# Modeling and simulation of hydrogen injection into a blast furnace to reduce carbon dioxide emissions

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## ABSTRACT

In light of climate change and the desired transition toward a sustainable energy system, the reduction of greenhouse gas emissions must be a goal for all economic sectors. The steel industry depends largely on fossil energy carriers and is therefore one of the largest industrial $CO_2$ emitters. The conventional blast furnace/converter route is used to produce roughly two-thirds of the annual steel production. In the present study, the potential to reduce $CO_2$ emissions from blast furnace processes by using hydrogen as an auxiliary reducing agent, which is generated renewably by water electrolysis, is examined. For this purpose, a suitable blast furnace model is constructed using Aspen Plus in combination with FactSage/ChemApp and is validated on the basis of actual operational data. The simulation results show that the $CO_2$ emissions can decrease significantly when the suggested measure is employed. At the optimal operation conditions with a hydrogen injection rate of 27.5 kg/$t_{HM}$ ($t_{HM}$ = ton of produced hot metal), the $CO_2$ emissions of the blast furnace can be reduced by 21.4% relative to typical operations that use pulverized coal at an injection rate of 120 kg/$t_{HM}$.

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## 1. Introduction

### 1.1. Background

Without question, transitioning toward a sustainable energy system is inevitable in order to effectively address climate change. An essential goal in this respect is to decarbonize conventional energy systems, including those used in industrial and transportation sectors. The current target for 2050 is to reduce greenhouse gas (GHG) emissions in Europe by 80–95% compared with the level in 1990 (European Commission, 2012). This will mainly be achieved by the transition from fossil fuels to renewable energy sources, mostly photovoltaic systems and wind turbines. As a result, electricity will gradually replace conventional primary energy carriers and gain more prevalence as an energy source in other sectors as well (e.g., the steel industry).

However, current iron and steel production depends substantially on fossil energy carriers because iron oxides are commonly reduced by carbon monoxide (CO), which is originated from a carbon source and is then oxidized to carbon dioxide ($CO_2$). Therefore, the steel sector accounts for a large amount of the annual GHG emissions, with the majority being $CO_2$ emissions. For instance, 223 Mt $CO_2$-eq/a in the European Union alone were released in 2010 (EU-27 in 2010 (Wörtler et al., 2013)), which is equivalent to approximately 5% of the overall GHG emissions of the EU-27 in that year (EUROFER, 2013). Thus, the reduction of emissions from the steel sector is an on-going and important research topic. In this regard, a number of new production processes or modifications of existing ones have been developed (e.g., as part of the Ultra-Low $CO_2$ Steelmaking (ULCOS) project (Birat et al., 2017); the findings of the project were summarized by Abdul Quader et al. (2016)). One possibility that offers great potential is the use of hydrogen ($H_2$) to replace CO as the reductant in direct reduction processes (Tacke and Steffen, 2004). The $H_2$, in turn, can be generated by electricity with very low emissions via water electrolysis, which is a promising approach to future renewable energy systems as a part of power-to-gas and other existing applications.

The most firmly established direct reduction process is the Midrex® process, which is commercially operated worldwide (Midrex Technologies, 2017). Today, these types of industrial plants use a mixture of CO and $H_2$ from natural gas reforming as the reduction gas, but using pure $H_2$ is also feasible (Tacke and Steffen, 2004).

Another possible way to reduce the emissions from the steel sector is to use $H_2$ as an auxiliary reducing agent (ARA) for the blast furnace (BF) to partly replace the CO derived from burning pulverized coal (PC), coke, and others (Fig. 1). The oxygen by-product can also be integrated conveniently into the process as an input to enrich the hot blast. Since the traditional BF/converter route amounts to 59% of the annual production of crude steel in Europe (Wörtler et al., 2013), this concept offers great potential to reduce GHG emissions. Moreover, it represents a good option to use electricity (rather than fossil fuels) as an energy carrier in the steel sector.

## 1.2. Literature review

Although the following discussion focuses on the use of different reducing agents in the BF process, further information on the process itself can be found in the literature and will not be addressed here (Von Bogdandy and Engell (1971), for example, deal with BF ironmaking particularly addressing the thermodynamic principles and the basis of reaction kinetics for the reduction of iron ores. Geerdes et al. (2009), on the contrary, give a rather practice-oriented overview of all aspects of BF ironmaking while Babich et al. (2008) discuss BF ironmaking in general covering the use of ARA with great emphasis). The utilization of alternative reducing agents to decrease the specific coke consumption of BFs is an established practice, mainly for economic reasons. By this measure and various other developments, the mean equivalent fuel rate in Germany, for example, has decreased from 800 kg/$t_{HM}$ ($t_{HM}$ = ton of produced hot metal (pig iron)) in the 1960s to an average of 505 kg/$t_{HM}$ in 2014. Therefore, the mean coke rate of the BFs amounts to 334 kg/$t_{HM}$ (Stahlinstitut VDEh, 2015). According to Großpietsch et al. (2001), a minimum of 270–300 kg/$t_{HM}$ is necessary to ensure stable furnace operation; however, Babich et al. (2002) claimed that a theoretical minimum of below 200 kg/$t_{HM}$ is necessary. At present, PC, oil, natural gas (NG), or a combination of these reducing agents is typically injected by tuyeres as an ARA, with PC being the most common reducing agent, particularly in

Germany. Experimental studies and industrial experiences have shown that PC rates of up to 250 kg/$t_{HM}$ can be achieved in some cases, resulting in a coke rate of equal value. Nevertheless, the applied PC rates still average 130–150 kg/$t_{HM}$ due to problems resulting from the incomplete conversion of coal (i.e., char generation), which cause poor furnace operation (Babich et al., 2002). To address this issue, Babich et al. (2002) investigated the injection of a hot reducing gas (HRG), which was essentially a mixture of $H_2$ and CO, as an addition to or a replacement of conventional ARAs.

The idea of using an HRG in BFs has been of interest since the beginning of the 20th century. In fact, this strategy has been investigated by several research groups but has not yet been implemented in an industrial setting. A detailed literature review on this topic can be found in Van der Stel et al. (2011). The major advantage of this approach is that higher quantities of CO and $H_2$ can be fed into the BF by injecting the HRG via the hearth tuyeres than with conventional fuels (Babich et al., 2002). HRG injection into the shaft or the furnace belly is also feasible, but its implementation is likely to be more difficult. Some ways to generate an HRG include coal gasification, NG reforming, or top gas (TG) recycling. The latter is a concept that involves $CO_2$ removal from the TG followed by reinjection of the cleaned gas into the BF as a reducing agent (Hirsch et al., 2012). Recent progress with this technology have have been achieved within the ULCOS project, whereby TG recycling with $CO_2$ capture has been explored (i.e., ULCOS blast furnace). Various theoretical studies, as well as tests using an experimental BF, have been conducted (Van der Stel et al., 2014). Overall, the technology was proven to be both feasible and safe. During the trial experiments, a carbon saving of 24% was achieved (Hirsch et al., 2012). Further research has been proposed, such as the development of a new tuyere technology for the simultaneous injection of an HRG and PC, as well as improvements to the shaft gas injection (Van der Stel et al., 2011). Additionally, an industrial-scale demonstration of the ULCOS BF has been intended as a consequence of the promising research results (Guangqing and Hirsch, 2009). Babich et al. (2002) concluded that effective HRG injection into the BF hearth is possible under certain conditions, including a constant gas composition, high oxygen content in the hot blast, and high injection temperature of the HRG. Moreover, the combined injection of PC and HRG was also identified to benefit the process by saving coke. Notably, the authors also concluded that reducing gases with high hydrogen contents (e.g., 71 vol%) achieved the best results in terms of reducing the amount of coke required.

Overall, these results demonstrate the benefit of injecting pure hydrogen into the BF as an ARA, which has already been considered in various publications. For instance, Barnes (1975) was one of the first authors to report that 42 kg/$t_{HM}$ of hydrogen at 1000 °C can replace 140 kg/$t_{HM}$ of coke. Subsequently, Astier et al. (1982) reported a coke replacement of 27 kg/$t_{HM}$ per 9 kg/$t_{HM}$ of hydrogen injected at 900 °C. Simulation results by Nogami et al. (2012) revealed a coke rate of 324 kg/$t_{HM}$ when 44 kg/$t_{HM}$ of hydrogen at 1200 °C was injected, though other furnace parameters were also changed (e.g., a modified hot blast with a very low nitrogen content). Lastly, Schmöle (2015) presented a theoretical examination of injecting 40 kg/$t_{HM}$ of hydrogen, which resulted in a coke rate of 392 kg/$t_{HM}$. This last work also reported an increased energy demand while having significantly lower $CO_2$ emissions compared with a conventional operation. To summarize, a number of publications have considered the injection of pure hydrogen into the BF as an ARA. However, these studies have examined only one or very few operating conditions and have not described the relevant boundary conditions, such as the coke rate without hydrogen injection, which are important metrics to evaluate the results in a comprehensive manner. Furthermore, the influence of the injection
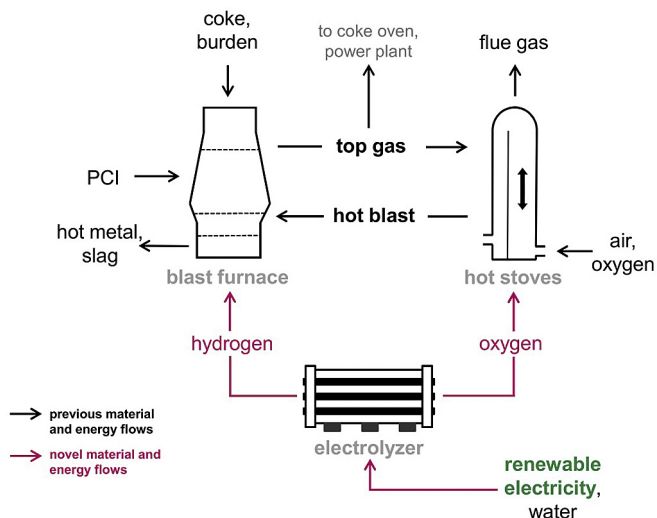
**Fig. 1.** Hydrogen generated by water electrolysis as an auxiliary reducing agent within the blast furnace process (PCI: pulverized coal injection).