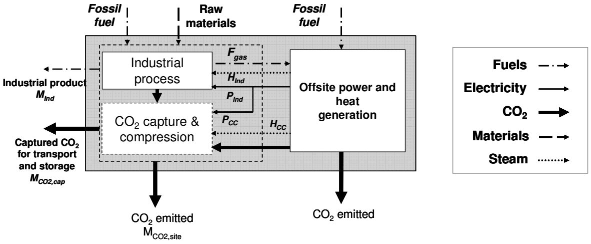


Figure 1 System boundaries of an industrial process defined for this study.

2.2.1. Technical indicators

This study uses specific CO_2 emissions $Em_{Sp,Ind}$ (tCO_2/t product) as the main technical indicators of CO_2 capture performance. $Em_{Sp,Ind}$ is defined as:

$$\mathrm{Em}_{\mathrm{Sp,Ind}}=\frac{\mathrm{M}_{\mathrm{CO_2,site}}+\left\{\left(\mathrm{P}_{\mathrm{Ind}}+\mathrm{H}_{\mathrm{Ind}}*\eta_{\mathrm{ST,Ind}}\right)+\left(\mathrm{P}_{\mathrm{CC}}+\mathrm{H}_{\mathrm{CC}}*\eta_{\mathrm{ST,CC}}\right)-\mathrm{F}_{\mathrm{gas}}*\eta_{\mathrm{PP}}\right\}*\mathrm{Em}_{\mathrm{Sp,Elec}}}{\mathrm{M}_{\mathrm{Ind}}} \quad (1)$$

where:
$M_{\mathrm{CO2},site}$: onsite CO_2 emission rate (tCO_2/s),
M_{Ind}: production rate of the industrial product (tonne/s),
E_{imp}: total imported energy (MW electricity-equivalent),
P_{Ind}: electricity import for the industrial process (MW),
P_{CC}: electricity import for CO_2 capture and compression (MW),
H_{Ind}: steam import for the industrial process (MW);
H_{CC}: steam import for CO_2 capture and compression (MW),
η_{ST}: steam turbine electricity generation efficiency,
$\mathrm{F}_{\mathrm{gas}}$: net process gas export from the industrial process to power plants (MW),
η_{PP}: gas-fired power plant efficiency, and
$Em_{Sp,Elec}$: CO_2 emission factor of grid electricity (tCO_2/MJ_e).

Subscript symbols *CC* and *Ref* indicate the CO_2 capture case and the reference (no CO_2 capture) case, respectively. An important assumption here is that the exported process fuel gas and the imported/exported process steam are converted to electrical terms.

2.2.2. Economic indicator

We use *CO_2 avoidance cost* (C_{CO2}) as the main economic indicator for CO_2 capture (Eq.(2)):

$$C_{CO_2}=\frac{\alpha*\Delta\mathrm{I}+\Delta\mathrm{C}_{\mathrm{energy}}+\Delta\mathrm{C}_{\mathrm{O\&M}}+\Delta\mathrm{C}_{\mathrm{Mat}}}{(\mathrm{Em}_{\mathrm{Sp,Ref}}-\mathrm{Em}_{\mathrm{Sp,CC}})*\mathrm{M}_{\mathrm{Ind,annual}}} \quad (2)$$

where α is the annuity factor (a^{-1}), ΔI is the incremental capital requirement (€), ΔC_{energy} is the additional annual cost of energy due to CO_2 capture (€/a), $\Delta C_{O\&M}$ is the incremental operation and maintenance (O&M) costs (€/a), $\Delta C_{O\&M}$ is the additional annual cost of raw materials due to CO_2 capture (€/a), and $M_{Ind,annual}$ is the annual production of the industrial product (t/a).

In some industrial sectors a variety of manufacturing routes can be found for a single product, e.g. steel production. In such cases, costs of manufacture (€/t industrial product) are also calculated (Eq.(3)):

$$C_{CO_2}=\frac{\alpha*\mathrm{I}+\mathrm{C}_{\mathrm{energy}}+\mathrm{C}_{\mathrm{Mat}}+\mathrm{C}_{\mathrm{O\&M}}}{\mathrm{M}_{\mathrm{Ind,annual}}} \quad (3)$$

2.2.3. Other indicators

Additional indicators that are used in the research include, e.g. possibilities for retroffiting and the influence of CO_2 capture on the process operations.

2.3. Data collection and standardization of key parameters

An extensive literature review was performed to assess the technical and economic performance of the three industrial processes with and without CO_2 capture. To enable a fair comparison of technologies, some underlying parameters need to be standardized. We follow the procedure suggested by Damen et al. [8]:

- Normalization of technical parameters: CO_2 compression pressure, grid electricity CO_2 emission factor,
- Normalization of economic parameters: capital investment, fuel and electricity prices, indexation (all cost figures presented in $€_{2008}$)

With regard to capital investment, we consider total capital requirement (TCR), which includes the following cost components:

  - Process plant cost (costs for the equipment pieces and their installation) plus engineering fees and contingencies;
  - Owner costs (royalties, preproduction costs, inventory capital, land costs and site preparation) and interests during construction
- Normalization of plant scales. For instance, in the case of iron and steel production, the scale has been normalized to 4Mt crude steel production per year.

Table 1 presents the key parameters used for the technical and economic indicator calculations.

Table 1 Parameters standardized for technical and economic performance calculations in this study.

Parameters		***Unit***	***Value***	***Range***
Annualized capital cost		%- total capital requirement	11.7	7.7 – 15.7
Non-coking coal		€/GJ	2.5	2 – 3
Natural gas		€/GJ	8	5 – 11
Electricity price		€/MWh	50	30 – 100
Grid electricity CO_2 emission factor		g/kWh	380	160 – 600
Conversion factor: steam → electricity	High temperature steam ($\eta_{ST,Ind}$)		40%	
	Low temperature steam ($\eta_{ST,CC}$)		20%	
Gas turbine combined cycle power plant efficiency (η_{PP})			50%	
CO_2 compression pressure		bar	110	

3. Assessment of CO_2 capture technologies for the iron and steel sector.

Table 2 presents an overview of CO_2 capture technologies for the iron and steel sector proposed in the literature. In this section a brief overview of key aspects related to the technologies are presented

Table 2 Various CO_2 capture options for blast furnace and other steelmaking processes reported in the literature.

CO_2 capture technologies			***References***
Short-mid term	Air-blown BF	MEA	[9]
		MDEA	[10]
		Selexol	[11]
		Shift + Selexol	[9, 11]
	TGRBF	MEA	[12]
		VPSA	[12]
		Selexol	[12]
	COREX	MEA	[9]
		Selexol	[9, 13, 14]
		Shift + Selexol	[9, 15]
Long term	Air-blown BF	Shift membrane reactor + Selexol	[15]
		Selective carbon membrane	[16]
		Hydrate crystallization	[17]
	TGRBF	Selective carbon membrane	[12, 16]
		Hydrate crystallization	[17]
	Advanced smelting reduction	Purification only	[18]

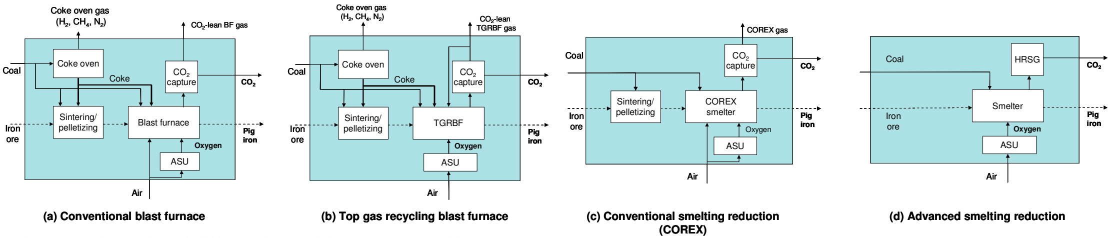
3.1. Short-mid term technologies

Conventional integrated steelmaking process (Figure 2 (a)) has around 70% of the carbon introduced into the process flows through a blast furnace (BF) [10]. BF gas exits the BF at 2-3 bar [10] and contains CO_2 (17-25%), CO (20-28%), H_2 (1-5%), N_2 (50-55%) [19]. After dust removal, BF gas flows through expansion turbines to recover some power before being distributed as a fuel [10]. Some BF gas is used for other processes within the iron and steel plant, and the rest is sold to other industries or power plants.

Chemical absorption CO_2 capture is generally considered as a short-term technology. A major limitation of CO_2 capture directly from BF gas is that it captures less than 50% of the total carbon contained in the BF gas because about half the carbon is in the form of CO. The capture of CO_2 directly from BF gas is deemed more expensive compared to other options [20]. A potentially feasible technology for BF in the short-mid term is to capture CO_2 after CO in the BF gas is converted to CO_2 via a shift reaction [15], enabling a higher carbon removal rate (85-99.5% of the carbon in the BF gas). The BF gas after shift reaction and CO_2 removal is H_2-rich, which could be both advantageous and disadvantageous. The main advantage is that a higher electrical efficiency can be achieved when the H_2-rich BF gases are used in a power plant. The major disadvantage regarding the use of shift reaction is that the energy plant using the BF gas may require important modifications in the gas turbines [14].

Another promising technology in the short-mid term is the Top Gas Recycling Blast Furnace (TGRBF) (Figure 2 (b)) technology, which enables a more energy efficient blast furnace operation when CO_2 capture is to be incorporated [12, 20]. TGRBF is oxygen-blown so its top gas contains little nitrogen and is rich in CO (40-50 vol.%), thus enabling the top gas to be recycled as a reducing agent after CO_2 is removed. Consequently, the coke consumption can be reduced by up to 30% compared to conventional air-blown BF. With CO_2 capture, onsite CO_2 emissions can be reduced up to 76% compared to the conventional BF [21]. The overall CO_2 emissions reduction will be somewhat smaller because the reduced BF gas export needs to be compensated for, and a large amount of electricity is required to produce high-purity oxygen. TGRBF can be retrofitted to conventional blast furnaces, although it may require major modifications to the furnace.

Smelting reduction process (Figure 2, bottom left) is the latest development in pig iron production, which omits coke production by combining the gasification of non-coking coal with the reduction of iron ore in a liquid bath [22]. The smelting reduction reactor resembles the lower part of a blast furnace, and the reduction process generates a large amount of residual gas which, in the most effective designs, is used for pre-reduction of the solid ore (IEA, 2009). Smelting reduction facilitates CO_2 capture because the flue gas has a higher CO_2 concentration than conventional blast furnace gas as the furnace is blown with pure oxygen (some nitrogen needs to be injected in order to maintain momentum and heat transfer within the furnace). As of 2008, the COREX process is the only smelting reduction process commercially operating around the world [23]. CO_2 capture from the smelting reduction process gas (Figure 2 (c)) is considered to be more cost-effective than that from air-blown BF gas because of higher CO_2 concentration, around 25-35 vol%. CO_2 capture from smelting reduction process gas is already in operation at commercial scale. At Saldanha steel plant in South Africa, CO_2 is removed from the COREX gas by vacuum pressure swing adsorption (VPSA) before being used as reduction gas for DRI production [24]. When the COREX gas is used for power generation, a study suggests that the energy penalty for CO_2 capture using physical absorption is marginal because the COREX gas has to be compressed anyway for the combustion in a power plant [14]. This study also shows a small increase in the electrical output of the CHP due to fuel quality improvement.



(a) Conventional blast furnace

(b) Top gas recycling blast furnace

(c) Conventional smelting reduction (COREX)

(d) Advanced smelting reduction

Figure 2 Schematics of different ironmaking processes with CO_2 capture.

3.2. Long-term technologies

The integrated steelmaking process using BF is expected to keep on playing a dominant role in the industry in the longer term [25]. The production efficiency of BF is not expected to improve significantly because it is already very efficient [26]. Regarding CO_2 capture, some advanced technologies are proposed in the literature. Water gas shift membrane reactor with CO_2 capture using Selexol has been proposed for BF and TGRBF gases by [15]. Other advanced CO_2 removal technologies for BF and TGRBF found in the literature are: selective carbon membranes [16] and hydrate crystallization [17].

A number of innovative iron and steel production technologies with low CO_2 emissions may become available in the long term. One of them is advanced smelting reduction (Figure 2 (d)) [20, 27]. The main characteristics of a potentially promising advanced smelting reduction process, called Hisarna, are that both iron ores and non-coking coal can directly be put into the smelter, the input carbon is fully oxidized within the smelter so that CO_2 removal unit is unnecessary. Some heat is recovered from the off-gas to generate steam. The Hisarna process will be developed in a pilot plant at Corus steelworks in IJmuiden (the Netherlands) in the next couple of years [28], and is expected to capture 95% of the carbon input to the iron making process [29].

4. Preliminary results

Figure 3 presents the production costs for one tonne of crude steel from various steelmaking processes and their respective specific CO_2 emissions. Regarding the BF-based process, specific CO_2 emissions is nearly halved when the CO in the BF gas is shifted or the BF is converted to TGRBF. Advanced CO_2 capture technologies do not seem to have significant economic advantages over conventional technologies. The figure also shows that the COREX process with CO_2 capture enables lower crude steel production cost and lower specific CO_2 emissions compared to the reference BF-based process. However, the reduction in specific CO_2 emissions compared to the reference BF-based process is of only 15%. Advanced smelting reduction process shows very promising results: reducing crude steel production cost by 15% and specific CO_2 emissions by 90% compared to the reference BF-based process.

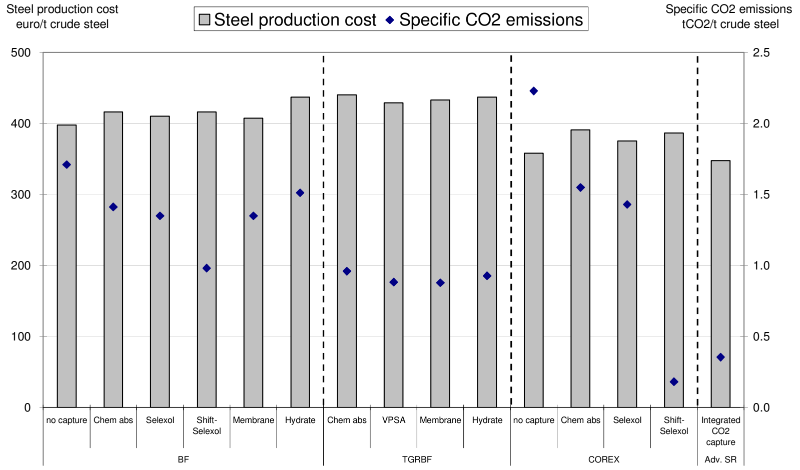


Figure 3 Production costs for one tonne of crude steel from various steelmaking processes and their respective specific CO_2 emissions.

Figure 4 shows CO_2 avoidance costs calculated for different steelmaking processes with CO_2 capture in the short-mid term. The uncertainty of the economic performance is found to be significant, especially for the TGRBF options. This is mainly because the modification from air-blown BF to TGRBF reduces the process gas export significantly, leading to a considerable reduction in electricity production. Our preliminary results also indicate that CO_2 avoidance potential is also largely affected by the CO_2 emission intensity of the grid electricity.

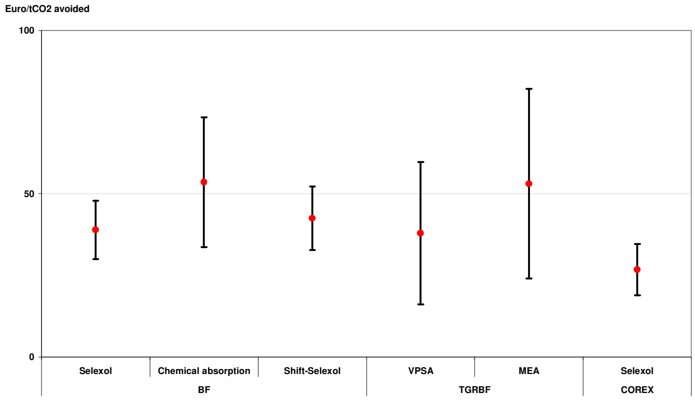


Figure 4 CO_2 avoidance costs (compared to identical plant) for different steelmaking processes with CO_2 capture. The error bars show the influence of key parameters (annualized capital cost, coal price, natural gas price, electricity price, and grid electricity CO_2 emission factor). The range of parameter values are presented in Table 2.

5. Preliminary conclusions

The technical and economic assessment and comparison of CO_2 capture from industrial processes based on a consistent basis has been performed. We presented the methodology and the preliminary results of the assessment on the iron and steel sector.

Our results have shown that for the short-mid term, a CO_2 avoidance cost of less than 50 €/tonne at a CO_2 avoidance rate around 50% are possible. TGRBF with VPSA seems to be the best option from an economic point of view. TGRBF showed a potential for relatively low-cost CO_2 capture because of significant reduction in coking coal consumption. However, large additional power consumption for CO_2 removal and oxygen generation, and reduction in BF gas export, makes the economic performance of the technology very sensitive to energy prices. Add-on CO_2 capture for air-blown blast furnace using VPSA or Selexol will also enable CO_2 capture at similar costs (40-50 €/tCO_2 avoided), but the CO_2 avoidance rate will be only about 15% of the specific CO_2 emissions.

For the long term future, although there are large uncertainties, advanced CO_2 capture technologies do not seem to have significant economic advantages over conventional technologies. Selective carbon membranes will enable CO_2 capture from air-blown BF at around 30 €/tonne, but this still was found to be more expensive than using VPSA for oxygen-blown BF.

When a new plant is considered, smelting reduction technologies such as the COREX process may become a strong competitor to conventional blast furnace based steel making process in a carbon-constrained society when equipped with CO_2 capture. Moreover, our results show that smelting reduction technologies can achieve considerable reduction in CO_2 emissions compared to the BF process, while keeping the steel production cost on par. Although conventional iron and steel making using BF is expected to dominate the market in the long term, strong need for drastic CO_2 emissions reduction may drive the sector towards large scale implementation of advanced smelting reduction technologies.

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