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

Report with categorized applications and technologies for low CO_2 heating

Deliverable 2.3

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Dissemination level: Public

Version 2.0

Published 2023-11-29

Content

1 Introduction

The DissHEAT project evaluates and promotes research carried out over the last 20 years in the field of reheating technology in the steel industry. To this end, past projects have been critically reviewed and categorised into different topics.

The processing of ferrous and non-ferrous metals in reheating furnaces is always aimed at achieving the best possible product quality while minimising costs, air pollution and, in recent years, CO_2 emissions. In this document, several state of the art and emerging, low TRL reheating technologies relevant to low CO_2 heating have been identified.

The identified technologies are divided into technologies with high TRLs above 7 and emerging technologies with TRLs below 7. The review of the technologies is mainly based on the CO_2 reduction potential, but also considers the impact on auxiliary equipment and economic implications. Advantages and disadvantages are listed for the technologies.

The identified technologies are classified into five different topics:

1. Heating and burner technology
2. Modelling of entire furnaces, Level-2 control
3. Sensors and controls (Level-1), standards, regulations
4. Materials in the furnace and product quality
5. Heat transfer, heat recovery, productivity, economy

2 Methods

Due to the limited availability of quantified CO_2 emission reduction figures, the technologies are further categorised according to their area of action for CO_2 reduction to provide an approximation of their potential. To illustrate these potentials, the energy flows of a pusher-type furnace heated with natural gas, coke oven gas and air are presented as an example in a Sankey-diagram in Figure 1. Considering a carbon intensity of 200.88 g_{CO2}/kWh for natural gas and 147.6 g_{CO2}/kWh for coke oven gas [1], the total CO_2 footprint of this furnace is approximately 59.34 kg_{CO2}/t_{steel}. Several measures can be adopted to reduce the CO_2 footprint of the furnace, but these measures have different degrees of impact. In the following, the CO_2 emission reduction potential has been calculated for different areas of the furnace to illustrate the level of impact the different technologies can have. To keep the calculation simple, it has been assumed that the measures have no effect on the other energy flows in the furnace. However, in a real application, most changes in the process can affect the rest of the furnace energy balances. The goal of the calculation is to give an order of magnitude for the different areas of action for the CO_2 reduction.

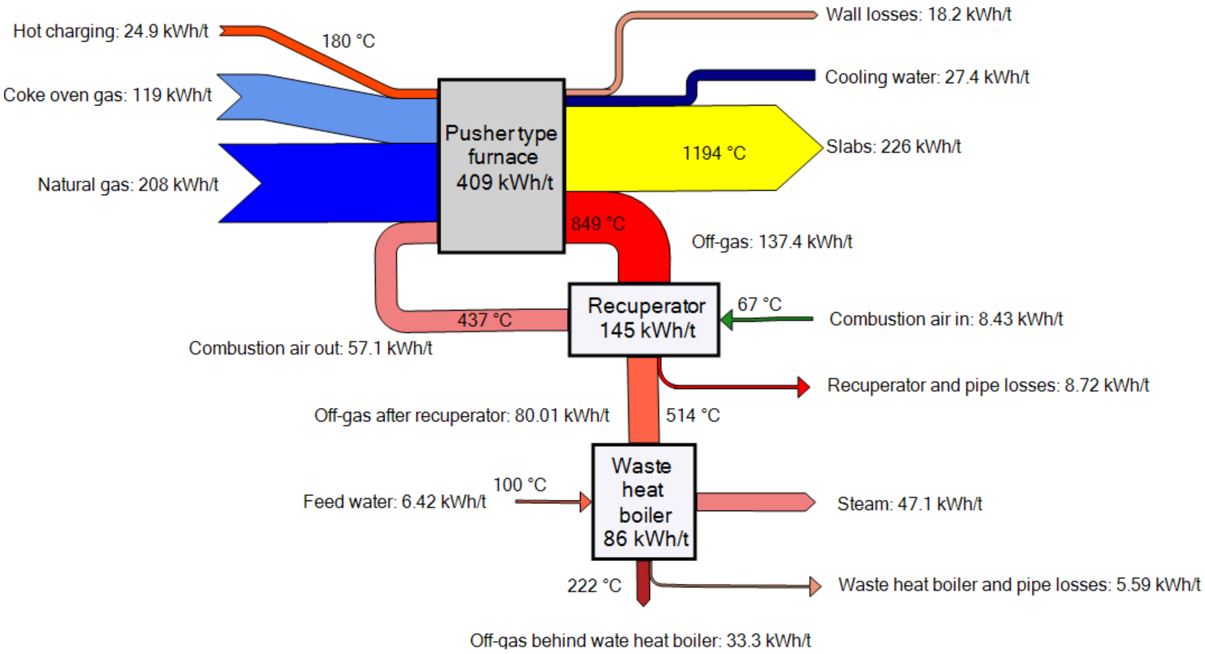

Figure 1: Sankey-diagram of a pusher-type furnace, 2005 [2]

A first area for CO_2 emission reduction measure is furnace losses. Reducing the losses leads to a reduction in the fuel consumption of the furnace. For example, reducing the furnace losses by half could reduce the CO_2 emission of the furnace by approximately 1.65 kg_{CO2}/t_{steel} (2.8%).

Another area of action would be to reduce the fuel consumption by increasing the temperature of the preheated air. This could be achieved, for example, by improving the efficiency of the recuperator. For combustion air temperatures of up to 650 °C [3] there is a potential reduction in CO_2 emissions of up to 5 kg_{CO2}/t_{steel} (8%) in this case.

Another possibility to reduce the fuel consumption of the furnace is to increase the temperature of the charged slabs to, e. g., 400 °C. This increase in slab temperature would result in a reduction in CO_2 emissions of approximately 5.4 kg_{CO2}/t_{steel} (9%). For the sake of simplicity, the calculation was made assuming that the total energy demand

and capacity of the furnace didn't change. However, changing the temperature of the slab would have a non-negligible impact on both.

Finally, the substitution of carbon intensive fuels with carbon free fuels or electricity would have a much more significant impact on reducing CO_2 emissions than the previous technologies. It could potentially reduce the CO_2 emission of the furnace to almost zero, assuming the use of green energy.

3 List of high TRL technologies for low CO_2 heating

This section describes high TRL (> 7) technologies that help reduce the CO_2 emissions from reheating furnaces.

Table 1: Overview of high TRL technologies for low CO_2 heating

Identified technology	Related topic	TRL today	Area of action for CO_2 reduction	CO_2 emission reduction (scope 1)	CO_2 emission reduction (scope 2)
Self-recuperative burners [4]	1	9	Fuel savings by reducing off-gas heat losses through heat recovery.	Equivalent to fuel savings. Up to 30% fuel savings compared to cold air combustion.	No significant impact.
Regenerator burners, regenerative air preheating through off-gas heat recovery [5–8]	1	9	Fuel savings by process internal heat recovery from off-gases.	From 12% to 40% compared to recuperative systems with an average of 300 °C recuperative preheated air.	No significant impact.
Oxy-fuel combustion [9,10]	1	9	Fuel savings by decreasing off-gas heat losses.	From 20% to 60%.	No significant impact.
Oxygen lancing [11–13]	1	9	Fuel savings by decreasing off-gas heat losses.	From 15% to 30%.	No significant impact.
Fossil free CH_4	1	9	Substitution from fossil fuels with a low CO_2 energy source.	No direct emissions if the carbon is biogenic.	Electricity based CH_4 would be similar to H_2 based on electrolysis. No numbers available for biomass-based methane.
Fuel preheating of blast furnace gas with or without oxy-fuel combustion/ OEC [14]	1	7-8	• Substitution of natural gas by process gases in heating processes. • Increased efficiency by heat recovery from exhaust gases.	50-60 kg_{CO2}/t_{Steel} assuming the BFG has no CO_2 footprint.	No significant impact.

Identified technology	Related topic	TRL today	Area of action for CO_2 reduction	CO_2 emission reduction (scope 1)	CO_2 emission reduction (scope 2)
Indirect resistive heating [15]	1	4-9	Substituting fossil fuels with a (potentially) low CO_2 energy source.	No direct emissions.	No impact.
Inductive heating [16,17]	1	4-9	Substituting fossil fuels with a (potentially) low CO_2 energy source.	No direct emissions.	Higher than electric resistive heating due to lower efficiency.
Diagnostics, Warning and Suggestion system (DWS) [18]	2	7	CO_2 reduction by fuel saving, obtained by decreasing heat demand to achieve target temperature.	Up to 3% reduction in CO_2 emissions.	No impact.
Dynamic Furnace Model [19]	2	7	CO_2 reduction by fuel saving.	From 3% to 6% reduction in CO_2 emissions for high productivity (> 350 t per day) and from 7% to 13% for low productivity (< 350 t per day).	No impact.
Furnace Model coupled to microstructural model [20]	2	7	CO_2 reduction by fuel saving.	Decrease CO_2 emissions up to 7%.	No impact.
Air ratio controllers [21]	3	9	Fuel savings by reducing off-gas losses through minimum excess air.	From 2% to 6% depending on the furnace.	No impact.
ADP Sensor [22]	3	8-9	Fuel savings by reducing off-gas losses through heat recovery.	720 kt_{CO2}/y for European steel industry.	No impact.
Coating application	4	9	Material saving by reducing scale formation.	Not available.	No impact.

Identified technology	Related topic	TRL today	Area of action for CO_2 reduction	CO_2 emission reduction (scope 1)	CO_2 emission reduction (scope 2)
High emissivity coatings for furnace refractory [23]	4	9	CO_2 reduction by fuel saving.	Up to 5%.	No impact.
Waste heat boiler [4]	5	9	Substitution from the fuel that would otherwise be used to produce hot water/steam/electricity.	No direct emissions.	Depends on the fuel that is substituted by the hot water/steam/ electricity produced.
Feedstock preheating [4]	5	9	Fuel savings by reducing off-gas losses through heat recovery	Depends on the extent the feedstock can be preheated. Fuel savings of 20% have been reported for preheating the feedstock from ambient temperature to 400 °C.	No impact.
Warm or hot charging in rolling mills not coupled to continuous casting [4]	5	8-9	Increased efficiency by avoiding heat loss: The heating process starts with a product at high temperature instead of ambient temperature.	19% when charging the product at 400 °C.	No impact.
Direct charging in coupled continuous casting and rolling mills [4]	5	9	Increased efficiency by avoiding heat loss: The heating process starts with a product at high instead of ambient temperature.	39% when charging the product at 750 °C.	No impact.

3.1 Topic 1: Heating and burner technology

3.1.1 Self-recuperative burners [4]

This technology consists of preheating the combustion air by sensible heat recovery from the off-gas. This technology is only applicable for air combustion and cannot be used to reach high air preheating temperatures. Self-recuperative burners are typically not used in pusher-type and walking beam furnaces due to the required burner sizes and powers. However, they are commonly used for the reheating process of thin-slabs in tunnel furnaces after thin-slab casting.

3.1.2 Regenerator burner, regenerative air preheating through off-gas heat recovery [5–8]

This technology consists of burners with integrated ceramic accumulators that transfer off-gas heat to the combustion air. Air preheating of above 1,000 °C is achieved and up to 80% of the off-gas heat is recovered for process heating.

The burner systems are state of the art and are available from most burner suppliers.

Different types of burners are available: conventional flame burners with ultra-low NO_x-systems and flameless burners. In addition, the shape of the flame can vary from flat to long with high momentum.

Regenerators are mainly operated in an on/off mode with ceramic ball-fill/different shaped parts for fills or ceramic honeycomb accumulators. Regenerators can also be used in continuous systems with rotating honeycomb accumulators.

The benefits of regenerators are as follows:

- They increase the efficiency of the heating processes by recovering heat from off-gas and providing high combustion air pre-heating, thereby reducing operating costs and CO_2 emissions.
- They increase the productivity and reduce the specific energy consumption (e.g. kWh/t) by reducing the heating time in the furnace by achieving higher furnace temperature in the heating zone.
- Flameless combustion is possible for low NO_x combustion with NO_x emissions below 150 ppm (for 3 vol% O_2 in the off-gas).
- They help increased heating uniformity. When operating in a flameless combustion mode and if there is sufficient space above or below the product in the furnace, increased uniform heating of the product can be achieved compared to combustion with flames.

However, regenerators also have disadvantages. Investments costs are higher than for recuperative heating systems. Additional maintenance is required to clean the ceramic accumulators, depending on the type of regenerator.

In comparison with recuperative burners with an average of 300 °C recuperative preheated air, reduction in CO_2 emissions of between 12% and 40% have been reported.

3.1.3 Oxy-fuel combustion [9,10]

Oxy-fuel combustion consists in burning a fuel using pure oxygen instead of air as the oxidiser. The absence of nitrogen in the oxidiser significantly reduces the off-gas volume as well as the energy losses through the off-gas. This increases the thermal efficiency of the system and the radiative heat transfer due to the higher concentration of highly radiative CO_2 and H_2O particles in the furnace atmosphere.

When installing oxy-fuel combustion systems, consideration must be given to the tightness of the furnace and proper pressure regulation to prevent air leakage resulting in significant NO_x emissions. If the furnace is operated carefully, low NO_x emissions can be achieved. If ambient air enters the furnace, high NO_x emission will result due to the high combustion temperature of oxy-fuel. Flameless oxy-fuel application has also been investigated to reduce NO_x emissions. In addition, the use of oxy-fuel requires a complete retrofit of the burner technology. However, retrofitting has been done many times and is a well-known technology.

The disadvantages of using oxyfuel include the higher cost of running pure oxygen, which has to be considered. The economics need to be assessed on a case-by-case basis.

Fuel consumption reductions of around 20 to 26% and CO_2 emission reductions of 15% have been reported. A further 20 to 30% improvement in throughput has been reported for semi-flameless oxyfuel applications.

3.1.4 Oxygen lancing [11–13]

Oxygen lancing consists in installing oxygen lances on the furnace walls near the burners. Oxygen is injected into the furnace at high velocity through the lances. Approximately 75% of the combustion air is replaced by the oxygen. Oxygen lancing reduces the off-gas volume by 50%, thereby reducing off-gas losses. Reduction in fuel consumption of 11% and 15% have been reported, which also reduces CO_2 emission from the furnace. In addition, the oxygen lancing was reported to have minimum impact on NO_x emission, scale formation on the slab furnace and it improves production capacity by up to 20%. The technology requires low maintenance and the investment costs are low if existing air equipment can be re-used.

3.1.5 Fossil free CH_4

This technology consists of replacing fossil fuel with CH_4 produced from electricity or biomass. This technology doesn't reduce local CO_2 emissions at the furnace, but in the overall balance of the system, the net CO_2 emission are zero if the biogenic carbon is rated net-zero.

The advantages of fossil free methane are that it is easy to add to the fuel and can be implemented without major modifications to existing reheating furnaces. In addition, biomass-derived methane is currently potentially cost-competitive with fossil fuels.

However, this technology can be potentially expensive depending on the price of biomass and electricity. Due to losses associated with the production of the fuel, the cost would be higher than using electricity directly for heating.

3.1.6 Fuel preheating of blast furnace gas with or without oxy-fuel combustion/OEC [14]

This technology involves recuperative fuel preheating of low calorific process gases in integrated steel mills. It is interesting to note, that regenerative fuel preheating is not possible for safety reasons, as regenerators always have leakage.

The reduction in CO_2 emissions is achieved by substituting natural gas for process gases and by increasing the efficiency of the systems through heat recovery of the off-gas. Increasing efficiency also reduces operating costs. However, investments costs are high due to the need for additional plant components.

As an application, a 150 t/h reheating furnace in steel mill currently is working with 80% Blast Furnace Gas (BFG). The reduction in CO_2 emission is 50-60 kg_{CO2}/t_{steel}, assuming that the BFG application in the reheating process has no CO_2 footprint.

3.1.7 Indirect resistive heating [15]

This technology consists of reheating steel using electric radiant heaters. A few industrial scale implementations already exist, but they are rare and typically operate at temperatures below 1,000 °C. One of the advantages of this technology is the low specific energy consumption per ton of feedstock (high efficiency). In addition, the furnace control system is relatively simple and achieves high precision (low ΔT). However, the cost of electricity is typically higher compared to fossil fuels, and the power density of electric radiant heaters at higher temperature is low compared to combustion-based systems, thus requiring more space.

3.1.8 Inductive heating [16,17]

This technology consists of reheating steel using inductive heaters. There are a few industrial-scale implementations, but they are rare and typically operate at temperatures below 700 °C.

The advantage of this technology is that very high heating rates can be achieved (high energy density). However, this technology is inflexible in terms of feedstock geometry and efficiency is relatively low compared to other electrical heating solutions. Finally, the process is difficult to optimise for a wide temperature range, as the conductivity and ferromagnetic properties of steel vary with temperature.

3.2 Topic 2: Modelling of entire furnace, Level-2 control

3.2.1 Diagnostics, Warning and Suggestion system (DWS) [18]

This system consists of a database for data collection and both physical and statistical models to suggest improvement in operating practices or to detect operating errors (e.g. burner imbalance). The reduction in CO_2 emissions is achieved by reducing the amount of heat required to achieve the target temperature, thus reducing fuel necessity. CO_2 emission reduction up to 3% have been reported in SSAB's hot strip mill slab furnace. This technology can be implemented without major modifications to existing reheating furnaces. However, it requires an extensive data collection system and time to tune a reliable warning system and model.

3.2.2 Dynamic Furnace Model [19]

This technology consists of a dynamic model to monitor and control the temperature and oxygen content of the reheating furnaces, even during stoppages and interruptions. As for the DWS, the technology can be implemented without major modifications to existing reheating furnaces, but requires an extensive data collection system and time to tune a reliable system and model. In addition, more temperature and oxygen measurement systems will need to be implemented for the model. The reduction in CO_2 emissions will be achieved by reducing fuel consumption. A reduction of 3% to 6% has been reported for high productivity furnaces (more than 350 t per day) and between 7% and 13% for low productivity furnaces (less than 350 t per day).

3.2.3 Furnace Model coupled to microstructural model [20]

This model consists of an off-line model to simulate the thermal behaviour and microstructure of the product with the aim of developing optimised operating practices. As for the preceding technologies, the system can be easily implemented in existing furnaces, but requires extensive data collection and time to achieve a reliable model. The system can achieve CO_2 emission reductions of up to 7%. A system has been implemented and tested at ACRONI (implementation of new reheating strategies) and Sidenor (improvement of heating time to reach drop-out temperature).

3.3 Topic 3: Sensors and controls (Level-1), standards, regulations

3.3.1 Air ratio controller [21]

Air ratio controllers are a well-known system for optimising the oxygen content in the furnace, thereby reducing off-gas heat losses. They can be pneumatic or electronical, or the controller can be implemented in an industrial controller or PLC. Depending on the furnace, CO_2 emissions can be reduced by between 2% and 6%, as fuel consumption can be reduced by minimising off-gas losses through minimum excess air content.

3.3.2 Acid Dew Point sensor (ADP) [22]

Acid Dew Point (ADP) sensors are used to monitor the concentration of sulfuric acid in stack gases. ADP sensors work by cooling a sensor, causing a sulfuric acid film to form on its surface when it is cooled below the ADP. The conductivity between the sensor's ring electrode and the thermocouple indicates the thickness of the film. When the sensor is at the ADP temperature, the rates of evaporation and deposition are equal, so the thickness of the film and, hence, its conductivity are constant. This product is available from several manufacturers (Ametek, Walsn, Sidph). This technology has the potential to reduce the European steel industry's CO_2 emissions by 720 kt_{CO2}/year.

The advantages of this technology are as follow:

- Optimised off-gas temperature and improved waste heat recovery efficiency.
- Reduced cold-end corrosion in heat exchangers, ducts and stacks resulting in fewer maintenance problems.
- Reduced sulphate aerosol emissions.

It is important to note that detection of ADT can be slow at very low sulphuric acid concentrations.

3.4 Topic 4: Materials in the furnace and product quality

3.4.1 Coating application

In most long product mills, a protective glass coating is applied to the surface of the product before it enters the reheating furnace.This has a significant impact on the quality of the steel and therefore the number of downgraded materials.

The use of coatings to reduce oxide formation in reheating furnaces has been widely investigated. The current state of the art is that an oxide layer of approximately 300 µm is formed after casting and during reheating. This results in a material loss of 1 to 2% or 1.5 €/t. Limiting oxidation reduces the amount of steel required and therefore the CO_2 emissions in primary processing.

Laboratory studies have shown that the use of coatings can reduce scale formation by 40% and even 100%. However, there is an important limitation related to the grade. Coatings must be adapted to each steel family. If a particular coating reduces scale formation on low carbon grades, it may increase it on high strength grades.

3.4.2 High emissivity coatings for furnace refractory [23]

High emissivity coatings are a well-established technology in small furnaces. Energy savings of up to 5% can be achieved compared to uncoated refractory. It is not used in large reheating furnaces, such as hot strip mills, due to the complexity of application and the wear resistance of the coating.

3.5 Topic 5: Heat transfer, heat recovery, productivity, economy

3.5.1 Waste heat boiler [4]

This technology consists of sensible heat recovery from the off-gas to produce hot water/steam and/or electricity. This technology doesn’t reduce the specific energy consumption per ton of steel and requires a demand for hot water/steam.

3.5.2 Feedstock preheating [4]

This technology consists of preheating the feedstock through convective heat transfer (direct contact) from the off-gases. This helps decrease the fuel consumption by improving the utilization of sensible heat in the off-gas (at low temperature). However, feedstock preheating is generally not possible for batch processes and the utility of feedstock preheating decreases as the temperature of the incoming feedstock increases.

3.5.3 Warm or hot charging in rolling mills not coupled to continuous casting [4]

This technology consists of storing the product from the continuous casting after the cutting process in insulated boxes or under insulated hoods for later charging in the reheating furnace of the rolling mill at temperatures between 300 and 600 °C.

The necessary insulated hoods and boxes are available or can be built by suppliers.

By shortening the time between casting and reheating and/or insulating the feedstock during transfer, the feedstock enters the reheating furnace at a higher temperature, lowering the energy demand for heating. This technology therefore helps reduce the CO_2 emissions and operating costs of the plant.

However, this technology requires space close to the reheating furnace, well-planned production cycles and higher costs for low-tech components. Furthermore, it limits the possibility of using feedstock preheating and increases stack temperature, which can lead to a decrease in the efficiency of furnaces which utilise recuperative systems and feedstock preheating. It can also result in significant variation in the temperature of feedstock going into the furnace which can present a problem for the control system of the reheating furnace in terms of temperature variation.

3.5.4 Direct charging in coupled continuous casting and rolling [4]

This technology consists of feeding the product from the continuous casting after the cutting process directly into the reheating furnace of the rolling mill at temperatures between 600 and 850 °C.

This technology helps to improve production efficiency, reduce CO_2 emissions and lower operating costs. However, this technology is only suitable for production processes with little or no change in product or product quality. In addition, a complete production process study is required.

Continuous steel casting and rolling mills are available from suppliers.

The TRL of this technology varies depending on the feedstock geometry. For long products with small dimensions the TRL is high, but for other types of feedstock geometries it is low. Inductive heating units are available from 20 to 50 MW (i.e. ABP induction).

4 List of emerging technologies for low CO_2 heating

This section describes low TRL (< 7) technologies that help could potentially reduce the CO_2 emissions from reheating furnaces.

Table 2: Overview of low TRL technologies for low CO_2 heating

Identified technology	Related topic	TRL today	Area of action for CO_2 reduction	CO_2 emission reduction (scope 1)	CO_2 emission reduction (scope 2)
Multi-fuel burner for reheating furnaces [24,25]	1	5-6	Substitution from fossil fuels with a low CO_2 energy source.	No direct emissions when using hydrogen or ammonia as gas.	Depending if the energy is produced by renewable sources.
Biofuels as a fuel for reheating furnaces [26]	1	5-9, depending on the gas	Substitution from fossil fuels with a low CO_2 energy source.	100% if the carbon is biogenic.	No emissions if the energy is produced by renewable sources.
Hydrogen as a fuel for reheating process [27–29]	1	7	Substitution from fossil fuels with a low CO_2 energy source.	No direct emissions.	100 % if energy is produced by renewable sources.
Ammonia as a fuel for reheating process [30,31]	1	4-5	Substitution from fossil fuels with a (potentially) low CO_2 energy source.	No direct emissions.	Electricity based NH_3 would be similar to H_2 based on electrolysis
Plasma heating [32]	1	4-5	Substitution from fossil fuels with a (potentially) low CO_2 energy source.	No direct emissions.	Depends on the local electricity mix, would be higher than indirect resistive heating due to lower efficiency.
Direct resistive heating [33,34]	1	3-7	Substitution fossil fuels with a (potentially) low CO_2 energy source.	No direct emissions.	Depends on the local electricity mix. Efficiencies as high as 90-95% have been reported which would make it one of the most efficient electrical heating options.
Online Furnace Model coupled to microstructural model [20]	2	4-5	CO_2 reduction by fuel saving.	Decrease CO_2 emissions up to 7% (offline tests).	No impact.

Identified technology	Related topic	TRL today	Area of action for CO_2 reduction	CO_2 emission reduction (scope 1)	CO_2 emission reduction (scope 2)
Organic Rankine cycle [35,36]	5	4-5	Substitution from the fuel that would otherwise be used to produce electricity.	No direct emissions.	Depending on the local electricity mix, e.g. 29 or 417 $g_{CO2/kWh}$ when comparing Sweden and Germany.
Thermo-electric generator [37]	5	4-5	Substitution from the fuel that would otherwise be used to produce electricity.	No direct emissions.	Depends on the local electricity mix, i.e. 29 or 417 $g_{CO2/kWh}$ when comparing Sweden and Germany.
CCS/CCU [38,39]	5	7	Capturing CO_2 from flue gas.	From 70% to 95%.	No impact.

4.1 Topic 1: Heating and burner technology

4.1.1 Multi-fuel burner for reheating furnaces [24,25]

This technology consists of a hybrid burner design for reheating furnaces that allows the use of different fuels, such as natural gas, hydrogen or ammonia. This technology gives the operator flexibility in fuel choice, depending on availability and price.

The CO_2 emissions of the system can be reduced using hydrogen or ammonia supplied from renewable sources. The CO_2 emissions can be reduced by up to 100% when only using ammonia or hydrogen as fuel. However, the burner can also be operated using natural gas or mixtures of natural gas, hydrogen and ammonia depending on the availability of the gases. Operating costs can also be reduced by using the cheapest energy source. Multi-fuel burners have been successfully investigated in the laboratory, but haven't been demonstrated in the long-term in industrial furnaces. Therefore, long-term operational studies are still required for this technology.

The multi-fuel burner poses some issues concerning the regulation and control of the burner, due to the difference in gas properties of the different fuels.

4.1.2 Biofuels as a fuel for reheating furnaces [26]

The use of biofuels such as biogas, renewable dimethyl ether (rDME) or syngas as fuel for reheating furnaces provide an opportunity for low carbon heating. The CO_2 footprint of biogas and rDME is higher than that of natural gas, 90.6 g_{CO2}/MJ [1] and 66.74 g_{CO2}/MJ [40] respectively. This would result in an increase in CO_2 emission of approximately 20% for rDME [27] and approximately 62% for Biogas [1,27] compared to natural gas. This technology doesn't reduce the local CO_2 emissions at the furnace. However, in the overall balance of the system, the net CO_2 emission can be zero if the carbon in the biofuel is biogenic.

Biofuels are derived from biomass coming from industrial, agricultural or household waste. Biogas is a mixture of methane and carbon dioxide produced by the organic decomposition of biomass. Syngas is mostly a mixture of carbon monoxide, hydrogen and smaller amounts of hydrocarbons, such as methane, produced by the partial combustion of biomass.

At the Björneborg Steel's free-form forge, the substitution of 20 % propane with rDME has been tested. At Calderys' Höganäs plant in Sweden, biogas has replaced the natural gas. No figures are available on the actual reduction of CO_2 emissions from these installations.

4.1.3 Hydrogen as a fuel for reheating processes [27–29]

Hydrogen is a promising option that offers the potential to reduce CO_2 emissions when substituting conventional fossil fuels or steel mill gases. In order to use hydrogen as fuel, new burners, adapted for hydrogen combustion, need to be developed.

The technology faces many challenges: The influence of hydrogen on the heating process, product heating, scaling, product quality and on the refractory of the furnace, which are currently under investigation. In addition, the hydrogen supply, transport and storage in Europe is not yet established up and fuel prices are unknown. Finally, standards and regulations for hydrogen combustion and pollutant emissions are missing.

The substitution of fossil fuels with hydrogen offers several advantages:

- Complete avoidance of CO_2 emissions:
  By substituting fossil fuels or process gases with green hydrogen, a significant reduction in CO_2 emissions can be achieved. Unlike fossil fuels, hydrogen combustion only produces water vapor as a by-product, making it a clean and environmentally friendly alternative when produced using renewable energy.
- Oxy-fuel combustion is possible, especially when on-site electrolysers are used and oxygen is therefore available as a by-product.

However, this technology also has downsides:

- CO_2-Emissions are only avoided if hydrogen is produced by regenerative energy sources.
- Hydrogen and electrolysers are currently not available in required amounts.
- Hydrogen is difficult to store.
- The costs for hydrogen are unknown for the future.

4.1.4 Ammonia as a fuel for reheating processes [30,31]

Replacing fossil fuels with Ammonia (NH_3) produced using electricity offers the advantage of low CO_2 emissions when replacing conventional fossil fuels. Cost considerations may arise depending on biomass or electricity prices, and NH_3 combustion requires additional burner adjustments compared to H_2 and CH_4 combustion. Addressing the challenge of potential NO_x emissions is also crucial for sustainable NH_3 implementation in steel reheating processes. Direct CO_2 emissions can be reduced to zero by using NH_3 produced from renewable energy sources.

4.1.5 Plasma heating [32]

Electric plasma heaters are being considered for steel reheating due to their ability to achieve high temperatures, high power density, and control over the furnace atmosphere. However, this technology has lower efficiency and higher maintenance costs compared to conventional electric heating solutions. The challenges include the durability of the plasma torches, scaling up the technology, and the potential for high NO_x emissions.

4.1.6 Direct resistive heating [33,34]

Direct resistive heating methods, whether using DC or AC, offer advantages such as high efficiency, high power density, and fast heating rates in steel reheating processes. However, it is mainly suitable for long products with large dimensions. Overcoming the challenges of ensuring proper contact with the feedstock, particularly at higher temperatures (T > 1,000 °C), will be critical for the successful implementation of direct resistive heating in steel reheating applications. The reduction in CO_2 emissions depends on the local electricity mix. Efficiencies of 90-95% have been reported, which would make it one of the most efficient electrical heating options.

4.2 Topic 2: Modelling of entire furnaces, Level-2 control

4.2.1 Online Furnace Model coupled to microstructural model [20]

An online furnace model can be used to simulate the thermal behaviour and microstructure of the product in order to develop optimised operating practices, thereby reducing the fuel consumption of the furnace. This system is easy to implement in existing furnaces but requires extensive data collection. Offline tests have shown reductions in CO_2 emissions of up to 7%.

4.3 Topic 3: Sensors and controls (Level-1), standards, regulations

No relevant low TRL measurement technologies regarding CO_2 emission reduction have been identified for reheating furnaces.

4.4 Topic 4: Materials in the furnace and product quality

No relevant low TRL material technologies regarding CO_2 emission reduction have been identified for reheating furnaces.

4.5 Topic 5: Heat transfer, heat recovery, productivity, economy

4.5.1 Organic Rankine cycle [35,36]

The Organic Rankine Cycle (ORC), uses sensible heat recovery from the off-gas to generate electricity. The main challenges at present are cost and safety. The CO_2 emission reduction potential depends on the local electricity mix (e.g. 29 g_{CO2}/kWh for Sweden or 417 g_{CO2}/kWh for Germany [41]).

The advantages of ORC are as follow:

- Simplicity compared to Steam Rankine Cycle: ORC is generally less complicated than the Steam Rankine Cycle. It operates at lower temperatures and pressures, allowing for the use of simpler equipment.
- Discontinuous operation is possible.

However, ORC also has a lower efficiency than the Steam Rankine Cycle. The lower efficiency is mainly due to the lower operating temperatures of the ORC.

4.5.2 Thermoelectric generator [37]

This technology consists of heat recovery from the off-gas to produce electricity. The thermoelectric generator is less complicated than the Steam Rankine Cycle or Organic

Rankine Cycle. It has low space requirement and is well suited to small and/or discontinuous heat sources. However, this technology has a very low efficiency. Cost is currently the main issue. As for the Organic Rankine Cycle the CO_2 emission reduction potential depends on the local electricity mix (e.g. 29 g_{CO2}/kWh for Sweden or 417 g_{CO2}/kWh for Germany [41]).

4.5.3 CCS/CCU [38,39]

The principle of Carbon Capture Storage (CCS) or Carbon Capture Usage (CCU) is to capture the CO_2 contained in the off-gases from i.e. reheating furnaces, which represents approximately 20 to 30% of the off-gas content of blast furnace gas combustion with oxy-fuel, for further storage or utilisation. Approximately 70 to 95% of this CO_2 can be captured in the reactor.

For example, the CO_2 capture technologies CASOH (for blast furnace gas) and DISPLACE (for reheating furnaces) developed and demonstrated in the C4U project have a general potential to capture up to 94% of the CO_2 emissions from a steel mill. Both technologies use high-temperature gas-solid separation processes, which in turn reduce the exergy penalty associated with CO_2 capture technology. These technologies have the ability to recover heat at very high temperatures, such as those associated with reheating furnaces. It also produces H_2/N_2 fuel gases that can decarbonise the energy consumption of the steel mill. The project has advanced and demonstrated the TRL level to TRL 7, with the possibility of scaling up to TRL 9 through modelling [39].

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Acknowledgement

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

This report reflects only the authors' view. The European Commission is not responsible for any use that may be made of the information it contains.