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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.

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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

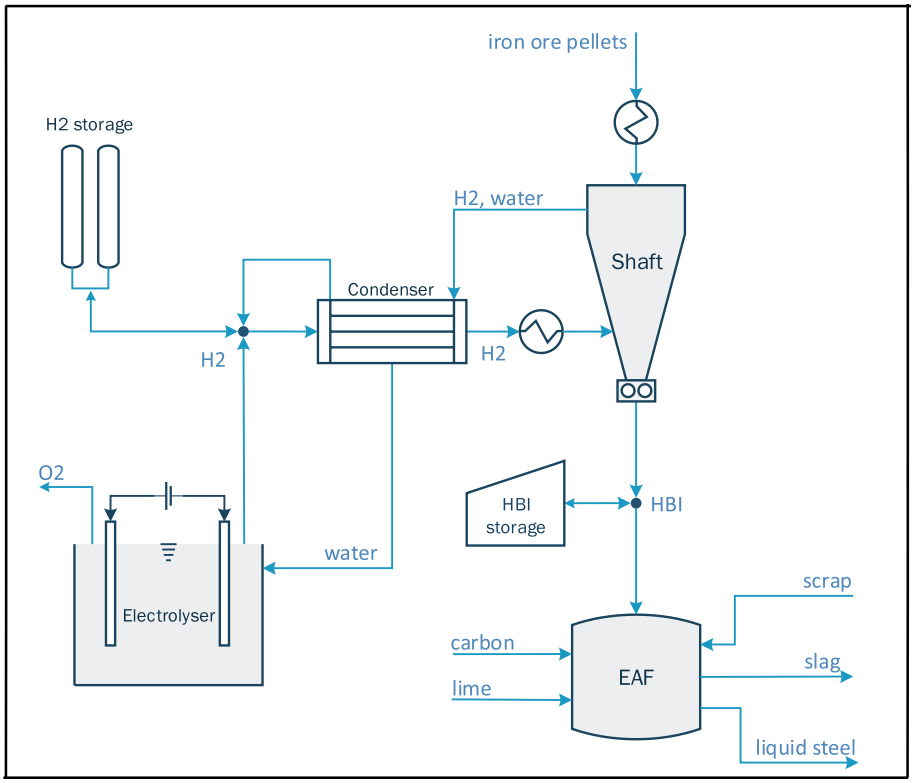

Fig. 1. Proposed process design for hydrogen direct reduction (H-DR) process.

substances. The liquid steel product contains only iron, whereas all other elements leave the EAF through the slag. Heat capacities of inert substances have been assumed equal to the main component of the corresponding flow.

Besides material balances several chemical reactions occur in the process. Water is split into hydrogen and oxygen in the electrolyser and iron ore is reduced to sponge iron in the shaft. The reactions considered in the electrolyser and the reduction shaft are shown in equations (1)–(3). To keep the model simple only the major reactions of the process have been considered and simplifications were made. The reactions in the EAF were, for example, not considered and replaced by a linear energy model based on literature data. It is assumed that all iron entering the EAF leaves the process through the liquid steel product. The equilibrium nature of the reduction reactions in the shaft was also neglected. Instead it is assumed, that hematite reacts to iron and wuestite (FeO) depending on the prescribed metallisation that can be achieved in the shaft. Metallisation is defined as the share of moles present as pure iron among all iron leaving the shaft. All non-metallised iron is assumed to be bound in FeO. All modelled reactions are listed below. Data to determine reaction enthalpies and heat capacities was adopted from VDI heat atlas for hydrogen (Kleiber and Joh, 2010) and water (Wagner and Kretzschmar, 2010) as well as the U.S. Department of Commerce for all iron materials (Domalski and Hearing, n.d.). The reaction enthalpies of the FeO formation reactions were neglected as only high metallisation (>90%) is investigated and the amount of FeO is thus always small.

$$H_2O_{(g)} \rightarrow H_2 + \frac{1}{2}O \qquad \Delta H_R = +242\frac{kJ}{mol} \tag{1}$$

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O_{(g)} \quad \Delta H_R = +99.5\frac{kJ}{mol} \tag{2}$$

$$Fe_2O_3 + H_2 \rightarrow 2FeO + H_2O_{(g)} \tag{3}$$

Solving the set of equations is informed by a series of assumptions and boundary conditions (a complete list is provided in the supplementary information). The operating temperatures of the electrolyser and the shaft are 70 °C and 800 °C respectively. As reference conditions, 25 °C is used and all system components are considered to operate under atmospheric pressure.

The condenser serves as a heat recovery unit and enables the separation of water from hydrogen gas in the shaft off-gas stream. The recovered heat is used to heat the hydrogen feed to the shaft. An efficiency of 70% based on the higher heating value and a water outlet temperature of 70 °C was assumed for the condenser. The amount of hydrogen supplied to the shaft is characterised by the value of λ (see equation (4)). λ is defined as the moles supplied to the moles necessary for full conversion of iron ore in the shaft. A value of λ = 1.5 therefore means a 50% oversupply of hydrogen. The amount of heat recovered thereby varies due to the set value for λ, the metallisation of HBI and the efficiency of the condenser. It is assumed that surplus heat can be used to partially heat the reduction shaft. This is the case if the reduction off-gas energy content exceeds the heating demand of the hydrogen fed to the shaft. All additional heating for the process is assumed to be electric and further heating losses are neglected. Heating is necessary to provide energy in the electrolyser and the shaft as well as for ore feed and hydrogen feed to the shaft depending on the value of λ.

$$\lambda = \frac{\text{H}_2 \text{ feed to shaft}}{\text{H}_2 \text{ needed for complete reduction of ore}} \left[\frac{\text{mol}}{\text{mol}}\right] \tag{4}$$

The specific energy consumption (SEC) of the arc furnace is based on literature data by Worrell et al. (2008) combined with a submodel that draws on the work of Cárdenas et al. (2007). It adjusts the energy consumption with regards to the metallisation of HBI and the amount of scrap charged to the EAF. A SEC of 0.667 MWh per tonne liquid steel (tLS) was used for the operation on pure scrap feed. The SEC is then adjusted upwards if the share of HBI in the EAF charge increases. If the metallisation of HBI is lower than 94% this additionally increases the SEC of the EAF. Both dependencies (HBI charge, metallisation) were implemented as linear functions. Moreover, a lime consumption in the EAF of 50 kg/tLS was assumed for the EAF.

For the electrolyser an efficiency based on the lower heating value (LHV) of 72% was assumed. This is in line with recent 2030 projections for proton exchange membrane (PEM) electrolysers (Schiebahn et al., 2015; Mergel et al., 2013; Bertuccioli et al., 2014; Saba et al., 2018). The emission intensities of Germany and Poland of electricity draw on national CO_2 emission intensities[1] reported by the European Environment Agency (2016). National grid emission intensities use the emissions arising from public electricity production and excluding heat production, which were reported as greenhouse inventory under the UNFCCC, and divide them by national gross electricity consumption. To estimate the implications of a switch from BF/BOF to H-DR on a national scale, steel production data for the primary production were adopted from the World Steel Association (2017). National energy cost (2016/2017 values) and total gross production (2016 values) are based on data from Eurostat (2017).

$$CaCO_3 \rightarrow CaO + CO_2 \tag{5}$$

The CO_2 emissions from in the EAF were estimated through the corresponding chemical reactions. For lime, 1 mol of CO_2 is created for each mole of calcium oxide according to equation (5) and the flow to the EAF is considered to be pure CaO. Graphite electrodes emit 1 mol of CO_2 per mole of carbon that is consumed according to the abovementioned chosen consumption rate. Emissions from carbon added to the EAF are also considered. It was assumed that half of the supplied carbon enters the steel, whereas the other half is converted to CO_2.

2.1. Economics

Capital expenses (CAPEX) are comprised of values for electrolyser, EAF and shaft. The electrolyser CAPEX is based on an estimation for proton exchange membrane (PEM) and alkaline electrolysis in 2030 by Mergel et al. (2013), who reported specific investment cost of 0.585 EUR/W installed capacity for both PEM and alkaline technology. Data for the EAF and the shaft were adopted from Wörtler et al. (2013) and their Midrex shaft CAPEX was adopted for the H-DR shaft in the present process. It was assumed that capital expenses for the shaft and the EAF for the present process are equal to current commercial DRI plants based, which work with natural gas.

Operating expenses (OPEX) comprises of resource cost (ore, lime, scrap, alloys), electricity cost and other variable cost (O&M, labour, graphite electrodes). Iron ore, scrap, lime and graphite electrodes are internationally traded commodities with fluctuating market prices. The cost assumptions for these materials were based on market prices reported between 2015 and 2018. For iron ore pellets, a cost of 100 EUR/t have been assumed based on current market prices of iron ore plus a pellet premium. The assumed scrap cost is 180 EUR/t, which is in line with the values used in similar studies (Pardo et al., 2012; Germeshuizen and Blom, 2013). For lime,

[1] National grid emission intensities are used solely for illustrative purposes. The authors are aware that European electricity grids are interconnected and grid intensities are not bound the nation borders.

a cost of 100 EUR/t was assumed. Alloy use in the EAF was set at 11 kg per tonne of steel (Remus et al., 2013). In the EAF graphite electrodes are consumed at a rate of 2 kg/tLS (Remus et al., 2013) and costs of 4 EUR/kg was assumed for the electrodes. Operation and maintenance cost (3% of total CAPEX, which includes refractory lining), the alloy costs (1777 EUR/t) and labour cost (53.2 EUR/tLS) were adopted from Fischedick et al. (2014a). Returns from oxygen are included in variable costs and we adopted the assumptions by Pardo et al. (2012) that 60% of oxygen can be sold at a price of 60.8 EUR/t. This rests on the assumption of one or more large near-by customer of oxygen, and that a part of it can be used in downstream heating and rolling, for example in oxyfuel burners. A complete list of data used for all calculations is provided in the supplementary information, including the breakdown of costs included in the OPEX calculations.

Production cost are the sum of OPEX and annual capital cost. To derive annual capital cost from CAPEX a lifetime of 10 years at 8760 operating hours was assumed for the electrolyser, which is similar to the predicted lifetime of 80,000 operating hours reported by Schiebahn et al. (2015). For all other components, a lifetime of 20 years was used. A 5% interest rate was assumed. Hydrogen production cost are comprised of electrolyser energy and O&M cost, as well as annual capital cost for the electrolyser investment.

Marginal carbon abatement cost (MAC) were calculated for different electricity costs in three different cases: (a) the substitution of an existing BF/BOF plant at the point of necessary relining, (b) a decision between H-DR and a brownfield BF/BOF investment, and (c) between H-DR and a greenfield investment into BF/BOF. MAC were calculated as the difference in production cost over CO_2 abatement potential. This potential is 1817 $kgCO_2$/tLS, which is comprised of the emissions of the BF/BOF process (IEAGHG (2013)) minus the emissions of the H-DR process. CAPEX for blast furnace relining was adopted from IEAGHG (2013) as 48 EUR/t, for a BF/BOF brownfield investment as 170 EUR/t and for a greenfield investment as 442 EUR/t and discounted with the same lifetime and interest rate as shaft and EAF (20 years, 5%). For MAC calculations, the embedded CO_2 emissions from lime production were considered. A discussion of emissions embedded in lime and through addition of carbon to the H-DR process will follow in Section 3.2.

2.2. Modelling assumptions

Some general assumptions should be noted. No choice was made on the technology of the electrolyser, but an operating temperature of 70 °C was chosen so that results are relevant for either alkaline or PEM technology. The reduction shaft is a well-established technology and in operation in numerous DRI plants around the world, mainly in the form of commercially available Midrex or HYL/Energiron reactors. EAFs are under operation in scrap recycling as well as DRI plants, which together account for 29% of global steel production. While we regard the described configuration as the most realistic design option for hydrogen direct reduction, we do assume that other variants are possible.

The model purposefully includes only basic chemical process calculations, as it does not seek to go into detail of the chemical processes performed in the single unit operations. Furthermore, the aim is to go beyond the process level and analyse wider system implications of H-DR steelmaking. Minor material and energy flows, for example energy required to compact DRI to HBI, were thus excluded for the same reasons. The set system boundaries purposefully do not include downstream processes such as casting and rolling. As a consequence, not all emissions from the integrated route are considered. We assume that downstream processes in the H-DR route are similar to those operated in the integrated route and that emissions from these manufacturing steps can be brought to zero through electrification and energy efficiency measures.

3. Results and discussion

The following section presents the assessment of the H-DR process. We present a possible process design for H-DR as the basis for our assessment. Then we discuss the energy use of the process and its single components before we explain the influence of different parameters on the energy efficiency. Subsequently, results of a cost assessment are shown, including capital and operating expenses, as well as production and marginal carbon abatement cost. Finally, we discuss the flexibility of H-DR and the different operating strategies it allows, such as balancing variable electricity loads, for instance.

In Fig. 1, we show the design of the hydrogen direct reduction (H-DR) process on which the developed chemical process model presented later on in this chapter is based. Iron ore is pre-heated and fed into a reduction shaft, where it is converted to direct reduced iron (DRI) and further compacted to hot briquetted iron (HBI). Hydrogen generated in an electrolysis unit is pre-heated in a condenser before being supplied to the shaft where it acts as the reducing agent. Surplus hydrogen is recycled back to the shaft feed and generated water is supplied back to the electrolyser. HBI is fed into an electric arc furnace (EAF) where it is melted and converted to liquid steel.

This process design is based on existing technologies. It can be regarded as similar to direct reduction with natural gas for which the steam reformer is substituted by an electrolyser. State-of-the-art direct reduction plants have production capacities of 1.5 million tonnes of steel per year and higher. Electric arc furnaces are used widely in industry, but the introduction of hydrogen might require changes in the way carbon is brought into the process. A conventional Midrex reduction shaft is adopted in the ironmaking stage. Minor changes in reactor design may be necessary due to the switch from natural gas or syngas to hydrogen. Electrolyser technology is mature and usually provided in modular units that can be combined to yield large capacities.

For continuous operation on 100% HBI, the production of one tonne of steel requires 1504 kg of iron ore pellets. Without considering hydrogen losses, 51 kg of hydrogen is needed per tonne of steel output. If the EAF is charged with equal shares of HBI and scrap, 738 kg of pellets, 536 kg of scrap and 25 kg of hydrogen are needed per tonne of steel.

3.1. Energy

A specific energy consumption (SEC) of 3.48 MWh/t of liquid steel was calculated for the base case. A blast furnace within comparable system boundaries consumes 13.3 GJ/t steel (3.68 MWh/t) mainly in the form of coal and coke (Otto et al., 2017). The electrolyser consumes two thirds of the energy, with the electric arc furnace and the ore heating processes as further large energy users. The energy consumption of the shaft is very small, which can be explained through the use of recovered heat from the condenser. The breakdown for the unit operations is shown in Fig. 2. If scaled up to replace today's BF/BOF route this would represent a substantial increase in electricity demand. For example, if the current German (29.5 Mt/y) or Swedish (3.10 Mt/y) primary steel production would be operated on the H-DR process it would require about 103 TWh and 10.8 TWh of electricity, respectively. At the same time, fossil fuel use would be reduced by 392 PJ/y in Germany and 41.2 PJ/y in Sweden. These values do only consider iron- and steelmaking without the further energy demand in the pelletizing process as well as in secondary metallurgy, casting and rolling. For pelletizing and rolling an additional 2.2 GJ/t of fuel as

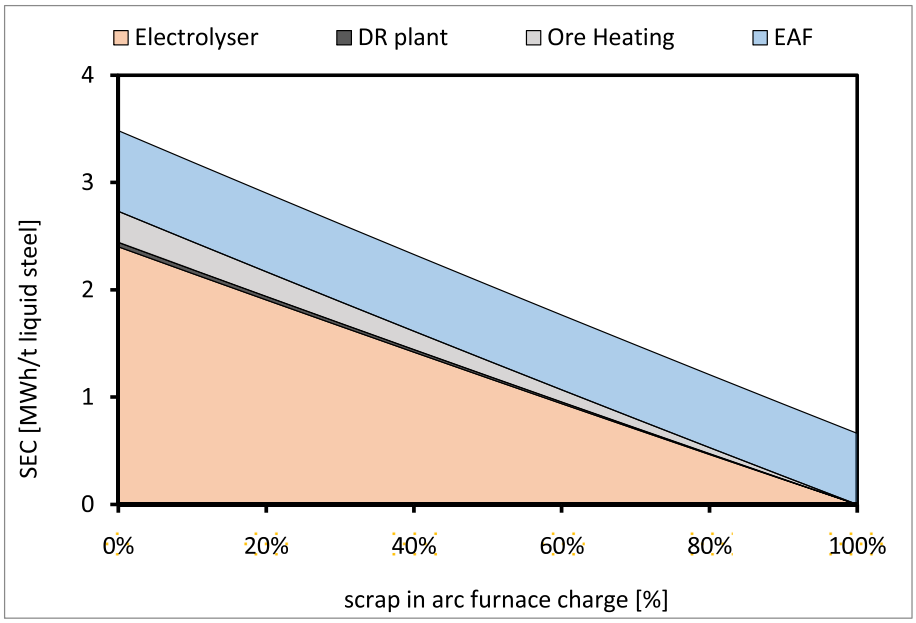

Fig. 2. Specific energy consumption (SEC) of the H-DR process as a function of the scrap charged into the EAF [MWh/tLS].

well as 140 kWh/t electricity are required irrespective of the production route (Worrell et al., 2008).

As shown in Fig. 2, the SEC is highly sensitive to the amount of scrap added to the EAF. The major reason for this is that less iron ore is required per output, which leads to lower energy consumption in all process steps before the EAF. For example, if the EAF charge consists of 50% scrap, the electrolyser energy consumption is halved. In addition, producing steel in the EAF from scrap requires less energy (0.667 MWh/tLS) than from pure DRI (0.753 MWh/tLS).

The SEC result is also sensitive to several other process factors. First, the achievable metallisation in the shaft influences overall energy consumption. While low HBI metallisation leads to an increase of energy consumption in the EAF, total SEC is reduced. This is mainly due to the smaller amount of hydrogen needed in the reduction and a consequently lower electrolyser load. In addition, a lower metallisation of the HBI means that less heat is consumed in the shaft, and less energy is available for recovery in the condenser. However, this effect is sensitive to the losses in the process' hydrogen cycle and losses in the EAF and could be reversed if the relative magnitudes of these losses change.

Second, energy consumption depends on how much excess hydrogen is supplied to the shaft. λ is defined as the ratio of hydrogen fed to the reduction shaft to the amount of hydrogen needed to convert the entire iron ore feed to pure iron (see equation (4)). Sensitivity analyses show that the SEC for the entire process increases by 41.0 kWh/tLS if λ is increased by one (for example from 1.5 to 2.5). Up to $\lambda = 5$ heat can be recovered in the heat exchanger. Above $\lambda = 6$ no heat can be recovered anymore and used to heat the shaft, but additional heating for the hydrogen feed to the reactor is required. Thus, low values of λ lead to low energy consumption. For the base case a value of $\lambda = 1.5$ was set. A more detailed optimisation of λ would have to take detailed reaction kinetics and the chemical equilibrium of the iron ore reduction into account.

Finally, heat might be lost between the shaft and the arc furnace. In the case of long HBI storage or other reasons, causing it to cool down additional energy is required to re-heat the HBI. For the base case, using cold HBI requires 159 kWh/tLS more than if the hot HBI is directly fed to the EAF. In the present case, liquid steel and slag leave the EAF as hot products. Energy efficiency can be increased if heat from EAF outputs can be recovered or used in further processing.

3.2. CO_2 emissions

As the process is assumed to be entirely electrified, the emissions mainly depend on the power grid emission intensity (GEI). A higher share of renewable energy in a power grid will thus increase the emissions saving potential for replacing a blast furnace with an H-DR plant. To compare the performance with a typical integrated production route, a break-even GEI was calculated. We define it as the emissions embedded in grid electricity (in $kgCO_2/MWh$), which would result in the same emissions from the H-DR and BF/BOF processes (1870 kg CO_2/tLS). In Fig. 3, we show the break-even GEI as a function of the scrap share in the EAF charge. At pure HBI operation, the break-even GEI is 532 kgCO2/MWh. Power grids in most European steelmaking countries have GEIs below this level today and they are projected to decrease as fossil fuels are phased out in electricity production. At a 25% scrap charge in the EAF, the break-even GEI reaches 661 kgCO2/MWh. This corresponds approximately to the current emission intensity of the Polish power grid (EEA, 2016). It can be concluded that a switch from the BF/BOF route to H-DR would reduce emissions in most of Europe today.

A large share of CO_2 emissions from BF/BOF steelmaking can be avoided in the H-DR route if renewable electricity is available. However, zero emission electricity is not sufficient for producing zero emission steel. CO_2 emissions are still embedded in, for example, the extraction and generation of iron ore and limestone, in lime calcination and through the addition of carbon as an essential component of steel. Avoiding the process emissions from lime calcination would require carbon capture and storage in lime production. Another option is the substitution of lime with other materials that can provide the functions of lime in the EAF, namely slag foaming, sulphur removal and slag basicity adjustment. Similarly, the iron ore may have embedded emissions unless it is extracted and processed in an emissions-free manner.

Furthermore, small amounts of carbon must be added to the EAF in the H-DR process to make steel from iron. In commercial direct reduction, carbon is added through the natural gas stream.

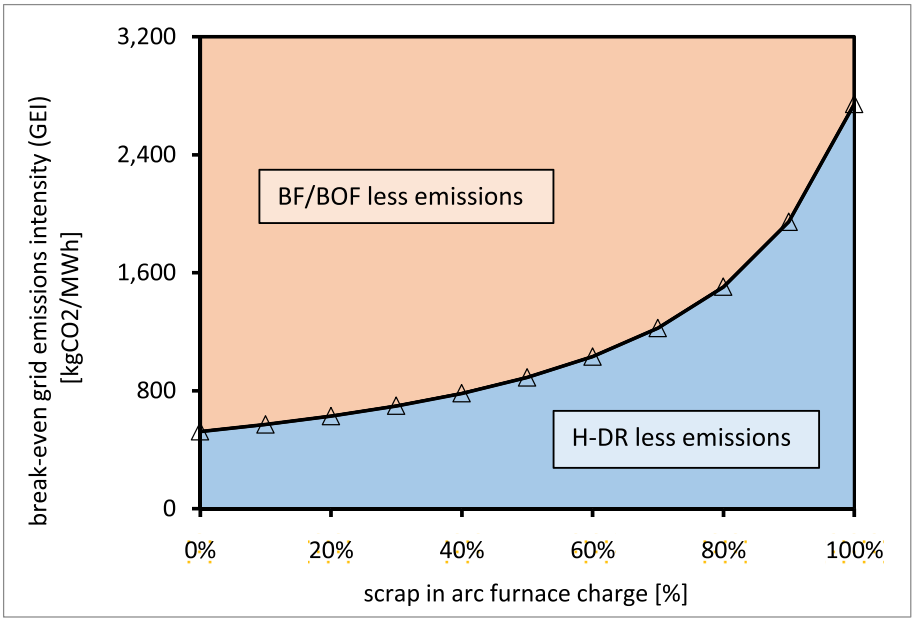

Fig. 3. Break-even grid emission intensity (GEI) as a function of the scrap charged into the EAF. The break-even GEI describes the emissions embedded in electricity for H-DR to result in the same emissions as the BF/BOF route.

However, when pure hydrogen is used as the reducing agent another carbon source is needed. This could be done through the injection of pulverised coal, but also bio-methane or other sources of biogenic carbon could be used. Even if the CO_2 emissions from carbon and lime are taken into account, this would result in much lower emission intensities than those of today's integrated route. Emissions from carbon and lime use and consumption of the graphite electrodes would result in emissions of 53 kg CO_2 per tonne of steel, which is equal to 2.8% of emissions from the BF/BOF route.

3.3. Economics

Capital expenditures (CAPEX) and operational expenses (OPEX) were calculated for the base case and based on the energy results. Production costs were further derived from these results and finally, marginal carbon abatement cost are reported. Our CAPEX assessment is based on 2030 technology for the main components of the system. While electrolyser CAPEX are expected to decrease, shaft and EAF are mature technologies so we assumed no significant cost reductions. Operating expenses were assessed with respect to current market prices and with the aim to use average market prices between 2015 and 2018.

The CAPEX for a H-DR plant was calculated as 574 EUR per tonne capacity, which is 30% higher than for a greenfield integrated BF/BOF steel plant (Wörtler et al., 2013). It includes 160 EUR/t capacity for the electrolyser, 230 EUR/t for the shaft and 184 EUR/t for the EAF (Mergel et al., 2013; Wörtler et al., 2013). Another study (Fischedick et al., 2014a) reported a CAPEX of 874 EUR per tonne capacity for the H-DR route. However, they assumed electrolyser operation mainly in times of inexpensive peak electricity, which requires a much larger investments in electrolyser capacity running on fewer operating hours and including large-scale storage of hydrogen.

Production costs for steel in the proposed process are presented in Figs. 4 and 5 for pure HBI operation and a 50% scrap charge respectively. The results show that the production costs are highly sensitive to the electricity price. Energy costs account for 32% of production costs at electricity costs of 40 EUR/MWh and 47% at 80 EUR/MWh. This sensitivity is reduced when more scrap is charged to the arc furnace. A 50:50 charge of HBI and scrap reduces the overall production cost compared to pure HBI operation. Resource costs increase slightly with more scrap fed into the arc furnace as a result of the higher scrap than pellet prices. Both ore and scrap market prices vary substantially, which can reverse this trend in certain market conditions. Electrode costs amount to 8 EUR/tLS, but assume the easing of recent price increases for graphite electrodes. The production cost of the H-DR process are generally higher than those of the BF/BOF route, but come close to competitive if the electricity price is low.

At an electricity cost of 60 EUR/MWh hydrogen cost is 3.30 EUR/t (0.270 EUR/Nm^3). It is a linear function of the electricity cost and varies between 1.43 EUR/kg (20 EUR/MWh) and 5.17 (100 EUR/MWh) for the base case. Mergel et al. (2013) estimate possible hydrogen cost of 2–4 EUR/kg 2030 from renewable energy through electrolysis. Next to hydrogen, large amounts of oxygen are produced in the electrolyser. For every tonne of liquid steel, 411 kg of oxygen are produced. Finding a market for these large amounts of oxygen would reduce operating expenses considerably. Oxygen revenues of 14.9 EUR/tLS are included in the non-energy variable cost. However, if all oxygen could be sold at current market prices this revenue would be several times higher.

Marginal carbon abatement costs are shown as a function of electricity cost for six cases in Fig. 6. We assume emission-free electricity and compare against a traditional BF/BOF route with an emission intensity of 1870 kg CO_2 per tonne crude steel. Three cases for BF/BOF replacement are considered: (a) at the time of relining of an existing blast furnace (called MAC relining), (b) for a brownfield investment choice between a blast furnace or H-DR (called MAC brownfield), and (c) for a greenfield investment choice between a blast furnace or H-DR (called MAC greenfield). The results show that a carbon price of 46 EUR/tCO_2 is needed for brownfield investments to be competitive at an electricity cost of 40 EUR/MWh and 50% scrap use. If only DRI is charged to the EAF this value increases to 62 EUR/tCO_2. An H-DR plant can be competitive with BF relining at a carbon price of 68 EUR/tCO_2 (only DRI) and 52 EUR/

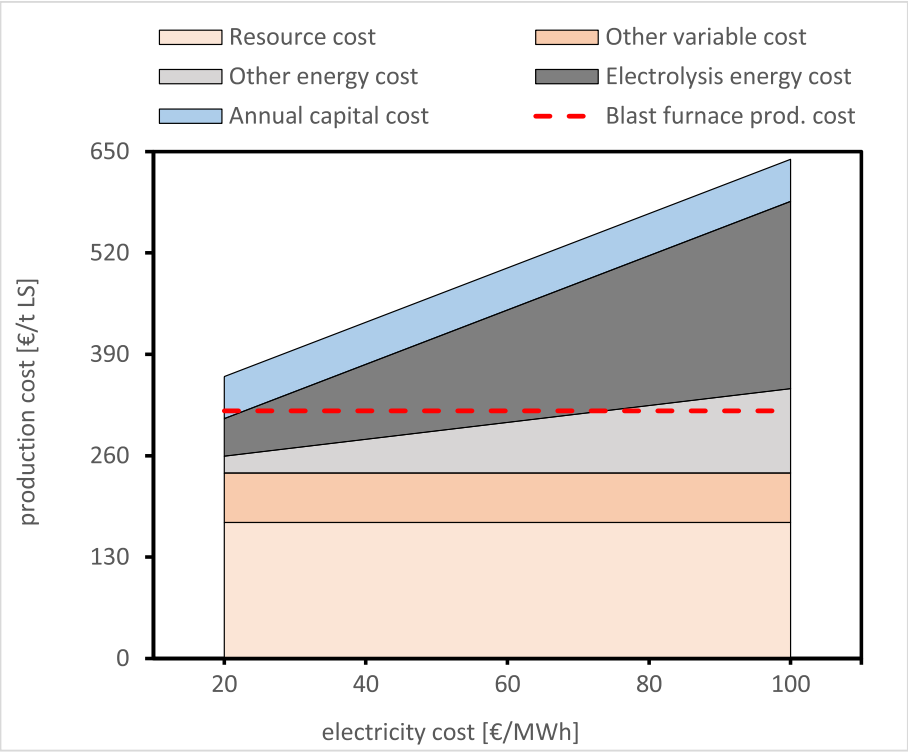

Fig. 4. Production cost of steel via the H-DR process route as a function of the electricity cost (scrap charge 0%).

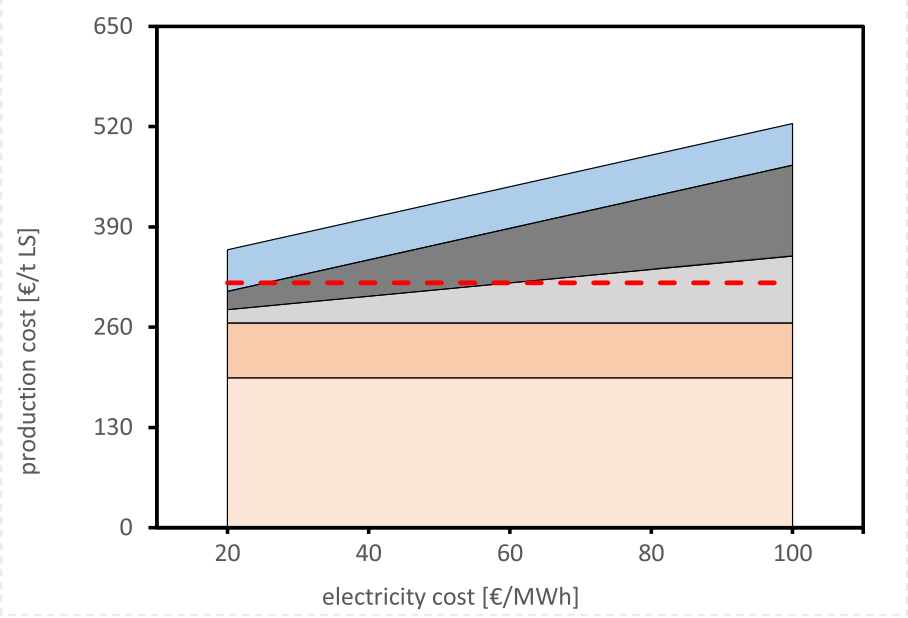

Fig. 5. Production cost via the H-DR process route as a function of the electricity cost (scrap charge 50%).

tCO_2 (50% scrap) respectively. If greenfield investments are compared, carbon prices need to be 52 EUR/tCO_2 and 34 EUR/tCO_2 respectively for the projects to be competitive. However, in light of global overcapacities the industry might not consider any greenfield investments in the near future.

Finally, it should be noted that the efficiency of the electrolyser is a key parameter for both energy consumption and subsequent production cost. Electrolyser efficiency is primarily influenced by the choice of technology. PEM electrolysers are a promising option for the process. Saba et al. (2018) expect improvements in PEM technology due to technical developments, economies of scale and learning effects. In addition, the use of alkaline or solid oxide electrolysis (SOE) is possible. Alkaline electrolysers already operate in industry today with capacity installations of over 100 MW in Norway and Egypt. However, their efficiency potential is lower and their load range for dynamic operation smaller than that of PEM

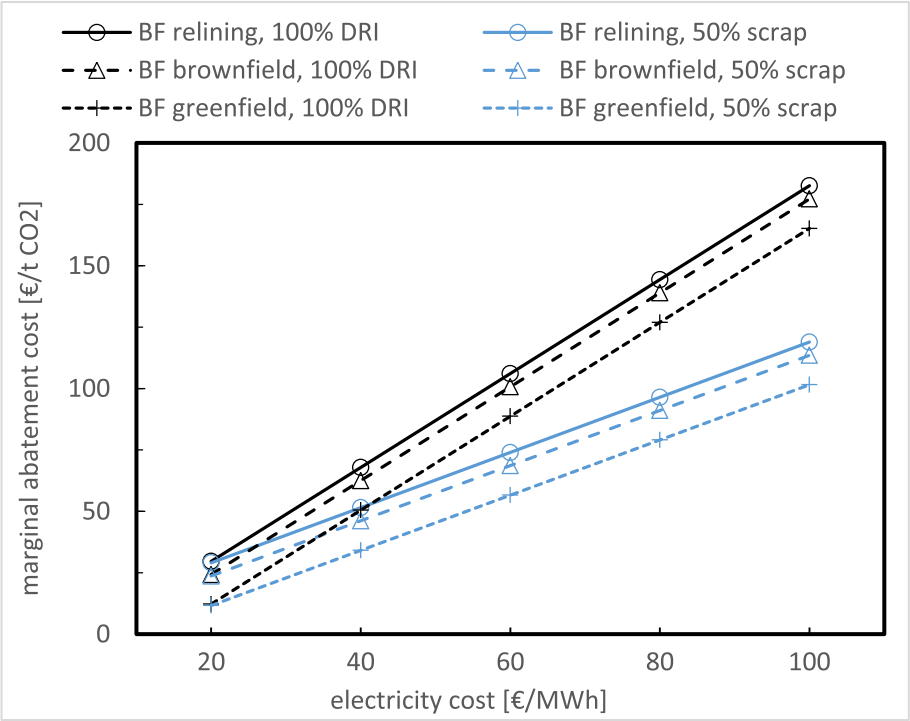

Fig. 6. Marginal abatement cost (MAC) for investing in an H-DR plant versus (a) relining a blast furnace, (b) a BF/BOF brownfield investment, and (c) a BF/BOF greenfield investment. Two cases are shown: 100% HBI operation and a 50% scrap charge to the EAF.

technology (Schiebahn et al., 2015; Saba et al., 2018). SOE is not yet a commercial reality, but promises high efficiencies and lower investment cost than PEM and alkaline options (Mathiesen et al., 2013). The similarly high operating temperatures of the SOE and the shaft make it possible to integrate heat demand between the processes, which in turn could improve the overall energy efficiency.

3.4. Flexibility of operation and load balancing

The development of the H-DR process as a fossil-free option depends on the concurrent transition to emission-free and zero-GEI power systems. The H-DR process if scaled-up represents a large additional electricity demand (3.5 TWh per million tonne steel) but it can also support the grid through its operational process flexibility. This in turn allows for electricity demand flexibility and grid balancing services.

A key feature of the H-DR process is that the set-up allows for operational flexibility and this for several reasons. The only part of the system in Fig. 1 that is designed to run in continuous mode is the reduction shaft. The electric arc furnace is a batch process (approximately 2 h per batch) and the electrolyser is built of many single units, which allows for flexible operation. The extent of balancing ability depends on whether PEM, alkaline or solid oxide electrolyser design is used. The amount of scrap charged to the electric arc furnace can be adjusted in the H-DR process allowing for flexibility in total electricity use. Quality requirements for the steel product might set boundaries to the flexible use of scrap. By using the hydrogen storage and through the possibility to store DRI as HBI the continuous operation of the shaft can be maintained. If these options are combined, a number of different operating strategies can be pursued.

Hydrogen storage enables a detachment of the electrolyser from the rest of the process and can act as a buffer, so that part of the H-DR process can still be operated continuously. By installing additional electrolyser capacity, excess stored hydrogen can then be used in times of high electricity prices or alternatively sold or even re-converted to electricity in fuel cells. The extra investment cost in electrolyser capacity must be motivated by varying electricity prices or balancing payments.

Additional degrees of freedom are gained from storing DRI through conversion to HBI. Due to the flexible use of HBI and scrap, the H-DR process resembles a hybrid between primary and secondary steelmaking. Through increasing the charge of scrap to the EAF the process becomes more like a mini-mill, whereas it resembles a typical DRI plant for steelmaking from mainly HBI. DRI cannot be stored but compaction to HBI allows for long-term storage and transport over long distances, which in turn opens the way for new operational strategies. When scrap prices are low, HBI can be stored and the amount of scrap increased in the EAF, and vice versa. HBI can also be transported and sold to other secondary steel makers. When combined with HBI storage, the EAF process can, as a batch process, be flexible on a *day-to-day basis* and would enable production strategies that react to electricity, scrap and HBI markets in a dynamic manner.

To illustrate the order of magnitude for grid balancing services of an H-DR steel plant, we assume a plant capacity of 1.5 Mt/y[2] that for optimal continuous operation needs 129 MW of installed EAF capacity and 411 MW in electrolyser, resulting in an electricity consumption of 5.22 TWh/y. If the electrolyser is dimensioned 30% larger than required, an instantaneous negative reserve power of 123 MW could be provided when electricity prices are low. This would result in a storage flow of 8.8 tonnes hydrogen per hour (107,000 Nm^3/h). Hydrogen from storage then opens up the

[2] For DRI using natural gas the trend seems to go to bigger plants. The largest DRI plants by Tosyali in Algeria (Midrex) and Nucor in Louisiana (HYL/Energiron) have capacities of 2.5 Mt/y.

possibility to offer positive reserve power by reducing the electrolyser load when electricity prices are high. An option for positive reserve power on the day-ahead spot market is a flexible EAF operation, which is already practiced today. If the EAF is used as a positive reserve (shut down), the HBI produced in the shaft can be stored or directly sold to customers. Finally, adjusting the scrap share of the EAF charge leads to significant changes in electricity consumption. A switch from pure DRI to pure scrap operation frees up 468 MW, if both the electrolyser and the shaft are shut down.

The economics of flexible operation need further investigation. Its actual use in practical operations depends on electricity price volatility and electricity market design, as well as steel and scrap markets and on technical considerations.

4. Conclusion and outlook

The assessment of a hydrogen direct reduction steelmaking process shows that total energy demand is similar to the traditional steelmaking route (blast furnace - basic oxygen furnace), but instead of coal and coke the process runs on electricity. The total production costs for liquid steel from HBI depend strongly on the price of electricity and the amount of scrap used in the process. Production cost range from 361 to 640 per tonne for electricity costs of 20–100 EUR/MWh. Production cost of the H-DR route are generally higher than those of the integrated BF/BOF route, but come close to competitive at very low electricity cost (20 EUR/MWh). At 40 EUR/MWh production cost of the H-DR route are 36% higher than for the BF/BOF route. Consequently, an H-DR plant becomes competitive with a BF/BOF brownfield investment at a carbon price of 62 EUR per tonne of CO_2. The economic viability of the hydrogen-based process is thus highly dependent on the availability of low cost clean electricity or, conversely, higher prices for carbon emissions.

The process can be flexible in production and electricity demand through storage of hydrogen and hot-briquetted iron, or variations in the share of scrap used. The process design allows for new operational strategies and businesses beyond traditional steelmaking, such as grid balancing through load shifting and large-scale oxygen production. The expected variability of electricity prices over hours, days, weeks and seasons is therefore important to consider in the sizing of unit operations and storage capacity of hydrogen and hot briquetted iron.

The assessment shows that the outlook for hydrogen direct reduction steelmaking appears promising assuming successful technology and process development and favourable market conditions in terms of relative prices for electricity and carbon emissions. Technological developments in the fields of hydrogen storage and electrolysis are crucial to the competitiveness of the process. H-DR is an option to achieve EU emissions targets for 2050 as CO_2 emissions for the process are minimal compared to today's production. A precondition for this, however, is the decarbonisation of electricity production.

Contributions

V.V. is the main author and developed the flowsheet and process model with inputs from the other authors. M.Å. and V.V. co-wrote the flexibility section. L.J.N. and V.V. co-wrote the introduction and the conclusion and outlook sections. All authors read and commented the manuscript.

Competing interests

The authors declare no competing financial interests.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2018.08.279.

References

Abdul Quader, M., Ahmed, S., Dawal, S.Z., Nukman, Y., 2016. Present needs, recent progress and future trends of energy-efficient Ultra-Low Carbon Dioxide (CO2) Steelmaking (ULCOS) program. Renew. Sustain. Energy Rev. 55, 537–549.

Åhman, M., Nilsson, L.J., Johansson, B., 2017. Global climate policy and deep decarbonization of energy-intensive industries. Clim. Pol. 17 (5), 634–649.

Allwood, J.M., Cullen, J.M., 2012. Sustainable Materials: with Both Eyes Open. UIT Cambridge Ltd., Cambridge, England.

Bertuccioli, L., Chan, A., Hart, D., Lehner, F., Madden, B., Standen, E., 2014. Development of Water Electrolysis in the European Union, Fuel Cells and Hydrogen Joint Undertaking, Lausanne, Switzerland.

Cárdenas, J.G.G., Conejo, A.N., Gnechi, G.G., 2007. Optimisation of Energy Consumption in Electric Arc Furnaces Operated with 100% DRI', Paper Presented to Metal 2007. Hradec nad Moravicí.

Domalski, ES & Hearing, ED 'Condensed phase heat capacity data', in PJ Linstrom & WG Mallard (eds), NIST Chemistry WebBook, NIST Standard Reference Database Number 69, National Institute of Standards and Technology, Gaithersburg MD, 20899.

European Commission, 2011. In: A Roadmap for Moving to a Competitive Low Carbon Economy in 2050, by Commission, E.

European Environment Agency, 2016. CO2 emission Intensity, 15.12, 2016 edn, 8.1. European Union. 2018. https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-3#tab-googlechartid_chart_11_filters=%7B%22rowFilters%22%3A%7B%7D%3B%22columnFilters%22%3A%7B%22pre_config_ugeo%22%3A%5B%22European%20Union%20(28%20countries)%22%5D%7D%7D.

Eurostat, 2017. Energy Statistics - Prices of Natural Gas and Electricity (Nrg_price) European Union. http://ec.europa.eu/eurostat/web/energy/data/database.

Fischedick, M., Roy, J., Abdel-Aziz, A., Acquaye, A., Allwood, J.M., Ceron, J.-P., Geng, Y., Kheshgi, H., Lanza, A., Perczyk, D., Price, L., Santalla, E., Sheinbaum, C., Tanaka, K., 2014a. Industry. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, S.S.J., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Fischedick, M., Marzinkowski, J., Winzer, P., Weigel, M., 2014b. Techno-economic evaluation of innovative steel production technologies. J. Clean. Prod. 84, 563–580.

Germeshuizen, L.M., Blom, P.W.E., 2013. A techno-economic evaluation of the use of hydrogen in a steel production process, utilizing nuclear process heat. Int. J. Hydrogen Energy 38 (25), 10671–10682.

Hasanbeigi, A., Arens, M., Price, L., 2014. Alternative emerging ironmaking technologies for energy-efficiency and carbon dioxide emissions reduction: a technical review. Renew. Sustain. Energy Rev. 33, 645–658.

IEAGHG, 2013. Iron and Steel CCS Study (Techno-economics Integrated Steel Mill). IEAGHG, Cheltenham, UK.

Kleiber, M., Joh, R., 2010. D3.1 liquids and gases. In: Chemieingenieurwesen, V-GVu (Ed.), VDI Heat Atlas, second ed. Springer-Verlag Berlin Heidelberg, Dusseldorf, Germany.

Mathiesen, B.V., Skov, I.R., Connolly, D., Nielsen, M.P., Vang Hendriksen, P., Bjerg Mogensen, M., Højgaard Jensen, S., Dalgaard Ebbesen, S., 2013. Technology Data for High Temperature Solid Oxide Electrolyser Cells, Alkali and PEM Electrolysers. Department of Development and Planning, Aalborg University.

Mergel, J., Carmo, M., Fritz, D., 2013. 'Status on technologies for hydrogen production by water electrolysis. In: Stolten, D., Scherer, V. (Eds.), Transition to Renewable Energy Systems, first ed. Wiley-VCH Verlag GmbH & Co. KGaA, pp. 424–450.

Milford, R.L., Pauliuk, S., Allwood, J.M., Muller, D.B., 2013. The roles of energy and material efficiency in meeting steel industry CO2 targets. Environ. Sci. Technol. 47 (7), 3455–3462.

Nuber, D., Eichberger, H., Rollinger, B., 2006. Circored Fine Ore Direct Reduction. Millenium Steel.

Otto, A., Robinius, M., Grube, T., Schiebahn, S., Praktiknjo, A., Stolten, D., 2017. Power-to-Steel: reducing CO2 through the integration of renewable energy and hydrogen into the German steel industry. Energies 10 (4), 451.

Pardo, N., Moya, J.A., Vatopoulos, K., 2012. Prospective Scenarios on Energy

Efficiency and CO2 Emissions in the EU Iron & Steel Industry. European Commission, Luxembourg.
Pauliuk, S., Milford, R.L., Muller, D.B., Allwood, J.M., 2013. The steel scrap age. Environ. Sci. Technol. 47 (7), 3448–3454.
Ranzani da Costa, A., Wagner, D., Patisson, F., 2013. Modelling a new, low CO2 emissions, hydrogen steelmaking process. J. Clean. Prod. 46, 27–35.
Remus, R., Monsonet, M.A.A., Roudier, S., Sancho, L.D., 2013. Best Available Techniques (BAT) Reference Document for Iron and Steel Production. European Commission, Luxembourg.
Saba, S.M., Müller, M., Robinius, M., Stolten, D., 2018. The investment costs of electrolysis – a comparison of cost studies from the past 30 years. Int. J. Hydrogen Energy 43 (3), 1209–1223.
Schiebahn, S., Grube, T., Robinius, M., Tietze, V., Kumar, B., Stolten, D., 2015. Power to gas: technological overview, systems analysis and economic assessment for a case study in Germany. Int. J. Hydrogen Energy 40 (12), 4285–4294.
Wagner, W., Kretzschmar, H.-J., 2010. D2.1 properties of water and steam. In: Chemieingenieurwesen, V-GVu (Ed.), VDI Heat Atlas, second ed. Springer-Verlag Berlin Heidelberg, Dusseldorf, Germany.
Weigel, M., Fischedick, M., Marzinkowski, J., Winzer, P., 2016. Multicriteria analysis of primary steelmaking technologies. J. Clean. Prod. 112, 1064–1076.
World Steel Association, 2017. World Steel in Figures.
Worrell, E., Price, L., Neelis, M., Galitsky, C., Nan, Z., 2008. World Best Practice Energy Intensity Values for Selected Industrial Sectors.
Wörtler, M., Schuler, F., Voigt, N., Schmidt, T., Dahlmann, P., Lungen, H.B., Ghenda, J.-T., 2013. Steel's Contribution to a Low-carbon Europe 2050. VDEh.
Yilmaz, C., Wendelstorf, J., Turek, T., 2017. Modeling and simulation of hydrogen injection into a blast furnace to reduce carbon dioxide emissions. J. Clean. Prod. 154, 488–501.