Dissemination of the heating technology research results for emission minimization and process optimization towards todays fossil-free heating agenda

RFCS-2021

Grant agreement No 101057930

State of the art report

Deliverable 3.2

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Publication date: March 31st, 2023

Dissemination level: Public

Content

1 Scope

In this report the findings and results from the review and analysis of the state of the art and best available technology (BAT) of industrial heating in steel industry is documented. The analysis is performed over the dissHEAT topics:

- Topic 1 - Heating and burner technology
- Topic 2 - Modelling of entire furnace, model based predictive control (level 2)
- Topic 3 - Measurement and sensors, measurement-based furnace control (level 1); standards, regulations
- Topic 4 - Materials in the furnace
- Topic 5 - Heat transfer, heat recovery, productivity, economy, CAPEX, OPEX

The performed review and analysis of the state of the art and best available technology (BAT) in this project focus on the reheating process and therefore applied technology. The Topic heat treatment referring to heating processes and technology is not specifically considered here.

Topic 1 covers information related to heating and burner technology applied for reheating furnaces. Burner and heat recovery technologies for furnace-heating with natural gas, process gases as well as alternative heating technologies (hybrid heating) have been analyzed and are reported here. Technologies as combustion techniques for NO_X reduction, heat recovery, as well as heating technology and furnace design for efficiency, productivity. The burner operation like power modulation and flow control influences the combustion but significantly influences the furnace atmosphere which is relevant for the product surface quality and scaling. Control is focus of topic 3 and product quality of topic 3 and 4 and described more deeply in the sections of these topics. Economic performance of the reheating process is concern of topic 5.

Topic 2 covers the models used in simulation of reheating furnaces. Simulations can regard the whole furnace (furnace zone model, concentrated parameters model) or just about the burners (CFD, combustion simulation). The aims are to improve the regulation and control of the furnace by simulating scenarios in advance and the testing of new procedure before application to industrial facilities. This can lead to reduction of fuel consumption and the development of more efficient technologies, such as low NO_X burners.

Topic 3 covers the main sensors and measurement technologies used in reheating furnaces to help regulate and control the furnace. The main measured parameters are furnace temperatures, gas temperature, gas and air flows, furnace pressure, furnace atmosphere (mainly O_2 and CO) and off-gas composition (O_2, CO, CO_2, NO, NO_X). In addition, the topic covers furnace control regulations and standards. Topic 3 focuses specifically on Level 1 process control, e. g. only the measurement of operating conditions and measurement-based control are covered. Aspects such as data transmission are not part of the scope. Although there may be some overlap, model-based predictive controlling won’t be covered in topic 3 but will be the subject of topic 2.

Topic 5 covers information related to the efficiency, productivity, and economic performance of steel reheating furnaces. This includes the amount of energy required per ton of feedstock, increases in productivity rates, heat transfer rates, as well as economic measures such as payback times, CAPEX and OPEX of implemented techniques/measures. Burner and heating technology is closely related to efficiency and productivity and is therefore highly relevant for topic 5 but as it is the main focus of topic 1, it will not be covered in detail in this section. Similarly, as economic performance is specific to the technique/measure used, economic performance related to the topic 1 - 4 will not be covered.

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2 Abbreviations

Table 2: Abbreviations

ADP	Acid Dew Point
BAT	Best Available Technology
BFG	Blast furnace gas
BOF	Basic oxygen furnace
CAD	Computer Aided Design
CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CFD	Computational Fluid Dynamic
COG	Coke oven gas
GHG	Greenhouse gas emissions
HEC	Hydrogen enhanced combustion
IR	Infrared
LPG	Liquefied Petroleum Gas
NG	Natural gas
NO_X	Nitrogen Oxide in Exhaust from combustion as mixture of NO, NO_2 (N_2O here neglectable)
OPEX	Operational Expenditures
ORC	Organic Rankine Cycle
RANS	Reynolds-Averaged Navier–Stokes equations
SNG	Synthetic natural gas
SoA	Statement of Applicability
TRL	Technology readiness level

3 Literature review and past EU, RFCS/ECSC projects (Past)

This chapter presents the results and findings of the survey of past EU Horizon, RFCS/ECSC projects, international literature and publications as well as research reports on national projects over the past 25 years.

Topic 1 focuses on the heating and burner technology with which efficiency, productivity, flexibility related to steel quality/ type and the whole downstream process chain are considered. Furthermore, the temperature in the product during its heating process, scale loss as well as furnace atmosphere, NO_X or GHG emissions are influenced or controlled by this technology. This is only achieved by heating and burner technology in combination with automated control (topic 3), model-based furnace control (topic 2), well understood heat transfer and heat recovery (both topic 5) as well as considering the requirements of the material and different steel qualities (topic 4). Therefore, the investigations and review have in all topics an overlapping on and are dependent on each other.

Topic 2 focuses on the model base control of reheating furnaces taking into account furnace and operation parameters as well as process data of the complete process chain. The section of topic 2 in chapter 4.1 presents the main results and findings of furnace and heating process modelling as well over the last 25 years.

Topic 3 focuses on the use of automated control using measurement devices and sensors to collect process data on furnace parameters such as temperature or atmosphere. Process controllers such as PLC or loop controllers can then adjust the process parameters if process deviation is detected. This section presents the main results of research into measurement methods and Level 1 control over the last 20 years.

Topic 5 focuses on measures/techniques which are not specifically covered in topics 1-4 that can be used to improve heat recovery, efficiency, heat transfer, productivity, and economic performance. More specifically, this section covers the last 20 years of development in the motivation for change within the industry, general heat recovery techniques, electrical heating, and a literary overview of research activity related to reheating furnaces.

The main results of research into all 5 topics over the past 20-25 years is presented in chapter 3.1, in the sections of each topic.

3.1 Review of main relevant technologies

Historically, research and development of reheating furnaces have been driven by the effort to improve profitability, e.g., higher productivity, quality, and lower fuel consumption per ton of steel. However, in more recent years there has also been a rapid development towards the implementation of sustainable energy sources in steel reheating furnaces. The driving forces for these changes have to a large extent been due to policy changes within the EU, such as the Paris agreement in 2015, or the 2002 Kyoto protocol before that, which requires a major reduction in the CO_2 emissions from the steel industry.

In the following topic sections the findings and analysis from the review of EU reports and literature are presented relating to the specific field of each topic. Additionally, to evaluate activity within the literature related to reheating furnaces, a literature review was performed in Scopus using the following search term "TITLE-ABS-KEY (reheating AND furnace) AND PUBYEAR > 1989", which resulted in a total of 1212 documents. Based on this evaluation (see figure 1), scientific research related to reheating furnaces has increased since 1990 and has become increasingly dominated by the Asian regions since 2005, followed by the European region, and then the American region. Within their respective regions, China and the United States have a high share of the activity in the region, whereas publications among countries in the European region are more evenly distributed.

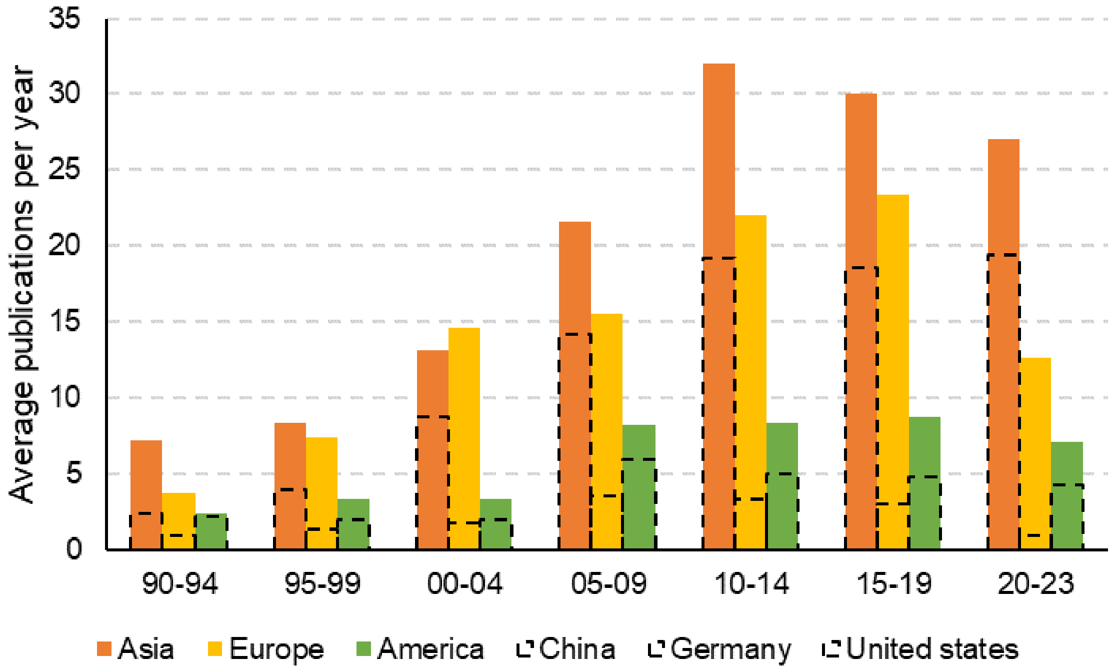

Figure 1. The average annual number of publications related to reheating furnaces in Scopus between 1990-2023 is based on region and the most active country in that region (dashed lines).

With respect to research topics (see Figure 2), the Asian region, and China in particular, publish the most journal articles and conference papers related to computer science and mathematics. The European region is most prolific for publications related to physics, energy, and chemistry, while the American region has the highest share of publications related to chemical engineering.

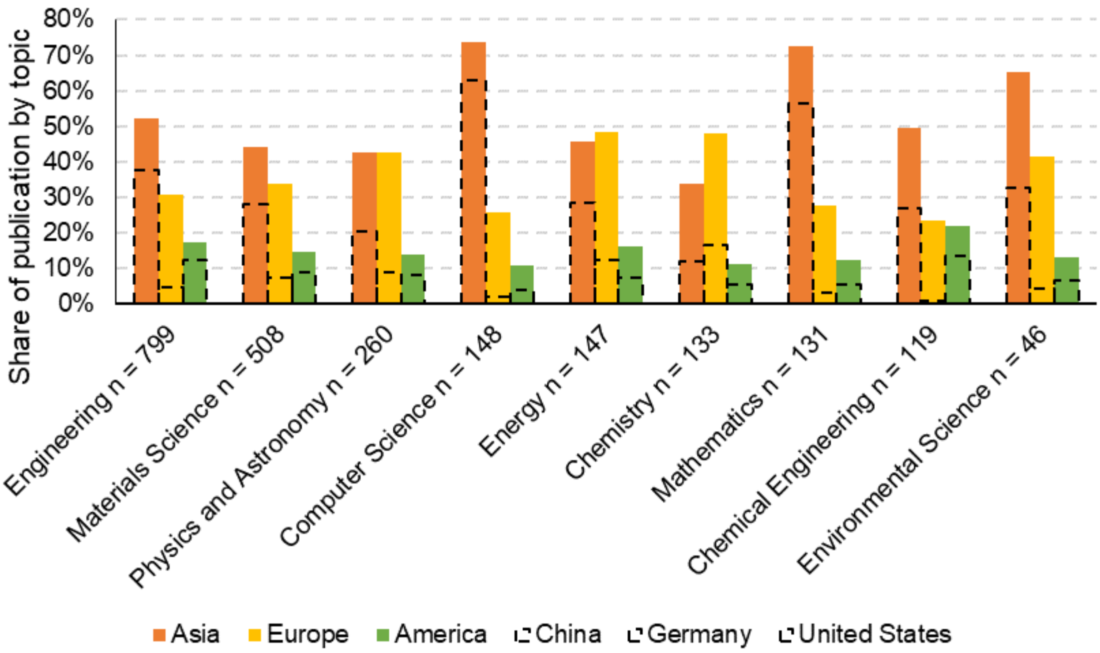

Figure 2. Share of publications by topic related to reheating furnaces in Scopus between 1990-2023 based on region and the most active country in that region (dashed lines).

Topic 1 - Heating and burner technology

Over the past 25 years the main relevant technologies/research topics in the field of heating and burner technology have been

- Energy consumption and CO_2 emission reduction (as well topic 5)
- Furnace productivity and product quality
- NO_X emission decrease
- Process gases as alternative fuels
- Latest research on Burners for HEC and 100% H_2,

Energy consumption and CO_2 emissions of with fossil fuel heated furnaces have been an issue in research and developments in projects and in literature over the complete reviewed period. The fuel consumption and CO_2 emissions are significantly reduced by heat recovery from flue gas to preheat combustion air. This has been investigated from 2000 on and reported since 2005 [1]-[3]. For heat recovery the sensible heat of the flue gas represents a major heat flow in reheating furnaces, which for a typical reheating process can account for as much as 40-45% of ingoing energy compared to systems without preheated air [4] – [5]. The sensible heat in the flue gas can be utilized by using it to preheat fuel, oxidant, and feedstock. For preheating of air and fuel, techniques such as central recuperators, or regenerative burners [6], [51] are used, whereas for feedstock preheating the furnace is designed with a long, non-heated “dark zone” which facilitates convective heat transfer between the flue gas and feedstock. Optimizing the heating process and the furnace atmosphere by furnace automation and control (level 1 and 2) have an additional effect on energy consumption and increase the efficiency of the heating process up to 10% (see Topic 2 and 3).

Furnace productivity has been an issue in the reviewed research projects in the fields of burner technology with regenerative heat recovery, oxy-fuel combustion, using process gases in heating zones and furnace automation (topic 1, 2, 3 and 5) [2], [6], [7], [8], [9] Productivity is increased by

- heating the preheating or dark zone (1st Zone) i.e., by regenerative burners instead applying the dark zone for heat recovery from flue gas.
- Optimised combustion and heat transfer with recuperative burners [10] and regenerative Burners [9] by increasing the mixing of heating gases combined with long flames for uniform heating with on/off operating burners. Additionally, temperature uniformity in the product i.e., slabs is achieved by optimized heat transfer.

Applying regenerative burners is possible to achieve very high preheating temperatures (>1000 °C), which allows for very low sensible heat loss [9]. Historically, this caused issues related to NO_X emission [11]. However, with the development of low-NO_X, or ultralow-NO_X regenerative burners and flameless combustion which can be coupled with regenerative air preheating, it is now possible to achieve very low sensible heat loss while keeping NO_X emissions low [1], [12], [13]. For regenerative burners with flame low NO_X emissions were decreased by applying process gases like blast furnace gas (BFG) instead of natural gas (NG) as shown in investigations with BFG preheating [6], [51].

Research focus of the past 25 years

The research topics of last 25 years focused on

- Furnace automation (level 1) and control (level 2) from 1998 onto current development [14], [15]
- Furnace productivity, efficiency and regenerative heating from 2000 to 2018
- Heating the heating zones with process gases instead of NG from 2009 to 2015
- Preheating process gases 2008 [3] and from 2018 on.
- NO_X emissions in connection with high preheated air from before 2000 to 2005 and due limits in regulations from 2008 on and again from 2019 on for again decreased limits as well as NO_X formation by applying Hydrogen as alternative fuels to substitute NG.

Latest research in furnace heating focusses on hydrogen combustion in the EU Horizon project [16], hydrogen enhanced combustion HEC [17]. Pilot testing and first installations in steel mills are reported since 2019 for HEC and 100% H_2 combustion [13], [18], [19].

Table 3.1 in **chapter 3.2.1** gives a technical overview of the state of the art on topic 1.

Topic 2 - Measurement and sensors, measurement-based furnace control (level 1); standards, regulations

Over the past 25 years, the main KPIs reported for furnace measurement technologies have been as follows:

- <u>Energy consumption</u> (e.g., GJ/t): Fuel consumption decrease through design of ideal heating curves and through of dynamic temperature control (model based).

- Furnace productivity (e.g., in t/h): Reducing energy consumption, better production planning and early detection of anomalies can of the process efficiency. This can increase furnace productivity.
- Scale loss (e.g., g/m²): Early detection of anomalies, predictive diagnosis preventing failures occurrence and avoiding failures propagation (not quantified) and reduction of unplanned machines shut downs can reduce scale loss

Table 3.2 in **chapter 3.2.1** gives a technical overview of the state of the art on topic 2.

Topic 3 - Measurement and sensors, measurement-based furnace control (level 1); standards, regulations

Over the past 25 years, the main KPIs reported for furnace measurement technologies have been as follows:

- Energy consumption (e.g., GJ/t): Optimizing the air ratio and the furnace temperature by avoiding overheating and thereby reducing fuel consumption through correct temperature and atmosphere measurement helps to improve the energy efficiency of the furnace.
- CO_2 emission (e.g., kg/t): The reduction of CO_2 emissions has become increasingly important in recent years. For level 1 measurement technologies, the reduction of CO_2 emissions is mainly linked to the reduction of energy consumption (see above).
- Furnace productivity (e.g., in t/h): Ensuring homogeneity and repeatability of the furnace temperature and atmosphere helps to ensure constant product quality and reduce product waste. This in turn increases furnace productivity.
- Scale loss (e.g., g/m²): Optimizing the oxygen content in the furnace through correct oxygen measurement helps to reduce scale loss.

The key technologies identified in topic 3 focus on improving the energy efficiency of furnaces and enhancing product quality using advanced measurement and control technologies. Many parameters such as temperatures, pressures, flows or atmosphere composition are continuously recorded in a reheating furnace. However, the most important parameters studied in recent years have been the charge temperature and the furnace atmosphere, in particular the oxygen content. Better temperature control aims both to reduce steel waste by ensuring sufficient and uniform reheating and to reduce the plant’s energy consumption. Better atmosphere control helps minimize fuel consumption and scale formation.

The **measurement and control of temperatures** inside the furnace has been the subject of several RFCS projects [20]-[23] over the past 20 years. In particular, the projects have focused on improving the accuracy of the methods used to determine the hot charge temperature during the process and the control algorithms to ensure optimum reheating conditions. Indeed, effective temperature control is crucial to achieving uniform stock temperature and product consistency. However, the charge temperature is difficult to access during the process, due to product movement and surface scaling. In some cases, it is possible to measure the charge temperature along the process using a prepared charge with shielded thermocouples (“tow test”). However, this technique is only used for research or calibration purposes. In practice, the charge temperature is controlled by measuring the temperature of the furnace atmosphere using thermocouples and then calculating the charge temperature using mathematical heating models. The furnace is usually divided into control zone, each with its own temperature sensor and controller [24]. However, the accuracy of this technique is quite low. Firstly, the temperature measured by the thermocouple is a mix of several variables such as gas temperature, wall temperature and stock temperature. Secondly, thermocouples give an insufficient temperature map of the furnace since the measurement is punctual. Therefore, new methods to measure the temperature distribution throughout the furnace and to obtain more information on the temperature of the charge where needed. The RFCS Project [25] and [26] both researched advanced temperature measurement technologies such as thermal imaging and IR pyrometry. These methods enable direct and contactless measurement of the surface of the product and of the furnace refractory. Both pyrometers and thermal imaging systems are already being used in reheating furnaces (i.e., at Celsa). Pyrometers can only measure a single spot and are usually placed at the inlet and outlet of the furnace. They require reliable values for emissivity of the object or material in the wavelength range used at the given temperature and their measurement can be influenced by dust, vapor and absorbing gases. Using thermal imaging, measurements over large areas is possible. This enables whole temperature mapping of the stock and furnace background [26]. Both systems can be affected by the hot combustion gases in the furnace, requiring an adapted wavelength of the system to avoid furnace atmosphere radiation. The systems also require a safe optical access to the product continuously. The projects [25] and [27] focused on optimization of the process control to achieve uniform temperature profile of the charge. Parameters such as the distance between the slabs and the firing time of burners were optimized to achieve uniform temperature profile of the charge.

Another important parameter is the **furnace atmosphere and more specifically the air-to-fuel ratio**. To ensure a safe combustion, it is necessary to control the oxygen and carbon monoxide content of the furnace atmosphere. Sufficient supply of oxygen is needed to have a complete combustion; however, an excess of oxygen causes heat loss and the gas consumption of the plant increases. The regulation of the air-to-fuel ratio can be done in different ways. The most conventional way is to control the air and gas flow measurement. The variables are then processed in an industrial controller or a PLC [28]. Other options such as pneumatic and electronic gas/air ratio controllers for gas burners and gas burning appliances can be purchased on the market (i.e., Honeywell) and have to comply with EN 12067-1 or EN 12078, respectively EN 12067-2. In [29], different sensors for oxygen measurements in the furnace were tested. Results recommend the use of zirconium dioxide-probes. Furthermore, a software controller for air-ratio control was developed and can be implemented to already existing furnace control systems.

In [29], continuous and portable flue gas analysis equipment to **measure the off-gas composition** were investigated. Both technologies are currently used in furnaces to monitor the furnace atmosphere and adjust the combustion settings. For the measurement of off-gas composition emitted in off-gas duct, the Standard Reference Methods (SRM) are defined in the following European Standard:

- EN 14789: Determination of volume concentration of oxygen – Standard reference method: Paramagnetism
- EN 14792: Determination of mass concentration of nitrogen oxides – Standard reference method: chemiluminescence
- EN 15058: Determination of the mass concentration of carbon monoxide – Standard reference method: non-dispersive infrared spectrometry

In [30], a novel inline **Acid Dew Point (ADP) sensor** was investigated. The driving force for the development of this technology was the strong temperature variation of steel mill gases. By measuring the off-gas temperature and dynamically adjusting it above the ADP, recovering waste heat from combustion can be improved up to 20%.

Further measurement devices and control strategies are currently being used in reheating furnaces but were not the main subject of the reviewed literature. I.e., creating a slightly positive **pressure** inside the chamber is a well-known measure to prevent outside air from entering the furnace [24]. For **gas temperature measurements**, suction pyrometers are typically used. These consist of a thermocouple and a suction probe that enables the measurement of the extracted gas flow [31]. In [20] further gas temperature measurement methods such as tunable diode laser absorption spectrometer (TDLAS) and ultrasonic (acoustic) gas temperature measurement devices were also investigated. Finally, gas and air flow meters are also important for reheating furnaces. Although many different types of flow sensors have been developed and are available on the market, such as vortex, ultrasonic, thermal or vane wheel anemometer, orifice meters are typically used to measure the flow rate using the Differential Pressure Measurement principle. These systems are known to be economical, durable and suitable for rugged applications, so not much has changed in recent years.

For industrial thermoprocessing equipment (IThE), EN 746-2 (2011) defines the safety requirements for burners and fuel handling systems. It describes more specifically the safety requirements for gaseous fuels, fluids, fossil material and oxygen. I.e., it deals with the design of the gas and air pipe, or the design requirement for the electrical and electronic equipment for control and protection systems. The latter section was not present in the 1997 version of the norm and was added to the 2010 version and defines the behaviour of the system in the event of a malfunction.

Table 3.3 in **chapter 3.2.1** gives a technical overview of the state of the art on topic 3.

Topic 5 - Heat transfer, heat recovery, productivity, economy, CAPEX, OPEX

Energy efficiency and mitigation of CO_2 emissions are analysed in this study in topic 1 and 5. Reducing CO_2 emission by reusing sensitive heat of the flue gas in the heating process is described in the topic 1 section therefore, reference is made here to this section (see above).

Another route to reducing CO_2 emissions is to switch from fossil-based fuel sources to green electricity I.e., electricity produced with sustainable power. Resistive and inductive heating is a commercially available technology and has been for some time but is implemented in a very limited capacity. For instance, the reheating furnace at Hallstahammar in Sweden which reheats billets, rods, and wires up to 1300 °C has been in operation for over 30 years, or the 20-50 MW inductive heating unit at ABP induction [32].

The use of inductive heating is typically limited to continuous operation at lower temperatures and smaller dimensional ranges. For larger dimensions like slabs or billets, there is ongoing research, but commercial installations are yet rare if any for the complete reheating to rolling temperature. While inductive heating offers very rapid reheating, the heating rate slows down and it is less effective above the Curie-point of the material, which is generally the case in reheating of steel.

The development of resistive heating has enabled the use of much higher process temperatures in the furnace. For instance, molybdenum disilicide elements can be operated at temperatures as high as 1800 °C and they can be replaced without cooling down the furnace [33]. The downside is that resistive heating elements are sensitive to contaminants, such as residual casting powder, which can significantly lower life expectancy. Furthermore, at high process temperatures, the specific hearth load of resistive heating is lower than a typical natural gas-fired furnace, and therefore requires more space for a given output [4].

Table 3.5 in **chapter 3.2.1** gives a technical overview of the state of the art on topic 5.

3.2 State of the art (current), Best available technology (BAT)

3.2.1 Technology overview

For topic 1 to 5 the current state of the art technologies based on the surveys in each topic are described in the following tables 3.1 to 3.5.

Table 3.1: Overview state of the art technologies of topic 1

Topic 1	**Heating and burner technology - Energy consumption and CO_2 reduction**
Description	Decrease of energy consumption of fossil-fuel-fired furnaces and resulting CO_2 reduction.
Technical description	Technologies applied to decrease of energy consumption in heating processes are: a) Heat recovery from flue gas by transferring the sensitive heat to the combustion air, fuel gas and/or the product in the dark zone of continuously operating reheating furnaces. b) Furnace automation (level 1) and control (level 2) with temperature and furnace atmosphere control optimizes the product heating as well as the heating process itself and reduces the flue gas flow by reducing the oxygen concentration in the furnace and flue gas (see topic 2 and 3). Additionally for production of frequently changing steel qualities the product heating is optimized regarding furnace loading, the following rolling process and the whole process chain by model-based control. This optimization leads to significant energy savings of 5 to 10 %. c) Substituting natural gas by process gases in integrated steel mills reduces the overall energy consumption if flaring of is avoided. d) Fuel heating of low calorific gases by heat recovered from flue gas.

Achieved environmental benefit	Reduced fuel consumption and CO_2 emissions.
Environmental (scope 1) and performance related operational data	For reheating furnace heated by fossil-fuels, the reduction in GHG emissions is equivalent to the amount of fuel savings. See table topic 5.
Broader environment impact (scope 2-3)	*
Technical limitations	Heat recovery systems require more space at the furnace. Preheating in a dark zone requires space as the furnace is much longer compared to those with complete heating by burners.
Economics	Reported in national funded projects i.e., in Germany return of in invest was 5 to 8 years (before 2010) but is directly dependent on fuel prices.
Driving force for implementation	Increased yield, improved product quality, modernization of processes, prices for fuel and energy and introduction of GHG certificates.
Case studies	Numerous research projects. For batch type furnaces/ forging furnaces with regenerative heat recovery the national project KINAMI in Germany [3]. In this project 3 batch type furnaces where fully equipped with regenerative burner system and one of these furnaces with the process gases COG and BOF. Because of good results at least 300 regenerative burner systems for natural gas where worldwide sold. The systems are in operation mainly in batch type furnaces.
Reference literature	[1], [2], [3], [6], [9], [10], [34], [51]

*) no information available in analysed reports or literature

Topic 1	**Heating and burner technology - Furnace productivity and product quality**
Description	Increase productivity of the reheating process in steel mills. Increase product quality by measures of the heating process.
Technical description	The furnace productivity is increased by heating the dark zone of a reheating furnace. Therefor new burners are installed in this zone. Furthermore, the productivity has been increased by replacing non preheated air burners or recuperative burners of the 1st or 1st and 2nd heating zone (furnaces

	without dark zone) in reheating furnaces by regenerative burner systems. The heating with regenerative systems increases heat transfer into the product because of higher flame temperature. This is often combined with burner designs to increase momentum at burner output or at its vicinity to increase flame length for large heat source volume. Flameless combustion is combined with regenerative air preheating to achieve furnace productivity in combination with energy savings and NO_X decrease (see table below). Furnace productivity is increased as well by applying NG or LPG oxy-fuel combustion with which a higher flame temperature compared to combustion with or without preheated air is achieved. Heating with oxy-fuel burners is attractive when there is only limited space available at the furnaces. Increased temperature uniformity in product is achieved by temperature uniformity in the furnace and by avoiding hot spots. Therefore i.e., burner design for high volume and long flames, uniformly distributed burner positions in the furnace, side and top-firing and by on off burner operation for high momentum in heating gases are targeted applications that have been reported on. Even wall cooling was successfully combined with these applications taking efficiency loss of about 1% into account, as reported in a research project. But no further application was found in further reports. Increased longitudinal temperature uniformity is achieved by accurate temperature control in Furnace as well. (See topic 2)
Achieved environmental benefit	*
Environmental (scope 1) and performance related operational data	*
Broader environment impact (scope 2-3)	*
Technical limitations	Limitations for replacing burner systems or changing burner positions and applying other or additional heat recovery systems are limited by existing space at the furnace and the furnace design. For applying furnace

	control (level 2) and measurement systems no technical limitations are reported.
Economics	*
Driving force for implementation	Increase the yield, improve the product quality, rolling characteristics and rolling behaviour of the heated steel as well as form stability before and after rolling.
Case studies	Numerous reports of research projects and reports/publications of furnace retrofits and upgrading.
Reference literature	[1], [3], [7], [9], [10], [13], [34], [35], [36], [37]

*) no information available in analysed reports or literature

Topic 1	**Heating and burner technology – NO_X - emissions**
Description	Decrease of NO_X - emissions from reheating furnaces by primary matters of the burners.
Technical description	In reheating furnaces NO_X originates from the combustion of natural gas, LPG or process gas in the furnace burners and is mainly thermal NO_X arising at high temperatures in the flame. Measures to reduce NO_X formation and emissions in heating processes are mainly primary measures at the burner as secondary measures like de-NO_X systems (SNR, SNCR) in the flue gas are accompanied by high investment and operating costs. Primary measures are mainly flue gas recirculation, air staging and flameless combustion. Due to furnace efficiency increasing by regenerative air-preheating and accordingly increased flame temperatures NO_X decrease is an issue. Flameless combustion is a very suitable technique to mitigate NO_X when applying regenerative air preheating. Further investigations will be necessary for furnaces where flameless combustion cannot be applied.
Achieved environmental benefit	Improved air quality in industrial regions, cities and improved protection of people and nature by reduced NO_X - emissions.
Environmental (scope 1) and performance related operational data	*

Broader environment impact (scope 2-3)	*
Technical limitations	Primary measures at the burner cause a significant modification of the system and requires in most cases a burner system exchange. Depending on the requirements for product heating and the available space in the furnace chamber, the most effective NO_X decreasing systems cannot always be applied. The existing space at the furnace is a further issue when exchanging burners.
Economics	Nowadays necessary ultra-low-NO_X burner systems and systems with flameless combustion usually afford higher investigation costs compared to conventional burner systems.
Driving force for implementation	Due to the harmful effects of NO_X on humans and nature and the increased use of combustion systems in industry and other sectors in the past, the reduction of emissions is constantly being set by repeatedly lowered limit values in the regulations for heating processes. (See topic 3)
Case studies	*
Reference literature	[3], [9], [13], [38]

*) no information available in analysed reports or literature

Table 3.2: Overview state of the art technologies of topic 2

Topic 2	**Computational fluid dynamic model of burner and combustion**
Description	Simulation of burners and furnaces in model to investigate heat and pollutant production.
Technical description	CAD software for building the model CFD software to perform the simulation through several approaches (e.g., RANS), describing kinetic chemistry and turbulence interaction Machine learning techniques to investigate combustion process Detailed kinetic schemes to simulate combustion process

Achieved environmental benefit	Simulation of innovative burners can lead to reduction of fuel consumption and to a lower pollutant production
Environmental (scope 1) and performance related operational data	*)
Broader environment impact (scope 2-3)	*)
Technical limitations	No limitations in the sector Kinetic schemes reliability can be improved
Economics	CAD software: CAPEX ~ 3.000 - 20.000€ CFD software: CAPEX ~ 20.000 - 60.000€ Some opensource and/or freeware software exist, for both kind of software, but they are less efficient
Driving force for implementation	*)
Case studies	- walking beam furnace No. 304 at SSAB (Tunnplat AB, Borlänge)
Reference literature	[1], [39], [40]

Topic 2	**Furnace Models**
Description	Simulation thermal simulation of zone of the furnace and heating curve of the product.
Technical description	Zone model Statistical model Machine learning model. Dynamic furnace model for predictive control
Achieved environmental benefit	Simulation of whole furnace can lead to better scheduling, more stable and efficient productivity and problem detection in advance

Environmental (scope 1) and performance related operational data	*)
Broader environment impact (scope 2-3)	*).
Technical limitations	No limitations in the sector Great amount of data required for statistical and machine learning model
Economics	Most of economic expenses are due to data collecting
Driving force for implementation	Data availability
Case studies	- Thyssen Krupp Steel AG in Bochum (Germany) - hot strip mill at SSAB Tunnplat AB Works in Borlänge - Acciai Speciali Terni Walking Beam furnace
Reference literature	[41], [42], [43] [44], [20]

*) no information available in analysed reports or literature

Table 3.3: Overview state of the art technologies of topic 3

Topic 3	**Temperature measurement and control**
Description	Implementation of temperature measurement techniques and control of the furnace and of the charge
Technical description	Thermocouples: measurement of furnace atmosphere temperature and estimation of the charge temperature using mathematical heating models Infrared pyrometers: non-contact single point radiation thermometer Thermal imaging: complete temperature measurement of an area using infrared radiation; provides a complete picture
Achieved environmental benefit	Improved temperature measurements help to optimise heating, reducing the plant’s energy requirements and emissions. It also helps to ensure a uniform temperature and product quality, reducing wastage.

Environmental (scope 1) and performance related operational data	*)
Broader environment impact (scope 2-3)	*)
Technical limitations	No limitation throughout the sector. Technical restriction for pyrometers and thermal imaging: optical access (viewing angel 30° to 60°). Thermocouples: 9 IR pyrometers TRL:9 and thermal imaging cameras: 8-9
Economics	Thermal imaging: CAPEX ~ 60.000€
Driving force for implementation	*)
Case studies	- Sansera Engineering Ltd Plant 7 (India) - Nervacero (Celsa group)
Reference literature	[20 – 23] https://visiontir.com/temperature-monitoring-solutions-for-metal-reheat-furnaces-application-note/ https://www.ametek-land.com/applications/steel/hotrollingreheatfurnace
Topic 3	**Furnace atmosphere control**
Description	Control and monitoring of air-to-fuel ratio
Technical description	- Measurement of the oxygen content or air flow and software controller to adjust air-fuel ratio - Pneumatical or electrical air-fuel controller
Achieved environmental benefit	Ensure a safe combustion (no air deficiency), minimize fuel consumption, minimize scale loss, minimize flue gas emission
Environmental (scope 1) and performance related operational data	Energy consumption and CO_2 emissions: decrease between 2.4 to 6% Scale loss: decrease *)
Broader environment impact (scope 2-3)	*)

Technical limitations	Measurement of the oxygen content or air flow and software controller to adjust air-fuel ratio: no restrictions. TRL: 9 Pneumatical or electrical air-fuel controller: not all applications are applicable for hot air operation. TRL: 9
Economics	OPEX decrease (according to fuel consumption)
Driving force for implementation	EN 746-2 requires in section 5.2.3.3 that the air and gas mass flow to each burner be in ratio that allows stable and safe burner operation.
Case studies	Walking beam furnace of "Neue Max Hütte”
Reference literature	[29, 30]

*) no information available in analysed reports or literature

Table 3.5: Overview state of the art technologies of topic 5

Topic 5	**Heat transfer, heat recovery, productivity, economy, CAPEX, OPEX**
Description	Reduction of sensible heat loss in the flue gas by preheating of combustion air, fuel, or feedstock.
Technical description	Preheating the fuel, oxidizer or feedstock significantly increase the thermal efficiency of the furnace and lows the total energy usage per ton of produced feedstock. This can be achieved using techniques such as central recuperators, regenerative burners, or long, non-heated “dark zone” in the furnace. The potential for heat recovery is dependent on the type of fuel and oxidizing media used. With fuels and oxidants with a high amount of thermal ballast such as CO_2 and N_2, the relative share of input energy stored as sensible heat in the flue gas increases, which also increases the requirement for convective heat transfer in the process. This is also the case for hot/direct charging, as the temperature of the flue gas will increase with the temperature of the incoming feedstock.

	Depending on the above, techniques, or combination of techniques that can reduce flue gas exit temperature of reheating furnaces to 400-500 °C can be considered best available technology, whereas 200-300 °C can be considered state of the art. If there is no possibility to use excess sensible heat to preheat air, fuel, or feedstock, a secondary option is to produce additional value for the process using a waste heat boiler. While this increases the total efficiency of the process and can provide additional revenue, it does not lower the specific energy consumption per ton of feedstock.
Achieved environmental benefit	Reduced fuel consumption. Enabling the use of low calorific process gases
Environmental (scope 1) and performance related operational data	For reheating furnaces using fossil-based fuels, the reduction in GHG emission is equivalent to the amount of fuel saved. Regenerative and recuperative system can also enable the use of low calorific process gases, which can substantially lower GHG emissions compared to a fossil-based fuels if there are no alternate uses for the process gas at the plant. Recuperative systems in reheating furnaces can typically achieve air preheating temperatures up to 600 °C, with typical flue gas stack temperatures of 400-500 °C. This can result in fuel savings up to 30 % compared to a system that does not implement sensible heat recovery. While it is technically possible to achieve higher preheating temperatures by using more heat resistant material in the heat exchanger, it is not cost effective. Higher efficiencies are possible if recuperative systems are paired with effective feedstock preheating techniques, which makes it possible to reach flue gas stack temperatures of 200-300 °C. State of the art regenerative combustion systems can achieve air preheating temperatures of more than 1000 °C, and regenerator efficiency of 75%, while keeping NO_X - emissions low. Implementation of this technique can result in fuel savings of up to 50% compared to a system that does not implement sensible heat recovery and 10-20% fuel savings compared to a typical central recuperative with a flue gas stack temperature of 400-500 °C. Beside of reheating furnaces in rolling mills regenerative burner

	systems are well suited for batch processes as well as they can accommodate the cyclic nature of these processes. Continuously operating regenerative burner systems based on the Ljungstrom air preheater [45] have been developed as well and investigated for furnace heating in a national project [34] but further investigations in this technology are necessary.
Broader environment impact (scope 2-3)	*
Technical limitations	The installation of regenerative burners or a recuperative heat exchanger will require more space to be installed, as would the installation of a preheating system using flue gas which can limit implementation. Preheating of feedstock is limited by the temperature of incoming feedstock and would be limiting in the case of hot/direct charging.
Economics	Productivity increases of up to 15% have been reported when regenerative burners were installed in previously cold fired systems. No reliable information was found with respect to investment costs of recuperative/regenerative systems with respect to installed capacity while operating expenses would decrease equivalent to the amount of fuel saved. However, the installation of recuperative and regenerative system is likely to increase running maintenance cost as depending on the ceramic heat exchanger geometry heat transferring surfaces needs to be serviced to operate at high efficiency. In comparison to older cold fired systems, payback times of a few years were reported as the installation of a heat recovery system affords new and suitable burners. The payback is directly dependent on the fuel price.
Driving force for implementation	*
Case studies	*
Reference literature	[1], [2], [5], [9], [12], [46], [47]

*) no information available in analysed reports or literature

3.2.2 BAT, related to topic

The relevant BATREF for dissHEAT is:

BAT document on the ferrous metals processing industry (2022-11) [12]. (https://op.europa.eu/en/publication-detail/-/publication/0923f1e0-751f-11ed-9887-01aa75ed71a1)

This document has been analysed for each topic regarding ecological impact and applicability: what is nowadays available technology BAT for current and future questions on the pathway to green deal. A summary of BAT for all topics and an assessment is listed in table 4.

Table 4: Overview BAT

Topic 1 to 5	**Reheating process in steel mills and forging plants**
Current and future question/concerns for choice of BAT	Boundary conditions of existing plants, processes, process chains and requirements based on steel grades in steel mills, rolling mills or forging plants are significantly relevant when defining BAT for the reheating process. Additionally, ecological impact, availability of resources and green deal have been taken into account when assessing BAT here. In addition to the demand for steel and economical aspects, from the technical point of view, energy consumption and emissions are the main focus of the evaluation and selection of BAT. Energy consumption levels of natural gas or process gases for reheating processes are 560 – 2.500 MJ/t and even above 5.000 MJ/t for feedstock reheating. NO_X - emissions from reheating furnaces heated by NG and process gases are currently 30 to 330 mg/Nm³ some > 1000 mg/Nm³ (at 3% Oxygen) These levels and values indicate how wide the range is and that there is potential for reducing consumption and emissions. It is necessary to examine from plant to plant which technologies are applicable in each case to reduce these values. In the following BAT to achieve this is chosen and describe. Note: 1. As in the analysed BATREF document fuels are NG and process gases the CO_2 emissions are proportional to energy savings. 2. Future technologies are not topic in BATREF and of the assessment in this chapter/table.

BAT	Techniques for **efficient** state of the art furnaces (BATREF) are: An optimized and customized furnace design for the specific heating function in the process. A well-insulated furnace chamber with either refectory lining, ceramic fibre insulation or combination of both referring to heating procedure (continuously or batchwise operated furnace). Additionally optimised furnace door design to avoid leakage considering the heating procedure. In integrated steelworks the **efficiency** is increased by substituting the fuel NG by process gases COG, BFG and BOF for furnace heating. It reduces CO_2 relating to scope 1 for the whole steel production process. Increased **efficiency**, improved product quality, decreased CO- and NO_X - **emission** are as well achieved by furnace automation (level 1) and control (level 2) for optimized product heating – topic 2 and 3 in combination with model-based (computer program/application) furnace and process control (level 2) to predict needed optimal heating conditions for optimal product quality and the following step of product treatment (rolling/forging) in the process chain. BATREF: Energy reduction 10%. Heat recovery from furnace flue gas either by regenerative or recuperative systems (topic 1 and 5) increase the **efficiency** compared to heating with non-preheated air: BATREF (chapter 2.4.2.3) regenerative heating - energy reduction 40% BATREF (chapter 2.4.2.4); recuperative heating - energy reduction 25%. Regenerative systems in heating zone can **increase productivity** or reduce furnace size as unchanged productivity as well as reduce energy demand but affords additional maintenance due to cleaning of ceramic heat exchangers. NO_X **emissions** increase as with highly heated combustion air the flame temperature increases which causes thermal NO_X

	formation. Primary low NO_X techniques are necessary. Heat recovery from a cooled transport system as in a walking beam furnace with skids cooling can lead to an overall energy reduction if skids are not well insulated. Oxy-fuel combustion is a technique if due to limited space in the production process a **production increase** is necessary. Oxy-fuel combustion with 100% oxygen significantly decreases **energy consumption** in the heating process due to reduced sensitive heat loss in the flue gas. But an analysis of energy consumption concerning scope 2 is necessary to produce the afforded oxygen and the operating costs increase due to cost for oxygen. Above mentioned techniques and measures achieve significant energy savings in reheating processes. **The next level for energy saving** can be achieved in continuously operating reheating processes: High efficiency is achieved in continuous steel making process with continuous rolling and a **hot/direct charging** of reheating furnaces. BATREF (chapter 2.4.2.16) hot charging (300 – 600°C) energy reduction at 400° charging: 19 % direct charging (600 – 850°C) energy reduction at 750°C charging: 39 % If hot charging from continuous caster and reheating furnace is not foreseen in the steel mill the heat conservation of the feedstock by insulated covers can be achieved during the transfer to the reheating furnace. This is applicable if the storage time for casted product is not too high (below 24h) and enough space at the plant / feedstock storage is available. Combined casting and rolling offer further possibilities to **increase efficiency** of the production process by

	near-net-shape casting where the need for reheating the steel before rolling is significantly reduced. The energy consumption is reduced to < 900 MJ/t compared to conventional hot strip mills of 1.150 MJ/t to 1.700 MJ/t [BATREF Chapter 2.4.2.17]. NO_X **emissions** are significantly decrease by Flameless combustion. Flameless combustion is state of the art burner technology to decrease NO_X and CO emissions in heating processes. It can be combined with air preheating and oxy-fuel combustion. It is applicable if the reheating furnace design and the space for the flames inside the furnace has to be given in furnaces selected for modernization. If flameless combustion is not applicable, low-NO_X burners can be utilized instead. Low-NO_X techniques are internal flew gas recirculation, air staging, furthermore Low-NO_X systems can be combined with external flue gas recirculation to further decrease NO_X formation. This affords additional invest costs. If none of the primary measures to decrease NO_X is applicable de-NO_X techniques in the exhaust system like SCR or SNCR have to be equipped. These systems cause investigation costs and operating costs EUR 2 per kg of NO_X reduced. **Product quality** can be **increased** by the design of skids of the walking beam transport system in a continuously operated reheating furnace. A well-insulated transports system decreases energy loss of the reheating process.
Estimation of applicability of chosen BAT	All mentioned techniques except for hot or direct charging are more or less applied in current reheating furnaces. Hot charging is a question of the existing space near the furnace or the feedstock and, due to the simple technology it is not associated with high costs but rather with the question of handling. Direct charging is a question of the generally planned production process and well suited for consistent steel qualities.
Expected environmental benefit	Mentioned at the described technique itself.

Technical limitations	Space at the plant and near the reheating furnace. In case of direct charging the flexibility of the process concerning different steel qualities and the frequency of changing qualities.
Economics	**
Chosen for future roadmap	Yes. Especially direct heating and combined casting and rolling.
Reference	BAT Reference Document Best Available Techniques (BAT) Reference Document for the Ferrous Metals Processing Industry, year, 2021, [12]

**) no information available in BATREF document

4 Emerging technologies for future developments

For topic 1 emerging technologies are direct heating and combined casting and rolling for continuous production of one steel quality as well in future for frequently changing steel qualities. The combination of electrical heating and heating by combustion with Hydrogen. As the direct use of green electrical power for heating is preferable to combustion of hydrogen which is produced by renewable electrical power. As the reheating affords high heating density in the furnace which cannot be provided by resistive heating by now.

For Topic 2 the use of machine learning, joining of statistical models and physical models are emerging technologies. Additionally, Aspen Plus and plant simulators for the simulation of CO_2 capture [4] are of relevance for modelling in topic 2.

For topic 3 the emerging topics are

- temperature measurement: Thermal imaging (Emerging), IR pyrometers (SoA) -> accurate temperature measurement, whole image of furnace possible with thermal imaging
- Air-fuel-ratio detection by applying an oxygen probe in combination with a software controller.

Further emerging technologies relate to both topic 1 and 5:

Plasma heating (electric)

Plasma jet reheating of steel has been demonstrated in a pilot-scale chamber furnace at ScanArc, Hofors, Sweden in the PLATIS project [48]. Various steel alloys were reheated with a set of selected furnace atmospheres to examine the effect of the novel reheating method on the steel properties. Plasma jet technology offers a method to reach very high furnace temperatures, for example, in soaking zones. No commercial installations are known for steel reheating furnaces, and additional R/D is recommended to reduce the risk for high NO_X levels and reduce burner maintenance costs. A radiative gas like CO_2 or water vapour can be used to increase the radiative heat transfer in the furnace. Gas dissociation and recombination using the plasma burner can give a highly radiative jet with a similar appearance to the flame in a conventional combustion-fired burner (see **figure 3**). The dissociation of water vapour in the plasma burner into hydrogen and oxygen and recombination in a "combustion flame" would provide a process with similarities to hydrogen combustion in a traditional burner.

Figure 3: The plasma jet (or flame) from a laboratory plasma burner (Swerim)

Hydrogen combustion

Hydrogen is commonly used in steel reheating furnaces as a major component of coke oven gas (COG) but it is much less common to use fuels which are dominantly hydrogen. One example of the use of nearly pure hydrogen in a steel reheating furnace was the use of waste hydrogen gas as one of the fuels in the pusher furnace at Celsa, Mo-i-Rana, Norway. No major issues are anticipated for the replacement of fossil fuels with hydrogen for steel reheating furnaces.

A key point is to consider process efficiency. Hydrogen produced by the electrolysis of water could be used to provide oxygen for oxy-fuel combustion which has the potential to increase the productivity and efficiency of the furnace. Plus, the overall process efficiency could be improved by locating the electrolysis unit close to the steel mill so that the costs and energy requirements for the compression and transportation of the gases could be minimized. The overall energy efficiency of commercial electrolytic hydrogen production is in the range of 62-82%. A benefit is that oxygen is a by-product of the process which could be used for oxy-fuel combustion which has been shown to increase the overall process efficiency [49].

Synthetic fuel production

The storage and transportation of hydrogen can require large amounts of energy so the production of synthetic fuels should be considered for improving overall energy efficiency while providing additional revenue. One of the simplest alternatives is to produce methane, which is the main component of natural gas. Methane is easier to transport than hydrogen, since there is a large network of natural gas pipelines, plus existing natural gas storage sites could be used. Natural gas has historically been widely available at a reasonable price, so synthetic natural gas (SNG) has only been demonstrated in a few projects. There has been the ETOGAS project together with

Audi in Werite, Germany using waste CO_2 from a biogas plant to produce SNG in a 6 MW power-to-gas project. Another EU demonstration project HELMETH reached an efficiency of 76% [50].

Hybrid reheating (combining electric and combustion heating methods)

The combination of induction preheating with other GHG-free technologies for the soaking zone would be a topic of future research which could lower the cost compared to a pure combustion process. Electrical preheating of steel slabs followed by two combustion zones was demonstrated in a pilot furnace at SWERIM in the RFCS project [7].

Flameless oxy-fuel combustion of fossil fuels (oil/natural gas) with CCS/CCU

Carbon capture and storage (CCS) or use (CCU) would be theoretically possible for most steel reheating furnaces since there are processes for the separation of CO_2 from exhaust gases. The gas could be liquified and transported for underground storage in depleted oil wells. The economics of separation of CO_2 from furnace exhaust gases was evaluated as an option in the PLATIS project, but no steel reheating furnaces are known to commercially use this process.

5 Summary

Well-designed furnaces customized for the specific needs of production and process chain in steel mills, rolling mills and forging plants are the basis for an efficient industrial heating process in steel industry. Applying heat recovery to use sensitive heat from flue gas for combustion air or fuel preheating, using process gases in integrated steel mills as well as oxy-fuel combustion are measures to significantly increase energy efficiency of the heating process.

Additionally, the overall, temperature and furnace atmosphere measurement and control (level 1) are the main key technologies to reduce energy consumption, CO_2 emissions and scale loss. Technologies such as air ratio controller and continuous oxygen measurement devices are of main interest to adjust the optimum oxygen content inside the furnace. By minimizing the oxygen content whilst ensuring sufficient oxygen for a safe combustion, fuel consumption and scale loss can be decreased. Furthermore, measuring the composition of the off gas also helps adjust the burner settings and decrease pollutant emissions. In addition, contactless measurement methods can also help reduce fuel consumption through better temperature monitoring of the process. Contactless technologies such as IR pyrometers or thermal imaging can be used to measure the actual temperature of the charge before, during and after the reheating process. These technologies also help ensure uniform temperature across the charge and thereby avoid wastage due to inconsistent product quality. Temperature uniformity and fuel consumption can also be reduced optimizing the firing time of burners based on the position of the product in the furnace, the desired transverse temperature profile and the type of charge. In order to measure the temperature of the process gases, suction pyrometers can be used. Portable and fixed off-gas composition analysers help check and monitor the combustion settings of the furnace to reduce pollutant emissions. Finally, new ADP and corrosion sensors can measure and adjust the temperature of the off gas above the ADP to recover waste-heat.

The model-based furnace control (level 2) in combination with a furnace control system (level 1) and carefully selected measurement technology - as explained – further significantly increase energy efficiency of up to 10%.

Hot or direct charging in reheating furnaces is the next level to increase energy efficiency of up to 39%. Further significant increase of energy efficiency is - if applicable in existing steel works – achieved by combining continuous casting with continuous rolling and near shape casting. The energy consumption can be reduced to < 900 MJ/t compared to conventional hot strip mills of 1.150 MJ/t to 1.700 MJ/t.

Table 5 summarises the technical measures to increase efficiency and reduce CO_2 emissions identified in this study. Additionally, the relevant techniques to reduce NO_X emissions and to improve control and measurement technology for reheating furnaces are listed.

Table 5: Summary of technical measures used to improve performance of exiting or state of the art reheating furnaces

Measure/technology **Topic 1 and 5**	**Description**
Furnace design optimization	Minimizing the loss of heat due to furnace design, or optimizing placement of burners and flow patterns etc.
Regenerative burner	Regenerative burners consist of two burners which are operated alternately, and which contain beds of refractory or ceramic materials. While one burner is in operation, the heat of the flue gas is absorbed by the refractory or ceramic materials of the other burner and then used to preheat the combustion air.
Recuperative burner	Recuperative burners employ different types of recuperators to directly recover heat from the exhaust gases, which are then used to preheat the combustion air.
100% oxy-fuel	Combustion air is fully replaced by oxygen
oxygen enrichment	Combustion air is partially replaced by oxygen
Oxygen lancing	Instead of adding oxygen into the combustion air stream of each burner as done with traditional oxygen enrichment, oxygen is injected at high velocity at a short distance from the burner, allowing the oxygen to be diluted by furnace fumes before it takes part in the combustion
Flameless combustion	Flameless combustion is achieved by injecting fuel and combustion air separately into the combustion chamber of the furnace at high velocity to suppress flame formation and reduce the formation of thermal NOx while creating a more

	uniform heat distribution throughout the chamber. Can be used in combination with oxy-fuel combustion.
Pulse fired burner	The heat input to the furnace is controlled by the firing duration of the burners or by the sequential start of the individual burners instead of adjusting combustion air and fuel flows.
Flue gas recirculation	Partial recirculation of the flue-gas to the combustion chamber to replace part of the fresh combustion air, with the dual effect of limiting the O_2 content for nitrogen oxidation and reducing the combustion temperature, thus limiting NO_X generation.
Optimized skid design	The design of skids in reheating furnaces is optimised to minimise skid marks on the feedstock using skid riders, skid shifting or a skid mark compensation device
Heat recovery from skids	Steam produced when cooling the skids supporting the feedstock in the reheating furnaces is extracted and used in other processes of the plant.
Heat conservation during transfer of feedstock	Insulated covers are used between continuous caster and the reheating furnace, and between the roughing mill and the finishing mill.
Hot/direct charging	Continuous-cast steel products are directly charged hot into the reheating furnaces or directly transferred to the rolling mill in hot conditions
Organic Rankine cycle	Low-grade heat from the exhaust gases of hot rolling reheating furnaces is converted into electricity using high-molecular-weight fluids
Furnace automation and control	The heating process is optimised by using a computer system controlling in real time key parameters such as furnace and feedstock temperature, the air to fuel ratio and the furnace pressure (see table below for topic 3)
Feedstock preheating	Feedstock is preheated by blowing hot flue-gases directly onto it
Waste heat recovery boiler	The heat from hot flue-gases is used to generate steam or hot water that is used in other processes, district heating or for generating electricity.
Combustion optimization	Measures taken to maximise the efficiency of energy conversion in the furnace while minimising emissions. This is achieved by a combination of techniques including good design of the furnace, optimisation of the temperature, fuel-air mixing, and residence time in the combustion zone.

Measure/technology **Topic 3**	**Description**
Air ratio controller and furnace atmosphere measurement (O_2, CO)	Atmosphere control to improve the surface quality of rolled products (reducing scale loss) and to reduce the thermal energy loss caused by the mass flow of unused air, thereby reducing energy consumption.
Furnace control algorithm for pulse fired burners	Optimisation of the heating control with an algorithm that determines the firing time of the burners depending on the position of the product in the furnace, the desired transverse temperature profile and the type of charge. Helps improve temperature uniformity and fuel consumption.
Slab distance optimization for roughing mill	Periodic check of the distance between the slabs for better control of the temperature homogeneity of the slabs.
Contactless temperature measurement of hot surfaces	Improve thermal process control by measuring the true temperature of the load instead of calculating it using mathematical heating models and the furnace atmosphere temperature.
Furnace pressure measurement and control	Maintaining a slightly overpressure inside the furnace to prevent ambient air aspiration and thereby ensuring temperature uniformity and reducing energy requirement of the furnace.
Gas temperature measurement	Measurement of gas temperature inside the furnace for the control systems (e.g., to help model heat transfer to the charge) using i.e. pyrometers.
Off-gas composition measurement	Using portable or fixed analyzers to measure CO, CO_2, O_2, SO_2, NO, NO_X in the off-gas duct and optimize the burner settings to reduce pollutant emissions.
Stock temperature measurement	Using instrumented billet to measure stock temperature inside the furnace to improve and calibrate furnace models.
Acid Dew Point (ADP) sensor	Adjustment of the flue gas temperature above the ADP using an ADP sensor installed before the heat exchanger and increase the use of waste heat.

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Acknowledgement

This project has received funding from the Research Fund for Coal and Steel under grant agreement No 101057930.

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