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Experimental evaluation of a flexible natural gas and hydrogen burner in the electric arc furnace

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Abstract. In the context of the decarbonization of the steel industry, the electric arc furnace (EAF) has emerged as a primary focus of research. Historically, the EAF has been predominantly utilized in recycling-based steelmaking, specifically for the melting of scrap materials to produce crude steel. The recent surge in research interest in the EAF is driven by the objective of optimizing resource utilization and reducing emissions. Given its primary reliance on electrical energy, the EAF emerges as a promising solution for reducing steel production emissions. In addition to the electrical energy input, the EAF is equipped with auxiliary burners to prevent 'cold spots' during melting and shorten the process duration by increasing the energy input. These auxiliary burners typically operate with oxyfuel, natural gas and oxygen. The combustion of natural gas represents a potential for reducing CO_2 emissions through the substitution with hydrogen. In the RFCS-funded project "DevH2forEAF - Developing and enabling H_2 burner utilization to produce liquid steel in EAF," an innovative injector-burner designed for using oxygen and arbitrary mixtures of natural gas and H_2 (up to 100% H_2) as the fuel was developed for use in EAF, providing a flexible solution for a possible addition of hydrogen to the natural gas line. This injector-burner was subjected to rigorous testing in a range of trials within the environment of an EAF. A downscaled version of the burner, with a power output of 50 kW, was tested in the pilot-scale EAF at RWTH Aachen University, with a particular focus on analyzing its impact on steel quality. Subsequently, a 4 MW burner-injector was installed in two distinct industrial EAFs and utilized in operation. The results showed that switching one burner to hydrogen resulted in combined CO_2 emission reductions of up to 27% for the burner emissions, with no detectable increase in hydrogen pick-up in the liquid steel, confirming the technical viability of hydrogen as a drop-in fuel for EAF burners.

Keywords: electric arc furnace / hydrogen burner / natural gas burner / experimental trials / process model

1 Introduction

The steel industry is currently facing significant challenges in its efforts to reduce greenhouse gas emissions. The electric arc furnace (EAF) is a pivotal component of this transition, as it is primarily utilizing electrical energy which can be effectively transitioned to green energy sources. However, it is important to acknowledge the persistent presence of substantial sources of CO_2 emissions within the EAF, including auxiliary burners, coal injection, and electrode consumption. In the research project "DevH2forEAF", funded by the Research Fund for Coal and Steel (RFCS) of the European Commission, the focus is on the reduction of emissions from auxiliary burners through the substitution of natural gas with hydrogen. While the principle of hydrogen combustion is well-understood, its practical application in the complex, multi-phase environment of an industrial EAF, and the associated risks to steel quality, requires thorough investigation.

Within the scope of the project, an innovative injector-burner was designed for the use of oxygen and natural gas, as well as H_2 (up to 100%) as fuel. This burner has been subjected to rigorous testing in order to investigate the influence of a hydrogen burner on the EAF application.

The utilization of hydrogen as a fuel gas in place of natural gas confers the advantage of reduced CO_2 emissions. A notable concern associated with the utilization of hydrogen in the melting process of steel pertains to the potential hydrogen pick-up of the crude steel. Following operation, the removal of dissolved hydrogen

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from steel is a challenging process that necessitates vacuum degassing [1]. Should hydrogen remain within the steel during the process of solidification, the formation of hydrogen pores in the final product is to be expected. This phenomenon, known as hydrogen embrittlement, can have a detrimental effect on the mechanical properties of the material [2].

2 Material and methods

An exhaustive program of testing was carried out on the developed injector-burner. The project involves the execution of small-scale trials at a pilot plant EAF, utilizing a downscaled version of the burner with a capacity of 50 kW. Following the successful completion of the requisite trials to ensure the safety of operation in industrial EAFs, a 4 MW burner was installed in two different industrial EAFs. The present study investigates the impact of a hydrogen burner on the overall operation, as well as the off-gas and steel chemistry.

At the Department for Industrial Furnaces and Heat Engineering of the RWTH Aachen University, the downscaled burner was installed in a pilot-scale EAF. Throughout the course of the experiments, a variety of steel and slag samples were collected for comprehensive analysis of the chemistry and potential hydrogen pickup of the melt. In addition, extensive equipment was installed for measuring the furnace temperature and off-gas properties.

In this paper, the results for two steel plant will be presented. The focus of this study is to examine the impact of a hydrogen fired burner on the off-gas and the steel chemistry. Therefore, 20 experimental heats with the developed hydrogen injector-burner were investigated in the industrial EAF in the first steel plant and additionally, 13 heats with the hydrogen injector-burner were carried out in the second steel plant. In the context of the evaluation of the plant trials, a dynamic EAF process model, developed by Logar et al. [3–7] and further adapted at RWTH IOB [8–14], was employed to examine the impact of potentially substituting all burners with hydrogen-fired burners at the investigated EAF. The industrial trials that were conducted serve to validate the utilization of hydrogen burners within the EAF process model. The aforementioned study can be found in [15].

3 Results and discussion

In this section the results of the experimental campaigns are presented. First the results of the pilot scale EAF operating with a downscaled version of the burner are analyzed in detail, including the steel chemistry and off-gas. In a second step the industrial trials from two steel plants are subject of the analysis of the influence of a hydrogen burner-injector on the EAF operation. An overview of relevant key parameters for the EAFs under investigation can be found in Table 1. Moreover, the theoretical hydrogen solubility is taken into account to put the findings of all experimental heats into perspective and access the possibility of hydrogen pick-up of the melt further.

Table 1. Overview of relevant key parameters for the EAFs.

Parameter	Pilot scale EAF	EAF 1	EAF 2
Approximate capacity	100–200 kg	150 t	150 t
Number of burners	0–1 (50 kW)	12 (3–4 MW)	5 (4 MW)

3.1 Pilot scale EAF

Prior to the installation of the 50 kW burner in the pilot-scale EAF, preliminary free-flame tests were conducted to ensure the stability of the flame operation with a range of fuel gas compositions, extending from 100% natural gas to 100% hydrogen. The findings demonstrated that the incorporation of hydrogen led to a substantial enhancement in flame stabilization. It has been established that for all fuel gas compositions, the length of the visible flame remains within the same range, and is sufficient for utilization in the pilot-scale EAF.

In the following step, the burner was installed in the roof of the pilot-scale EAF, burning at a steep angle on the scrap and melt. Despite its deviation from the standard industrial EAF configuration, this installation position will nevertheless prove to be a viable method for assessing the impact of the flame on the steel surface. The burner's inclination results in a direct contact between the flame and the steel surface, as opposed to the industrial configuration where the flame is positioned above the steel surface. In the event that the collection of hydrogen from the melt is attributable to the utilization of hydrogen as a fuel gas, this particular installation angle is likely to augment the pick-up of hydrogen and increase the discernibility of potential effects on operational functionality. A downside of the roof installation of the burner is the proximity of the burner flame to the electrodes and the electric arc. Possible interference between the flame and arc can not be eliminated. This is only the case for the pilot scale EAF, as dimensions of industrial EAFs prevent these interactions by the burners being pointed from the furnace wall towards the melt surface. The burner configuration in the pilot scale EAF was intentionally selected to maximize the potential for hydrogen-steel interaction, thereby creating a stringent test for hydrogen pick-up that would be unlikely to occur in an industrial setting.

Due to the limited number of experiments, the burner is operated in all trials with 100% H_2. This ensures that the investigation represents the worst-case scenario for hydrogen pick-up of the melt. Two different scenarios of burner operation were tested. In the flat bath phase following the scrap meltdown, the burner is utilized to enhance hydrogen pick-up of the melt as a worst-case scenario (trial 1 and 3). In addition to this, the burner operation was assessed during the melting of scrap, mirroring typical operating conditions in an industrial EAF (trial 2).

The experiments are characterized by an emphasis on the chemical composition of steel, slag, and off-gas. This emphasis is deliberate, as it is essential to ensure that the

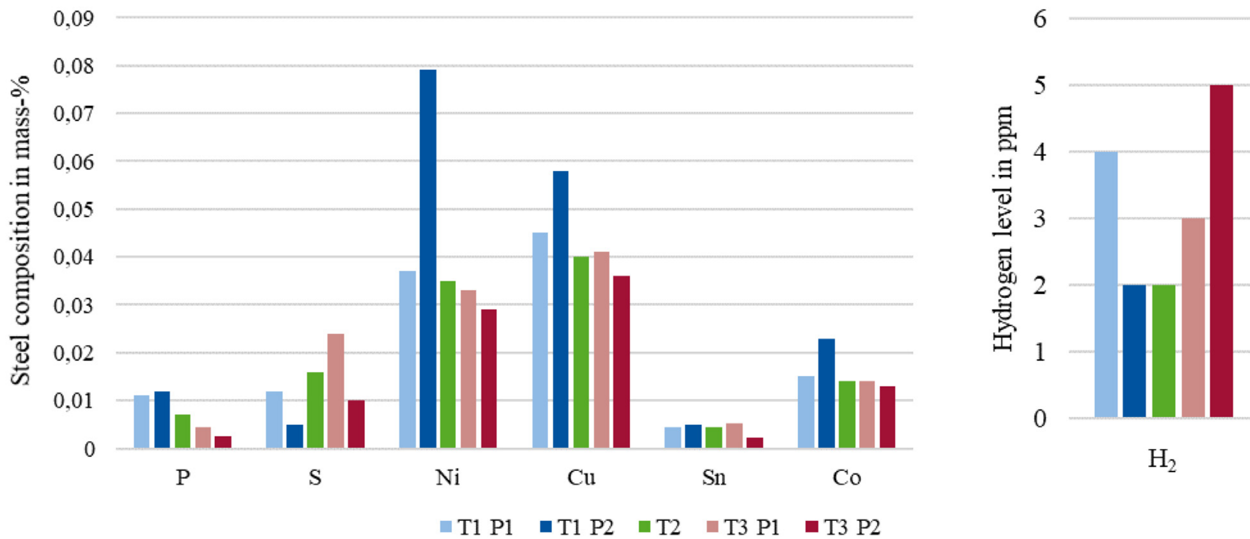

Fig. 1. Steel analysis.

operation produces steel of consistent quality. During the experiments, multiple steel samples were collected with the objective of conducting a comparative analysis of the operating conditions prior and following the utilization of the H_2 burner. The operation conditions in the pilot scale EAF were kept constant for all trials to ensure comparability. The scrap used in all trials consisted of screws from railroad sleepers and pure iron flakes, therefore the steel samples taken during the trials consist of over 99% iron (Fig. 1). In the experiments with the burner operated during flat bath phase, a steel sample is taken before (probe 1) and after (probe 2) burner usage, enabling a comparison for the direct influence of the hydrogen burner on the steel chemistry. For the trial with the burner used during melt-down only one steel sample at the end of the operation is taken. The hydrogen content of the steel was also determined in order to investigate the effects of the hydrogen burner on the hydrogen pick-up of the steel. The analysis revealed that the hydrogen content in all samples was found to be in the low ppm range (2 – 5 ppm). For a single trial involving the utilization of the burner in the flat bath phase, a notable decrease in hydrogen levels was observed (trial 1). Specifically, the hydrogen level diminished from 4 ppm to 2 ppm following the operation of the burner.

The hydrogen level in the off-gas has an influence on the hydrogen pick-up of the melt. Therefore, the off-gas analysis is an important part of this analysis. Figures 2 and 3 show the off-gas analysis for trial 1 and 2. The grey colored background indicates the power on time of the hydrogen burner. On the right side of the diagram the off-gas composition for CO_2 and CO is shown and on the left side for H_2 and O_2. During the first trial (Fig. 2) very little CO was produced as for the most part of the operation enough O_2 was present, therefore the CO is able to further react to CO_2. The peaks in the off-gas O_2 level and the minima in the CO_2 level correspond to the times the furnace is opened. Due to the problems while starting the burner at around 150 min, very high levels of CO_2 can be found in the off-gas. Furthermore, H_2 can be found at an increasing level during the burner operation leading to the assumption of an uncomplete H_2 combustion. The absence of O_2 in the off-gas during the burner use confirms this assumption. As the burner is installed close to the electrodes, a part of the O_2 introduced by the burner for the combustion oxidizes the electrodes instead, forming CO and CO_2 and leading to higher CO and CO_2 levels in the off-gas. Moreover, the combustion of H_2 generates water vapor which cannot be detected by the installed off-gas analysis and the moisture measurement could not operate in the EAF conditions. The analysis results show the dry off-gas, so the values are distorted during burner operation, as water is formed which is not taken into account. The overall presence of CO and CO_2 in the off-gas is due to the fact that in the EAF multiple sources of carbon are available. These include the electrode, the carbon introduced with the scrap and for industrial sized EAF there are even more carbon sources available e. g. the natural gas burner or a coal lance used during the operation.

In the second trial (Fig. 3) the burner is used at the beginning of the operation. With the start of the burner it can be seen that all of the hydrogen fully combusts and is not found in the off-gas. About 30 min into the operation this changes with the increasing temperature in the furnace. The H_2 does not fully react and increased levels of CO and CO_2 are present in the off-gas, leading to the assumption of a high oxidation of the electrodes. In between the two power-on times of the burner the EAF was opened to observe the melt-down progress. As no melt-down had yet occurred the burner was ignited again and the furnace closed. For the second burner power-on the same characteristic can be observed as for the first. After the usage of the burner a low H_2 level is still present in the off-gas. This may arise from water vapor that is present in the furnace after the usage of the hydrogen burner and reacts at the high arc temperatures to H_2 and O_2.

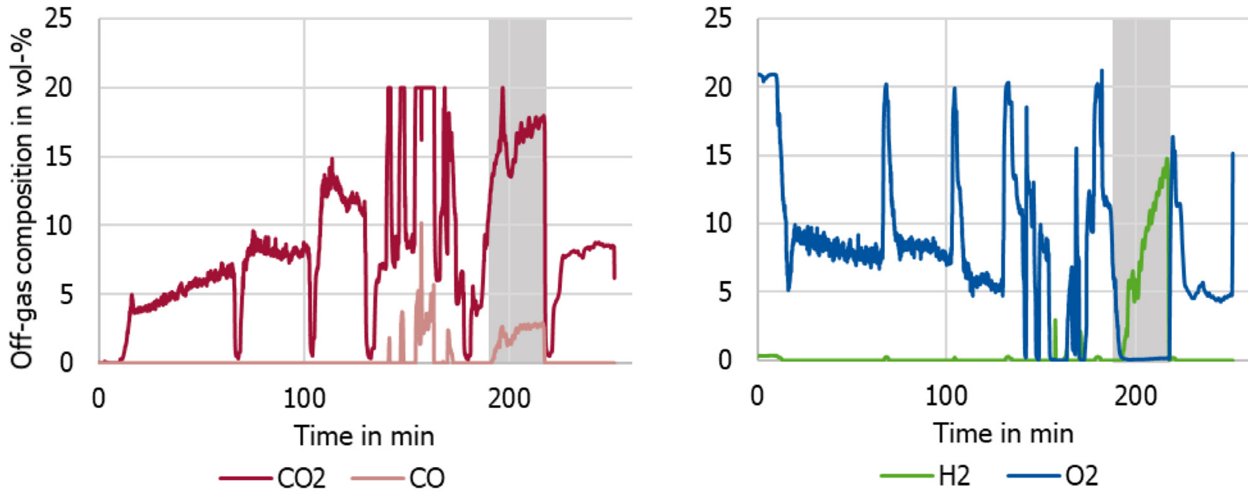

Fig. 2. Off-gas analysis of trial 1.

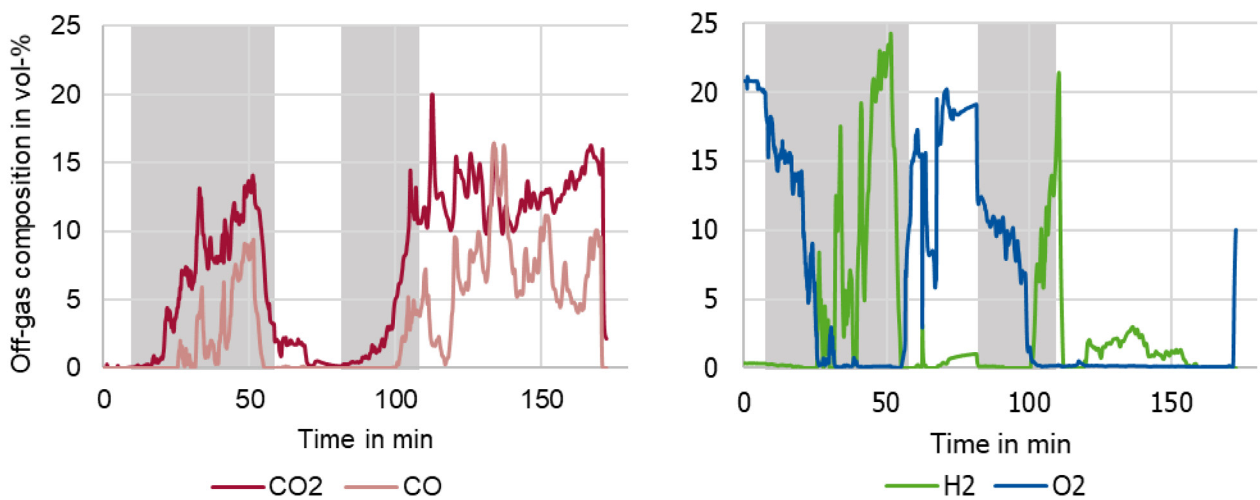

Fig. 3. Off-gas analysis of trial 2.

Overall, the electrodes were changed twice during the trials and the usage of an additional burner in the pilot scale EAF. This indicates an increased electrode consumption because the burner is installed close to the electrodes and the oxygen jet through the burner provides oxygen close to the electrodes. Furthermore, the electrodes exhibited intense incandescence during the tests, indicating a significantly higher temperature of the electrodes than usual. A higher electrode temperature also explains the cause of the leakage in the electrode cooling system. The increased temperature and the availability of oxygen from the burner increase the oxidation of the electrodes to CO and CO_2 [16]. This leads to more CO and CO_2 in the exhaust gas, as well as H_2, which does not burn completely as the O_2 is consumed at the electrodes. This problem will not arise in industrial sized EAFs as they are already equipped with burners which are located in a safe distance from the electrodes. Therefore, this phenomenon can be seen as a limitation to the setup in the pilot scale EAF and not an effect of the hydrogen burner technology itself.

In addition to the chemical analysis, the microstructure of the steel samples was examined microscopically. The analysis revealed that none of the samples exhibited pores that could be attributed to hydrogen pick-up. The low hydrogen levels detected in the samples, as well as the microscopic analysis, indicate that the use of a hydrogen-fired burner does not affect the hydrogen pick-up of the produced steel (Fig. 4). A microscopic examination was conducted, but no gas inclusions were detected. This finding is consistent across both the burner use during the meltdown of the scrap and the usage during the flat bath phase.

Given the absence of discernible impact from the hydrogen burner on the operational dynamics or the quality of the steel in the pilot-scale EAF trials, it was not anticipated that any disadvantages would emerge during the industrial trials.

3.2 Industrial trials

After the pilot-scale trials with a hydrogen burner showed no detrimental effects on the steel quality, the 4 MW hydrogen injector-burner was installed in two steel plants.

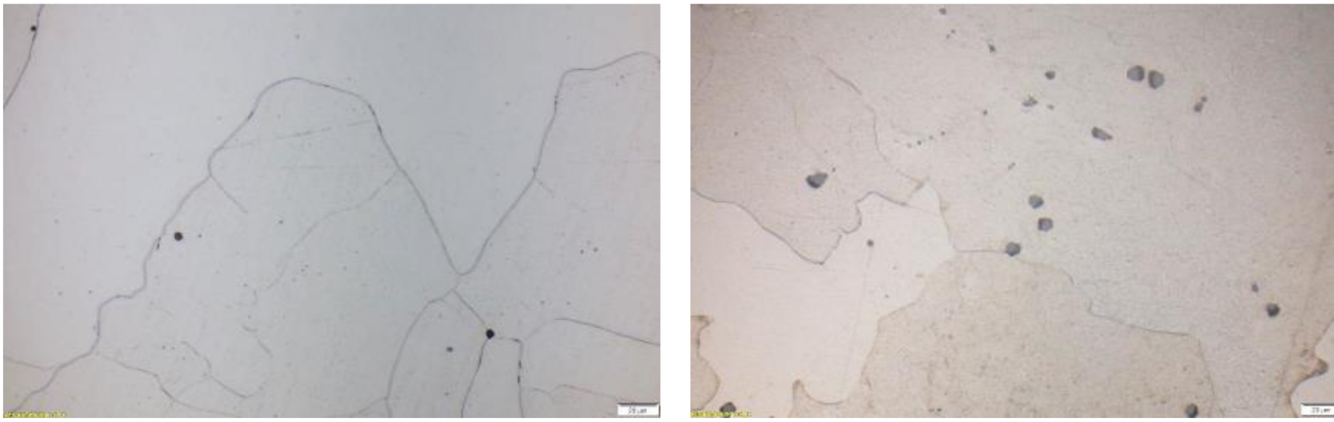

Fig. 4. Structural analysis after the burner usage during flat bath phase (left) and during melt down (right).

Therefore, one burner-injector used in the industrial EAFs is replaced with the innovative hydrogen injector-burner and supplied with a hydrogen trailer. In the first steel plant under investigation 20 heats were executed, employing hydrogen as fuel gas in one of its 10 burners (specifically, burner 1) installed in the furnace. In the initial two trials, a blend of natural gas and hydrogen was utilized as a fuel gas for burner 1, exhibiting no adverse impacts on operational efficiency or steel quality. In the subsequent 18 trials, pure hydrogen was utilized as fuel gas. The following analysis focuses on CO_2 emissions from the burners and how these can be reduced by replacing natural gas with hydrogen. Total process-related CO_2 emissions are not considered, as these can originate from many sources in the EAF depending on the operating mode. In Figure 5 an overview of the CO_2 reduction for the trials with the hydrogen burner is shown. In this diagram 100% of the CO_2 emissions correspond to a heat with the same operating conditions supplied with 100% natural gas in all burners. The substitution of hydrogen for natural gas in burner 1 led to a decrease in CO_2 emissions from this specific burner. The reduction in emissions is represented in green, and the percentage of reduction is indicated above the diagram. The CO_2 emissions resulting from the operation of the remaining burners and natural gas supplied in the innovative hydrogen burner are represented in red.

In the initial two trials, the minimal CO_2 reduction was observed due to the utilization of a blend of natural gas and hydrogen. However, in the subsequent trials, the use of pure hydrogen resulted in a more pronounced reduction. In addition, it has been demonstrated that certain heats exhibit a heightened degree of CO_2 reduction in comparison to others, a phenomenon that is particularly evident in heats 16 and 17.

For further analysis of the different CO_2 emission reduction potentials a comparison of the power distribution of the burners for heat 3 and 16 is shown in Figure 6. The power input of burner 1 is represented by the blue line, which illustrates the natural gas usage. The hydrogen usage is represented by the green line. The other burners with natural gas used in the EAF are combined in the red line. The burner is used in different operation modes during each heat. After the introduction of a new scrap basket burners are operated in the burner mode, producing a long flame which is used to speed up the scrap melt down and also avoid 'cold spots' close to the furnace wall. During flat bath phase the burners are usually operated in an anti-splash mode, only supplying a small flame that prevents a possible burner clogging from slag. During heat 3 (which exhibited a burner CO_2 reduction of 8.9%), 100% hydrogen was utilized in burner 1 exclusively in the burner mode, while the anti-splash mode continued to operate with natural gas. Conversely, during heat 16, the burner mode and the anti-splash mode were supplied with pure hydrogen, with no natural gas utilized in burner 1. Furthermore, the remaining burners in the EAF were operated in anti-splash mode only, resulting in reduced power output and natural gas consumption. Nevertheless, the predominant power input from the burners originates from the supplementary burners present in the EAF. This underscores the significance of incorporating hydrogen usage in the anti-splash mode, along with the substitution of all burners in the EAF. This approach has the potential to eliminate all CO_2 emissions connected to the operation of the burners.

In the second steel plant the hydrogen injector-burner is replacing one of four burners (specifically, burner 2). The normal production of this steel plant hardly uses any chemical energy supplied by the burners and operates the burners mainly in anti-splash mode. For the 13 trials carried out using hydrogen as a fuel gas, the power of the injector-burner is varied between 2 and 4 MW, using 20 and 50 vol-% hydrogen in the fuel gas. In Figure 7 the reduction of CO_2 emissions by the usage of hydrogen in the injector-burner is shown. It is evident, that for a substitution of 20% hydrogen in the fuel gas about 5% of the CO_2 burner emissions can be avoided, while at 50% hydrogen in the fuel gas a decrease of up to 23% of the CO_2 emissions is evident. For the different burner powers, no difference is visible in this diagram as the percentages and not the absolute values are taken into account. Operating the burner at a higher energy input, more fuel gas is needed including natural gas which leads to greater CO_2 emissions.

The difference in the burner usage becomes more evident comparing the operation diagram of specific heats. In Figure 8 the power distribution between the natural gas and hydrogen supplied from burner 2 and the additional burners is outlined for heat 9 and 11. In both heats the

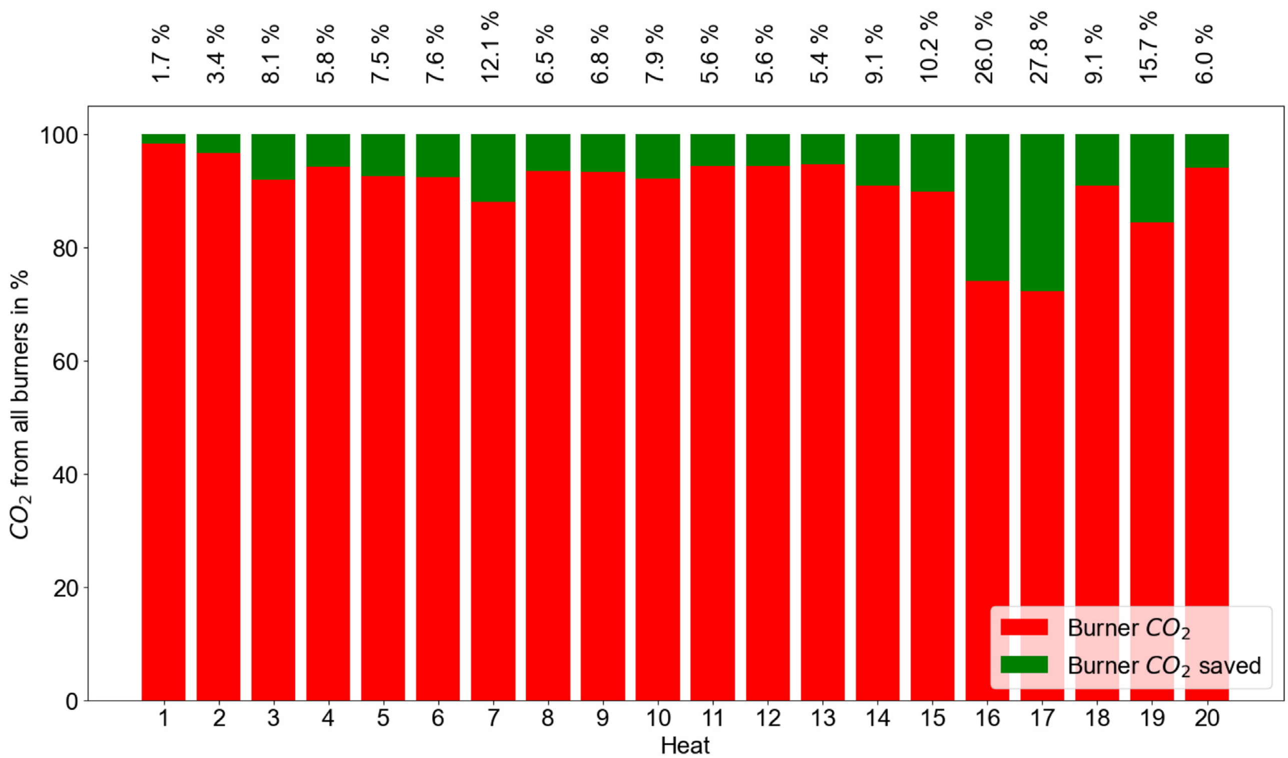

Fig. 5. CO2 reduction of the burner emissions (first steel plant).

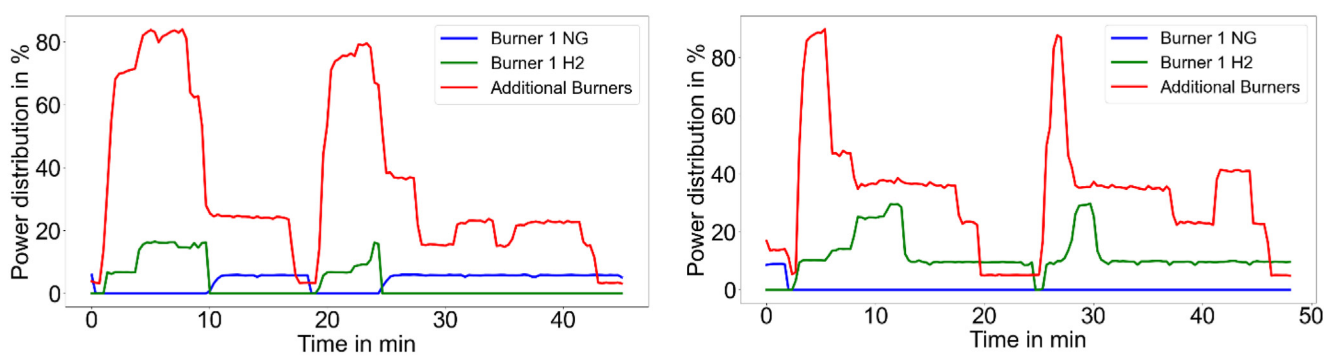

Fig. 6. Power distribution between the burners for heat 3 (left) and heat 16 (right).

burner is operated with 4 MW. Heat 9 uses 20 vol-% hydrogen in the fuel gas and heat 11 uses 50 vol-% hydrogen. One difference to the first steel plant is the usage of the burner is limited to the phases of scrap melt-down. During the power-off of the burner no fuel gas is used at all, eliminating the anti-splash mode of the burners. As seen in the first steel plant the anti-splash mode of the burners contributes a great deal to the overall CO_2 emissions from the burners. With the second steel plant turning off the burners completely during power-off times, overall CO_2 emissions are already reduced.

The steel samples obtained during the campaign with the hydrogen burner were also subjected to investigation for dissolved hydrogen. For the first steel plant 25 samples were collected during the experimental campaign, 49 samples of the liquid steel and 17 samples of the finished product were analyzed from the regular production without hydrogen usage. During the trials in the second steel plant, for all 13 trials with hydrogen samples were taken. As a comparison 7 samples were taken of the liquid steel with the injector-burner using 100% natural gas.

The results, shown in Figure 9, demonstrate that the hydrogen levels in the steel samples from the experimental campaign were on a similar level with those of the samples without the hydrogen burner. The utilization of a hydrogen burner ensured that the residual hydrogen present in the liquid steel remained below 2 ppm for the first steel plant. In contrast, during conventional production, a maximum of 6 ppm hydrogen in the liquid steel was detected in two samples. For the second steel plant the overall residual H_2 in the liquid steel is higher for both the usage of a hydrogen and a natural gas burner. The reason is the different sample positions, as for the first steel plant the samples were taken after refining, while the samples from the second steel plant were taken before refining.

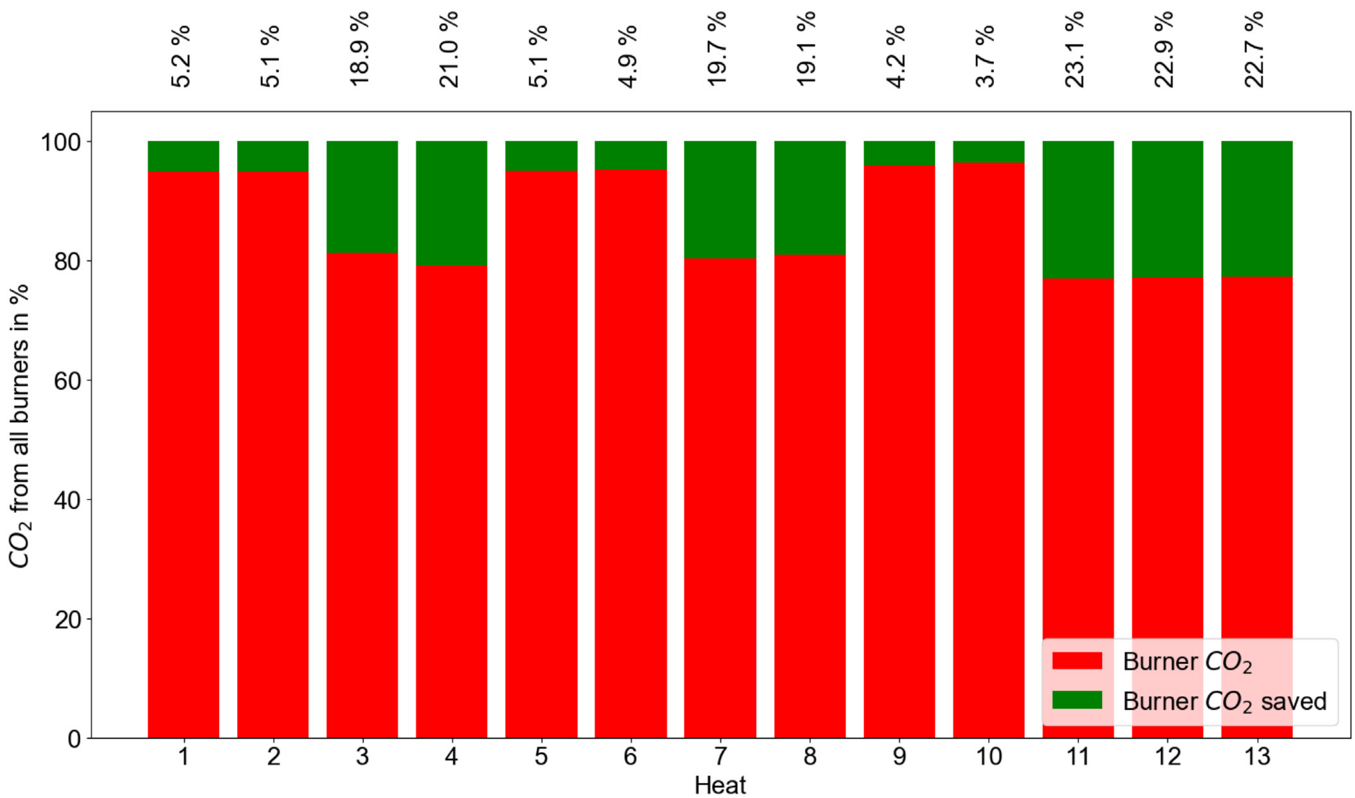

Fig. 7. CO2 reduction of the burner emissions (second steel plant).

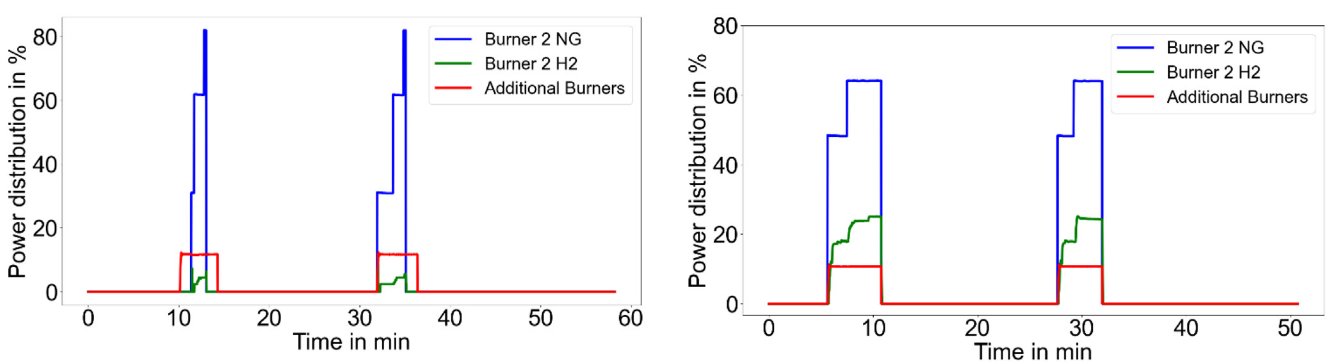

Fig. 8. Power distribution between the burners for heat 9 (left) and heat 11 (right).

A comprehensive evaluation revealed that the implementation of a hydrogen-fired burner did not result in any adverse impacts on the EAF operation.

3.3 Hydrogen solubility

The solubility of hydrogen in the melt depends on a number of factors, namely the hydrogen partial pressure, the temperature, the composition of the melt and the free bath surface in contact with the gas phase. In literature multiple values for the hydrogen solubility in pure iron at 1600 °C and 1 atm H_2 can be found, ranging from 21.8 to 27.9 ppm H [17]. According to investigations by Sieverts et al. [18], the amount of dissolved hydrogen in iron is proportional to the square root of the partial pressure of hydrogen. In the pilot-scale trials the highest concentration of hydrogen detected in the dry off-gas is 25 vol-% during the second trial. Due to the additional water content of the off-gas the H_2 level in the wet off-gas will be below 25 vol-%. In a worst-case scenario with 25 vol-% H_2 in the off-gas at atmospheric pressure in the furnace the partial pressure of hydrogen is 0.25 atm. According to the relation between the hydrogen solubility and the hydrogen partial pressure this results in a hydrogen solubility of 10.9 to 14 ppm H for pure iron at 1600 °C. In comparison with the hydrogen level of the samples taken in the pilot scale EAF, ranging from 2 to 5 ppm H_2, it is evident that the measured values are well below the theoretical limit. This supports the conclusion of safe operating conditions with regards to steel quality.

In general, the hydrogen solubility increases with increasing temperature with multiple steps in between [19]. The measured temperature in the trials ranging from 1527 °C to 1560 °C are below the temperatures for the literature values at 1600 °C. Therefore, the theoretical

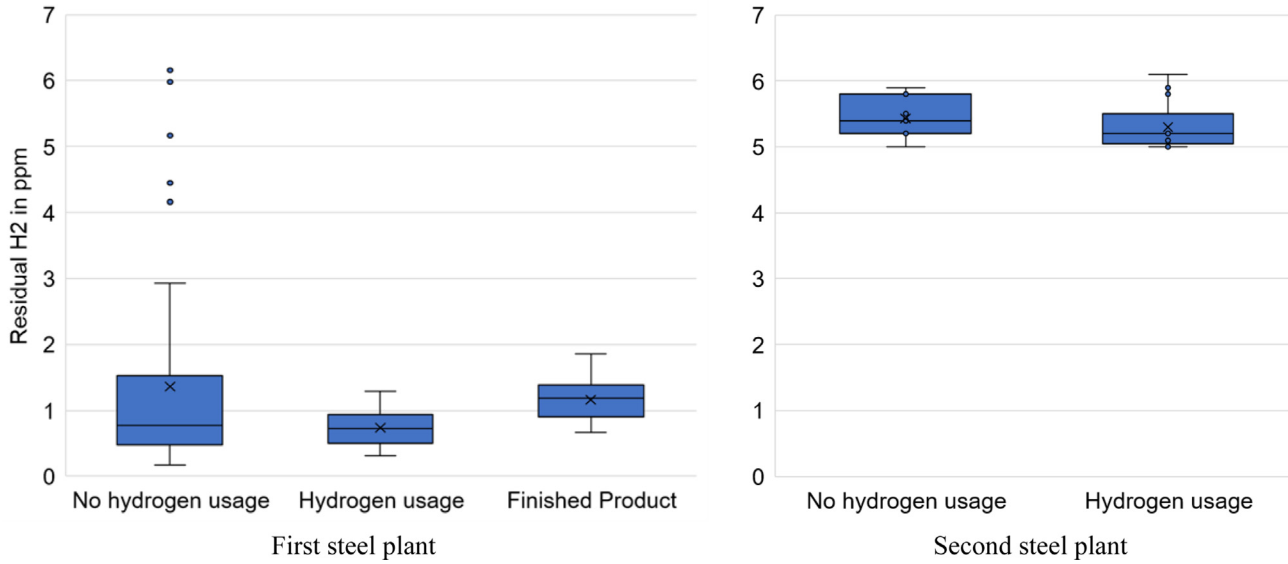

Fig. 9. Hydrogen level in various samples with and without hydrogen usage.

possible hydrogen solubility will decrease further. The composition of the melt is close to pure iron in the EAF burner trials, thus minimizing the influence of alloying elements on the hydrogen solubility. Overall, the typical steel composition includes elements that increase as well as decrease the hydrogen solubility. It is important to consider the influence of different elements on the hydrogen solubility when producing varying steel grades. As Al, C, O, P, S, Si and Sn increase the solubility of hydrogen in the melt, the presence of Cr, Cu, Mn, Ni, Ti and V decrease the solubility of hydrogen [20]. For the industrial trials the steel composition has to be analyzed to be able to provide precise predictions for the hydrogen solubility.

The free bath surface enables the absorption of hydrogen from the furnace atmosphere. During melting, the resulting melt is in contact with the furnace atmosphere. As the melt down progresses, the slag layer covers the molten metal and partially protects it from contact with the furnace atmosphere. Bath movements caused by the burners and the electric arcs also bring the molten metal into contact with the furnace atmosphere later during the flat bath phase.

4 Conclusion

The research conducted within the "DevH2forEAF" project highlights the promising potential of hydrogen as a fuel source in EAF for steel production. The innovative injector-burner, designed for this purpose demonstrated effective performance during both pilot-scale and industrial trials, with significant implications for reducing CO_2 emissions. Despite the incomplete combustion in pilot scale EAF and high concentrations of H_2 in the exhaust gas (up to 25 vol-%), H_2 was only detected in the low ppm range in all steel samples. The incomplete combustion of the hydrogen in the trials is due to the installation position of the burner. Due to the proximity to the electrodes, the electrodes became significantly hotter than when the EAF is operated without a burner. The burner also increases the amount of oxygen available near the electrodes. The burner oxygen thus also oxidizes the electrode and CO and CO_2 are produced. This phenomenon is irrelevant for the industrial tests, as the distance between the burner and the electrode is greater.

The experimental results from the industrial sized EAFs indicate that substituting natural gas with hydrogen does not adversely affect the quality of the produced steel. Importantly, the hydrogen levels in the steel remained low and in the same range as during normal production, suggesting that hydrogen pick-up is manageable and does not compromise material integrity.

The findings from this study underscore the viability of integrating hydrogen-fired burners into existing EAF processes, paving the way for more sustainable practices in the steel industry. Future work should focus on the economic and infrastructural challenges of large-scale hydrogen supply in order to exploit this technology fully for the deep decarbonization of steel production.

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Conflicts of interest

The authors have nothing to disclose.

Data availability statement

Data associated with this article cannot be disclosed due to confidentiality agreements.

Author contribution statement

Conceptualization, L.S., A.R., J.G. and F.V.; Methodology, L.S., T.E., J.G. and F.V.; Software, L.S. and A.R.; Validation, L.S. and A.R.; Formal Analysis, L.S. and A.R.; Investigation, L.S.; Resources, T.E., J.G. and F.V.; Data Curation, L.S., A.R. and T.E.; Writing – Original Draft Preparation, L.S.; Writing – Review & Editing, A.R., T.E., J.G. and F.V.; Visualization, L.S.; Supervision, T.E., J.G. and F.V.; Project Administration, T.E.; Funding Acquisition, T.E.

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