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Assessment of hydrogen direct reduction for fossil-free steelmaking

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ABSTRACT

Climate policy objectives require zero emissions across all sectors including steelmaking. The fundamental process changes needed for reaching this target are yet relatively unexplored. In this paper, we propose and assess a potential design for a fossil-free steelmaking process based on direct reduction of iron ore with hydrogen. We show that hydrogen direct reduction steelmaking needs 3.48 MWh of electricity per tonne of liquid steel, mainly for the electrolyser hydrogen production. If renewable electricity is used the process will have essentially zero emissions. Total production costs are in the range of 361–640 EUR per tonne of steel, and are highly sensitive to the electricity price and the amount of scrap used. Hydrogen direct reduction becomes cost competitive with an integrated steel plant at a carbon price of 34–68 EUR per tonne CO2 and electricity costs of 40 EUR/MWh. A key feature of the process is flexibility in production and electricity demand, which allows for grid balancing through storage of hydrogen and hot-briquetted iron, or variations in the share of scrap used.

1. Introduction

A rapid and deep reduction of emissions in the energy-intensive industries is needed to avoid the risk of dangerous climate change. Global industrial CO_2 emissions account for 31% of the total, with steel and cement industries as the largest single contributors (Fischedick et al., 2014b). The Paris Agreement implies that these sectors must reach zero emissions by 2060–2080 (Åhman et al., 2017), while the European Union seeks to achieve a 80–95% reduction of greenhouse gases by 2050 compared to 1990 (European Commission, 2011). For the steel industry, meeting these targets requires fundamental technology and process changes combined with a reduction of material demand and increased recycling (Fischedick et al., 2014b; Allwood and Cullen, 2012; Milford et al., 2013).

Today's dominant blast furnace – basic oxygen furnace (BF/BOF) production route relies on the use of coking coal and its mechanical properties, which makes it difficult to switch to other reduction agents in the blast furnace. Global steel production is forecast to double between 2012 and 2050 with demand growth mainly in developing countries (Allwood and Cullen, 2012; Pauliuk et al., 2013). Consequently, fundamental changes in steelmaking processes are required and there are two principal options for low emission steelmaking: (i) continued use of fossil fuels but with carbon capture and storage (CCS), and (ii) the use of renewable electricity for producing hydrogen as reduction agent or directly in (yet undeveloped) electrolytic processes.

In light of climate targets and the reductions in costs for renewable electricity, the option of electrification and the use of hydrogen for ironmaking has gained increased attention. Several European steelmakers initiated major projects in 2016–2017 on the use of hydrogen in steelmaking. These include GrInHy (Salzgitter) and H2FUTURE (Voestalpine) focussing on electrolyser development, and HYBRIT (SSAB, LKAB and Vattenfall) aiming to develop an entire fossil-free value chain for primary steel. In the latter, the basic concept is to use a hydrogen direct reduction (H-DR) process to produce direct reduced iron (DRI) which is then converted to steel in an electric arc furnace (EAF).

There is so far very little information on the hydrogen direct reduction (H-DR) process in the scientific literature. The only commercial application of hydrogen in direct reduction was in Trinidad, where DRI was produced in fluidised bed reactors with hydrogen from steam reforming (Nuber et al., 2006). Otto et al. (2017) used this process as a basis for their assessment of the emissions saving potential of direct reduction with hydrogen. Fischedick et al. (2014a) and Weigel et al. (2016) identified H-DR as the most promising production route through a multi-criteria analysis (including economy, safety, ecology, society and politics), comparing it with electrowinning and blast furnace steelmaking with and without the use of carbon capture and storage (CCS).

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Abbreviations

H-DR	Hydrogen direct reduction
tLS	Tonne liquid steel (metric)
BF/BOF	Blast furnace/basic oxygen furnace
DRI	Direct reduced iron
EAF	Electric arc furnace
SEC	Specific energy consumption
CAPEX	Capital expenses
OPEX	Operating expenses
MAC	Marginal abatement cost
HBI	Hot-briquetted iron
FeO	Wuestite
Fe2O3	Hematite
λ	Hydrogen feed ratio
LHV	Lower heating value
HHV	Higher heating value
PEM	Proton exchange membrane
O&M	Operation and maintenance
GEI	Grid emission intensity
SOE	Solid oxide electrolysis

Germeshuizen and Blom (2013) studied direct reduction with hydrogen produced in a hybrid sulphur process using nuclear process heat. Other options to reduce BF/BOF emissions were reported, such as through hydrogen injection or top gas recycling, for example, but maximum CO_2 reductions reported were 21% and 24%, respectively, thus insufficient for the necessary deep decarbonisation (Yilmaz, Wendelstorf & Turek, 2017; Abdul Quader et al., 2016). Although several publications mention H-DR as a possibility to decarbonise steelmaking (Hasanbeigi et al., 2014; Ranzani da Costa et al., 2013; Abdul Quader et al., 2016) there are no studies published on process designs and their performance.

Our objective in this paper is to present a potential process design for the H-DR process and assess its energy use, CO_2 emission mitigation potential and economic performance. A better understanding of H-DR technology is important for developing viable decarbonisation pathways for the steel industry and for its integration into decarbonised electricity systems.

2. Method

To assess H-DR steelmaking a mechanistic process model was developed. The approach was chosen to be able to identify causal links in the process and thus to improve process understanding. The model was designed to enable the variation of crucial input parameters and to analyse their effect on energy consumption and production cost. These parameters include the metallisation of HBI, the amount of hydrogen fed into the shaft, and the amount of inert substances representing impurities in pellet and scrap feeds. Furthermore, the amount of scrap fed into the EAF and the cost for electricity is varied in order to investigate their influence on energy demand and costs.

Material and energy balances were set up for the system in order to determine the energy demand and act as a foundation for further calculations on production cost. The system boundaries were drawn around the system depicted in Fig. 1. Inputs to the modelled system are iron ore pellets, carbon, lime and scrap, whereas liquid steel as the main product as well as slag and oxygen represent outputs. In a continuous operation without hydrogen losses, no water flows across system boundaries. The iron ore pellets considered contain 95% hematite (Fe_2O_3) and 5% inert substances. Scrap charged to the EAF contains 95% iron and 5% inert

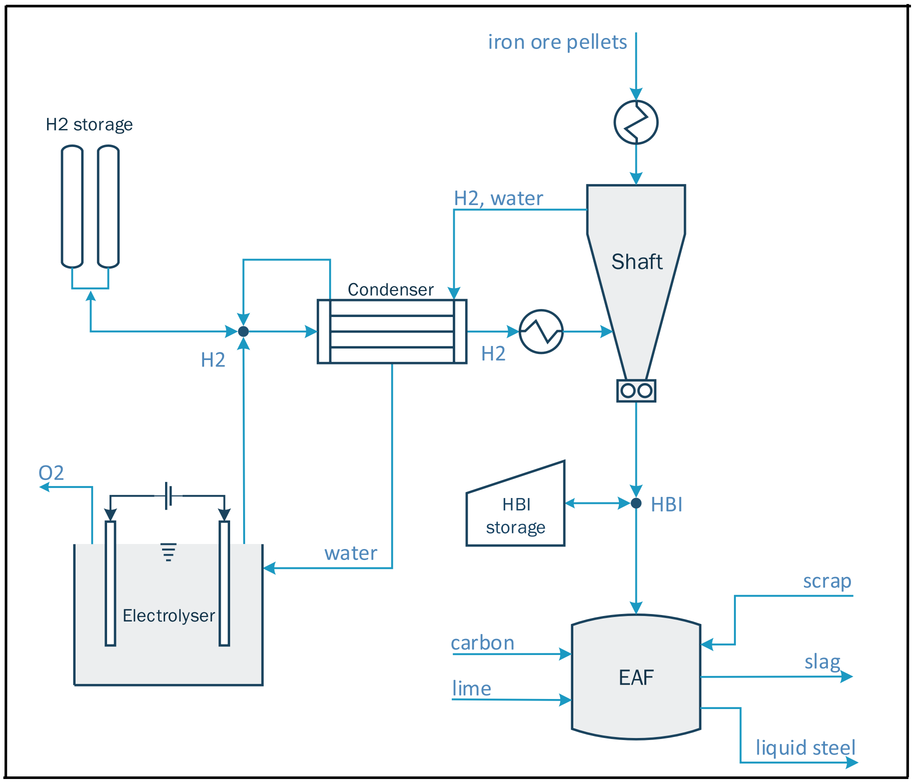

Fig. 1. Proposed process design for hydrogen direct reduction (H-DR) process.