



Development of Heating Technologies for the
Efficient Renewable Energy Consumption of
CO₂-Neutral Downstream-Processes

Deliverable 4.1

Process KPIs as fundamental background information

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Summary

In the hot rolling process, reheating plays a vital role not only in achieving the necessary temperature for deformation in the rolling stands but also in controlling oxidation rates, as excessive oxidation can reduce plant yield, and in influencing metallurgical properties, since temperature variations can affect mechanical characteristics by impacting the dissolution of alloying elements.

WP4 aims to develop and evaluate a hybrid heating system that combines combustion and electrical resistive elements within a pilot walking beam furnace. As primary industrial users, ADI and Feralpi play a central role in this project; hence, thorough background research and parameter definition are crucial for designing the pilot tests. These include zone temperatures, soaking zone temperature (where resistive elements will replace burners), residence time, and discharging temperature, ensuring the tests are accurately tailored to optimize performance and outcomes.

ADI and Feralpi have conducted a comprehensive analysis of their background operations, taking into account the management of slab and billet reheating, countermeasures implemented, and steel qualities selected for the pilot test. This analysis was complemented by a literature review to determine the oxidation rate and the impact of reheating on product quality, as well as optimal plant management. By utilizing production data for slabs and billets, several reheating conditions were identified and, in conjunction with the set point temperatures for each furnace zone, various key performance indicators (KPIs) – 5 for ADI and 7 for Feralpi – have been selected.

1 Literature review

WP4 aims to test hybrid concepts with different combustion atmospheres, mirroring both current industrial conditions and future scenarios involving mixtures of biofuel and natural gas. This investigation will impact the oxidation behavior of slabs and billets during the reheating process. A notable study by Schwarza et al. [1] conducted a comparative analysis, examining the influence of various combustion atmospheres (with natural gas and hydrogen in normal and oxy-combustion conditions) on the reheating of 12 steel qualities with distinct alloying element contents (nickel, chromium, and molybdenum) and varying carbon levels, using a fuel oxidizer equivalence ratio between 0.95 and 0.98. This work revealed that increased hydrogen content significantly thickens the scale for most steel qualities, a finding consistent with the results of Cirilli et al. [2] and Haapakangas et al. [3] who investigated the effects of full hydrogen use in reheating. Their studies also showed that high silicon content can degrade surface quality and increase scale adhesion, compromising the overall product quality.

Beyond fuel type, several parameters influence oxidation, as explored by Xiang Liu et al. [4], who conducted experimental studies on process variables affecting high-temperature oxidation, including chemical composition, surface condition, and furnace atmosphere, to calibrate a scale growth model. Similarly, H. T. Abuluwefa [5] investigated the mechanisms of scale formation in low-carbon steels, finding that reducing free oxygen content from 3% to 1.5% can slow scale growth. His work also derived a general equation for predicting scale formation, which will be utilized in the following sections. Notably, he discovered that the oxidation rate of low-carbon steel in binary gas follows a linear law proportional to CO_2 and H_2O partial pressures, whereas in ternary and quaternary gases containing O_2 , CO_2 , H_2O , and N_2 , the initial oxidation rate depends on free oxygen concentration. Over multiple reheating cycles, the overall oxidation rate tends to fall between linear and parabolic behaviours under isothermal conditions, influenced by the air-to-fuel ratio.

Reheating is an energy-intensive process and optimizing furnace zone temperatures during temporary stops can lead to significant energy savings. Researchers such as Zhi Yang et al. [6] have proposed control strategies to optimize reheating furnace operations, leveraging the Entropy-TOPSIS method and MPC approach to achieve a substantial increase in control accuracy, from 74% to 99%. Similarly, Wei-Hsin Chen et al. [7] conducted a numerical study on optimal slab heating, focusing on process efficiency and quality metrics, including internal thermal uniformity, target discharge temperature, and residence time, resulting in valuable insights for improving process performance. The analysis yielded the following key findings: the temperature gradient between the surface and core of the slab increases rapidly during the initial heating phase in the preheating tunnel, reaching its maximum value at the inflection point of the heating curve. This highlights a critical operational challenge: achieving the desired temperature within a specified time frame while maintaining uniform temperature distribution throughout the slab. Additionally, from an energy efficiency perspective, thinner slabs in the furnace demonstrate a significant advantage, as they enable more efficient energy use compared to heating thicker slabs.

From a metallurgical perspective, reheating temperature significantly influences the precipitation strengthening effects of niobium, vanadium, and titanium. Studies by Shyi-Chin Wang [8] and Dian Zhang [9] have shown that lower reheating temperatures result in reduced precipitation strengthening of $\text{V}(\text{C}, \text{N})$, while higher temperatures cause a decrease in the size of niobium and titanium precipitates within austenite. This reduction diminishes their pinning effect, leading to ferritic grain coarsening. These phenomena are closely related to the material's dissolution temperature, which can be estimated based on its chemical composition.

2 Industrial cases

2.1 ADI case

As outlined in paragraph 1, reheating is crucial for ensuring product quality, such as scale removal and mechanical properties, as well as maintaining the correct temperature for the roughing and finishing stands. Of particular importance is controlling the temperature at the last roughing stand (R6), which varies depending on the steel grade and the size tolerances of the hot-rolled strips. For pipe production, it is preferable to maintain a temperature between 1000°C and 1040°C during the thermomechanical process, ensuring rolling occurs below the recrystallization temperature in the finishing stand. Conversely, for strips with tighter tolerances, a higher reheating temperature is necessary to prevent issues like bending of the work rolls, which can hinder reaching the target thickness.

Thus, the reheating temperature must balance the reduction of rolling forces and power consumption with the need to achieve a lower discharging temperature for energy efficiency. Accordingly, several investigations were conducted for the ADI case, focusing on the reheating curve, residence time in the furnace, Larson-Miller parameter, and oxide scale formation to optimize this balance.

Reheating curve

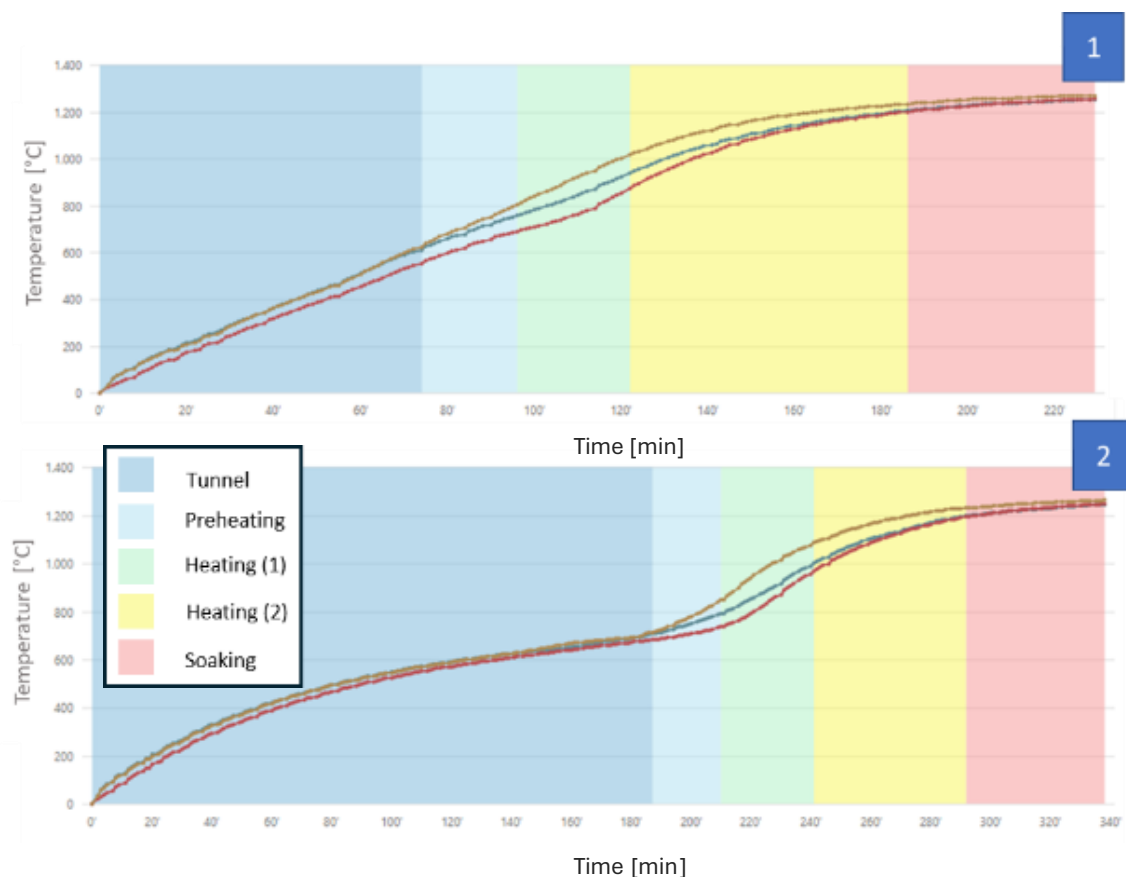


Figure 2.1 Example of calculated reheating curve (comparison between curves with high and low throughput)

Based on the furnace's throughput of mixed slabs, the plant determines optimal management of slab residence time and furnace set points. The reheating curve, generated by the process control system, illustrates the surface and core temperature trends throughout the slab's residence in the furnace prior to rolling. A linear increase in core temperature typically indicates high furnace productivity, while the presence of an inflection point between the preheating and heating zones suggests a pause, where the slab remained stationary in one of the zones (Figure 2.1). For greater clarity, the difference in throughput can be deduced from the residence time of the slabs in the tunnel zone, which is shorter for the slab 1. Another parameter is the ΔT between surface and core temperatures: a high value could compromise the rolling of the slab (e.g., shape and surface defects). For ADI, the target value is less than 30°C but for strips it could be requested to have a ΔT of about 20°C .

Since ΔT is a key KPI, a simplified 2D model was developed to estimate surface and core temperatures based on zone temperatures, as it is currently not possible to directly extract these curves from the furnace control software. This model, grounded in finite element formulas, effectively approximates the temperature profiles that would be obtained from the main furnace software, as illustrated in Figure 2.1 (1) and Figure 2.2.

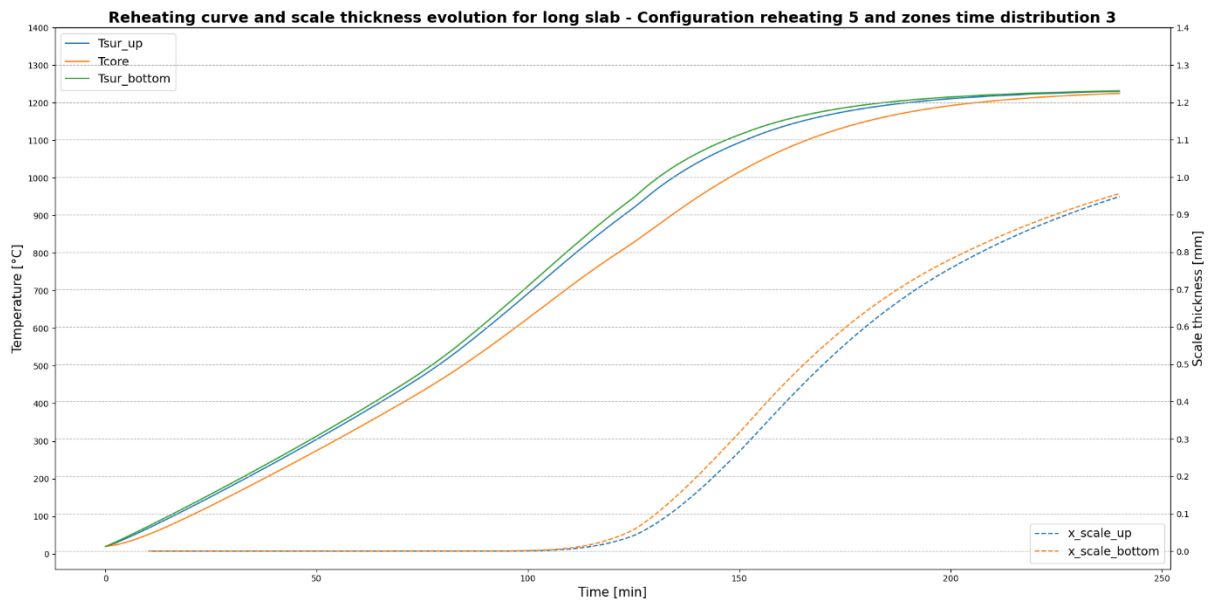


Figure 2.2 Calculated reheating curve considering the simulation parameters in paragraph 2.1.1

Larson-Miller parameter

Based on experience with slab reheating in the hot plate mill, it was observed that a low Larson-Miller parameter (*LMP*) value negatively affected the mechanical properties of the plate. The respective formula is:

$$LMP = T_{dis} \cdot (20 + \log_{10} t_{900})$$

where, T_{dis} is the discharging temperature expressed in K and t_{900} is the residence time above 900°C expressed in hours.

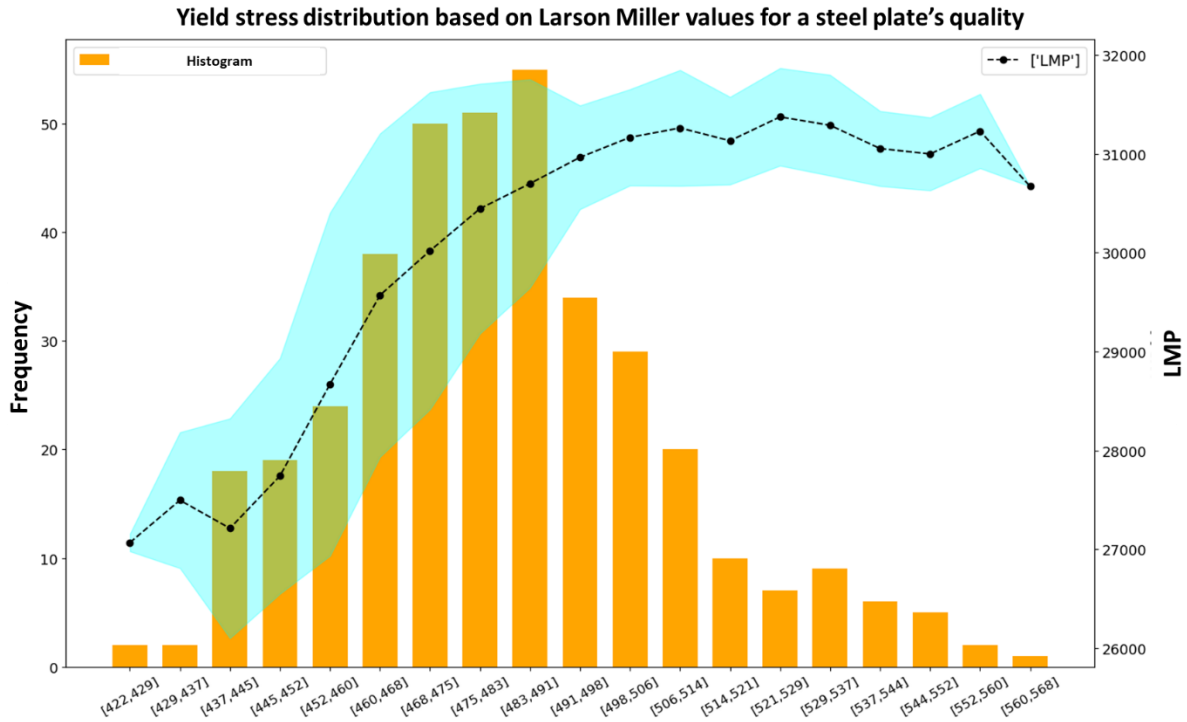


Figure 2.3 Distribution of yield strength as a function of the Larson-Miller parameter for micro-alloyed steel

Larson-Miller parameter is a parameter used for the creep behaviour of the steel. However, it can be used to carry out a comparison between reheating curves of the same product. In a past analysis for some slabs reheated in the plate mill (micro-alloyed steel), it was seen how the effect of the residence time and discharging temperature summarized by the Larson-Miller parameter influence the mechanical characteristics of the product (Figure 2.3).

Oxide scale thickness

Finally, the oxide scale thickness of the slab quality considered was evaluated, providing an indication of this value under the reheating conditions. Although the model is not calibrated, comparing the current conditions with similar reheating scenarios using natural gas can offer a useful estimate of the oxidation rate.

Building on the expressions presented in the article of Gomez [10], the oxide scale thickness (x_{scale}) was calculated considering the following expression:

$$x_{scale} = \frac{-1/k_l + \sqrt{\left(\frac{1}{k_l}\right)^2 - 2\frac{t}{k_p}}}{\frac{1}{k_p}} [mm]$$

Where t represents the time in [s], k_l the oxidation constant for linear growth and k_p the oxidation constant for parabolic growth of the scale. In particular, the linear and parabolic constant are calculated with the following expressions:

$$k_l = k_{lO_2} + k_{lCO_2} + k_{H_2O}$$

$$k_{lO_2} = M_O \frac{4}{3} \frac{D_O}{w_{slab}} Re^{1/2} Sc^{1/3} (C_{O_2}^g - C_{O_2}^i)$$

$$k_{lCO_2} = M_O \cdot 18490 e^{\frac{-274362}{R \cdot T_s}} a_{CO_2}^1 {}^{-2/3} \left(1 - \frac{a_{CO_2}^1}{a_{CO_2}^2} \right) P_{CO_2}$$

$$k_{lH_2O} = M_O \cdot 28282 e^{\frac{-263555}{R \cdot T_s}} a_{H_2O}^1 {}^{-2/3} \left(1 - \frac{a_{H_2O}^1}{a_{H_2O}^2} \right) P_{H_2O}$$

$$k_{p_{ws}} = 2.88 e^{\frac{-169452}{RT_s}} \quad k_{p_M} = 0.137 e^{\frac{-169452}{RT_s}} \quad k_{p_{EM}} = 3.05 \cdot 10^{-2} e^{\frac{-169452}{RT_s}}$$

Where M_O is the molecular weight of oxygen, D_O is the binary diffusion coefficient of oxygen, Re is the number of Reynolds, Sc is the number of Schimdt, $C_{O_2}^g$ denotes the molar concentration of the oxygen in the gas, $C_{O_2}^i$ is the molar concentration of the oxygen in the interface, a_i are the activities of oxygen calculated based on the partial pressures of the gases, and T_s is the temperature on the slab surface.

2.1.1 ADI KPIs

Based on the parameters pointed out in the previous paragraph, a simulation for different times of reheating and configurations of temperature zones was carried out to individuate the best input parameters considering maintaining the air to gas ratio for the zones fixed.

Table 2.1 Temperatures in the upper zones for the ADI reheating furnace

Configuration	Tunnel	Pre-Heating	Heating (1)	Heating (2)	Soaking
1	700 [°C]	1290 [°C]	1330 [°C]	1330 [°C]	1330 [°C]
2	700 [°C]	1290 [°C]	1330 [°C]	1330 [°C]	1320 [°C]
3	700 [°C]	1280 [°C]	1320 [°C]	1330 [°C]	1320 [°C]
4	700 [°C]	1270 [°C]	1310 [°C]	1330 [°C]	1320 [°C]
5	700 [°C]	1260 [°C]	1310 [°C]	1320 [°C]	1310 [°C]

Table 2.2 Temperatures in the bottom zones for the ADI reheating furnace

Configuration	Tunnel	Pre-Heating	Heating (1)	Heating (2)	Soaking
1	700 [°C]	1290 [°C]	1290 [°C]	1300 [°C]	1300 [°C]
2	700 [°C]	1290 [°C]	1290 [°C]	1290 [°C]	1290 [°C]
3	700 [°C]	1280 [°C]	1280 [°C]	1290 [°C]	1290 [°C]
4	700 [°C]	1270 [°C]	1270 [°C]	1290 [°C]	1290 [°C]
5	700 [°C]	1270 [°C]	1270 [°C]	1290 [°C]	1280 [°C]

Since the λ ratio distribution varies in the furnace zones, a distribution from 1.2 in the preheating zone to 0.95 in the soaking zone was adopted for the simulations (Table 2.3) Additionally, five different total reheating times were examined, ranging from 160 to 320 minutes, while keeping the zone distribution ratios constant and assuming a continuous movement of the slab through the furnace.

Table 2.3 Distribution of λ values across the furnace zones considered in the simulations

Pre-Heating	Heating (1)	Heating (2)	Soaking
1.2	1.1	1.1	0.95

Using these values, 25 different configurations for 12-meter-long slabs were modelled, and for each configuration, four candidate KPIs were evaluated: the mean surface-core temperature difference, Larson-Miller parameter, total oxide scale thickness, and discharging temperature. As shown in the Figure 2.4, a residence time of 240 minutes with configuration 1 of the zone temperatures is sufficient to achieve a discharging temperature exceeding 1240°C, while maintaining a total oxide scale thickness of 2.2 mm and an average temperature difference (ΔT) of less than 7°C.

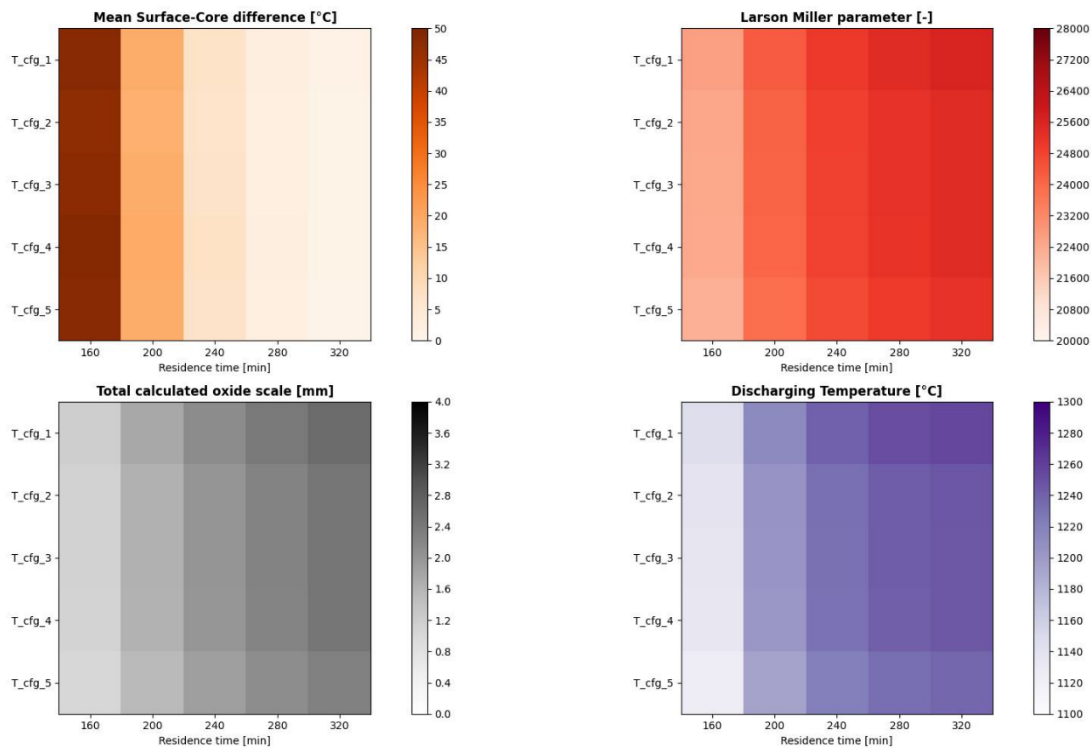


Figure 2.4 KPIs matrix calculated based on a slab length of 12 m, incorporating five different reheating time values and five distinct zone temperature configurations

For the WP4 pilot test, an initial selection of 2-3 steel qualities will be considered. ADI has identified a group of five steel qualities based on material availability for laboratory testing (Task 4.2) and pilot testing (Task 4.3). Table 2.4 provides detailed information on these steels, including their chemical composition and dissolution temperatures (T_{dis}), which are calculated using Gorni's formula [11].

$$T_{dis} = 203.6 \log C + 231.6 Nb + 33.86 \log Si - 1.48 \log Mn - 2.73 \log Cr + 17.1 / (3.61 - Ti / N_2) + 1657$$

Table 2.4 Limit of some critical elements for the steel qualities with the mean dissolution temperature

Quality	Manganese limit [%]	C limit [%]	Niobium limit [%]	Mean Dissolution temperature [°C]
Q1 – C-Mn	≤ 0.25	≤ 0.05	-	781
Q2 – C-Mn	≤ 0.35	≤ 0.06	-	786
Q3 – C-Mn	≤ 0.4	≤ 0.07	-	813
Q4 – microalloyed	≤ 0.6	≤ 0.08	≤ 0.03	1063
Q5 – microalloyed	≤ 1.5	≤ 0.2	≤ 0.03	1125
Q6 – microalloyed	≤ 1.2	≤ 0.2	≤ 0.04	1164

Based on the simulation results and taking into account the dissolution temperature and plant constraints, the KPIs and related limitations for the ADI case are summarized in the table below. In addition, the specific energy target (1.4 GJ/t), as reported in the reference table of the BREF document [12], has been included.

Table 2.5 KPIs values to take into account for the pilot test (ADI case)

ID	KPIs	Limits	Effect
KPI1_ADI	ΔT [°C]	≤ 10 °C	A higher ΔT compromises the quality of the rolled products (e.g., bar nose-up and nose-down defects).
KPI2_ADI	Scale thickness [mm]	≤ 2.3 mm	A greater thickness reduces process efficiency, resulting in a weight loss that may exceed 1%.
KPI3_ADI	Larson - Miller [-]	≥ 25000	A lower value is an indication of non-uniform reheating across the furnace zones, resulting in a deterioration of the mechanical properties.
KPI4_ADI	Discharging temperature [°C]	≥ 1240 °C	Risk of compromising the finishing process: excessively low temperatures may cause incidents in the finishing stands, resulting in plant downtime.
KPI5_ADI	Specific energy [GJ/t]	≤ 1.4 [GJ/t]	-

2.2 Feralpi Case

Description of the relevant KPIs for hybrid billet heating at Feralpi

The main KPIs considered relevant to demonstrate the feasibility of hybrid billet heating as an alternative to full gas heating are the following:

KPI1_FER: Energy input to the product – This item is relevant for ensuring the necessary heating evolution of the billets and achieving the intended temperature profile. Furthermore, this factor is fundamental to maintaining or increasing productivity relative to the original gas heating.

KPI2_FER: Balance between the cost of gas and electrical energy – This item is fundamental for evaluating the economic feasibility of new solutions in this sector.

This aspect has become especially relevant in recent years due to macroeconomic changes in energy prices, driven by events such as the Covid-19 pandemic, the war in Ukraine, and other factors. These events caused drastic changes, particularly in gas prices, making investment in process electrification more attractive. Naturally, a reversal of these price trends would also change the investment picture in the opposite direction.

Furthermore, these aspects affect Italy differently from other European countries, due to its higher electricity prices, which are detrimental to electrical heating solutions because of the resulting high OPEX.

KPI3_FER: Emissions under the EU ETS – This is a relevant target for this project, both for environmental and for economic reasons, given the impact of ETS prices on OPEX evaluations.

KPI4_FER: Scale formation and the associated material loss for billets – This item is very important due to the economic value associated with scale formation during billet heating, given the yearly production volume (almost 1,400,000 t/year of rolled products); therefore, it has a significant impact on OPEX and can influence strategic decisions on electrification. The main factors affecting scale formation are the O₂ content of the atmosphere surrounding the billets, the billet temperature, and the exposure time to scale-forming conditions. These parameters change significantly between gas heating and electrical heating, so the choice of hybrid heating configuration causes strong variation in this item. Under current conditions, the scale thickness generated on Feralpi billets is around 0.5–1 mm on average, taken as the reference value.

KPI5_FER: Discharging temperature – The reference billet temperature at the exit of the reheating furnace and entry to rolling is set at 1150 °C. However, this is only the billet surface temperature and does not reflect the internal temperature or the overall thermal state of the billet. Therefore, it can be considered a useful set point for managing the current heating configuration, but it is not a fully reliable parameter for comparing different heating configurations, such as electrical induction heating versus gas heating.

KPI6_FER: Percentage of total current at the first rolling stand – To ensure reliable billet feeding into the rolling mill, and to compare different heating configurations in long-product rolling, the load on the first rolling stand, expressed as a percentage of the total available current, is used as a reliable indicator. The reference limit considered reliable to maintain is 80% of the total current at the first rolling strand. This parameter takes into account the following variables:

- Electrical current supply at first rolling stand – **EI_Curr_Roll1**

- Max nominal value of electrical current supply at first Stand – **El_Curr_Roll1_Ref**
- % Range acceptability of Electrical supply at first rolling Stand – **El_Curr_Roll1_Renge**

The parameter is determined as follows:

$$\%_{Tot_Stress_1Roll_Stand} = 100 \frac{El_Curr_Roll1}{El_Curr_Roll1_Ref}$$

So this value has to be = 80 %

However, to allow for a certain degree of variability, the following control condition must be satisfied:

$$\%_{Tot_Stree_1Roll_Stand} - El_Curr_Roll1_Ref < El_Curr_Roll1_Range$$

Reference value: **El_Curr_Roll1_Range** = 2 %

KPI7_FER: Range of variability of mechanical strength and yield strength – As a final check on the rolled products, the mechanical characteristics of the wire rods are used as the reference for validating the correctness of the overall process, including reheating and rolling. The reference mechanical strength limit is around 540 MPa.

Table 2.6 - Characteristics of Feralpi's steel grades and limits

Quality	Manganese limit [%]	C limit [%]
Q1 – C-Mn	0.7 < C ≤ 1 (Average 0.79)	0,17 < C ≤ 0.22 (average 0,19)

Mechanical resistance (Ra) values for the Feralpi case

The following list and Figure 2.5 show the frequency distribution of mechanical resistance for the Feralpi case:

- Most frequent value: around 540 MPa
- 67% of cases between 530 and 550 MPa
- 88% of cases between 520 and 560 MPa

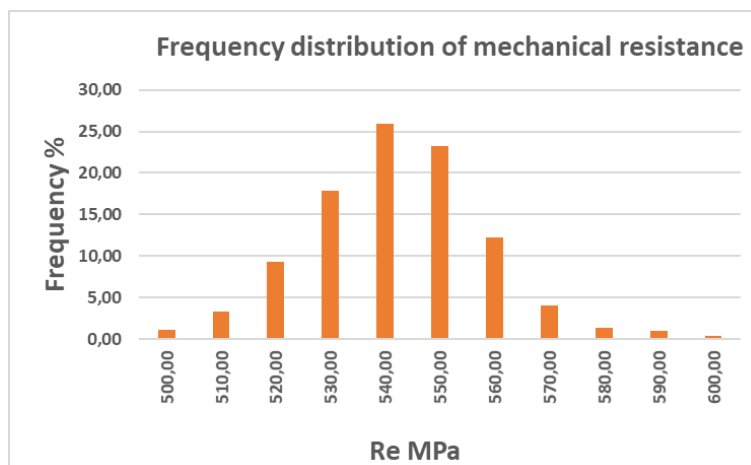


Figure 2.5 - Frequency distribution of Mechanical resistance of Feralpi's Steel Grades for wire rods

The parameters taken into account are defined as:

- Mechanical Strength and Yield Strength – **Mec_St**
- Acceptable % range at minimum value – **Delta_Min**
- Acceptable % range at maximum value – **Delta_Max**

The alert conditions to be satisfied are:

$$100 \cdot 520 - Mec_{St} < Delta_{Min}\% \quad \text{otherwise} \quad 100 \cdot Mec_{St} - 550 < Delta_{Max}\%$$

Main gas-heating parameters at Feralpi

The main characteristics of the billet-heating process with the gas furnace at Feralpi Siderurgica are reported in Table 2..

Table 2.7 Characteristics of Feralpi's gas furnace

Furnace Zones	Temperature	Nominal Power
	°C	kW
Zone 1	1000 - 1220	20.000 – 22.000
Zone 2	1000 - 1300	19.500 – 21.000
Zone 3	1000 - 1300	5.000 – 6.000
Zone 4	1000 - 1300	5.000 – 6.500

Feralpi's approach to scale formation determination

Given the interest in estimating scale formation for different process developments, and the need to combine these evaluations with the electrical heating options currently available and under investment consideration, Feralpi has developed its own approach to this estimation, adapted to industrial configurations.

In particular, the evaluation performed by Feralpi is based on the following expression

$$Scale_{mass} = \int_0^t Cp * \frac{DT}{K_T} * (\%O_2 - \%O_{2_{lim}}) / K_{O_2}$$

where, $Scale_{mass}$ is the total mass of oxide scale formed per unit area, t is the total residence time in the furnace, C_p is the specific heat capacity of the steel grade, DT is the temperature difference, K_T is a temperature proportionality constant, $\%O_2$ is the percentage of free oxygen in the gas within the furnace chamber, $\%O_{2_lim}$ is the limit of oxygen percentage, and K_{O_2} is an oxygen proportionality constant.

Different heating and scale-formation scenarios are hypothesized.

Figure 2.6 shows the scale-formation index as a function of the overheating temperature relative to a reference billet-heating temperature.

In particular, it shows the increase in scale formation above the reference temperature, comparing gas heating with electrical heating.

The same estimate, shown as a function of time (Figure 2.7), indicates that the increase in scale formation is smaller for electrical heating than for gas heating in both cases.

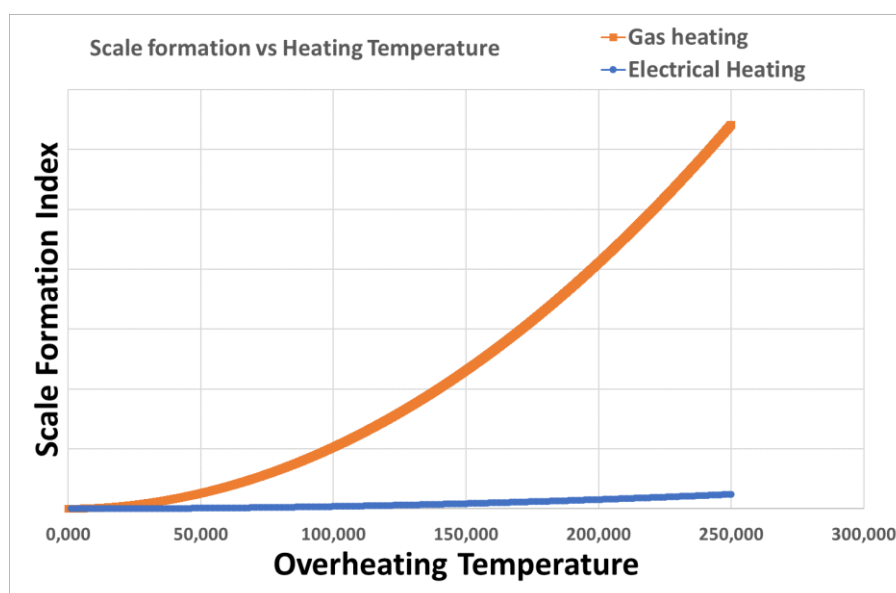


Figure 2.6 - Evolution of scale formation as a function of the overheating temperature, depending on the type of billet heating

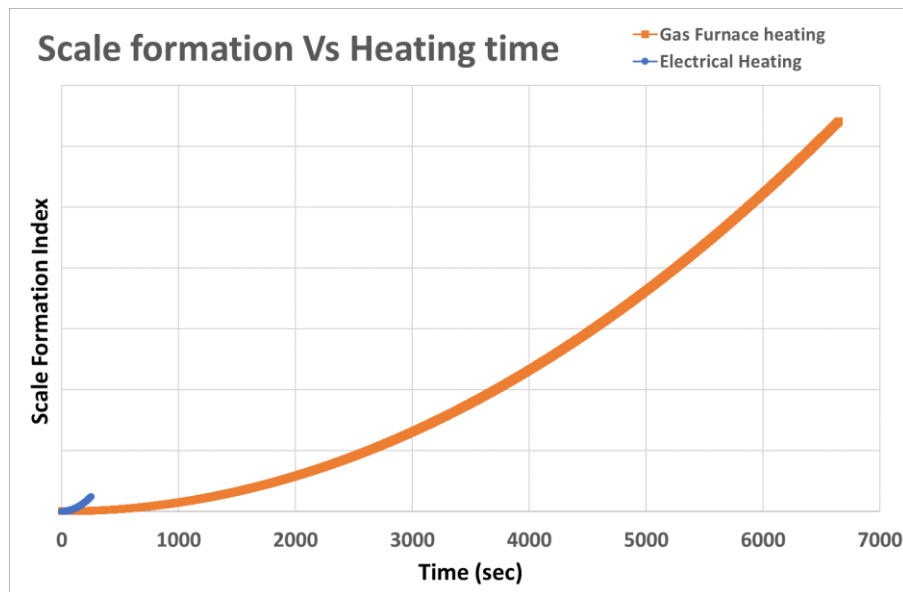


Figure 2.7- Evolution of scale formation over time, depending on the type of billet heating

Table 2.8 summarizes the main KPIs and the associated preliminary limits for Feralpi.

Table 2.8 Main KPIs and associated preliminary limits for Feralpi.

KPIs	Limits	Effect
Scale thickness [mm]	$\leq 0,5-1$ mm	A greater thickness reduces process efficiency, resulting in a weight loss that may exceed the acceptable values.
Discharging temperature [°C]	≥ 1150 °C	Risk of compromising the finishing process: excessively low temperatures may cause difficulties in rolling variability in the quality or problems in the finishing stands, resulting in plant downtime.
Mechanical resistance [MPa]	$520 < Ra < 560$ [MPa]	Out of tolerance values respect the expected Mechanical Resistance can be not acceptable.

Conclusions

The preliminary study carried out by ADI and Feralpi identified a set of KPIs to be monitored during the hybrid heating pilot tests at Swerim. Different approaches were adopted by the two industrial partners, reflecting the different product types and plant operating practices.

In particular, ADI identified a group of KPIs related to reheating process performance. To validate the proposed target values, several thermal simulations of slab reheating were performed, including the estimation of scale thickness. Specifically, ADI evaluated five different temperature set-point configurations (for both the top and bottom furnace zones) and five different residence times.

Based on these simulations, a reference configuration was selected for the burner-based heating phase of the pilot tests. In addition, the minimum and maximum values of the following parameters were determined: Larson–Miller parameter, discharge temperature, scale thickness, and thermal homogeneity. Finally, based on the BREF document and on a thermal balance developed for a furnace of ADI's hot strip mill, a maximum specific energy consumption of 1.4 GJ/t was established.

Feralpi identified a broader set of seven KPIs, reflecting the wider scope of its billet reheating and rolling process. These cover the energy input to the product (KPI1_FER), the balance between the cost of gas and electrical energy (KPI2_FER), the cost of emissions under the EU ETS (KPI3_FER), scale formation and the associated material loss (KPI4_FER), the discharging temperature at the furnace exit (KPI5_FER), the load on the first rolling stand expressed as a percentage of the available current (KPI6_FER), and the acceptable range of variability of the mechanical strength and yield strength of the final rolled product (KPI7_FER).

Based on these evaluations, the choice of how to implement billet heating before rolling can be affected by different aspects, such as energy source costs, CO₂ emissions, productivity, power, and scale formation.

This balance can differ depending on the site, steel quality, or region; for this reason, the specific plant configuration is highly relevant when deciding on investments in this area.

In particular, in regions where electricity costs are very high, increasing billet heating through electrical sources is detrimental to operating costs, whereas reducing gas heating can bring benefits in terms of CO₂ emissions reduction (Scope 1) and scale formation, which is significantly reduced with electrical heating due to the shorter exposure time to oxidation.

For these reasons, it is not possible to define a single pathway for implementing electrical or hybrid gas-electric heating; each specific configuration must be studied as an individual case.

These KPIs will be used in the design and evaluation of the pilot tests involving different steel grades (two provided by ADI and two by Feralpi) and various fuel and energy supply configurations.

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