**TECHNOLOGY FACTSHEET**

TNO

# STEELMAKING WITH TOP GAS RECYCLING BLAST FURNACE (TGR-BF/ULCOS BLAST FURNACE/OXYGEN BLAST FURNACE) WITH CCS

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| Date of factsheet | 7-9-2020 |
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| 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). The top gas recycling blast furnace (TGR-BF) (also known as an oxygen blast furnace or ULCOS blast furnace) replaces a conventional blast furnace in order to reduce CO2 emissions from the steelmaking process.<br><br>The basic principles of the steelmaking process with a top gas recycling blast furnace are the same as in the conventional BF-BOF route. In the blast furnace step, 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. In this process, 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 by heating to a high temperature (typically around 1000 degC) in vacuum conditions, or can be purchased from an offsite coke oven.<br><br>However, in TGR-BF configuration, the blast furnace is modified in several important ways: Combustion of coal in the blast furnace is in the presence of pure oxygen, instead of air or oxygen-enriched air. This increases the CO2 content of the top gas (to about 35% dry basis), and reduces nitrogen. CO2 is removed (for utilization or storage) from the top gases (exhaust gases leaving the top of the BF) after they leave the blast furnace, and the remaining CO & H2-rich gas (with less than 3% CO2 content) is reinjected into the BF. There are several designs being studied, with different reinjection locations. The reinjected gases act as reducing agents, which means less coke is needed (leading to less energy use, cost, and emissions from coke ovens). The resulting pig iron has the same characteristics as from a conventional BF, and the steelmaking process is completed using a conventional BOF. There are several variations on TGR-BF technology under investigation, which can lead to variation and uncertainty in cost and energy parameters in the literature.<br><br>The process also produces several off-gases from the coke ovens and basic oxygen furnace with energy content that can be used either in the process or in on-site utilities. Their composition and calorific value is shown below.<br>-Coke oven gas: 60% H2, 23% CH4, 6% N2, 4% H2O, 4% CO, 1% CO2, <0.5% O2, 3% other; 17.3 MJ/normal cubic meter (LHV)<br>-Basic oxygen furnace gas: 57% CO, 14% CO2, 14% N2, 12% H2O, 3% H2; 7.5 MJ/normal cubic meter (LHV) |
| TRL level 2020 | TRL 6 |
| | The top gas recycling blast furnace has been tested in 2007 in an experimental blast furnace facility operated by LKAB in Sweden (650 kt/y scale), without CO2 capture. A demonstration was planned at the ArcelorMittal blast furnaces in Florange, France (1.5 kt/y scale), but these were shut down in 2011 for economic reasons. No new demonstration has yet been planned, so the technology is not expected to be commercialized before 2030. |

## TECHNICAL DIMENSIONS

| | Functional Unit | | Value and Range | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Capacity | Mton crude steel | | - | | | | | | | | |
| | | | *Min* | | | - | | | *Max* | | |
| | | | Current | | | 2030 | | | 2050 | | |
| Potential | NL | Mton steel | - | | | 6.81 | | | - | | |
| | | | *Min* | – | *Max* | 6.81 | – | 6.81 | *Min* | – | *Max* |
| Market share | NL | % | - | | | - | | | - | | |
| | | | *Min* | – | *Max* | *Min* | – | *Max* | *Min* | – | *Max* |
| Capacity utlization factor | 0.87 | | | | | | | | | | |
| Full-load running hours per year | | | | | | | | | | | |
| Unit of Activity | Mton crude steel/year | | | | | | | | | | |
| Technical lifetime (years) | 25.00 | | | | | | | | | | |
| Progress ratio | | | | | | | | | | | |
| Hourly profile | No | | | | | | | | | | |
| Explanation | Potential is given as total production of crude steel in the Netherlands as of 2018. Capacity utilization factor is derived from 2018 data. Insufficient data was available to provide a typical capacity. | | | | | | | | | | |

## COSTS

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Year of Euro | 2015 | | | | | | | | |
| | **Euro per Functional Unit** | **Current** | | | **2030** | | | **2050** | |
| Investment costs | mln. € / Mton crude steel | - | | | 779.86 | | | - | |
| | | *Min* | – | *Max* | 389.20 | – | 938.40 | *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 | - | | | 65.03 | | | - | |
| | | *Min* | – | *Max* | 42.43 | – | 65.03 | *Min* | – | *Max* |
| Variable costs per year | mln. € / Mton crude steel | - | | | - | | | - | |
| | | *Min* | – | *Max* | *Min* | – | *Max* | *Min* | – | *Max* |
| Costs explanation | CAPEX is specified for greenfield construction; retrofits to existing BF-BOF steel mills would have a lower CAPEX. Fixed OPEX is given as mln € per Mt/yr steel capacity. Variable costs (including iron ore, purchased scrap and flux) range from €165 million - €239 million per million tonnes of crude steel. In IEAGHG 2013, oxygen is generated on site via an air separation unit (included in CAPEX); thus no purchased oxygen is considered in variable costs. Differences in assumptions about on-site CHP and use of process gases accounts for some of the differences in CAPEX. IEAGHG 2013 assumes imported iron ore pellets, while other sources include pelletizing within the plant boundary. European Commission (2016) provides annualized capital investment costs, without specifying a discount rate or equipment lifetime. The overnight capital costs from this source given in this factsheet were derived from the annualized costs assuming a range of discount rates of 5%-10% and equipment economic lifetimes of 10-20 years. | | | | | | | | |

## ENERGY IN- AND OUTPUTS

| | Energy carrier | Unit | Current | | | 2030 | | | 2050 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Energy carriers (per unit of main output) | *Main output:* Coal | PJ | - | | | 15.87 | | | - | | |
| | | | *Min* | – | *Max* | 11.28 | – | 15.87 | *Min* | – | *Max* |
| | Natural gas | PJ | - | | | 1.27 | | | - | | |
| | | | *Min* | – | *Max* | 0.91 | – | 1.69 | *Min* | – | *Max* |
| | Electricity | PJ | - | | | 1.88 | | | - | | |
| | | | *Min* | – | *Max* | 1.13 | – | 1.88 | *Min* | – | *Max* |
| | Basic oxygen furnace gas | PJ | - | | | - | | | - | | |
| | | | *Min* | – | *Max* | -0.55 | – | - | *Min* | – | *Max* |

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| Energy in- and Outputs explanation | The energy flows above are net energy inputs to the steelmaking process with boundaries (as specified above) from coking and sintering to tapping liquid crude steel from the basic oxygen furnace; intermediate energy flows are not shown.<br><br>Coal is processed into coke in a coking plant, which is injected into the blast furnace.<br><br>Energy-rich off-gases from the blast furnace are stripped of CO2 and recycled into the blast furnace (about 90% to blast furnace, and the remaining 10% combusted for pre-heating). Some of the off-gases from the coke oven and all of the basic oxygen furnace are directly combusted as energy sources in the process. The negative values represent surplus energy carriers beyond what is needed to produce crude steel. These can be utilised in various ways either within the steel sector or in other nearby industrial sites. For IEAGHG (2013), an on-site NGCC power plant, sized to meet on-site electricity demand, is assumed, and thus no electricity import or export occurs in this case (this accounts for the larger natural gas input according to this source). Here values have been adjusted to account for BOFG/BFG exported to the power plant, exclude NG for the power plant, and account for electricity generated. The utility assumptions in European Commission (2016) are unspecified. In each source, coke oven gas is considered to be fully utilized on-site, with no surplus available for export. For Keys, van Hout and Daniels, the BOF gas is sent to a CHP unit, which is excluded from the boundary here. However, this means that not all heat demand is met within the energy values given above, some additional heat is "imported" from the CHP.The values from IEAGHG 2013 are thus not directly comparable with Keys, van Hout and Daniels.<br><br>Energy needs for CO2 capture and compression are included for IEAGHG (2013) and Keys, Van Hout and Daniels (2019), but not European Commission (2016). European Commission (2016) also does not specify outputs of energy-rich processes gases. |

**MATERIAL FLOWS (OPTIONAL)**

| | Material | Unit | Current | | | 2030 | | | 2050 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Material flows | Iron ore | Mt | - | | | 1.24 | | | - | | |
| | | | Min | – | Max | 1.24 | – | 1.31 | Min | – | Max |
| | Crude steel | Mt | - | | | -1.00 | | | - | | |
| | | | Min | – | Max | -1.00 | – | -1.00 | Min | – | Max |

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| Material flows explanation | Only primary materials are shown here. Lump iron ore is further processed into sinter in a sinter plant, and then injected into the blast furnace to form pig iron, which finally forms the input to the basic oxygen furnace where crude steel is produced. Pellets are assumed to be imported from Brazil in IEAGHG (2013), and to be produced from iron ore fines in Keys, Van Hout and Daniels (2019). Oxygen is produced on-site using an air separation unit; energy needs to operate the ASU are included in this factsheet. |

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

| | Substance | Unit | Current | | | 2030 | | | 2050 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Emissions | CO2 captured | Mton CO2-eq | - | | | -0.78 | | | - | | |
| | | | Min | – | Max | -0.78 | – | -0.70 | Min | – | Max |
| | | | - | | | - | | | - | | |
| | | | Min | – | Max | Min | – | Max | Min | – | Max |
| | | | - | | | - | | | - | | |
| | | | Min | – | Max | Min | – | Max | Min | – | Max |
| | | | - | | | - | | | - | | |
| | | | Min | – | Max | Min | – | Max | Min | – | Max |

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| Emissions explanation | About ~0.7-0.8 MtCO2/Mton crude steel are captured from the blast furnace top gas. Several capture options are possible; sources used here consider either chemical absorption capture with amine solvents or VPSA + cryogenic flash capture. Net emitted CO2 (including both process and combustion related CO2 emissions) is about 0.6-1.0 MtCO2/Mton crude steel. Other emissions are not specified in the available literature, likely because of the limited experience with this technology; however, nitrogen emissions (NOx) will be significantly reduced compared to conventional BF-BOF steelmaking, due to the use of pure oxygen in the blast furnace, rather than air. |

**OTHER**

| Parameter | Unit | Current | | | 2030 | | | 2050 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Fluxes | Mt | - | | | 0.27 | | | - | | |
| | | Min | – | Max | 0.15 | – | 0.27 | Min | – | Max |
| Scrap | Mt | - | | | 0.13 | | | - | | |
| | | Min | – | Max | 0.13 | – | 0.17 | Min | – | Max |
| Oxygen | m^3 | - | | | 295.59 | | | - | | |
| | | Min | – | Max | 230.01 | – | 295.59 | Min | – | Max |
| Heat | PJ | - | | | - | | | - | | |
| | | Min | – | Max | - | – | 0.22 | Min | – | Max |
| Explanation | Flux and scrap consumption can vary significantly depending on the final product specifications. Fluxes include limestone, quartzite, olivine, CaC2 powder, and burnt dolomite. | | | | | | | | | |

**REFERENCES AND SOURCES**


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