D 7.1 Report on the technical evaluation of the developed technologies, processes and equipment

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June 2026

HYINHEAT

Credits

Disclaimer

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101091456.

Technical references

Grant Agreement N°	101091456	**Acronym**	HYINHEAT
Full Title	Hydrogen technologies for decarbonization of industrial heating processes		
Work Package (WP)	WP7		
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Leading organisation	Linde Sverige AB		
Date of publication	11/06/2026		
Contributors	AGA, EHS, CTEC, TME, DAN, SPE, AMI, BEF, SWER, AMS		
Document Type	Report		
Document Title	Report on the technical evaluation of the developed technologies, processes and equipment		
Dissemination Level		Public	

Document history

Version	Date	Partner	Author
1	22/05/2026	ALL	ALL
Final	11/06/2026	ALL	ALL

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Introduction

Hydrogen use is tested and evaluated for many different processes within HyInHeat. For each process, reference trials are conducted with the current fuel to measure KPIs such as consumption, efficiency, emissions. Afterwards, these values are measured in hydrogen combustion trials to assess the feasibility of using hydrogen for steel and aluminum processes.

Aside from the production values, product quality is measured for some of the processes. Changes in the oxidation, dross and scale formation, hydrogen pickup are important values while considering hydrogen use.

While some of the equipment and instruments are technically suitable for hydrogen combustion, some are developed for this project. In the earlier deliverable 2.1, refractory suitability for hydrogen combustion atmospheres is investigated and reported in depth. These studies gave the demonstrators the confidence to conduct their experiments in their current furnaces/ladles. Some adjustments are arranged for hydrogen combustion due to changing flue gas volumes and the desire to keep the process pressure equal to the benchmark. A greenfield study is used to compare the design principles between a natural gas and a hydrogen fired furnace. The results are reported in deliverable 6.4. In terms of measurements and sensors, a detailed deliverable reports the background and the technology used to develop these instruments. The trials in real production facilities served well to evaluate the performance of the newly developed sensors. In return, these sensors aided the hydrogen combustion trials in fuel and emission measurements.

This deliverable focuses on the technical evaluation of the tests comparing the key performance indicators of hydrogen combustion with the demonstrators operating fuel. While some demonstrators changed only the fuel, some also experimented with changing the oxidizer. In all cases, hydrogen performed well as a substitute fuel and all the demo trials were finalized without safety issues. HyInHeat consortium has shown that the hydrogen trials are possible for the large-scale industrial trials.

Evaluation of aluminum demonstrators

MYT ladle preheating case

The MYT demonstrator is presented in detail in earlier deliverables. It is a 4.5 t aluminum holding ladle equipped with a 160 kW natural gas cold airfuel burner. Four cases are investigated for hydrogen oxyfuel combustion; ladle preheating, full-ladle temperature holding, half-full ladle temperature holding, frozen aluminum melting. Only two of these cases are compared with the natural gas operation as the others are not in the operational practise, rather a confirmation of capability. During the trials, hydrogen oxyfuel burner is found easy to ignite compared to the cold air natural gas burner. It is also less noisy when the burner is lowered into the ladle. Although no measurement is taken for it.

Ladle preheating

Ladle preheating is common practise for steel and aluminum industries. It prevents the thermal shock of the hot metal when poured into the ladle as well as the undesired cooling of the metal. For the natural gas cold air operation, the energy requirement is 500 kWh. This value is measured for a return ladle. Therefore, the heating curve is from 580°C to 720°C. For the hydrogen operation, similar situation is created and 400 kWh energy is consumed. The gain is due to the lower off-gas losses of oxyfuel operation.

Full-ladle temperature holding

While the ladles are waiting for transport, they need to be kept hot. Hence a comparison is performed between the two different fuels/oxidizers. For the natural gas operation, consumption is 100 kWh/h. The unit is selected due to on/off burner operation for a fair comparison. With the hydrogen oxyfuel operation, the consumption was 33.3 kWh/h. It should be noted that the full power on/off operation of the hydrogen oxyfuel burner was not found compatible. It disturbs the aluminum surface more than the cold air burner. Therefore, it was kept at a pilot level around 25 kW for the entire time. Both the cold air and the oxyfuel burner in full power causes flames coming out of the off-gas duct. However, oxygen jets cause a greater concern about the dross performance.

Other scenarios

Holding temperature of the half full ladle was performed to see the effect of metal height on the flames coming out of the off-gas duct. There was no flame observed when the distance between the metal and the burner was large, unlike the full ladle scenario.

Melting the frozen aluminum at the bottom of a ladle was performed. This operation is not possible with the cold airfuel burner. This shows the efficient heat transfer to the bottom of the ladle with the oxygen jets. It was possible to melt about 1 t of frozen aluminum using the hydrogen oxyfuel burner.

BEF rotary recycling furnace case

The BEF demonstrator, described in more detail in Deliverable 5.1, is a 1.5-ton tilting rotary furnace equipped with a fixed 400 kW H_2/O_2 burner and designed for R&D trials at a pre-industrial scale to research of secondary aluminum alloys production.

The furnace geometry (2000x2000mm) provides a usable volume of 0.85 m^3, tilting angle for melting and charging is 18° between furnace axis and horizontal, and tilting angle for metal discharge is 37° between furnace axis and horizontal offering representative heat-transfer and flow conditions for oxyfuel combustion at industrial scale.

In order to perform the demonstration trials, one new Dilujet® -J NG/H_2/air/O_2 burner was developed and installed. The Dilujet® -J burner is a multiple fuel, ultra-low NO_x, non water-cooled, very low maintenance oxy-fuel burner.

The Dilujet® J burner system has been designed under the Diluted Oxygen Combustion philosophy that provides high flame stability and flame adjustability, allowing NO_x levels to be "fine tuned".

The burner is modulating type and the flame monitoring is done through UV.

The pilot burner is a classical Kromschroeder one to easily be found in the market as typical spare part. See figure 1.

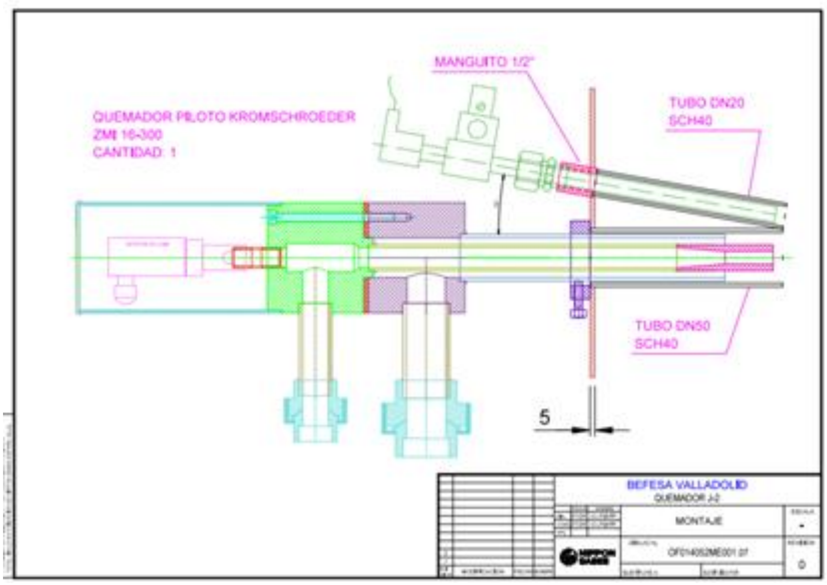


Figure 1: Reference J Burner.

The burner is able to operate with natural gas and hydrogen blends in the whole range (from 0 to 100%) and with oxygen as oxidizing agent. Trials with the burner have been performed in prototype scale, before the industrial trials take place. See figure 2 during burner (ready for hydrogen use) development.

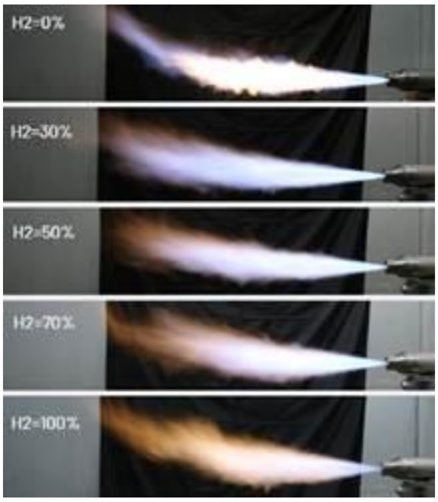


Figure 2: J Burner development trials with NG/H_2 blends.

Once developed and build, the burner was installed at the door of the furnace. This is one very sensible operation because the careful positioning of the burner at the door under certain premises, will contribute significantly to the furnace´s performance, furnace´s emissions and refractory´s life. See figure 3.

Figure 3: J Burner at furnace´s door.

Specific skid control, designed with hydrogen capabilities and under strict safety standards has been designed and built.

During the commissioning of the combustion system some small learned lessons were captured, One was the necessity of double check the pilot´s burner capacities to work under 100% Hydrogen use (learned that the sealing of the quartz glass should be H_2 ready).

Greening Combustion System worked as expected and without mayor problems. Very positive experience.

The melting trials are carried out in several stages.

I) Consists of high-power heating using an NG/O_2 burner (98% of burner capacity). This operation lasts approximately XX minutes. The control parameter is the off-gas temperature, measured by a thermocouple located in the furnace stack. The heating phase is considered completed when the flue gas temperature reaches values between XX and YY °C. Draft control is provided by the bag filter fan, which operates at 600 rpm during this stage. The temperature inside the furnace is close to 800-830°C, showing the refractory lining of the furnace walls exhibits a scarlet red color.

II) The furnace is charged with recovered aluminium concentrates (0.9 tn) and fluxing salts (NaCl/KCl) (0.12tn) using a feeder attached to a telescopic handler. Two loaders are required to complete the full furnace charging. This operation lasts approximately 5 minutes, causing the furnace walls to turn grey, which is indicative of a heat loss of approximately 100 °C. This operation has been optimized as much as possible; however, it has not been possible to further reduce this energy loss

Melting of the residue begins using H_2/O_2 combustion. The combustion system allowed operation with natural gas, hydrogen, and continuously adjustable NG/H_2 blends. Six firing configurations were investigated ranging from 0 to 100% H_2 (20, 40, 60, 80, and 100%).

The molar O_2-to-fuel ratios were adapted to the fuel composition, with typical values around 2.2 for natural gas and 0.52 for hydrogen, corresponding to a theoretical wet-basis flue-gas oxygen content of approximately 2 % in the exhaust.

During the first testing campaign, the combustion formula programming was incorrect. The same parameters were applied to both NG and H_2, resulting in anomalous consumption reporting, which indicated a 30% reduction in consumption per tonne when combustion was carried out with 100% NG. Following a thorough review and configuration update, the final test campaign was conducted

Adjusted parameters

- NG pressure: 1,5 bar in NG compensation formula (before 2 bar)
- H_2 pressure: 4 bar in H2 compensation formula (before 5 bar)
- DPT-41: 0-250 mbar (before 0-500mbar) in scaling DPT-41 (0 mA – 0 mbar // 20 mA – 250 mbar

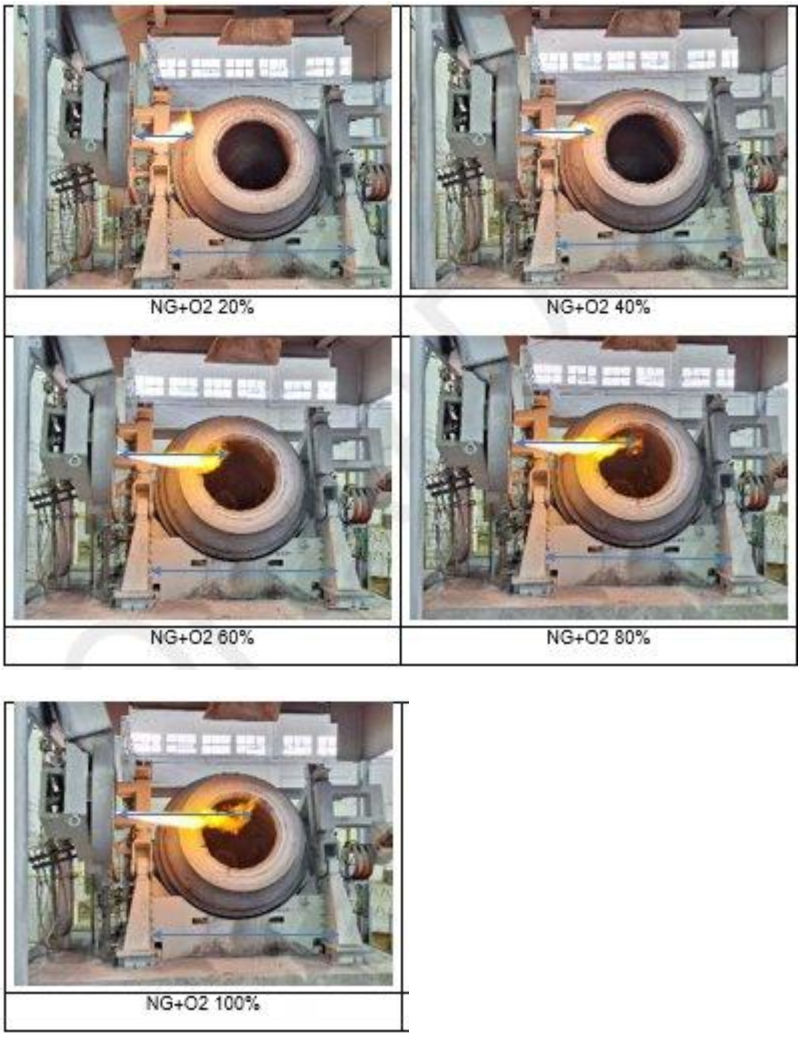
Operationally, combustion stability was maintained across the entire fuel range, including during transitions between natural gas and hydrogen

Table 1: Durations and flow rates for each trial.

Blending	NG flow (Nm^3/t)	H_2 flow (Nm^3/t)	Droping time (min)
100%NG	43.0		50
20%H_2/80%NG	35.6	30.6	52
40%H_2/60%NG	25.3	48.5	45
60%H_2/40%NG	15.5	74.1	48
80%H_2/20%NG	8.8	103.7	44
100%H_2		138.2	44

Evaluation of Flame behaviour

The flame length for each of the NG/O_2 and H_2/O_2 combustion configurations as a function of burner power (expressed as a percentage) was recorded. The images show the obtained measurements.



NG+O2 20%

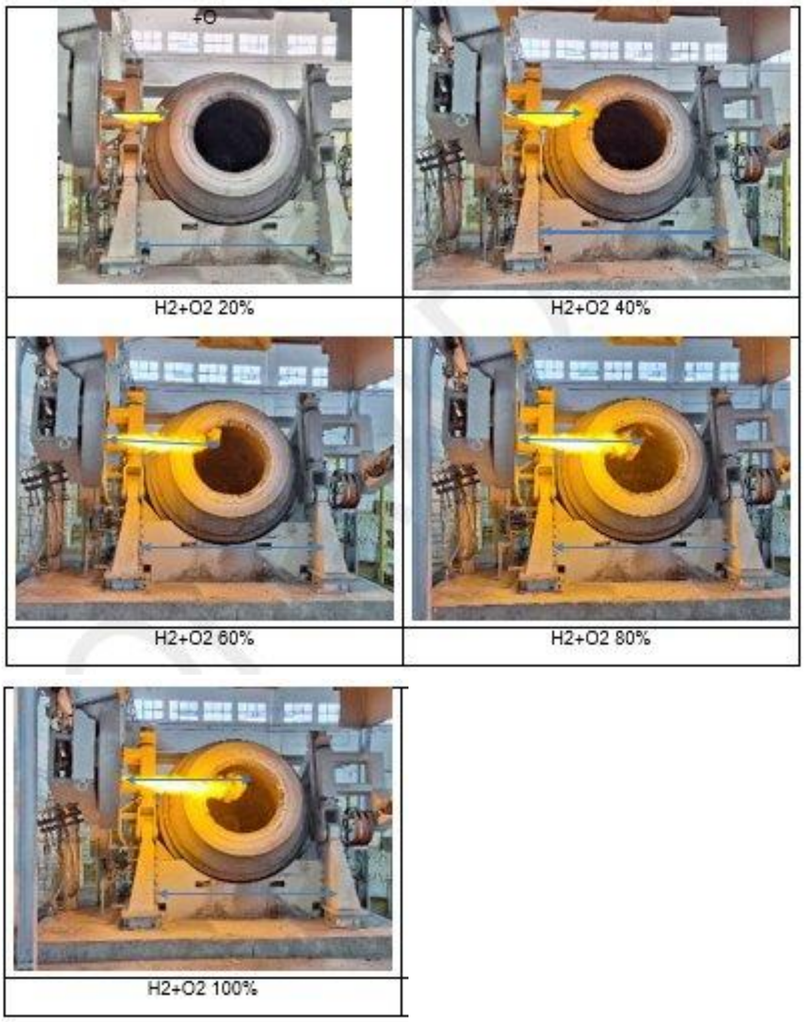
NG+O2 40%

NG+O2 60%

NG+O2 80%

NG+O2 100%

Figure 4: Determination of the total length of the flame in function of the applied power for NG+O_2 combustion.



H2+O2 20%

H2+O2 40%

H2+O2 60%

H2+O2 80%

H2+O2 100%

Figure 5: Determination of the total length of the flame in function of the applied power for H_2+O_2 combustion.

The numerical values, presented comparatively, are compiled in the table and plotted in the graph. As the power is increased, the difference in the total length of the flame between theH_2+O_2 and the NG+O_2 flames is increased.

Table 2: Total length of the flame in function of the applied powder and the combustion system.

Power regulation	**NG+O2** **Length (mm)**	**H2+O2** **Length (mm)**
20%	749	780
40%	884	928
60%	1.352	1.425
80%	1.476	1.545
100%	1.659	1.796

It can be observed more graphically in figure 6.

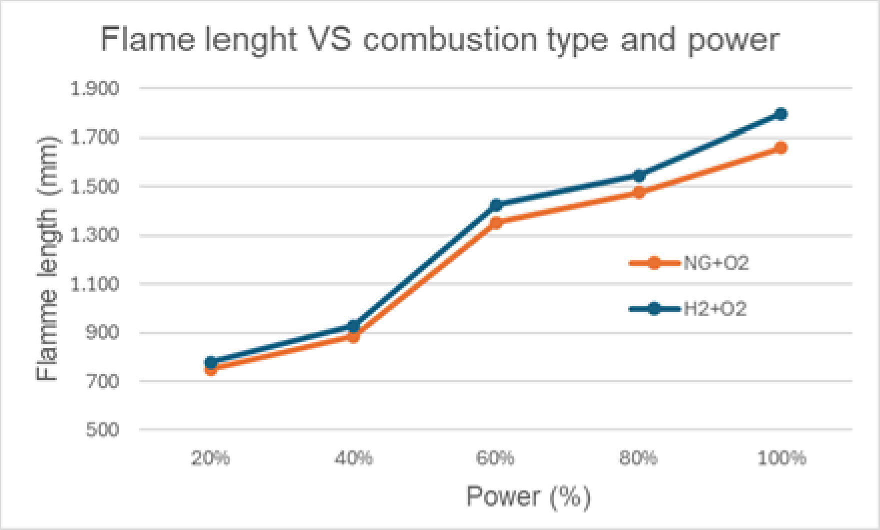


Figure 6: Comparison of the total length of the flame in function of the applied power and the combustion system.

We can observe how at low power rates, the temperature of the flame is quite similar between the $NG+O_2$ and the H_2+O_2 combustion systems. However, the difference increases to around 75 mm when applied a 60-80% of H_2 and up to around 150 mm at a 100% H_2+O_2 combustion. So, at 100% of H_2+O_2, the length will be longer in H_2+O_2 than with $NG+O_2$, and smaller at lower temperatures. This point must be taken into account into the furnace design, because changing to H_2+O_2 could lead to the direct impact of the flame against the furnace walls, promoting a quick degradation of the furnace wall refractory.

The different flame temperatures were also studied from the thermal images. Flame temperatures were adjusted with an emissivity coefficient of 0.15-0.2 for $NG+O_2$ and 0.25-0.3 for H_2+O_2. The burner power has been varied from 20 to 100%, both for $NG+O_2$ and H_2+O_2. We can see in figure 7 a sample of the flame approximative temperature determination:

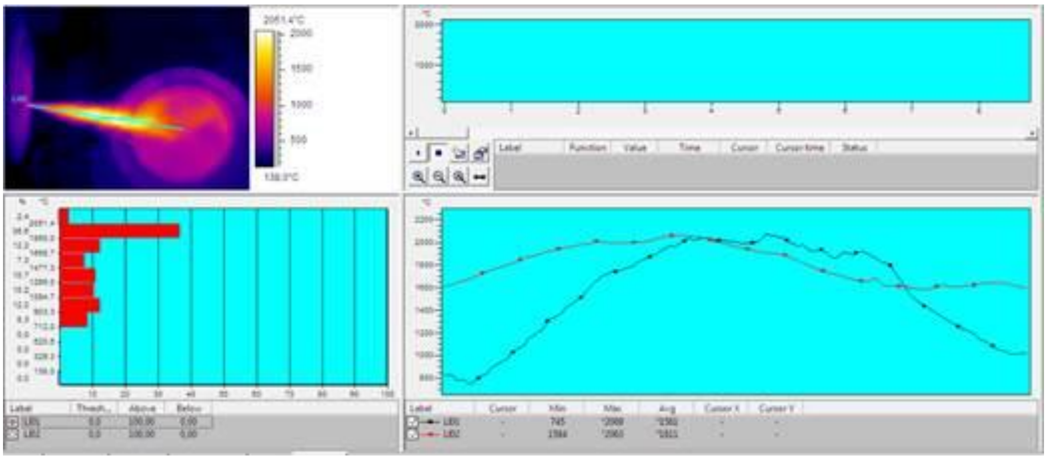


Figure 7: Flame length at 100% of H_2+O_2 power range.

An increase in the applied power increases the length and width of the flame, increasing the area with higher temperature but remaining the maximum flame temperatures stable for $NG+O_2$. There is an increase in the temperature of the flame in the case of H_2+O_2 in comparison to $NG+O_2$. The difference in the 100% power range of temperature between the $NG+O_2$ vs the H_2+O_2 combustion is about 150°C higher in the H_2+O_2 combustion, what it can increase the NO_x emissions related with the temperature of the flame.

A comparative example of the 3D thermographics when combustion is carried out with NG/O_2 and H_2/O_2 is shown figure 8.

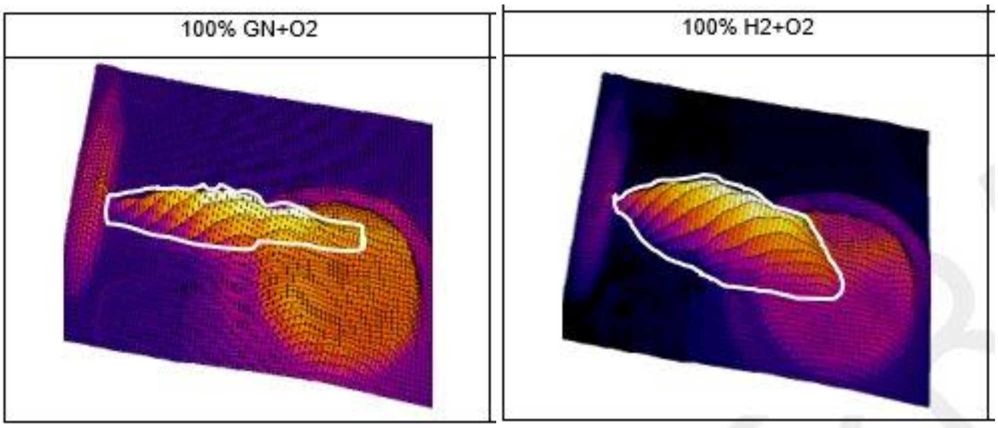


Figure 8: Flame length at 100% of NG+O_2 and H_2+O_2 at 100% power range.

In the case of employing H_2+O_2 instead of NG+O_2, the total length and especially the width of the flame is increased at the same combustion rate. This should be taken into account for the design of the furnace, because the flame can impact directly the metal, increasing the dross formation.

Evaluation of NO_x Emissions

Several trials have been performed to determine the changes in the production parameters and quality obtained with the 0.4 MW rotary furnace installed at Befesa Valladolid, to compare the NG+O_2, X% NG+ Y%H_2+O_2, and 100% H_2+O_2 ranges.

The analysis of the gas composition has been completed. A calculation of the total amount of external air that entries into the furnace has been performed with the obtained data, leaving out the calculations with a high percentage of H_2 (>80%), due to the fact that the measurement of CO_2 is done with an IR sensor, and it is not prepared to measure in high water vapor concentrations.

We can observe the different test data, with a difference between taking the data from the chimney or before the entry of the filter. The different phases of the process are detected in the analysis of the gases, and they have been correlated. More in concrete, we can observe the analysis of Test #1.

We can observe in the figure 9 the different stages of the combustion and the gas composition registered values in the chimney.

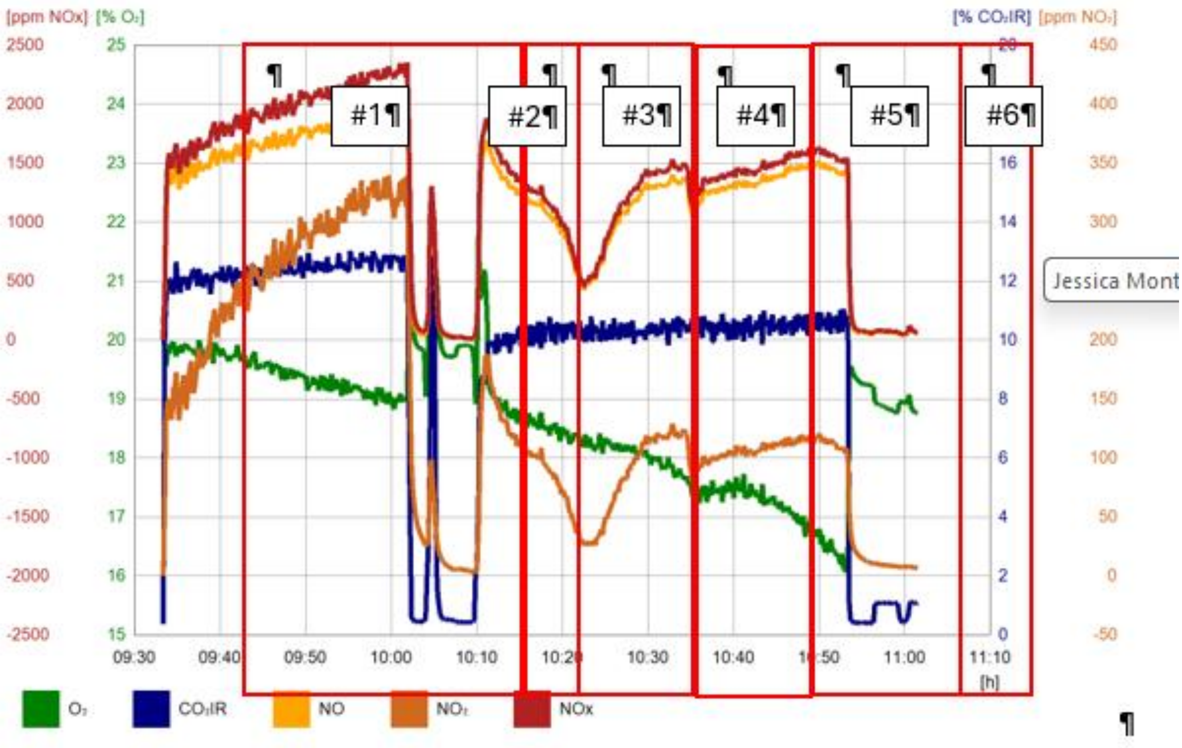


Figure 9: Test #1 20% H_2+O_2+80% NG profile in the chimney.

#1: Preheating of the furnace with NG+O_2.

#2: Charge of material. 2 steps.

#3: Starts of melting with 80%NG+20% H_2+O_2. Emissions decrease as the cold charge reduces the furnace temperature.

#4 ad #5: The temperature of the charge starts to increase, increasing emissions.

#6: The gas sensor equipment is moved from the furnace to the filter.

We can observe in Figure 10 the different stages of the combustion and the gas composition registered values in the filter tube.

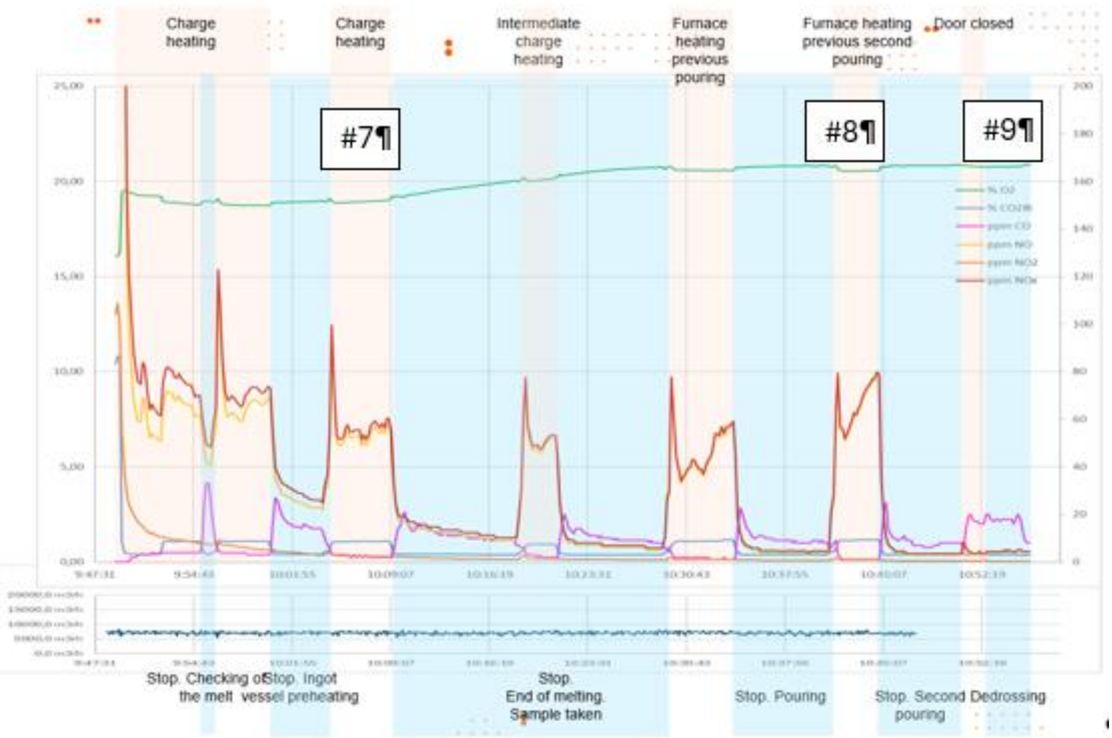


Figure 10: Test #1 20% H_2+O_2+80% NG profile in the filter tube.

#7: Finishing the melting.

#8: First pouring.

#9: Second pouring.

In table 3 we can observe the approximative combustion gases analysis in mg/MJ measured in the filter in the melting process:

Table 3: Approximate combustion gases composition analysis comparison in mg/MJ (wet).

Melting	NO mg/MJ (wet)	NO_2 mg/MJ (wet)	NO_x mg/MJ (wet)
100%NG	1.86	0.23	2.09
20% H_2	1.74	0.06	1.80
40% H_2	1.79	0.02	1.82
60%H_2	1.72	0.00	1.73
80%H_2	1.85	0.00	1.85
100% H_2	1.28	0.00	1.28

In figure 11 we can observe how the amount of NO_X increased near lineally by increasing the percentage of H_2 in the combustion mix.

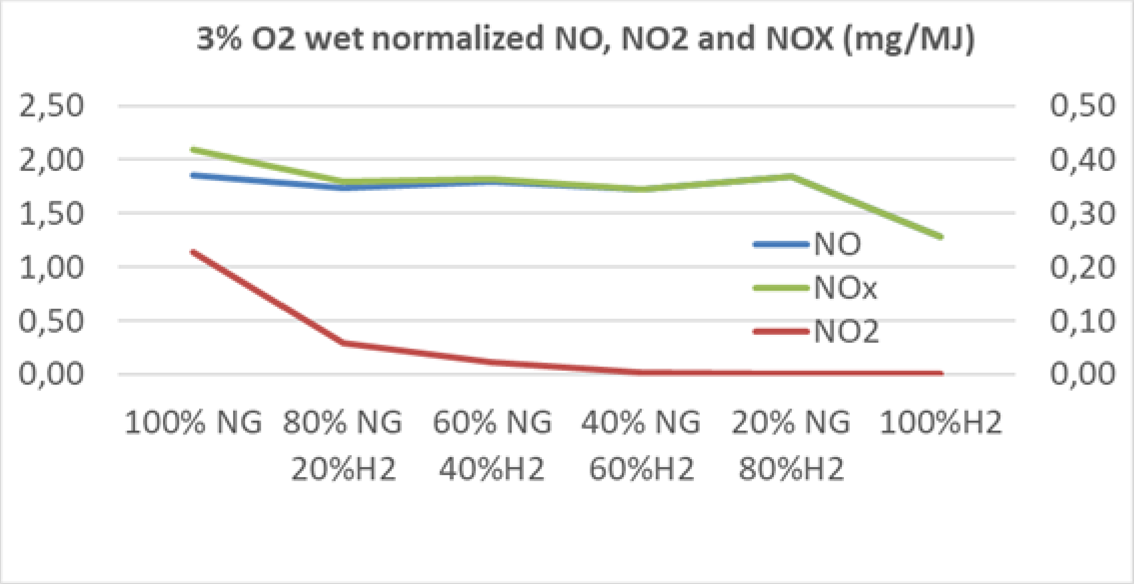


Figure 11: NO, NO_2 and NO_X variation in function of the percentage of H_2 in the combustion mix.

We can observe a slight decrease in the emissions with an increase with the %H_2, probably due to the decrease in the applied power and the higher emissivity of H_2+O_2 combustion over 1,200 °C (Figure 12).

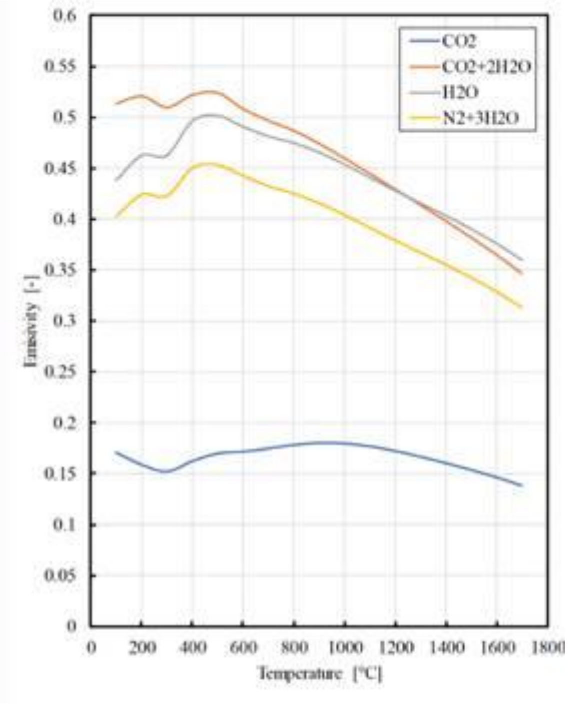


Figure 12: Emissivity in function of the combustion system and temperature (Source: Nippon Gases).

From the trials, some conclusions have been obtained:

- The continuous analysis of the flue gases composition could allow determining the different phases of the preheating, melting, pouring, and cleaning and controlling the furnace.
- When the % of H_2 is higher than around a 70%, the measurement of CO_2 by IR gives not correct values and regulate the furnace.
- The gas analysis at the entry of the filter allows control of the process, employing standard gas analysers, due to the high dilution of gases. Many standards for industrial processes stablished the point of measurement in the emission point, corresponding in this case with the filter exhaust tube.
- The change in the gas flow of the filter must be taken into account, because the higher the flow, the higher the dilution. The normalization to a 3% O_2 takes it into account.
- The percentage of NO_x in the process variates in function of the furnace inside temperature. The higher the temperature, the higher the NO_x values. It is observed a decrease in the temperature of the furnace is observed after the scrap is charged, and a consecutive increase when the metal is melted.
- Employing a 100% of H_2 instead a 100% of NG decreases the NO_x measured values. The obtained results are under the legal values admitted for aluminium foundries.

C-TEC reverberatory furnace case

General Characteristics of the Demonstrator and Experimental Conditions

The C-TEC demonstrator, presented with more details in deliverable 5.1, is a 12-tons reverberatory furnace equipped with two staged low-temperature oxy-fuel burners and designed for industrial-scale aluminum melting. The furnace geometry provides a molten bath surface of 10.4 m^2 and a freeboard volume of approximately 14 m^3, offering representative heat-transfer and flow conditions for oxy-fuel combustion at industrial scale.

Melting cycles followed a standardized operating sequence. Each cycle began with an initial high-power phase of approximately 2.5 hours, during which the burner or burners operated at full thermal input to raise the furnace roof temperature. Once the roof approached 1000–1050 °C, the control system modulated the burner power to maintain a stable temperature plateau. As the melting progressed and sufficient molten depth was reached, a thermocouple was inserted into the bath to track its evolution and to identify the end of the melting phase, defined by the bath temperature reaching 720 °C. Holding followed the melting cycle but is not considered here, as the performance indicators of interest were derived exclusively from the melting period.

The combustion system allowed operation with natural gas, hydrogen, and continuously adjustable NG/H_2 blends. Two firing configurations were investigated. In the first, a single burner delivered a nominal thermal input of 1.4 MW. In the second, both burners were operated simultaneously for a combined power of 1.8 MW. The molar O_2-to-fuel ratios were adapted to the fuel composition, with typical values around 2.19 for natural gas and 0.52 for hydrogen, corresponding to a theoretical wet-basis flue-gas oxygen content of approximately 2 % in the exhaust. These ratios remained adjustable throughout the campaigns depending on operational constraints.

Flue-gas oxygen and nitrogen oxides were measured on a wet basis using a LAMTEC NOx-Transmitter NT1 equipped with a KS2DNOx hot-extractive probe, which ensured reliable sampling in both natural-gas and hydrogen combustion conditions Furnace pressure was maintained near +9 Pa; deviations from this value occurred depending on the firing rate and influenced the degree of atmospheric air ingress.

Operationally, combustion stability was maintained across the entire fuel range, including during transitions between natural gas and hydrogen. The introduction of a second burner reduced the localized overheating of the aluminum in front of the burner observed in earlier single-burner configurations and improved spatial uniformity of heat input within the furnace. The wet-basis emissions instrumentation performed reliably despite the high moisture content characteristic of oxy-fuel combustion. Variations in furnace pressure were found to influence NO_x formation and were therefore monitored closely throughout the trials. No adverse effects on melting homogeneity, bath motion or metal handling were reported, confirming that the oxy-fuel system is suitable for both natural-gas and hydrogen combustion when correct burner staging and pressure control are applied.

Thermal Performance Evaluation

Thermal performance was quantified using the specific energy consumption (SEC) expressed in kWh_{LHV}/t_{Al} and the surface melt rate per hour (SMRH) expressed in kg h^{-1} m^{-2}. These indicators were extracted from a statistical dataset from 2024 and 2025 comprising 43 melting cycles at 1.4 MW, 35 cycles at 1.8 MW, and several hydrogen cycles carried out at both firing rates.

At 1.4 MW, the SEC associated with natural-gas oxy-fuel operation centered around 460 kWh_{LHV}/t_{Al}, with hydrogen trials falling within the same statistical interval. The SMRH exhibited a mean value of approximately 276 kg h^{-1} m^{-2}. The distributions illustrating the variability of SEC and SMRH for this regime are reported in Figure 13.

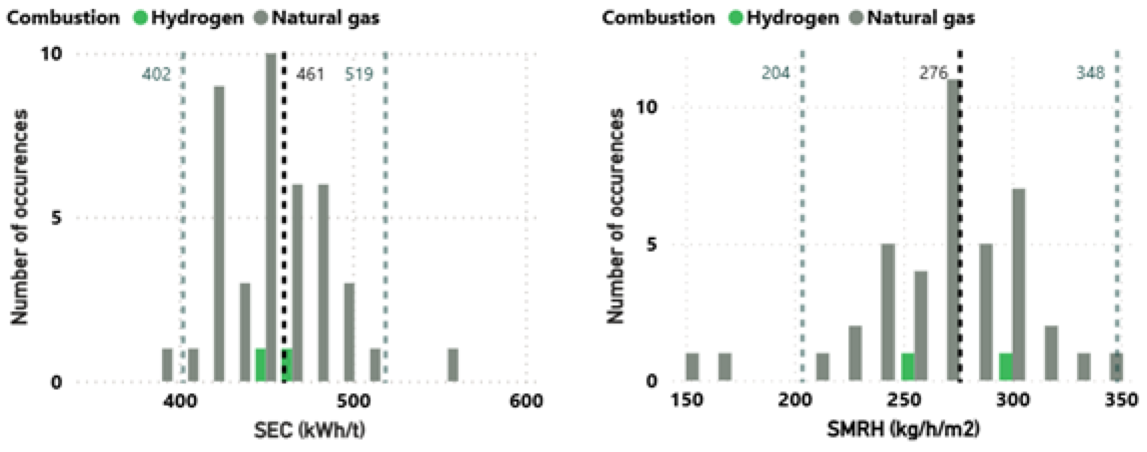


Figure 13: Statistical distribution of SEC and SMRH for low-power (1.4 MW) natural gas and hydrogen cycles.

At 1.8 MW, the SEC remained close to 460 kWh/t. In contrast, the SMRH increased substantially to approximately 355 kg h^{-1} m^{-2}, reflecting the higher heat flux delivered to the molten bath. The corresponding distributions are presented in Figure 14.

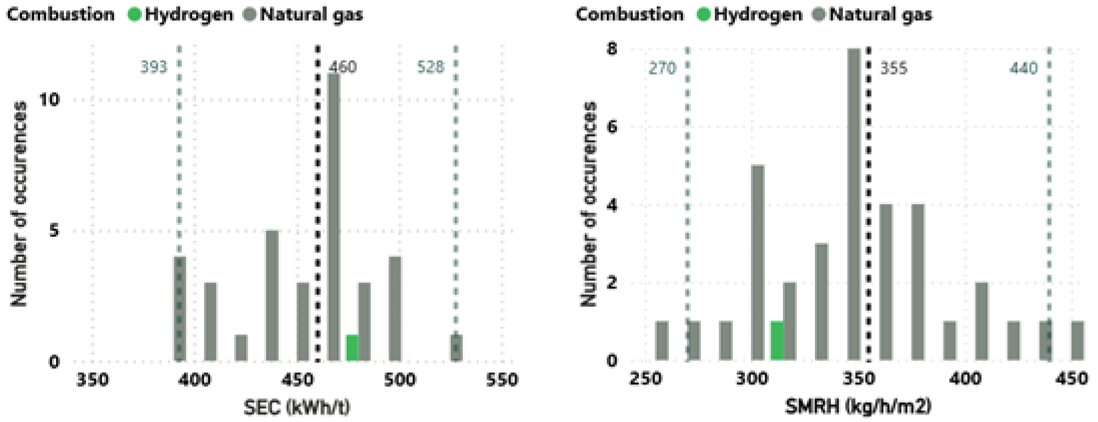


Figure 14: Statistical distribution of SEC and SMRH for high-power (1.8 MW) natural gas and hydrogen cycles

Across both firing regimes, hydrogen reproduced the melting performance obtained with natural gas. This behavior is consistent with the characteristics of hydrogen combustion. Indeed, the combustion efficiency is constant for both fuels since the higher flue-gas flow associated with hydrogen combustion is offset by the lower specific heat capacity of hydrogen-derived combustion products [1]. Therefore, neither SEC nor SMRH exhibited measurable sensitivity to the fuel used.

Evaluation of NO_x Emissions

To better analyze NO_x emissions for different blends, a series of short-duration tests was conducted during holding period of the melting furnace to establish controlled relationships between fuel composition, furnace pressure, burner power and NO_x formation. In these tests, the burners were operated at constant thermal input for several minutes so that the atmosphere could stabilize. Once stable combustion was achieved, the flue-gas composition (NO_x, O_2) and the average internal pressure were recorded. These measurements provided a clean dataset in which the effect of each operating parameter could be isolated without the thermal inertia, variable gas flows or atmospheric disturbances introduced by the melting charge. This methodology allowed the construction of a regression model identifying the respective contributions of fuel composition, pressure and power to the observed NO_x levels.

To obtain a pressure-independent indicator suitable for fuel-agnostic comparison, NO_x emissions were converted into gross mass emissions expressed in g_{NOX}/t_{Al} using estimated flue-gas volumes appropriate for each fuel [2]. The regression coefficients derived from the short-term tests were then used to adjust the measurements to the representative operating pressure of each regime. These pressure-corrected gross emissions are reported in Figure 15.

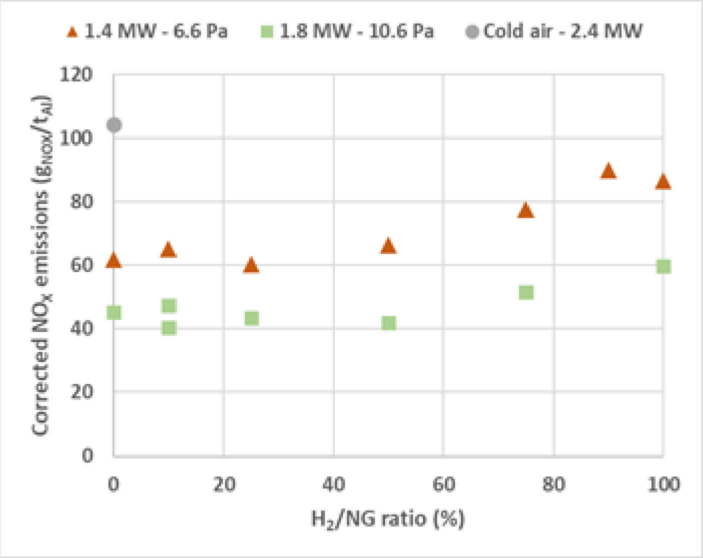


Figure 15: Gross NO_x emissions corrected for pressure and comparison with historical cold-air operation

The corrected emissions indicated that NO_x levels remained broadly comparable between natural gas and hydrogen up to hydrogen fractions of approximately 70 %. Beyond this value, a more pronounced increase was observed, probably due to the higher adiabatic flame temperatures associated with hydrogen combustion [2]. Despite this increase, the corrected NO_x values under hydrogen oxy-fuel operation remained below those historically recorded for the furnace under air-fuel combustion. The results underscore the importance of maintaining furnace pressure close to its nominal value to limit air ingress, and they confirm that staged oxy-fuel combustion constitutes an effective strategy for moderating NO_x formation even under high-hydrogen conditions.

Speira reverberatory furnace case

Before the oxyfuel conversion

The 1t furnace at Speira R&D is used as a device to test typical melt treatment procedures and melt quality measurements, which are usually applied on a larger scale in industrial furnaces. In its original configuration, it is equipped with a Kromschröder 350 kW annular excess cold air burner BIC140, allowing for a typical melting rate of 200 kg/h with specific energy consumption of 1150 kWh/tAl. In Speira's strategy to decarbonize its production chain, the furnace appeared to be an appropriate device to study the impact of a fuel switch on specific energy consumption, melting rate, dross generation, and hydrogen pickup in the melting process of different types of charging material. Prior to the tests, which are described in this document, a melting campaign using similar charge material had been carried out with the old furnace configuration to generate a baseline for comparison. These former tests had been conducted with both natural gas and with 100 % hydrogen using a slightly modified burner head.

Changes made

For the oxyfuel trials, the furnace was equipped with a very compact 200 kW Low Temperature Oxyfuel (LTOF) burner, which was designed by Linde especially for this furnace to fit into the existing burner flange. The central part of the burner consists of an ignition burner with natural gas as ignition fuel and a concentric tube for oxygen supply. The primary fuel is provided by a third concentric tube. At ignition, the oxygen is supplied by the central tube only. At medium to high power, most of the oxygen is injected through two additional lances, which are mounted on both sides of the central openings. The dimensions of the nozzles are chosen to achieve a maximum velocity at sonic speed to generate a very strong mixing of the combusted gases.

The burner can be run on natural gas, on hydrogen, or a blend of both as the main fuel. In order to provide a defined mixture, a completely new skid had to be installed for the new burner system. The new burner was designed to fit into the existing burner flange.

The burner is installed in the main chamber of the furnace at the same position and angle as the original airfuel burner. In the usual operation, cold metal is heated and melted in this chamber. Before the metal is completely molten, the condition to use the flameless mode, T>750°C, cannot be met. This means that in the usual melting operation, the LTOF burner is restricted to the semi-flameless mode.

After the oxyfuel conversion

During the natural gas oxyfuel trials, specific energy consumption, melt rate, dross formation, and NOx generation are measured for comparison. Material was charged into the preheated furnace. The specific energy consumption was estimated to be 550 kWh/tAl. This low value shows the potential of decarbonization by oxyfuel combustion without a fuel change. However, the melting rate values were unsatisfactory for this trial. In this furnace, the melting rate refers to the ratio of charged metal mass and the time between charging and reaching a bath temperature of 720°C.

LTOF could only achieve the same melting rate as the original airfuel burner when the furnace was charged with large pieces, around 200 kg/h. It is important to note that this furnace didn't have the option to change the burner angle towards the optimal oxyfuel direction. The LTOF was angled like an airfuel burner directly towards the molten bath, which limited the area to allow the flame to develop in its correct diluted way. Gases hitting the charged material earlier than the original design considerations caused a hot flame, which in turn created a hotspot on the material, and worse on the bath. This forced the melting process to be carried out on the 60% power level of the original 200 kW LTOF design. Expectedly, using only 35% of the cold airfuel power, this lowered the melting rate by 15% for some cases.

Another point to note here is the dross formation. The dross levels increased, especially for the high magnesium scrap melting, much due to the reasons already mentioned above. It is known to the aluminum producers that this kind of material is prone to dross formation; however, the increase was not negligible. Once again, the deep angle of the burner caused the suboptimal operation. When the high-velocity jets hit the melt surface and disturb it, it starts forming dross. This can be avoided only by angling the burner much less compared to the airfuel burners.

The reference NO_x measurements in the cold air burner system are typically around 40mg NO_2/MJ with natural gas at 350 kW (50.4 g/h). In the semi-flameless mode of the LTOF burner at 60 kW natural gas firing, 81 mg/MJ NO_x was generated (17.5 g/h). In the flameless mode at 180 kW, this value dropped to 2.4 mg/MJ NO_2 (1.5 g/h) When the oxygen lances work in their designed conditions in the flameless mode, specific NO_x values even lower than in the cold air burner system can be achieved.

Finally, hydrogen pickup was measured to ensure the quality. The natural gas cold air burner reference value was around 0.6 ml/100g at 800°C and around 0.5 ml/100g at 750°C. The oxyfuel operation increased these values to 0.9 ml/100g at 800°C and 0.55 ml/100g at 750°C which was found insignificant.

Hydrogen oxyfuel combustion

Hydrogen oxyfuel combustion was also tested in the same burner for melting trials. The specific energy consumption was around the same 550 kWh/t Al value as in natural gas trials. Like the natural gas trials, the burner angling limited the operable power range of this burner in this furnace. Running at 60% of its design capacity, the LTOF fired with hydrogen could not achieve the same melt rates as the airfuel burner achieved with natural gas. However, compared to the airfuel burner fired with hydrogen, it could keep the same melt rate.

The reference NOx measurements in the cold air burner generated around 116mg NO_2/MJ with hydrogen combustion at 300 kW (125 g/h). In the semi-flameless mode of the LTOF burner at 60 kW, hydrogen firing generated 209 mg/MJ NO_2 (45.1 g/h). In the flameless mode at 180 kW, this value dropped to 3.5 mg/MJ NO_2 (2.3 g/h). In this furnace, hydrogen combustion usually generates higher NO_x values than natural gas, but an LTOF in the flameless mode can achieve NO_x values even lower than in the cold air burner system.

Hydrogen combustion causes concerns about the hydrogen pick up of the melt. The measurements showed equal values to their natural gas counterparts. Hydrogen cold airfuel measurements were equal to the natural gas airfuel operation. Similarly, hydrogen oxyfuel burner achieved the same values as the natural gas oxyfuel hydrogen pick up measurements. These measurements indicate that the hydrogen fuel does not significantly contribute to an increase in hydrogen absorption in the melt.

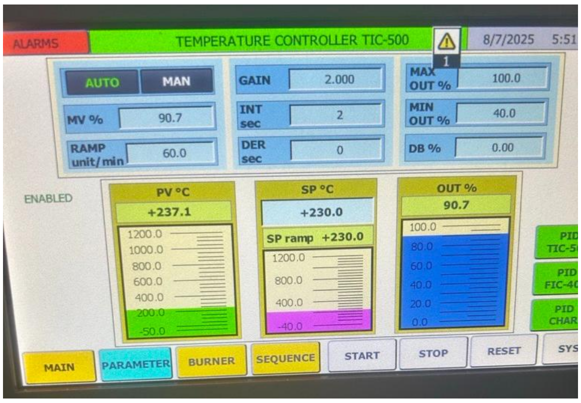
The general conclusions from these tests are: Comparing the switch of fuel from natural gas to hydrogen to the switch of the oxidizer from air to pure oxygen it was found that the latter had a higher impact on the melting process. While energy consumption, melting rates, dross generation and hydrogen pickup of the melt are only marginally affected by the fuel switch the combustion with pure oxygen in place of air has a more significant impact on the melting. The specific fuel consumption can be lowered significantly and even the NO_x generation can be kept at comparatively low levels with the applied LTOF technique. To avoid excessive dross formation and to maintain melting performance, careful positioning and alignment of the burner is essential.

TME batch heat treatment furnace case

The tests were conducted in heat treatment furnace. TME tested dual burner from Fives that was designed for TME to test from 0 to 100% of H_2.

Although prior the installation in tests were conducted at the supplier site and all required technical documentation and safety assessments were reviewed and verified in advance, several issues emerged during the execution of the tests. During 96% H_2 tests, unexpected pressure drops and incompatibilities in piping dimensions affected burner adjustability and led to damage of pressure measurement devices under real operating conditions. These findings could not be fully identified during the prior documentation review and only became apparent during live testing.

During the installation, also all the tests that were previously adjusted in PLC by supplier for valve openings and different percentages of H_2 and Natural gas needed to be adjusted. The PLC sensors were not responding as well and this need to be corrected.


TEMPERATURE CONTROLLER TIC-500

8/7/2025 5:51

GAIN 2.000

INT sec 2

DER sec 0

MAX OUT % 100.0

MIN OUT % 40.0

DB % 0.00

MV % 90.7

RAMP unit/min 60.0

PV °C +237.1

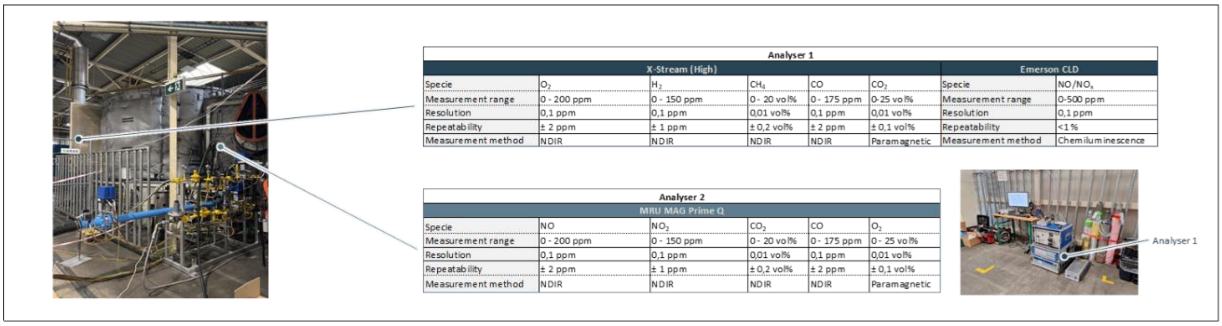
SP °C +230.0

SP ramp +230.0

OUT % 90.7

Figure 16: PLC adjustments

The installation for the emission measurement was also taking place and RWTH was doing all the set ups as shown in Figure 17.


Analyser 1

X-Stream (High)						Emerson CLD	
Specie	O_2	H_2	CH_4	CO	CO_2	Specie	NO/NO_x
Measurement range	0 - 200 ppm	0 - 150 ppm	0 - 20 vol%	0 - 175 ppm	0-25 vol%	Measurement range	0-500 ppm
Resolution	0,1 ppm	0,1 ppm	0,01 vol%	0,1 ppm	0,01 vol%	Resolution	0,1 ppm
Repeatability	± 2 ppm	± 1 ppm	± 0,2 vol%	± 2 ppm	± 0,1 vol%	Repeatability	<1 %
Measurement method	NDIR	NDIR	NDIR	NDIR	Paramagnetic	Measurement method	Chemiluminescence

Analyser 2

MRU MAG Prime Q					
Specie	NO	NO_2	CO_2	CO	O_2
Measurement range	0 - 200 ppm	0 - 150 ppm	0 - 20 vol%	0 - 175 ppm	0 - 25 vol%
Resolution	0,1 ppm	0,1 ppm	0,01 vol%	0,1 ppm	0,01 vol%
Repeatability	± 2 ppm	± 1 ppm	± 0,2 vol%	± 2 ppm	± 0,1 vol%
Measurement method	NDIR	NDIR	NDIR	NDIR	Paramagnetic

Figure 17: Emission measurement set up

When all the set ups were confirmed, the test took place for heat treatment of engine block. The temperature was reached with new burner, and the flame was stable for natural gas. However, when the H_2 of 95% was tested the pressure drops influence the flame and emissions. However, we adjust the NO_x emissions, and we could plot some of the min values.

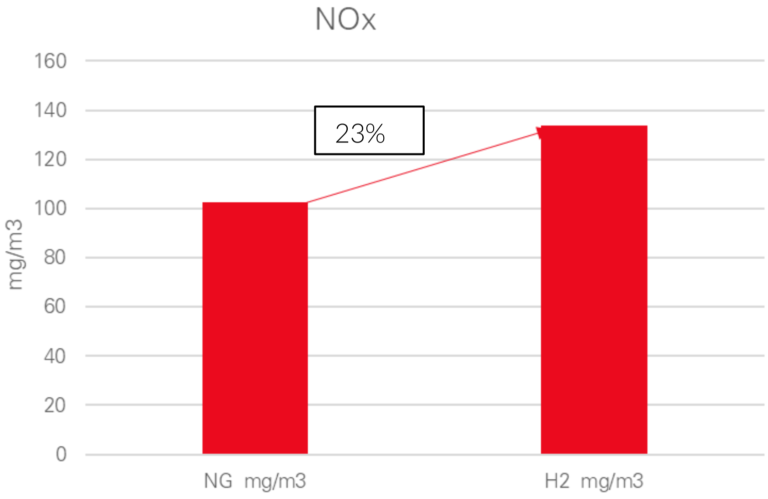


Figure 18: NO_x Emissions

Consequently, should permanent installation of this solution be considered within the project scope, further technical evaluation and validation under representative operating conditions will be required.

Evaluation of steel demonstrators

AMS/AMO reheating furnace case

The AM Sestao industrial demonstrator is described in detail in previous reports. It involves certain modifications made to a significant section of the facility's tunnel furnace to enable it to run on air/H_2 or air/NG. As part of the project, 10 heats were analysed in which hydrogen was burned as the slabs passed through the tunnel furnace. Some of the performance results achieved are described below, in addition to those already detailed in the Work Package 6 reports.

Number of heats using hydrogen and tonnes produced:

Production met the targets set at the start of the project. Ten heats were carried out (the 10 heats targeted at the start of the project, involving various steel grades (4 different grades)), with a total of 1,163 tonnes of steel produced (against a target of 1,250 tonnes).

Number of safety incidents

The tests were carried out under continuous supervision and with the aim of not detecting any incidents. During the tests, no incidents were detected, meaning they were conducted within the established framework.

Number of incidents registered by operators (poor heating, temperature spikes, etc.)

It was established at the beginning of the project that the tunnel furnace should operate with as few incidents as possible. During the testing period, incidents were only recorded during the preliminary trial (with no slabs inside the furnace), in which the temperature did not reach its set point. Following adjustments to the burners, all defined set points were achieved, so it can be concluded that no significant incidents were detected. The settling times achieved were not considered critical.

NO_x emissions

The objective was to remain within the legal limits set by the relevant legislation. During the test, an increase in NO_x emissions was recorded compared with the usual emissions from natural gas combustion. However, the increase recorded did not exceed the legal limits under operating conditions. It was noted that, in future plans, it would be advisable to control the air entering the tunnel furnace in order to reduce the emissions produced.

Quality issues recorded in real time during a preliminary surface inspection

It was established at the start of the project that the tunnel furnace should heat the slabs with as few quality issues as possible. During the trials, an operator was on hand to monitor the surface quality of the coil in real time, in order to detect, if necessary, any new defects or recurring defects in the production of the final coils. No significant anomalies were detected during the trials.

Despite the preventive attitude regarding the potential presence of extra scale on the coils, quality analyses have revealed scale similar to that found with natural gas. Neither the real-time checks nor the subsequent analyses carried out on these coils by AM Sestao have revealed any significant or detrimental changes in the coils.

New or aggravated quality defects in the coils produced with hydrogen combustion after in-depth inspection

At the start of the project, the objective was set to minimise defects in coils manufactured using hydrogen combustion within the tunnel furnace. During the tests, no new defects or aggravated defects associated with the use of hydrogen were detected (none worthy of note beyond those typically encountered in production). The objective was therefore more than achieved.

Refractory analysis on CEIT installation

One of the aims of the project set was analysing the refractory of the tunnel furnace. Due to the continuous usage of AM Sestao installations, the refractory will be changed during the shutdown of August 2026. Therefore, the refractory will be sent to CEIT when changed and results will be attached to their corresponding deliverables when available.

Most relevant operational results

1. The objectives of the trial were achieved, with safety generally ensured. The system is therefore ready for a future in which hydrogen can be burned in these areas as an alternative to natural gas.
2. Forcing all burners to adjust them at the same time minimised the oxygen present. It would be also beneficial to be able to increase the skid's outlet pressure to a higher level. Nowadays, pressure drops across the non-return valve make it difficult to adjust the burners quickly, as the skid's outlet pressure cannot be raised any further due to physical constraints.
3. This project has led to the installation of burners fitted with dual valves and BCUs and a variable excess air inlet regulator. This represents a significant improvement to the burners and ensures compliance with the updated safety standards in line with the new regulations. Furthermore, it would enable the zone's holding temperature to be lowered, as the burners can be switched on and off remotely and quickly. This could lead to a reduction in natural gas consumption, bringing both financial and environmental benefits.
4. High-cycle burner ON/OFF operation challenges the combustion tunning, but an improved methodology could be done to reduce excess air. Flue gas analysis shows a variable CO_2 level, meaning that the burner exhaust part of the flue gases from the combustion chamber, not only the generated itself.
5. There is a strong impact of the excess air on NO_X emissions. It is very important to tune properly the burner, which would have a positive impact also on energy consumption and scale losses.
6. Hydrogen firing increases NO_X by 2-3 times when firing hydrogen (depending on the excess air used), but emission level can be kept below the regulation limit.
7. No downgrading due to scale surface defect in the trial sequences. Downgraded coils in Trial 1 and 3 are due to long stay time in the furnace and out of the scope of the trial
8. The coils produced with H_2 trials, in general, do not show different behavior compared to coils produced during same period and similar descaler pressure (qualitative comparison as quantitative is not possible)
9. For continuous hydrogen-powered operation, it is still necessary a hydrogen pipeline that reaches the plant. This is part of the Basque Hydrogen Corridor project, which is currently delayed compared to the original 2026 target.

SWER walking beam furnace case

Swerim's principal contribution to the project is the operation of its pilot-scale walking-beam furnace (WBF) as one of eight demonstration units. The WBF is equipped with advanced gas flow control trains, flue-gas damper systems, and integrated process control and safety systems, enabling stable operation with hydrogen as the sole combustible fuel. Furnace operation is controlled on a zone-by-zone basis using a distributed instrumentation system comprising wall- and roof-mounted thermocouples for temperature monitoring and in-situ oxygen sensors for combustion control and atmosphere regulation.

Four test slabs (two steel grades) were used per experiment, and several dummy slabs (low-alloy steel) of similar dimensions and weight (~400 kg) were used. Temperatures, pressures, and mass flows (air, flue gas, fuel) are measured throughout the furnace to enable mass and energy balance calculations.

Several parameters govern furnace performance, particularly energy efficiency and product quality. In this study, the efficiency of the thermal process is evaluated under three distinct combustion regimes: air-fuel combustion (AFC), oxygen-enhanced combustion (OEC), and oxy-fuel combustion (OFC). Transitioning from air to oxygen-based oxidizers improve combustion efficiency mainly by eliminating nitrogen as a diluent, thereby reducing inert thermal ballast and enabling a system composed predominantly of fuel and oxidizer species.

The experimental design incorporates two target oxygen excess levels, namely 1% and 2.5%. Maintaining a controlled excess of oxygen is essential to ensure complete fuel oxidation. This requirement is especially critical when operating with fossil fuels, where insufficient oxygen can result in incomplete combustion and the formation of carbon monoxide (CO), which poses significant safety hazards. However, elevated oxygen concentrations may also increase the oxidation rate of steel surfaces, leading to higher scale formation. As a result, the study evaluates the influence of oxygen concentration on scaling behaviour under hydrogen-fired conditions.

Each operating condition was repeated twice, resulting in experiments conducted at both 1% and 2.5% oxygen surplus in the flue gas, yielding a total of eight test cases. To ensure consistency across the dataset, identical temperature setpoints were maintained in all heating zones for each experiment.

Four fuel–oxidizer configurations were investigated:

1. Light fuel oil (E01) with preheated air (baseline/reference condition). REFAFC
2. Hydrogen with preheated air. HAFC
3. Hydrogen with oxygen-enriched air (approximately 40% O_2), operated under flameless combustion conditions. HOEC
4. Hydrogen with pure oxygen, also under flameless combustion conditions. HOFC

The experimental campaign provided a comparative evaluation of furnace performance across multiple combustion configurations, including air-fuel combustion (AFC), oxygen-enhanced combustion (OEC), and oxy-fuel combustion (OFC), under varying excess oxygen levels.

Overall, the results demonstrate that increasing the oxygen concentration in the oxidant stream significantly influences both energy efficiency and thermal performance. Systems operating under oxygen-enriched or pure oxygen conditions showed improved energy utilization compared to conventional air-fuel combustion. This improvement is primarily attributed to the reduction of nitrogen dilution, which lowers flue-gas volumes and associated heat losses.

A clear progression is observed across combustion modes:

- AFC exhibits the highest specific energy consumption and flue-gas losses
- OEC provides high improvements
- OFC demonstrates the highest efficiency and lowest losses

At the same time, increasing the excess oxygen level from 1% to 2.5% ensures complete combustion but results in:

- Slightly reduced energy efficiency
- Increased heat losses

The results further indicate that hydrogen-based combustion systems can match or exceed the performance of conventional fuel systems in terms of energy efficiency, while fundamentally altering flue-gas composition due to the absence of carbon species.

Table 4 and 5 present a comparison of key performance indicators at excess oxygen levels of 1% and 2.5%. The results show a consistent trend of improved performance, characterized by reduced fuel consumption, higher thermal efficiency, and lower specific energy consumption. This improvement follows a clear progression across combustion modes, from conventional oil-based air-fuel combustion (REFAFC) to hydrogen air-fuel combustion (HAFC), and further to oxygen-enhanced (HOEC) and oxy-fuel combustion (HOFC), where the most favourable performance is observed. The figures further illustrate the qualitative energy distribution across combustion modes. Oxygen-enriched and oxy-fuel combustion reduce flue gas losses by decreasing nitrogen dilution, thereby increasing the fraction of useful heat transferred to the steel. This supports the observed improvements in energy utilization.

Table 4: KPI´s from tests with 2.5% excess oxygen level (wet)

2.5% Excess O_2 level	REF AFC	H_2 AFC	H_2 OEC	H_2 OFC
Δ T, °C	8	12	12	8
Fuel load, kW/h	1250	1116	924	878
Efficiency, %	53	58	73	77
Specific energy, kWh/ton	424	371	294	283
Efficiency (useful heat)	53,0%	58,4%	73,0%	77,0%
Flue losses	24,2%	14,8%	10,6%	4,2%
Other losses	23,2%	26,8%	16,8%	18,9%

Table 5: KPI´s from tests with 1% excess oxygen level (wet)

1% Excess O_2 level	REF AFC	H_2 AFC	H_2 OEC	H_2 OFC
Δ T, °C	8	15	9	5
Fuel load, kW/h	1195	1092	903	887
Efficiency, %	57	60	75	75
Specific energy, kWh/ton	391	369	290	286
Efficiency (useful heat)	57,2%	60,3%	74,9%	76,9%
Flue losses	20,1%	17,8%	8,4%	4,2%
Other losses	22,7%	22,0%	16,7%	20,4%

The difference between weight increase and the net change for the experiments is shown in figure 19. The net change is the weight gain change minus the descale change. A positive residual value indicates that the slab's weight increased from its starting weight, even after descaling. The weight added is only the oxygen added for the formation of the oxide(s), which means that the Fe part of the oxide weight is not included. A net but still positive change, compared to before heating weight, indicates that a considerable amount of oxides remains, suggesting poor descaling performance. The same can be said if the is a net zero net change comparing weight before heating and after descaling. However, to elaborate further, the remaining metallurgical investigation will provide more insights. The metallurgical investigation is performed by Oulu University and cut out sections of the heated test slabs were sent to them for analysis.

The material forms slightly more scale when hydrogen is used as fuel; however, the difference is not statistically significant. The amount of scale removed during descaling was also comparable and did not indicate a change in descaling difficulty. For both steel grades, scale growth increased for the HOEC and HOFC experiments. For steel grade 362, the weight after descaling indicates greater difficulty in scale removal, particularly in the HOEC and HOFC cases. No statistically significant difference was observed with experiments carried out at 2.5% or 1% excess oxygen. During the tests, the targeted excess O_2 level was maintained, whereas lower flue gas volumes with HOEC and HOFC led to larger fluctuations as material was charged and discharged and the furnace pressure dropped, with temporary spikes that increased the average excess O_2 measured.

Throughout all tests, the 1% excess oxygen level resulted in less or equal amounts of oxide formation compared to 2.5% excess oxygen.

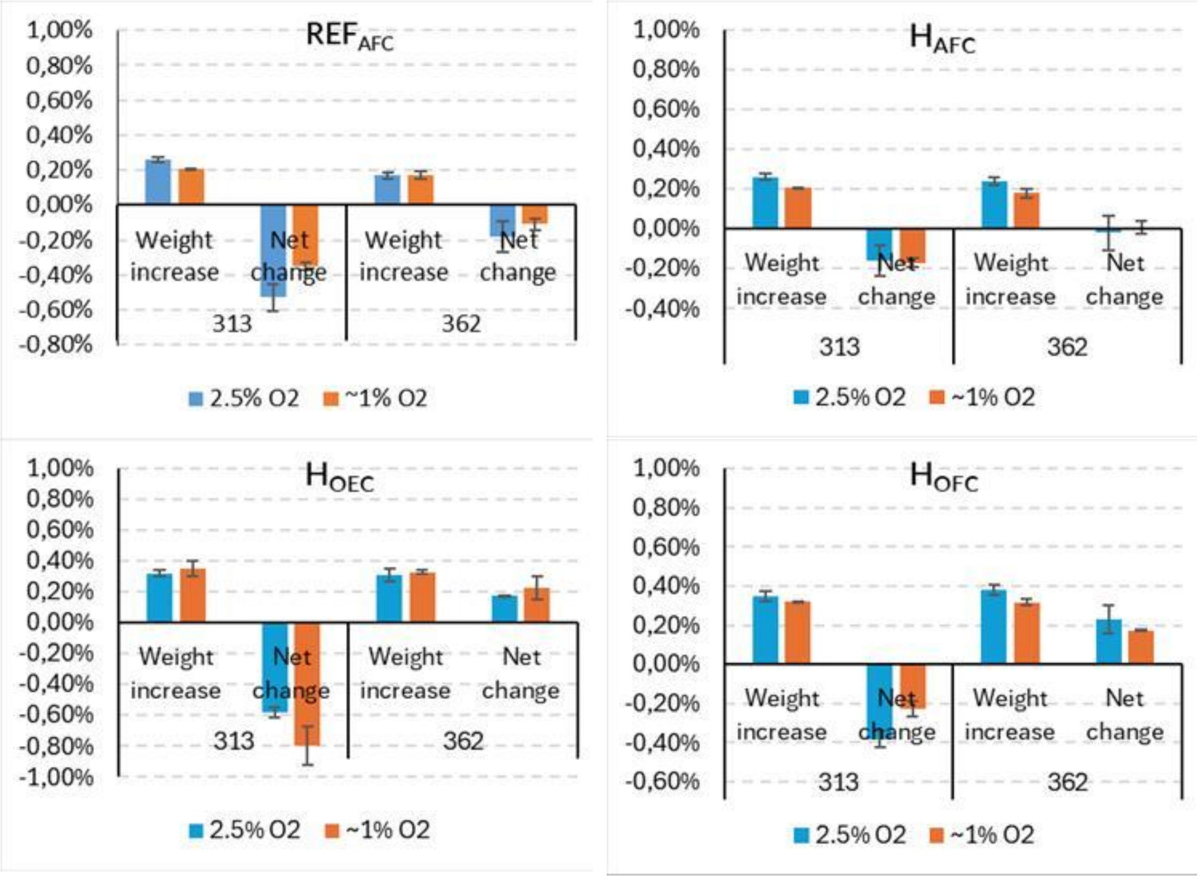


Figure 19. Measurements of oxide growth and removal

The tests and subsequent analysis of the results of the tests demonstrate that hydrogen combustion can be successfully integrated into walking beam furnaces, with performance primarily governed by radiative heat transfer conditions, while oxygen enrichment and oxyfuel combustion increases process efficiency and reduces energy losses.

7Steel ladle preheating case

The 7Steel case evaluated the difference between coke oven gas and hydrogen use for a steel ladle preheating. Coke oven gas used for this case is 79.9% CO, 8.6% H_2, 7.7% CO_2 and 3.8% N_2. Both fuels are tested under oxyfuel combustion atmosphere. The experience shows the quicker heat up with hydrogen. The bottom temperature reached 1200°C after 3 h 43 min when hydrogen was used, the coke oven gas reached the same temperature after 5 hr 46 min. The difference is due to the unreactive species that are in the coke oven gas. Total hydrogen consumption was 2880 Nm3 in 10 hours of trials. After the temperature was reached, the burner was kept on temperature holding mode. The same operating conditions are kept for the coke oven gas, with the total consumption of 1700 Nm^3 after 10 hours.

The burner and the preheating station were revamped right before these trials by Mefcon. It was found hard to adjust for the coke oven gas trials. The same burner was used for the hydrogen trials. Heating curves for both tests are shown below.

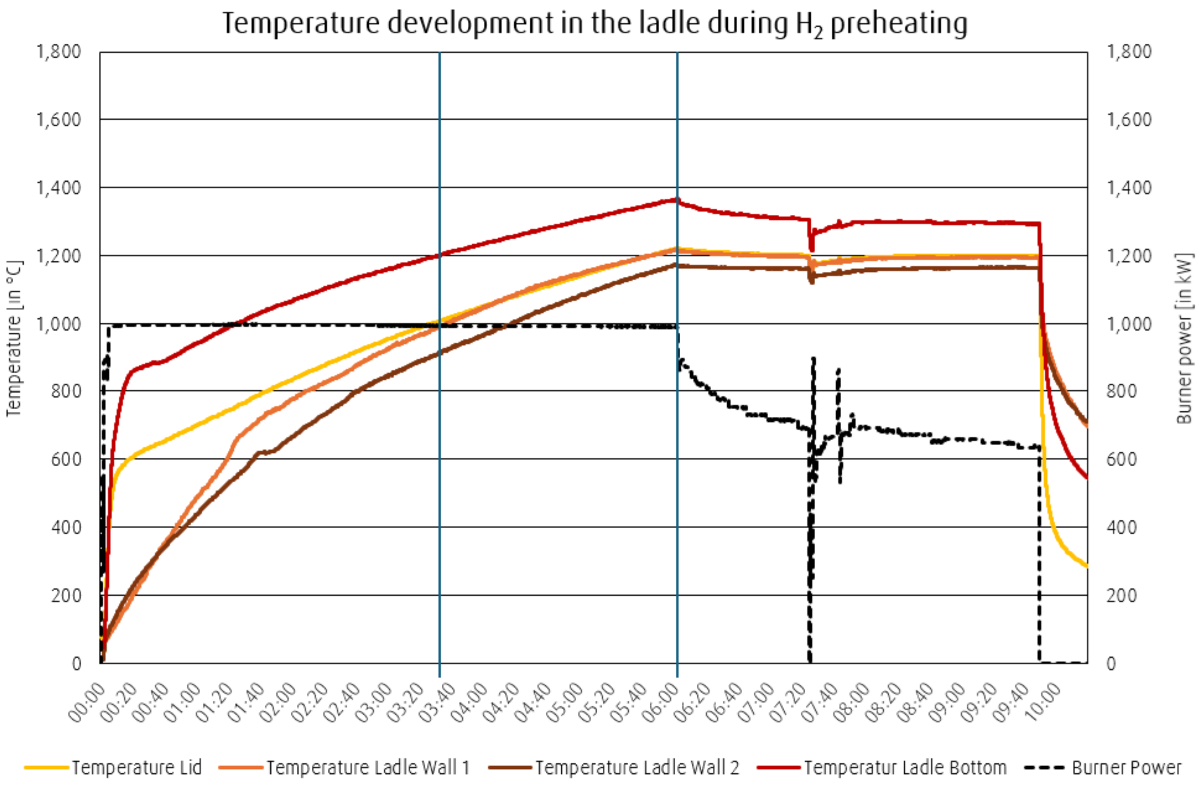


Figure 20: Hydrogen trial

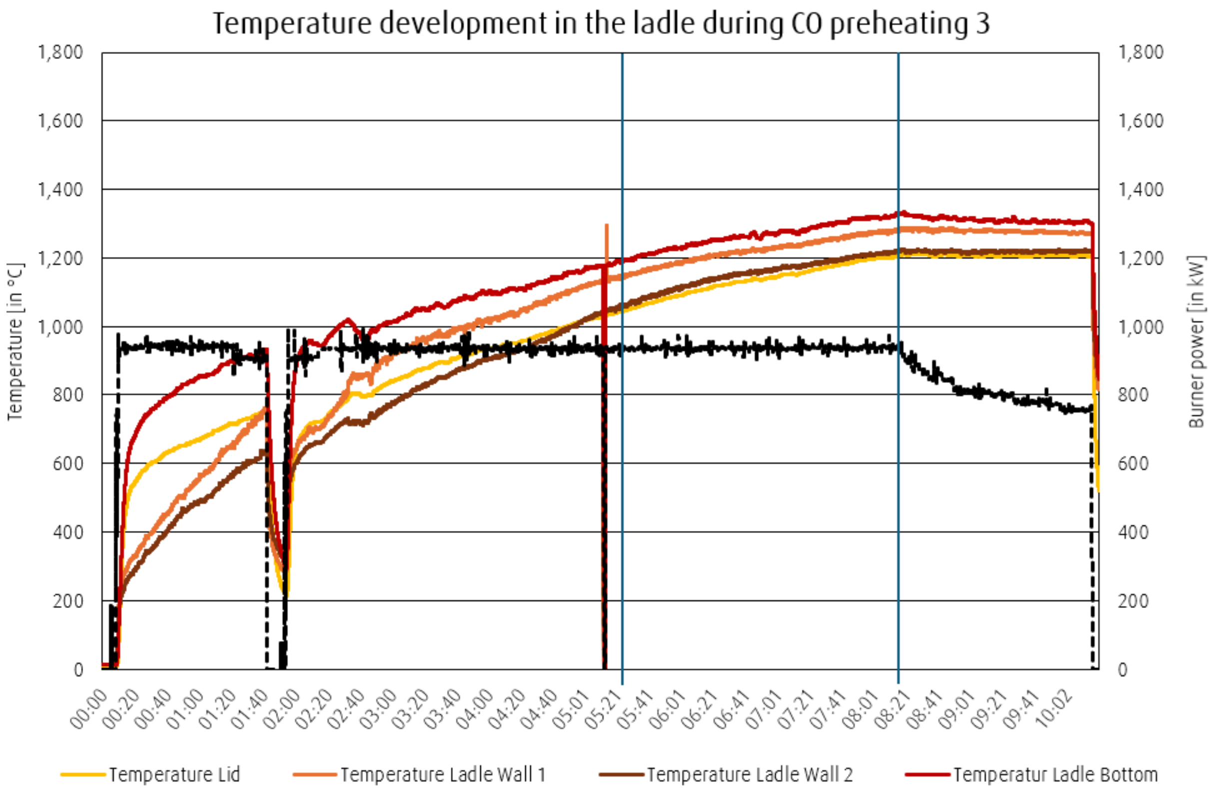


Figure 21: Coke oven gas trials

It is clear that the coke oven gas required higher power during the entire trial. During the hydrogen trial, the burner started regulating and lowering the power from hour 6, with the coke oven gas it happens after 8 hr 20 min.

DAN greenfield study

The DAN greenfield study evaluates the technical feasibility of a fully hydrogen-ready slab reheating furnace designed without the constraints of existing installations. The purpose of this work is to compare NG-fired, H_2-fired and oxygen-enriched configurations under consistent operating conditions, providing a reference framework for the industrial adoption of hydrogen-based heating in steel reheating. The study is based on detailed 3D transient simulations performed with DANIELI's EFESTO thermal model and on complete engineering of burners, gas systems and off-gas equipment.

General furnace characteristics

The furnace concept is a pusher-type slab reheating furnace sized for up to 100 t/h throughput. Slab geometries range from 900 to 3525 mm length, 1680 mm width and 220–290 mm thickness.

Thermal performance evaluation

The study evaluates three combustion modes:

- NG/air
- H_2/air
- NG or H_2 with 40% O_2-enriched air

All cases maintain identical furnace geometry, productivity, charging and discharging temperatures, enabling direct comparison of KPI variations caused exclusively by the fuel–oxidizer combination. Simulations capture heat transfer, slab temperature evolution, consumption, uniformity and flue-gas volumes.

Specific consumption

The EFESTO simulations show that hydrogen achieves energy performance comparable to natural gas.

- NG/air: 0.335 kWh/kg
- H_2/air: 0.329 kWh/kg
- NG/40% O_2: 0.309 kWh/kg
- H_2/40% O_2: 0.308 kWh/kg

Oxygen enrichment provides an efficiency gain of 6–8% over air firing for both fuels.

Temperature uniformity

Hydrogen firing shows a slightly higher thermal gradient due to its diffusivity (max ΔT: 7.9 °C vs. 6.6 °C for NG). However, oxygen enrichment significantly improves uniformity (4.2 °C for NG, 5.8 °C for H_2). All cases remain within typical industrial tolerance for reheating furnaces.

Waste gas characteristics

Hydrogen combustion produces lower exhaust-gas volumes than NG under air firing:

- NG/air: 38,165 Nm^3/h
- H_2/air: 34,076 Nm^3/h

With 40% O_2 enrichment, flue-gas volumes decrease dramatically:

- NG: –43%
- H_2: –39%

These reductions influence the sizing of recuperators, ductwork and fans. The engineered system includes a dome, dilution chamber, recuperator ensuring ≥500 °C air preheating, extraction fan (44 kW) and 25 m chimney.

Evaluation of combustion equipment

The furnace design employs DAN's hydrogen-ready burners:

- FAB flameless side-wall burners in preheating and heating zones
- HYDRO-RAD radiant burners in soaking zones

CFD evaluations confirm stable flameless/MILD operation for both NG and H_2, with wall-detached heat-release patterns and moderated peak temperatures. These burners maintain ultra-low NO_x performance (<60 mg/Nm^3 at 3% O_2 dry) even at high hydrogen fractions, validating their suitability for industrial hydrogen conversion.

Technical considerations for fuel and oxidizer systems

The study also includes a complete engineering package for NG, H_2 and O_2 lines. Hydrogen supply requires two-stage pressure reduction (200 bar → 30 bar → low-pressure), oversized piping to respect velocity constraints and dedicated purge systems. Oxygen lines are dimensioned considering both enrichment (≤40%) and the possibility of future oxyfuel operation. All line configurations were checked to ensure that flameless operation remains achievable with hydrogen.

Safety assessment

The greenfield configuration integrates PED-compliant pressure equipment, ATEX zoning minimization, gas-detection systems and nitrogen purging. A HAZOP was conducted on key nodes including fuel trains, mixing stations and burner manifolds. The evaluation confirmed that all identified risks can be controlled with standard industrial measures, and no redesign was required for safe hydrogen operation.

Evaluation summary

The technical evaluation finds that:

- Hydrogen achieves comparable or improved energy efficiency relative to NG.
- Temperature uniformity meets industrial requirements in all scenarios.
- Hydrogen firing reduces flue-gas volumes and associated system loads.
- DAN flameless burners maintain stable operation and ultra-low NO_x with H_2.
- Safety systems and gas-train architecture provide full compatibility with hydrogen.
- The greenfield furnace is fully hydrogen-ready and requires no conceptual redesign for future 100% H_2 operation.

Overall, the study demonstrates the technical viability of hydrogen firing for large-scale steel reheating and supports the conclusion that hydrogen can be deployed industrially when paired with appropriate burner technology, process control and safety engineering.

AMI direct/indirect heating cases

This deliverable for HyinHeat project is focused on testing indirect heating technology working with hydrogen and the comparison versus natural gas performance without any specific retrofitting in the lab, apart from new combustion fan, able to deliver higher air pressure burner manufacturer requirements.

In total, two different technologies have been tested at ArcelorMittal Gaslab radiant tube pilot plant (recuperative and self-recuperative burner technology). This laboratory is capable of testing two radiant tubes at the time. The maximum allowable power rate is 400 kW (200 kW by each radiant tube). This pilot plant allows high level of flexibility in terms of testing purpose (furnace temperature target, oxygen excess in flue gas, fix burner power rate…).

Main results

Different trials have been carried out for two different technologies for indirect heating in the steel industry. Hence, W-shape and PP radiant tubes have been covered with state-of-the-art new low emissions technologies.

All technologies tested could use pure hydrogen as fuel for a normal operation, with robust are replicable results.

As a summary, main conclusions for the units are listed here below.

Radiant tube recuperative burner. For recuperative burners with partial suction of product of combustion to reduce the emissions and enhance the efficiency.

- Better performance has been detected when using hydrogen as fuel.
- No major differences on the thermal profile.
- Enhanced efficiency when using hydrogen as fuel, with lower fumes temperature.
- Higher NOx emissions with higher trend to increase when raising the O2 content in the fumes.

Self-recuperative burner. For self-recuperative burner, main conclusions are:

- Thermal profiles are not different from fuel and operational mode. Lower Delta T on the surface of the radiant tube in comparison with W-Shape.
- Slightly better performance for hydrogen than natural gas in terms of efficiency.
- Higher demand needs for maintaining the temperature when using hydrogen
- Huge impact of the fuel for NOx emission. Low emissions hydrogen mode is getting higher figures than flame mode in natural gas firing.
- UV cell works properly with this unit. Not possible to use direct spark detection.

Finally, a full retrofitting of a continuous Annealing furnace or Galvanizing furnace has been analysed. The study assumed an average vertical furnace of galvanizing of 150 radiant tubes as a proposed approach, analyzing flue gas exhaust, emissions, burner, air train, tube heating, flame instrumentation, gas piping and fuel management.

Retrofitting design study for CAL/GAL.

Based on the results listed here above, a full retrofitting of a continuous Annealing furnace or Galvanizing furnace is analysed. The study is assuming an average vertical furnace of galvanizing of 150 radiant tubes as a proposed approach.

The major change is referred to water vapor volume, which is increased from 6.9% to 31.4%. However, there is no works required in the flue gas ducts for a retrofitting of firing natural gas to hydrogen mainly due to flue gas temperature and volume.

If the natural gas limit is adopted as a reference, the technology tested is valid when firing at normal air excess. However, the self-recuperative burner tested presented higher emissions and close to the limit adopted (250 mg/Nm^3).

For the revamping of the existing furnaces, since burners are not compatible with hydrogen fuel or compliant with NO_x emissions, all must be replaced. Average cost after consulting diverse burner manufacturers is in the range of 10.000-20.000 €.

Existing furnaces equipped with old firing systems, may require revamping of existing combustion fans. The deployed instrumentation remains valid. Piping diameter is valid, due to the required volumetric air is lower for same power deployed comparing natural gas and hydrogen firing. In case of pull burner technology, the piping installation and the related instrumentation (valves, orifice plates, pressure switches) could be around 2 M€.

Based on the results achieved in radiant tube pilot plant, the heating homogeneity is quite similar for the units tested. Therefore, there is not expected higher deformation grade or premature creeping with H2 firing.7

The ionization current level for hydrogen flames is not reliable with the current technology developed by burner and instrumentation manufactures. Therefore, the implementation of ultraviolet lamp sensor is required, and this could be traduced in the change of current supervision burner control systems from direct spark to an adapted ultraviolet lamp model. The estimated cost of this instrumentation is about 1500 € by burner in case of new burner control system is required in combination with UV lamp detection. Another possibility is the installation of pilot burner for flame ignition and supervision, only common in recuperative technology

The standard for industrial firing operations is under development. Therefore, same piping and instrumentation can be implemented for hydrogen firing at date of writing this report. However, changes in the standard are expected in coming years. Apart from that, changes in fuel flow measuring devices are required due to low density of hydrogen. Specific orifice plates must be installed at each regulation zone in combination with pressure transmitter in case pressure regulation would be different value from nowadays natural gas pressure values. Each orifice plate could cost about 500-1000 €.

The diameter of actual piping is valid due to no regulation of maximum speed for hydrogen, taking into account the pressure could be increased (checking of maximum pressure working service of all fuel elements must be checked in advance). to overcome different pressure drops along piping. Anyway, is recommended to renew fuel piping to ensure complete tightness of the system and to decrease hydrogen velocity in the piping. This work be estimated in 2 M€.

Since the standards are in preparation, existing valves and other instrumentation (thermocouples, manual valves, etc...) are valid for according to actual standards.

Evaluations from equipment, instrument and refractory suppliers

Equipment provided from Endress+Hauser SICK (EHS)

Endress+Hauser SICK provided on the one hand equipment to characterize the fuel supplied to the furnace and on the other hand sensors for combustion control and emission monitoring. Due to the use of Hydrogen new sensors needed to be developed or existing ones needed to be adapted. Especially the influence of the high water content in the exhaust gas when burning Hydrogen and using oxyfuel combustion needed to be investigated.

Overall, the equipment could be successfully adapted to the use of Hydrogen as fuel and used at the demonstrators of C-TEC and SWERIM. With this equipment it was possible to create data, which can be further used for the evaluation of the demonstrators. Detailed information of the equipment can be either found in the report of the deliverables D4.1 and D4.2.

Conclusions

Using hydrogen as fuel requires certain considerations, from safety to burner design but most importantly the availability. All the trials have shown the importance of the availability, there were delays and conflicting schedules when a large volume was needed. Burner manufacturers and technology providers are getting accustomed to use of hydrogen as fuel. They have burner and furnace designs available. When hydrogen is compared to other fuels, no significant process changes are observed for steel and aluminum industries. Just like natural gas, propane or coke oven gas require their own safety procedure, hydrogen safety should be taken into consideration. However, it doesn't make it harder to use, just different. In this deliverable, multiple demonstrators and other actors have shown their experience with hydrogen and report the KPIs such as energy consumption and emissions.

References

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