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

RFCS-2021

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1 Executive summary

One project objective is to highlight research excellence from the past 25 years, performed in Europe via RFCS and HEU projects, but also internationally so that large groups of stakeholders gain insight into what research questions and innovations have been tested and what was the outcome from the projects and to present this work via selected KPI´s and make the outcome accessible. It is often a tedious task to go over past research, and our objective is to carry that work. Another objective is to make an update of the present State of the Art in the area of industrial furnaces, and what is the BAT (Best Available Technologies) and to summarize this in an accessible way. The third objective is to work in webinar and workshop formats, together with discussions, literature reviews and supplier contacts to formulate a Road map, to provide a deeper understanding of where the area is headed going forward. To make this measurable we formulated some measurable objectives for the dissemination actions:

- To reach 90% of the EU steel industry with the various dissemination actions.
- Marketing the actions via LinkedIn, where the project partners as a whole have a very high reach if the LinkedIn promotion is also linked to each partner homepage.
- Holding 2 workshops with a minimum of 40 attendants and 8 contributions
- Presenting the project progress via at least 4 webinars and or seminars
- Setting up a webpage, where occurring events are promoted, the project is introduced, and results in the form of reports and publications are presented and made available.
- Collect and analyse at least 25 RFCS projects and 15 international publications.
- The publication of the project Road map on industrial reheating furnaces
- Publication and presentation of at least two conference proceedings

The work was approached by dividing areas of responsibilities for each beneficiary in the project. This was done by dividing the work in sub-categories where each category is its own special technical subtopic. Naturally there are some overlaps between the subtopics, but this was a natural way to share the large amount of literature, projects to be assessed and evaluated, and to avoid duplication of work. The subtopics selected were:

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

The project results summarized are:

- A comprehensive overview of the project was prepared and delivered as a part of the continuous reporting.
- The project work was divided between the project partners into five main topics, where each partner has the main responsibility of their respective area.
- The project application included a long list of RFCS and HEU projects considered relevant for the project to analyse, valorise and disseminate. During the initial part of the project a final selection was done based on a more thorough examination and a final list of projects to study was published.
- A project webpage was set-up, DissHeat.eu
- The project dissemination events were scheduled, including webinars and workshops.

- The selected RFCS and HEU projects that were selected in the final selection were distributed according to the main topic the project is focused on. This also included both previously listed international literature and an active extension of the international literature that was published since the submittal of the proposal. The relevant partner examined, analysed, categorized and determined relevant KPI´s for the projects and literature they were responsible for in a large set of data.
- A state-of-the-art report was compiled where, per main topic, the findings and results from the review and analysis of the state of the art and best available technology (BAT) of industrial heating in the steel industry is documented.
- Based on the selected HEU and RFCS projects considered relevant for the project to analyse and an extended literature review on recent publications, a summarizing table was completed including relevant applications and technologies for low CO2 heating.
- An open webinar series was held, where one main topic was presented per occasion. Each webinar was scheduled for about 2 hours, and included project findings and results from the last 25 years of research in each topic and a presentation on the topic State-of-the-Art. There was in each webinar also one or more invited speakers, well-known in the topic area who presented an industry perspective on the topic.
- A workshop on the project roadmap to be presented towards the end of the project was held during the ESTAD 23 event in Dusseldorf. The program included topic presentations, guest presentations and an open panel discussion and was held over a 4-hour session.
- A report on current practises for the reheating furnace in conventional steel rolling mills. The deliverable summarizes the typical furnace and the variations in operation practices.
- A webinar was held on the final roadmap. The roadmap had a focus on strategies for the future to apply the knowledge within the fields of burner technology, modelling, measurement techniques, materials in the furnace and productivity and efficiency, all related to ongoing and future circumstances to achieve high quality steel grades with a minimum of CO_2 emissions.
- Preparation of presentations for disseminations, in a deliverable format suitable for presentation format and based on the most vital findings from the State-of-the-art report was compiled. The presentation material was used in the initial presentation on the final roadmap as a reference of where the technology per topic is today before progressing to the forward outlook, which the roadmap represented.
- The market needs were analysed and presented as a report.
- Two abstracts for the upcoming conference INFUB 14 to be held April 2-5 2024 in Algarve, Portugal, were written, and accepted where one focuses on topic 1 and the other is focused on topic 5. After acceptance full manuscripts were delivered.
- A report on the final roadmap where an outlook is presented per topic

2 Results

2.1 Objectives

One project objective is to highlight research excellence from the past 25 years, performed in Europe via RFCS and HEU projects, but also internationally so that large groups of stakeholders gain insight into what research questions and innovations have been tested and what was the outcome from the projects and to present this work via selected KPI´s and make the outcome accessible. It is often a tedious task to go over past research, and our objective is to carry that work. Another objective is to make an update of the present State of the Art in the area of industrial furnaces, and what is the BAT (Best Available Technologies) and to summarize this in an accessible way. The third objective is to work in webinar and workshop formats, together with discussions, literature reviews and supplier contacts to formulate a Road map, to provide a deeper understanding of where the area is headed going forward. To make this measurable we formulated some measurable objectives for the dissemination actions:

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2.2 Work package 1 – Project coordination (Swerim)

The work has been completed according to the work plan description in the grant agreement.

The work during the first period of the project was mainly about dividing topics and projects to analyse, setting up the webpage, creating a logotype, analysing past projects, and studying BREF and state of the art documentation, writing reports on the findings and preparing for upcoming dissemination events. The work during the second and final period was mainly related to dissemination and communication activities, where 6 webinars were promoted and executed and a live workshop on the preliminary roadmap which was held at the ESTAD/METEC event in Dusseldorf, and lots of material that was collected, analysed, and evaluated for reporting.

A total number of 13 deliverable reports were submitted in the project, and most of them required lots of efforts as there was a vast amount of material to digest and analyse. Towards the end of the project two abstract were also written and accepted for the upcoming INFUB conference, INFUB14, April 2-5, 2024.

2.2.1 Task 1.1 Coordination (Swerim)

Swerim has monitored the progress and made sure the planned activities are performed on time and with high standard.

2.2.2 Task 1.2 Meetings (Swerim, all)

During the first half of the project there were three project meetings and one shorter teams meeting to discuss the two upcoming deliverables: analysis, categorization and valorisation of RFCS and HEU projects with KPI´s and the state-of-the-art report. (all partners). The project meetings have been one shorter online Kick-off meeting immediately after project start and two physical meetings, one 19th -20th October 2022, lunch to lunch, at CRM in Gent and the other, March 22nd-23rd 2023, lunch to lunch, at Swerim in Luleå. (all partners), *figure 1* shows the project team during these meetings.

Figure 1: left - meeting at CRM, right - meeting at Swerim

During the second period there was one physical project meeting, held October 25-26, at RINA-CSM facilities in Naples, *figure 2*, where the project progress so far and the planning for the project finalization and what is left to do was discussed. There were also several meetings to plan the webinar series, and one test session before each webinar. There were also three meetings to plan the execution of the workshop on the roadmap at ESTAD, where the agenda, the invited guest speakers and the task at hand were discussed.

Figure 2: Meeting at Naples.

2.2.3 Task 1.3 Project documentation (Swerim, all)

The following documents have been uploaded to the project portal and to the project website DissHeat.eu:

- ✓ D 1.1 Comprehensive overview
- ✓ D 1.2 Abstracts for journals and conferences (two accepted abstract for a conference), full paper was also delivered within the 2nd project period
- ✓ D 1.3 Publishable report
- ✓ D 2.1 Final list of RFCS/HEU projects for valorisation and dissemination
- ✓ D 2.2 Summarizing table of relevant applications and technologies with KPI´s
- ✓ D 2.3 Report with categorized applications and technologies for low CO_2 heating
- ✓ D 3.1 Website online
- ✓ D 3.2 State of the art report
- ✓ D 3.3 Presentations for dissemination (slideshow and document uploaded)
- ✓ D 4.1 Schedule of the dissemination events

- D 5.1 Report on current practises, an overview
- D 5.2 Report on market needs, an overview
- D 5.3 The roadmap, report

For documentation, website, presentations and social media, a project logo was also created, see *figure 3*.

dissHEAT

Figure 3: The DissHeat logotype.

2.2.4 Task 1.4 Project presentations (Swerim, all)

The project has been presented at a number of occasions.

- During each of the topic webinars (2, 9, 23, 30 of May and June 1st), aside from the in depth presentation within each topic, the entire project was presented as an overview over what has been done so far, and what is planned to be done within the project duration, by Swerim.
- A longer presentation of the entire project was given by Swerim during the half day workshop on the roadmap during the ESTAD conference, June 15.
- RWTH presented a summary of the ESTAD workshop and the overall project at AOTK (Aachener Ofenbau und Thermoprozess-Kolloquium) on the 17.-18.10.2023: " DissHeat - Analysis of the best available technologies and outlook on future developments for heating furnaces in the steel industry
- The project was presented during the annual TGA2 Downstream steel processing meeting on October 17, Swerim.
- The project was presented during the CSP Cluster event – Decarbonization of reheating and treatment furnaces, October 27 by BFI.
- The project was presented during the final roadmap presentation, which took place December 14, Swerim.

2.2.5 Task 1.5 Project publications (Swerim, all)

Two conference proceeding abstracts have been submitted for the 14th conference on industrial furnaces and boilers (INFUB) conference in Algarve, Portugal April 2-5 2024. Both abstracts are approved by the organizing committee. The INFUB conference is a technical conference where the main objective of the conference is to provide an improved up-to-date understanding of the fundamentals, principles and practices associated with the design and operation of industrial furnaces and boilers and, from a broader perspective, of industrial systems and processes generating, transforming or using thermal energy from combustion.

The Conference provides the opportunity to disseminate information on recent research and development activities in the field of furnace and boiler technology and related areas, such as process and combustion control, efficiency optimisation of high-temperature energy application, and reduction of pollutant emissions. Carbon-neutral fuels like i.e. biomass, hydrogen and ammonia and alternative fuels, like refuse derived fuels and production residues are represented in the conference. It provides a space for delegates involved in research, development, design and operation of furnace and boiler systems, and also to those working in nearby areas such as combustion science, fuel technology, energy management and air pollution control. The abstracts are presented below, and the full manuscripts have been delivered to the conference after they were both accepted by the conference committee.

Abstract 1: Electrification of reheating furnaces: state of the art and future research needs

Abstract 2: Dissemination and future research road map on heating and burner technology in industrial heating in the European steel industry

2.3 Work package 2 – Collection and analysis (RWTH)

2.3.1 Task 2.1 Individuation of significant RFCS/HEU projects (RWTH, all)

The beneficiary's work was divided in five subtopics. Each of the topics is a vital important contribution and cover specific technical aspects related to the reheating furnace. The subtopics are:

- Heating and burner technology
- Modelling and control of the entire furnace
- Sensors and control, standards and regulations
- Materials in the furnace and product quality
- Heat transfer, heat recovery, productivity and economy

To provide a more general indication of how the amount of projects, HEU and RFCS, were related to either of the subtopics *figure 4* provide a good summary. In the figure the international literature, based on relevancy and topic related focus is also included.

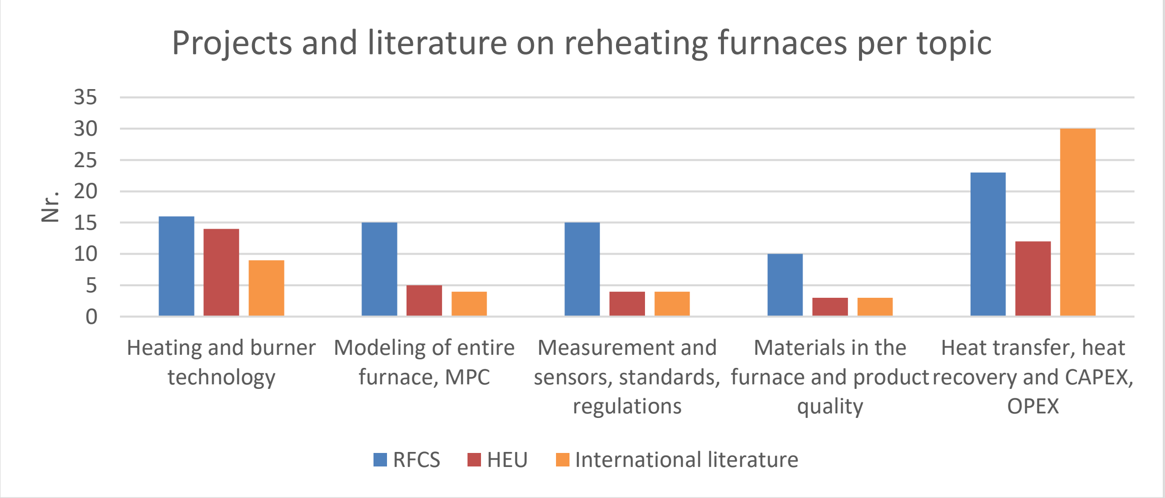


Figure 4: Projects and international literature per topic.

What is evident here is that the topics are all well represented based on past EU projects, and that there are intl. literature findings relevant to the topic of reheating furnaces.

The DissHeat project aims to elevate and promote the research performed within heating technology in the steel industry. For this purpose, past projects will be critically reviewed, classified in different topics and their results will be valorised.

In a first step, in an initial list of thirty-seven RFCS and twenty-five HEU projects was established and each project was assessed by the project partners. The focus was placed on reheating furnaces. Out of the initial list, twenty-two RFCS and thirteen HEU projects were selected for dissemination. The final lists can be found in *Table 1* and *Table 2*.

Table 1: Final list of RFCS projects for dissemination

Reference	**Project full name**	**Acronym**
R1	Regenerative firing of low calorific value gas for high temperature processes, EUR N° 12093	-
R2	Improved atmosphere control for product quality and combustion efficiency in reheating furnaces, EUR N° 19855	-
R3	Optimization of beam reheating conditions in the reheating furnace, EUR N° 20194	-
R4	Integration of reheating furnaces with rolling conditions at the roughing mill, EUR N° 20196	-
R6	New method for contactless measurement of true temperature of hot steel strips and control of the total thermal process by in situ spectroscopy, EUR N° 20463	-
R7	Performance of reheating furnaces equipped with highly preheated air combustion technology, EUR N° 21147	HPAC
R8	New ways to improve longitudinal temperature homogeneity of slabs in reheating furnaces, EUR N° 21334	-
R9	Rules base systems for improved monitoring and guidance of reheating furnaces, EUR N° 21992	-
R12	Metallurgical aspects of the compact reheating treatment of hot rolled strips before coiling, EUR N° 22831	-
R14	Minimizing NO_X emissions from reheating furnaces, EUR N° 23202	NOX-RF
R16	Improvement of top gas fired reheating and direct reduction furnaces for high temperature using innovative regenerative burners, EUR N° 24029	REGTGF
R17	Real-time intelligent diagnostics and optimisation of reheating furnace performance, EUR N° 24174	SMARTFIRE
R19	Quality improvement by metallurgical optimised stock temperature evolution in the reheating furnace including microstructure feedback from the rolling mill, EUR N° 25001	OPTHEAT
R20	CO2 reduction in reheating furnaces, EUR N° 25004	CO2RED
R25	Control of steel oxidation in reheating operations carried out with alternative fuels and new combustion technologies, EUR N° 27453	CONSTOX
R26	Advanced measurements and dynamic modelling for improved furnace operation and control	DYNAMO

R27	High efficiency low NOX BFG based combustion systems in steel reheating Furnaces	HELNOX-BFG
R31	Automatic surveillance of hot rolling area against intentional attacks and faults	AutoSurveillance
R33	Development of a new burner concept: Industry 4.0 technologies applied to the best available combustion system for the Steel Industry	BURNER 4.0
R34	Acid dew point and corrosion sensors for dynamic waste heat recovery from steel mill flue gases	SafeDewPoint
R35	Flexible Ladle Preheating Procedures using Plasma Heated Refractory	PlasmaPilot
R37	Green steel for Europe	GREENSTEEL

Table 2: Final list of HEU projects for dissemination

Reference	**Project full name**	**Acronym**
H3	Combustion for Low Emission Applications of Natural Gas	CLEAN-Gas
H5	Low Emissions Intensity Lime and Cement	LEILAC
H6	Renewable residential heating with fast pyrolysis bio-oil	Residue2Heat
H9	Green Industrial Hydrogen via Reversible High-Temperature Electrolysis	GrInHy
H10	VAlidation driven DEvelopment of Modern and Efficient COMbustion technologies	VADEMECOM
H11	Novel integrated refurbishment solution as a key path towards creating eco-efficient and competitive furnaces	VULKANO
H14	Simulation-as-a-Service Tool for Industrial Furnaces Innovative Engineering Design	SaaStified
H16	Energy Efficient Coil Coating Process	ECCO
H20	Development of an Efficient Microwave System for Material Transformation in energy INtensive processes for an improved Yield	DESTINY
H21	Simulation and Control of Renewable Combustion	SCIROCCO
H22	Towards a full multi-scale understanding of zero-carbon metal fuel combustion	MetalFuel

H23	Decarbonisation of carbon-intensive industries (Iron and Steel Industries) through Power to gas and Oxy-fuel combustion	DISIPO
H24	Predictive tools for turbulent combustion of hydrogen-enriched natural gas through carefully reduced kinetic mechanisms	HYGAS

2.3.2 Task 2.2 Extensive literature review (RWTH, all)

The extended literature review is focusing on what has been going on during the last years with focus on both the European and international level. The search has special focus on low CO_2 heating applications. If there is an interest to dig deeper into the findings, they are presented in the deliverable 2.3 “Report with categorized applications and technologies for low CO2 heating”, this is only an overview.

The processing of ferrous and non-ferrous metals in reheating furnaces is always aimed at achieving the best possible product quality while minimizing 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.

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 5*. 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.

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.

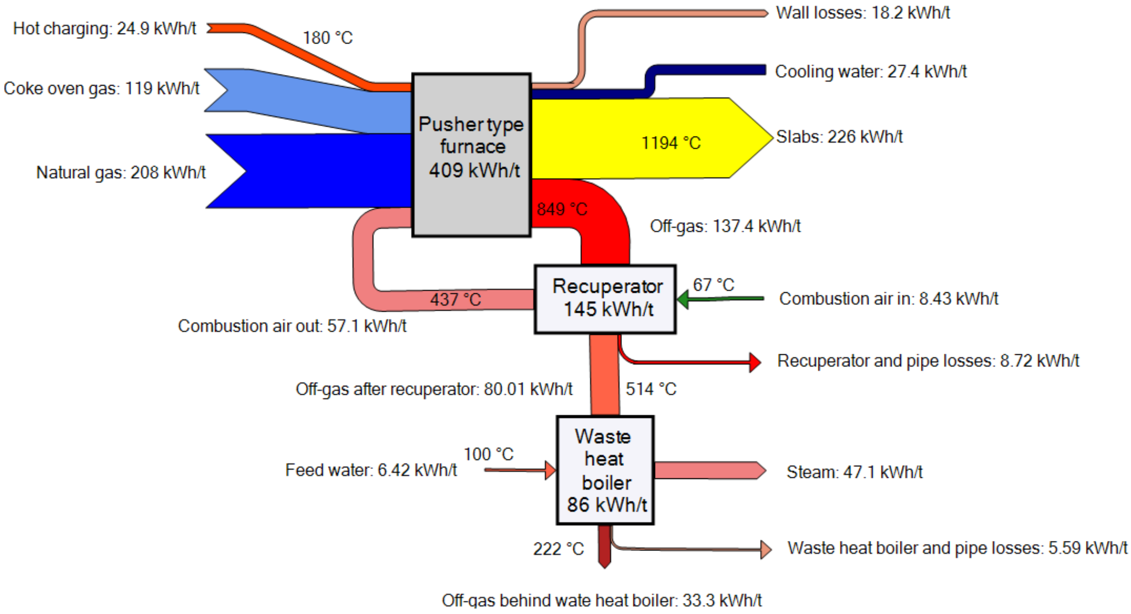


Figure 5: Sankey-diagram of a pusher-type furnace, 2005 [2]

Table 3 below describes high TRL (> 7) technologies that help reduce the CO_2 emissions from reheating furnaces.

Table 3: 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.

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)
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.
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.

Table 4 below describes low TRL (< 7) technologies that help could potentially reduce the CO_2 emissions from reheating furnaces.

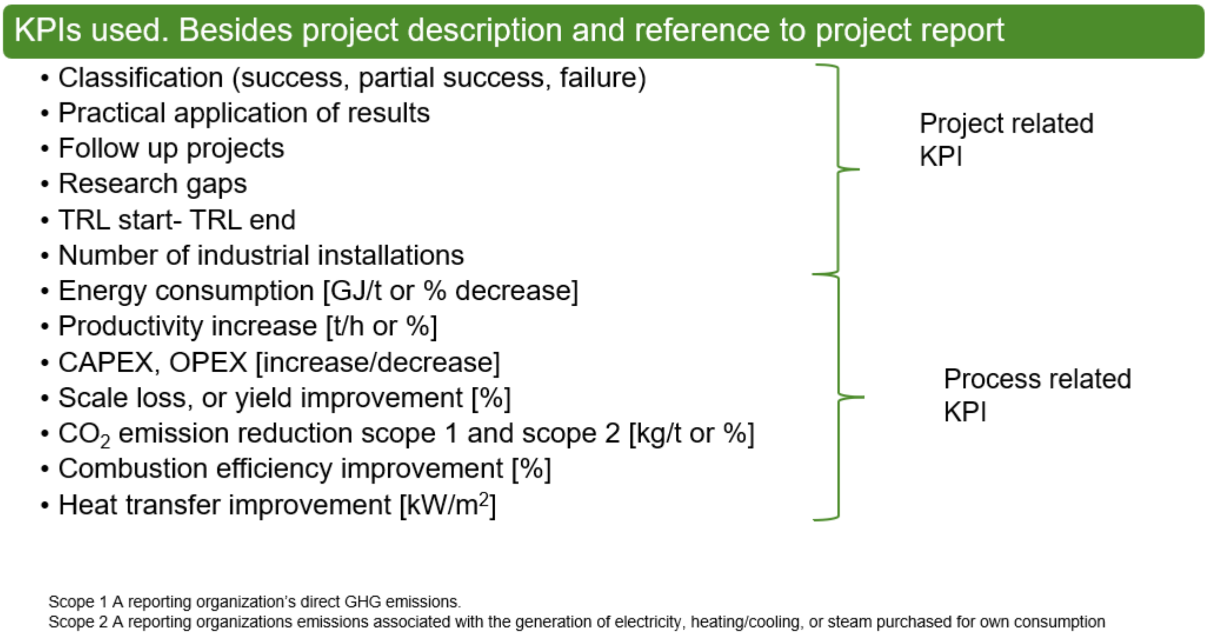
Table 4: Overview of high TRL technologies for low CO_2 heating

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)
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.

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)
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.
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.

2.3.3 Task 2.3 Categorization and valorisation of findings (RWTH, all)

In this task a large table was set up summarizing the evaluation of initially 37 RFCS, 25 HEU and 24 international publications. They were initially divided to the most relevant topic for each project and assigned to the partner working on this topic. When the project was relevant for more than one topic, it was assigned to more than one topic. These were later revised based on relevance to 23 RFCS and 11 HEU projects, which were thoroughly analysed and assessed with classifications related to a number of KPIs, which were subdivided in project KPIs and process related KPI according to *figure 6* below. The number of international publications evaluated in this classification was 24.



KPIs used. Besides project description and reference to project report

- Classification (success, partial success, failure)
- Practical application of results
- Follow up projects
- Research gaps
- TRL start- TRL end
- Number of industrial installations
- Energy consumption [GJ/t or % decrease]
- Productivity increase [t/h or %]
- CAPEX, OPEX [increase/decrease]
- Scale loss, or yield improvement [%]
- CO_2 emission reduction scope 1 and scope 2 [kg/t or %]
- Combustion efficiency improvement [%]
- Heat transfer improvement [kW/m^2]

Project related KPI

Process related KPI

Scope 1 A reporting organization's direct GHG emissions.
Scope 2 A reporting organizations emissions associated with the generation of electricity, heating/cooling, or steam purchased for own consumption

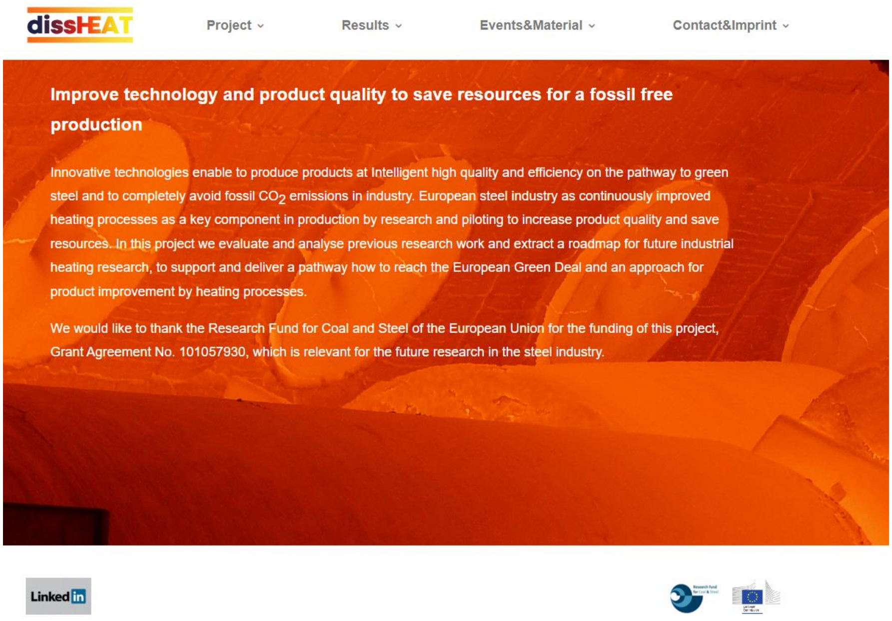
Figure 6: KPIs used in the evaluation.

The tables are too large to include here but can be found at the homepage DissHeat.eu.

2.4 Work package 3 – Dissemination, promotion and publication (BFI)

2.4.1 Task 3.1 Set up of the website (BFI)

The website DissHeat.eu was set-up, see *figure 7*, where general information about the project can be collected, project progress can be followed, reports and deliverables can be downloaded, and events are promoted.



Improve technology and product quality to save resources for a fossil free production

Innovative technologies enable to produce products at Intelligent high quality and efficiency on the pathway to green steel and to completely avoid fossil CO_2 emissions in industry. European steel industry as continuously improved heating processes as a key component in production by research and piloting to increase product quality and save resources. In this project we evaluate and analyse previous research work and extract a roadmap for future industrial heating research, to support and deliver a pathway how to reach the European Green Deal and an approach for product improvement by heating processes.

We would like to thank the Research Fund for Coal and Steel of the European Union for the funding of this project, Grant Agreement No. 101057930, which is relevant for the future research in the steel industry.

Figure 7: The DissHeat website

2.4.2 Task 3.2 State of the art report (BFI, all)

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.

Again, the document is a large compilation of the state of the art and BAT documentation and the summary alone is a vast amount of pages. A brief description of the compilation is not possible to show in a representative way so the advice is to visit DissHeat.eu for details, but a discussion/conclusions brief is presented below, and references [40-84].

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.

2.4.3 Task 3.3 Preparation of presentations (CSM, all)

A presentation slideshow was prepared originating from the State-of-the-Art report with clear explanations of the mechanisms relating to each of the main topics. The presentation was promoted via LinkedIn to be presented as an initial part of the workshop on the final roadmap. The promotion was directed to all our channels via the common large networks each project partner has access to. The content is accessible on the project homepage DissHeat.eu.

2.5 Work package 4 – Seminars, webinars and workshops (CSM)

2.5.1 Task 4.1 Planning of the dissemination events (CSM, all)

At the end of the reporting period, 5 webinars were scheduled to be held, one per topic. The registration is promoted via LinkedIn, partner webpages and dedicated invitations to known people active in subfields related to reheating furnaces. A workshop was planned to be arranged together with the ESTAD conference.

2.5.2 Task 4.2 Holding dissemination events and collecting feedback (CSM, all)

Five topic webinars were held during may and June 2024. The first webinar was on heating and burner technology, on may 2nd. The webinars were recorded and can be viewed on the DissHeat homepage, DissHeat.eu. The webinars were promoted via the respective beneficiaries channels, their respective homepages, via special invitations and over LinkedIn. The number of attendees per webinar and their allocation per area they are working can be seen in *figure 8*. RINA-CSM arranged with registration and set-up.

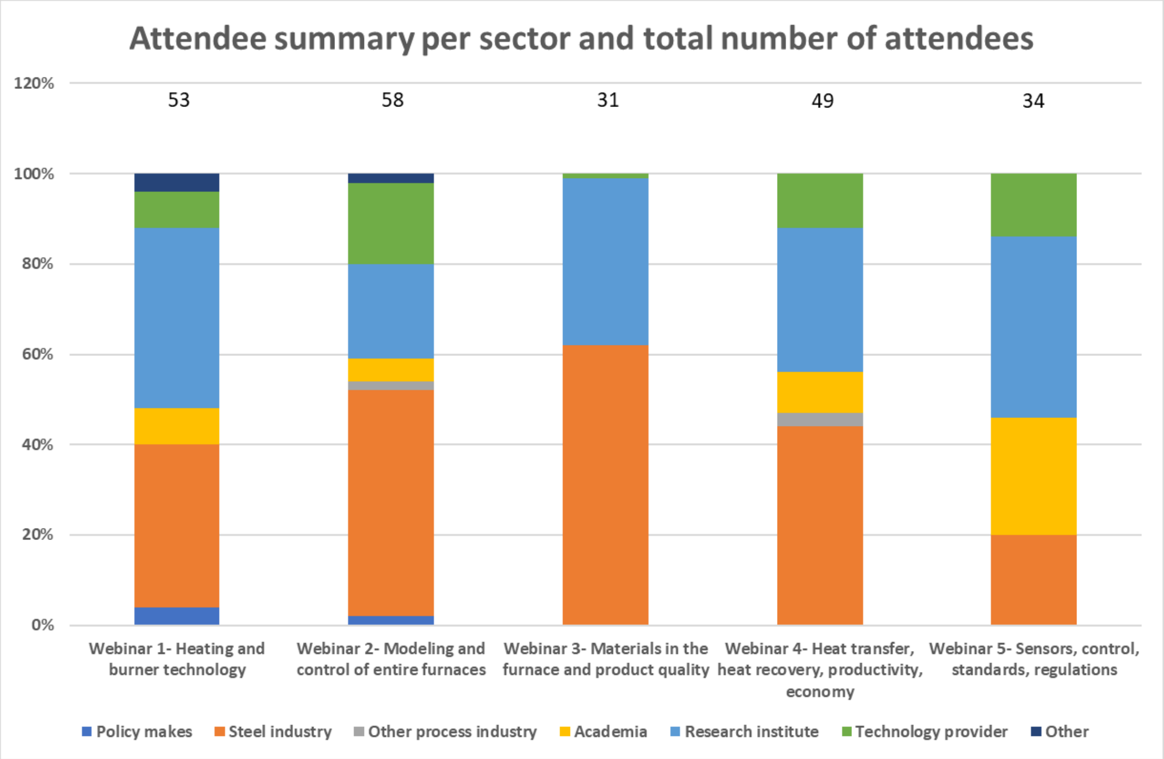
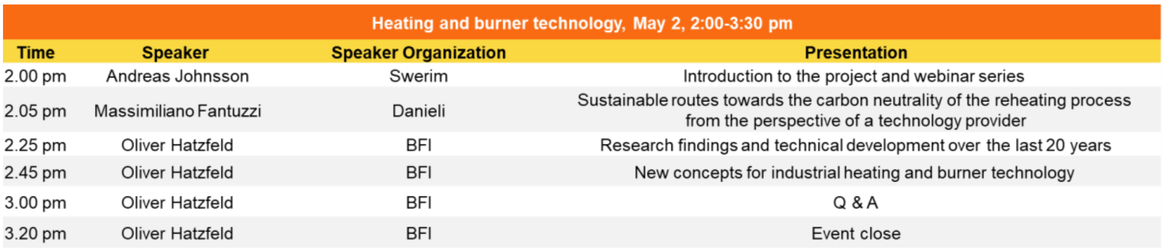


Figure 8: Attendee summary

The 1st webinar agenda, *figure 9*, carried out by BFI. Invited guest speaker from Danieli.

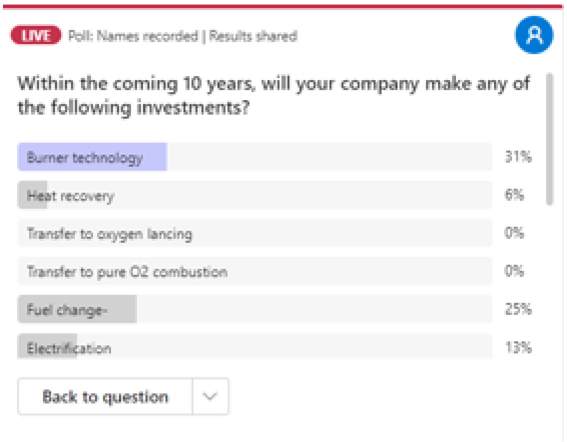


Heating and burner technology, May 2, 2:00-3:30 pm

Time	Speaker	Speaker Organization	Presentation
2.00 pm	Andreas Johnsson	Swerim	Introduction to the project and webinar series
2.05 pm	Massimiliano Fantuzzi	Danieli	Sustainable routes towards the carbon neutrality of the reheating process from the perspective of a technology provider
2.25 pm	Oliver Hatzfeld	BFI	Research findings and technical development over the last 20 years
2.45 pm	Oliver Hatzfeld	BFI	New concepts for industrial heating and burner technology
3.00 pm	Oliver Hatzfeld	BFI	Q & A
3.20 pm	Oliver Hatzfeld	BFI	Event close

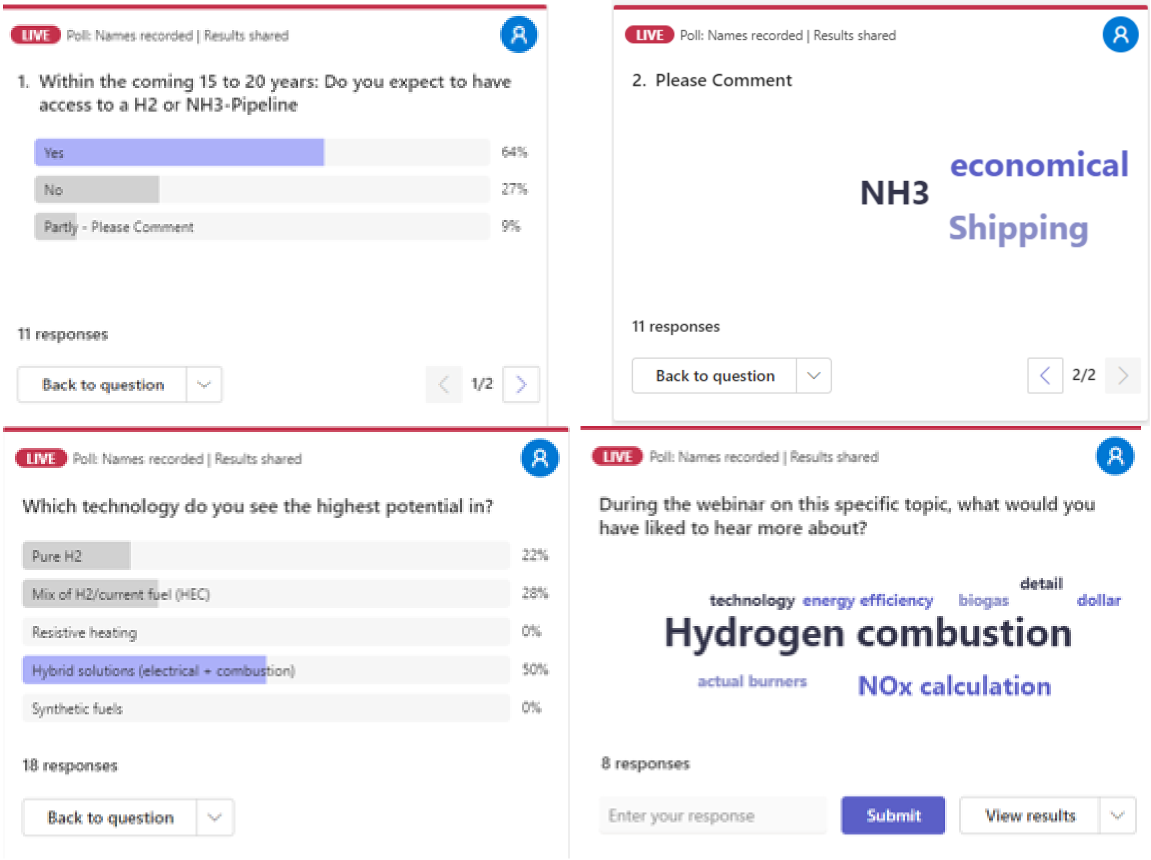
Figure 9: Agenda of webinar nr 1- Heating and burner technology

There were a Q&A and a poll session related to each webinar, where we could gather feedback on the webinar and answer questions from the audience. The poll session feedback from webinar 1 can be seen in *figure 10*.



Within the coming 10 years, will your company make any of the following investments?

Burner technology	31%
Heat recovery	6%
Transfer to oxygen lancing	0%
Transfer to pure O2 combustion	0%
Fuel change-	25%
Electrification	13%



LIVE Poll: Names recorded | Results shared

1. Within the coming 15 to 20 years: Do you expect to have access to a H2 or NH3-Pipeline

Option	Result
Yes	64%
No	27%
Partly - Please Comment	9%

11 responses

LIVE Poll: Names recorded | Results shared

2. Please Comment

11 responses

LIVE Poll: Names recorded | Results shared

Which technology do you see the highest potential in?

Option	Result
Pure H2	22%
Mix of H2/current fuel (HEC)	28%
Resistive heating	0%
Hybrid solutions (electrical + combustion)	50%
Synthetic fuels	0%

18 responses

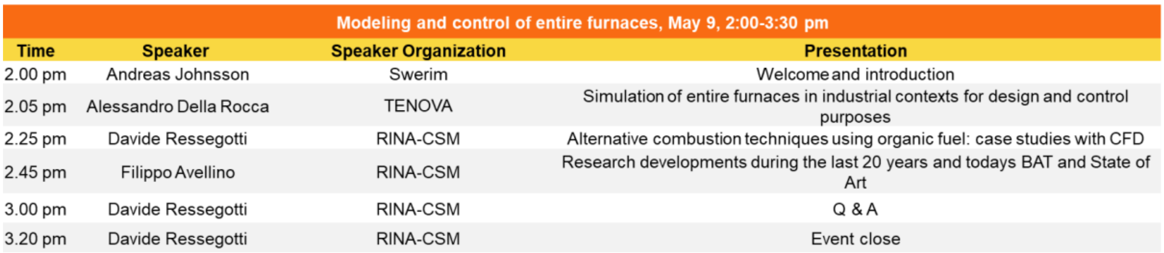
LIVE Poll: Names recorded | Results shared

During the webinar on this specific topic, what would you have liked to hear more about?

8 responses

Figure 10: Feedback on questions during the poll, webinar nr 1.

The 2nd webinar agenda, *figure 11*, carried out by RINA-CSM. Invited guest speaker from Tenova.



Modeling and control of entire furnaces, May 9, 2:00-3:30 pm

Time	Speaker	Speaker Organization	Presentation
2.00 pm	Andreas Johnsson	Swerim	Welcome and introduction
2.05 pm	Alessandro Della Rocca	TENOVA	Simulation of entire furnaces in industrial contexts for design and control purposes
2.25 pm	Davide Ressegotti	RINA-CSM	Alternative combustion techniques using organic fuel: case studies with CFD
2.45 pm	Filippo Avellino	RINA-CSM	Research developments during the last 20 years and todays BAT and State of Art
3.00 pm	Davide Ressegotti	RINA-CSM	Q & A
3.20 pm	Davide Ressegotti	RINA-CSM	Event close

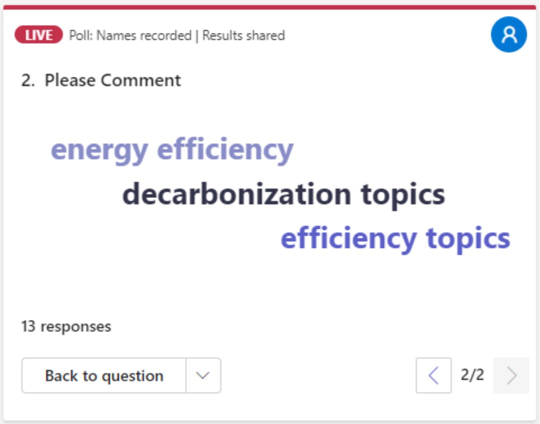
Figure 11: Agenda of webinar nr 2- Modelling and control of entire furnaces.

The poll session feedback from webinar 2 can be seen in *figure 12*.

1. Do you find European research in the heating technologies modeling being conducted in a way that will make the European steel industry develop in a positive direction in the coming decades

Yes 92%
No 0%
Partly - Please Comment 8%

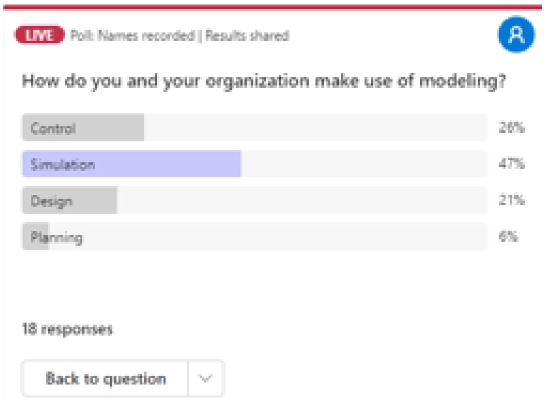
13 responses



2. Please Comment

energy efficiency
decarbonization topics
efficiency topics

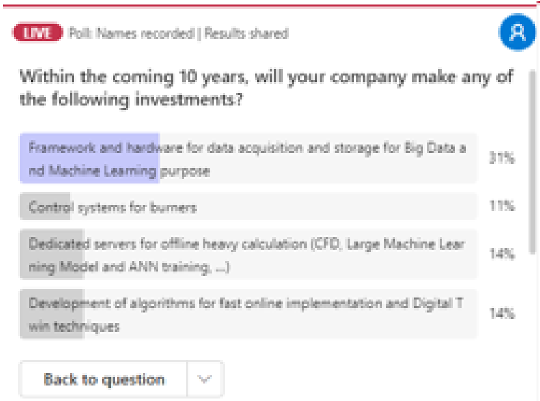
13 responses



How do you and your organization make use of modeling?

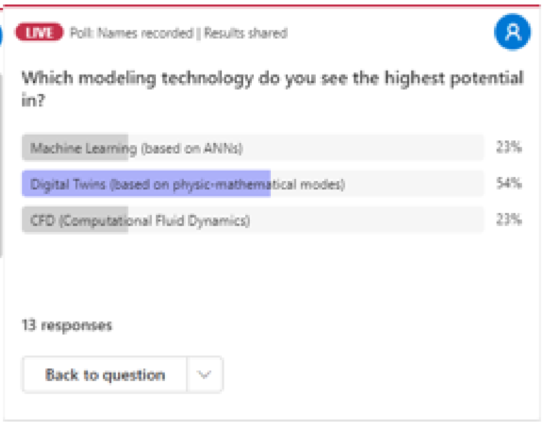
Control 26%
Simulation 47%
Design 21%
Planning 6%

18 responses



Within the coming 10 years, will your company make any of the following investments?

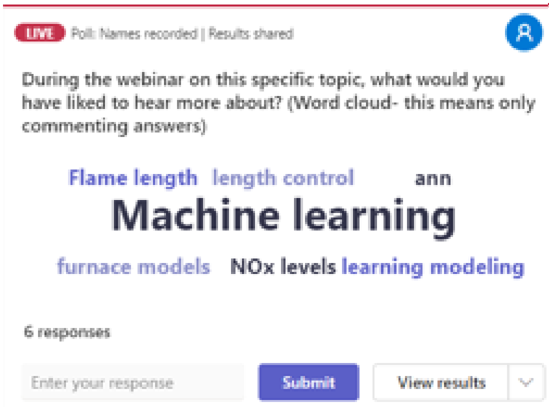
Framework and hardware for data acquisition and storage for Big Data and Machine Learning purpose 31%
Control systems for burners 11%
Dedicated servers for offline heavy calculation (CFD, Large Machine Learning Model and ANN training, ...) 14%
Development of algorithms for fast online implementation and Digital Twin techniques 14%



Which modeling technology do you see the highest potential in?

Machine Learning (based on ANNs) 23%
Digital Twins (based on physic-mathematical modes) 54%
CFD (Computational Fluid Dynamics) 23%

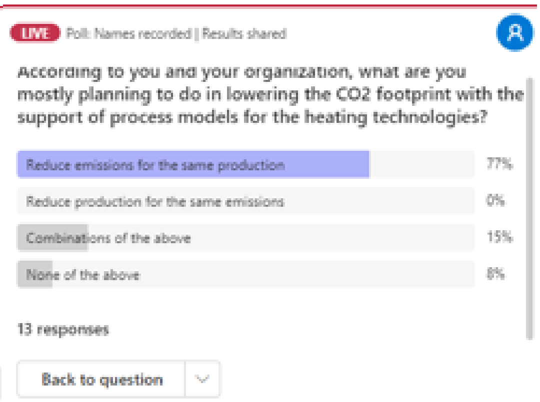
13 responses



During the webinar on this specific topic, what would you have liked to hear more about? (Word cloud- this means only commenting answers)

Flame length length control ann
Machine learning
furnace models NOx levels learning modeling

6 responses



According to you and your organization, what are you mostly planning to do in lowering the CO2 footprint with the support of process models for the heating technologies?

Reduce emissions for the same production 77%
Reduce production for the same emissions 0%
Combinations of the above 15%
None of the above 8%

13 responses

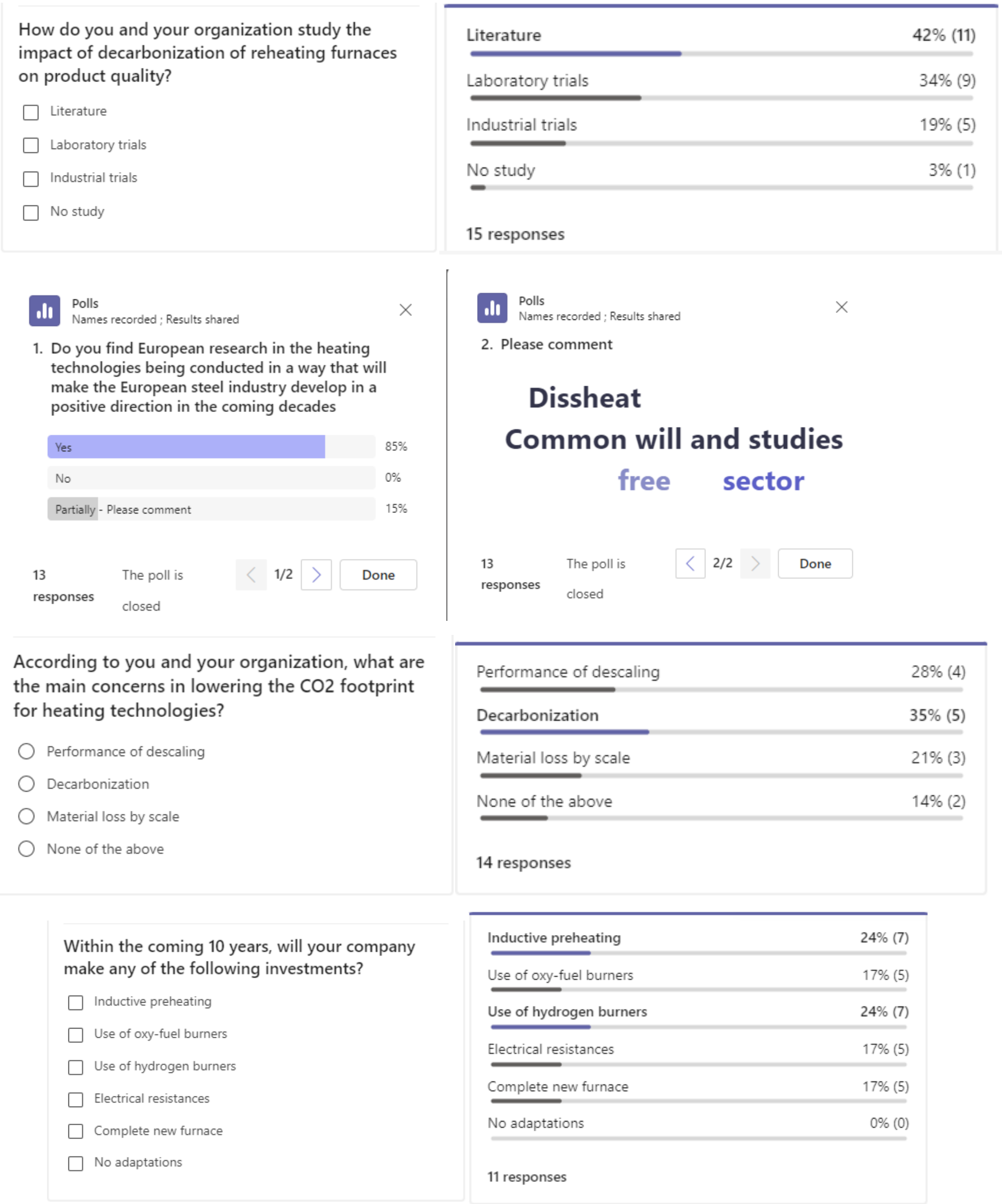
Figure 12: Feedback on questions during the poll, webinar nr 2.

The 3rd webinar agenda, *figure 13*, carried out by CRM. Invited speakers from Tata steel UK and Flanders make.

Materials in the furnace and product quality, May 23, 2:00-4:00pm			
Time	**Speaker**	**Speaker Organization**	**Presentation**
2.00 pm	Andreas Johnson	Swerim	Welcome and Introduction
2.05 pm	Didier Farrugia	Tata Steel UK	Primary reheating oxide scale and descaleability
2.30 pm	Irene Luzzo	RINA-CSM	Impact of combustion gasses on product quality
2.55 pm	Hugo Uijtdebroeks	CRM	Q & A
3.05 pm	Diana Espinosa	Flanders Make	Coating application for reheating
3.30 pm	Hugo Uijtdebroeks	CRM	Future outlooks related to quality
3.50 pm	Hugo Uijtdebroeks	CRM	Q & A
4.00 pm	Andreas Johnsson	Swerim	Event close

Figure 13: Agenda of webinar nr 3- Materials in the furnace and product quality.

The poll feedback from webinar nr 3 can be seen in *figure 14*.



How do you and your organization study the impact of decarbonization of reheating furnaces on product quality?

- ☐ Literature
- ☐ Laboratory trials
- ☐ Industrial trials
- ☐ No study

Literature 42% (11)
Laboratory trials 34% (9)
Industrial trials 19% (5)
No study 3% (1)

15 responses

Polls
Names recorded ; Results shared

1. Do you find European research in the heating technologies being conducted in a way that will make the European steel industry develop in a positive direction in the coming decades

Yes 85%
No 0%
Partially - Please comment 15%

13 responses
The poll is closed

Polls
Names recorded ; Results shared

2. Please comment

Dissheat
Common will and studies
free sector

13 responses
The poll is closed

According to you and your organization, what are the main concerns in lowering the CO2 footprint for heating technologies?

- ○ Performance of descaling
- ○ Decarbonization
- ○ Material loss by scale
- ○ None of the above

Performance of descaling 28% (4)
Decarbonization 35% (5)
Material loss by scale 21% (3)
None of the above 14% (2)

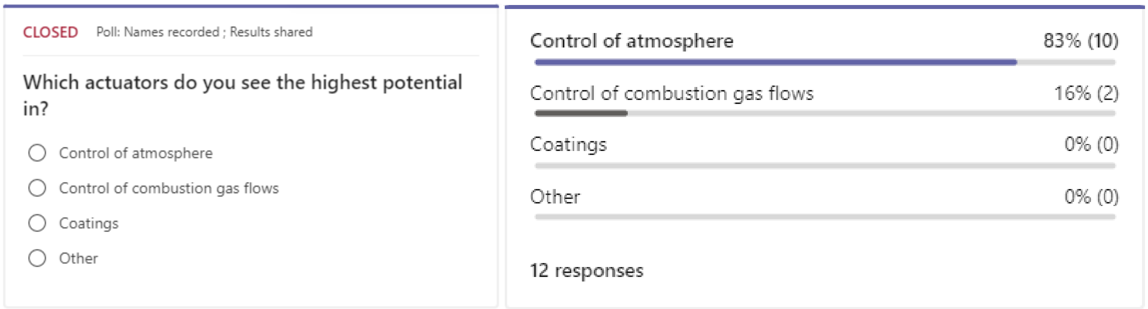
14 responses

Within the coming 10 years, will your company make any of the following investments?

- ☐ Inductive preheating
- ☐ Use of oxy-fuel burners
- ☐ Use of hydrogen burners
- ☐ Electrical resistances
- ☐ Complete new furnace
- ☐ No adaptations

Inductive preheating 24% (7)
Use of oxy-fuel burners 17% (5)
Use of hydrogen burners 24% (7)
Electrical resistances 17% (5)
Complete new furnace 17% (5)
No adaptations 0% (0)

11 responses



Which actuators do you see the highest potential in?

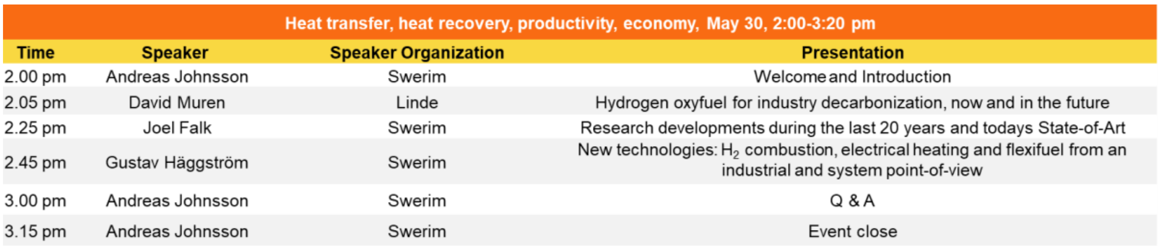
○ Control of atmosphere
○ Control of combustion gas flows
○ Coatings
○ Other

Control of atmosphere	83% (10)
Control of combustion gas flows	16% (2)
Coatings	0% (0)
Other	0% (0)

12 responses

Figure 14: Feedback on questions during the poll, webinar nr 3.

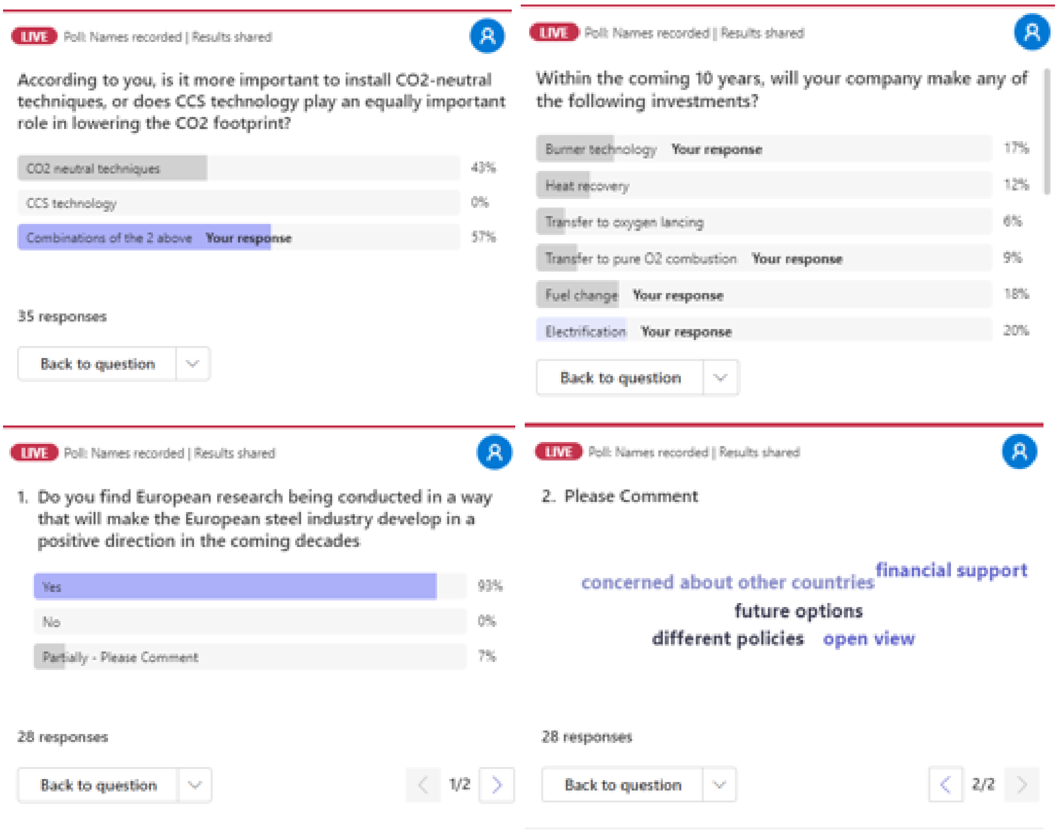
The 4th webinar agenda, *figure 15*, carried out by Swerim.



Heat transfer, heat recovery, productivity, economy, May 30, 2:00-3:20 pm			
Time	**Speaker**	**Speaker Organization**	**Presentation**
2.00 pm	Andreas Johnsson	Swerim	Welcome and Introduction
2.05 pm	David Muren	Linde	Hydrogen oxyfuel for industry decarbonization, now and in the future
2.25 pm	Joel Falk	Swerim	Research developments during the last 20 years and todays State-of-Art
2.45 pm	Gustav Häggström	Swerim	New technologies: H_2 combustion, electrical heating and flexifuel from an industrial and system point-of-view
3.00 pm	Andreas Johnsson	Swerim	Q & A
3.15 pm	Andreas Johnsson	Swerim	Event close

Figure 15: Agenda of webinar nr 4- Heat transfer, heat recovery, productivity, economy.

The poll feedback from webinar nr 4 can be seen in *figure 16*.



According to you, is it more important to install CO2-neutral techniques, or does CCS technology play an equally important role in lowering the CO2 footprint?

CO2 neutral techniques	43%
CCS technology	0%
Combinations of the 2 above **Your response**	57%

35 responses

Within the coming 10 years, will your company make any of the following investments?

Burner technology **Your response**	17%
Heat recovery	12%
Transfer to oxygen lancing	6%
Transfer to pure O2 combustion **Your response**	9%
Fuel change **Your response**	18%
Electrification **Your response**	20%

1. Do you find European research being conducted in a way that will make the European steel industry develop in a positive direction in the coming decades

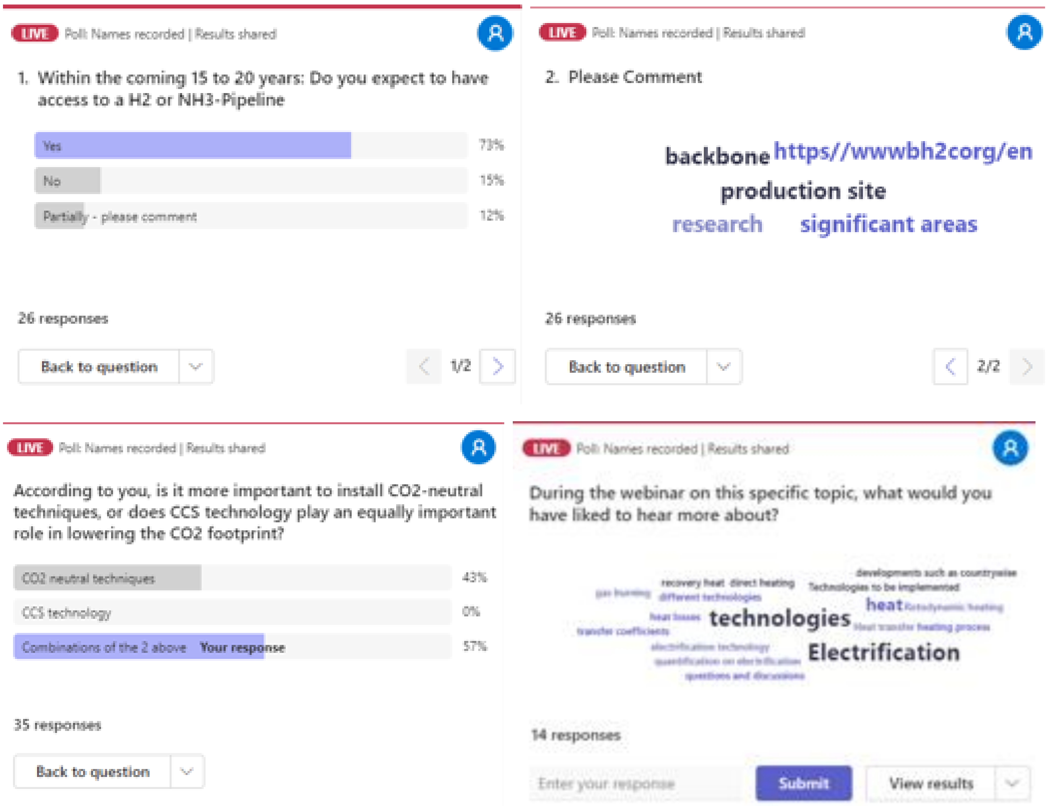
Yes	93%
No	0%
Partially - Please Comment	7%

28 responses

2. Please Comment

concerned about other countries
financial support
future options
different policies
open view

28 responses



1. Within the coming 15 to 20 years: Do you expect to have access to a H2 or NH3-Pipeline

Yes	73%
No	15%
Partially - please comment	12%

26 responses

2. Please Comment

26 responses

According to you, is it more important to install CO2-neutral techniques, or does CCS technology play an equally important role in lowering the CO2 footprint?

CO2 neutral techniques	43%
CCS technology	0%
Combinations of the 2 above Your response	57%

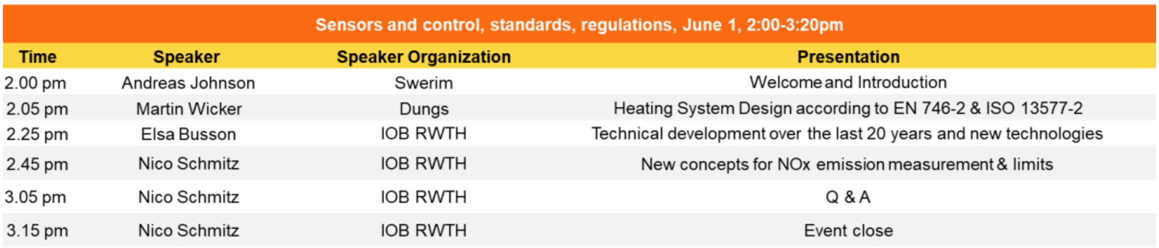
35 responses

During the webinar on this specific topic, what would you have liked to hear more about?

14 responses

Figure 16: Feedback on questions during the poll, webinar nr 4.

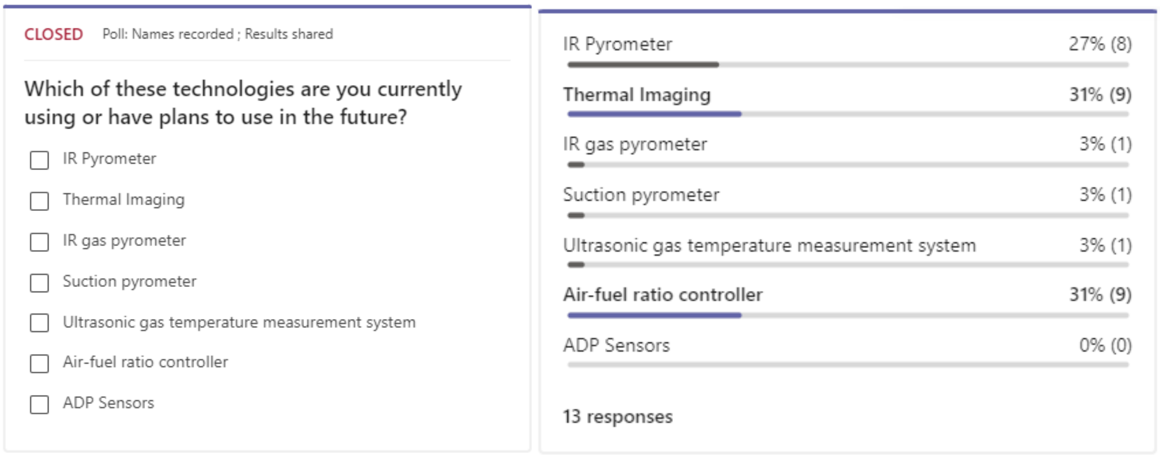
The 5th webinar agenda, *figure 17*, carried out by RWTH. Invited guest speaker from Dungs.



Sensors and control, standards, regulations, June 1, 2:00-3:20pm			
Time	**Speaker**	**Speaker Organization**	**Presentation**
2.00 pm	Andreas Johnson	Swerim	Welcome and Introduction
2.05 pm	Martin Wicker	Dungs	Heating System Design according to EN 746-2 & ISO 13577-2
2.25 pm	Elsa Busson	IOB RWTH	Technical development over the last 20 years and new technologies
2.45 pm	Nico Schmitz	IOB RWTH	New concepts for NOx emission measurement & limits
3.05 pm	Nico Schmitz	IOB RWTH	Q & A
3.15 pm	Nico Schmitz	IOB RWTH	Event close

Figure 17: Agenda of webinar nr 5- Sensors and control, standards, regulations.

The poll feedback from webinar nr 5 can be seen in *figure 18*.

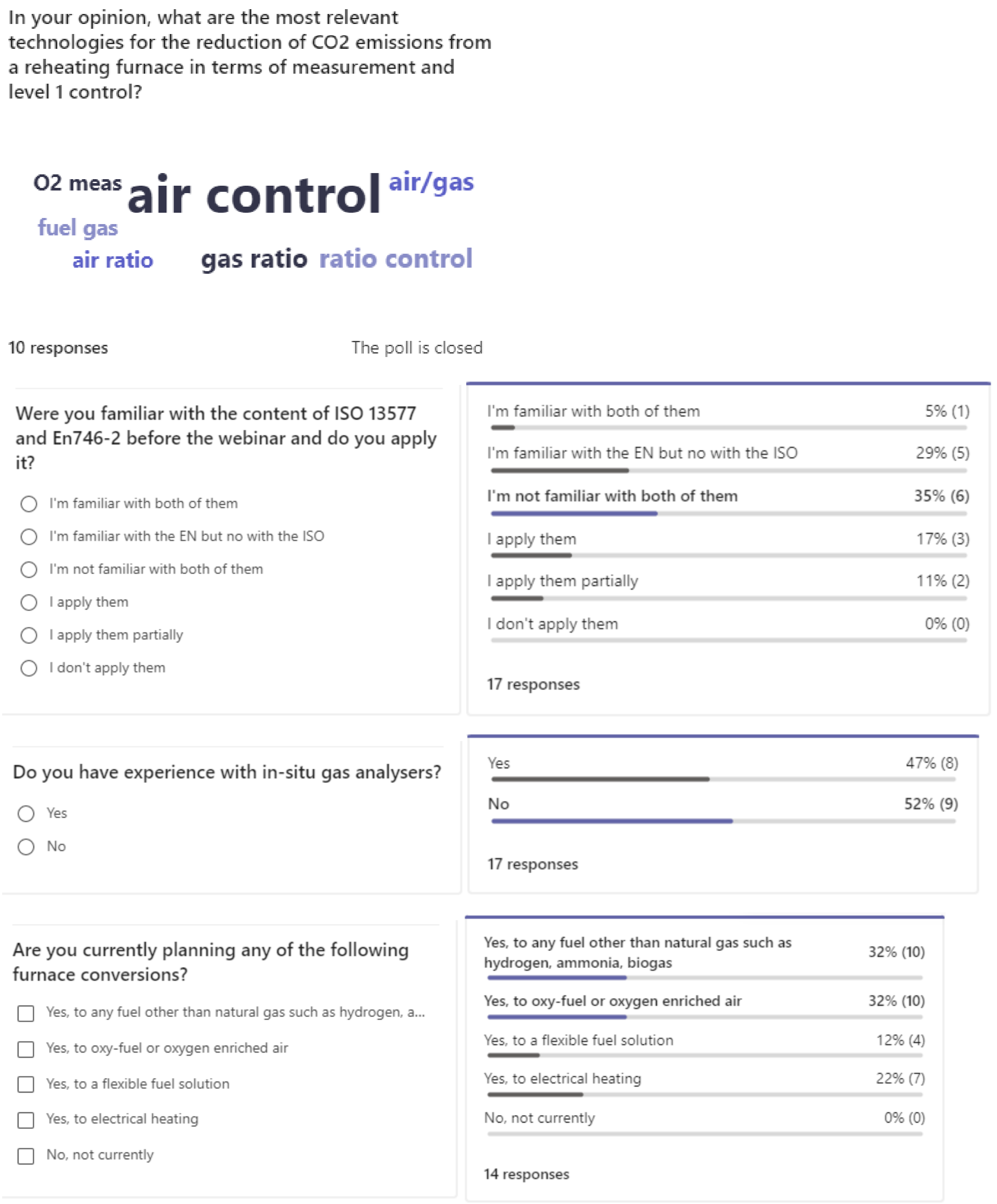


Which of these technologies are you currently using or have plans to use in the future?

☐ IR Pyrometer
☐ Thermal Imaging
☐ IR gas pyrometer
☐ Suction pyrometer
☐ Ultrasonic gas temperature measurement system
☐ Air-fuel ratio controller
☐ ADP Sensors

IR Pyrometer	27% (8)
Thermal Imaging	31% (9)
IR gas pyrometer	3% (1)
Suction pyrometer	3% (1)
Ultrasonic gas temperature measurement system	3% (1)
Air-fuel ratio controller	31% (9)
ADP Sensors	0% (0)

13 responses



In your opinion, what are the most relevant technologies for the reduction of CO2 emissions from a reheating furnace in terms of measurement and level 1 control?

10 responses

The poll is closed

Were you familiar with the content of ISO 13577 and En746-2 before the webinar and do you apply it?

○ I'm familiar with both of them
○ I'm familiar with the EN but no with the ISO
○ I'm not familiar with both of them
○ I apply them
○ I apply them partially
○ I don't apply them

I'm familiar with both of them	5% (1)
I'm familiar with the EN but no with the ISO	29% (5)
I'm not familiar with both of them	35% (6)
I apply them	17% (3)
I apply them partially	11% (2)
I don't apply them	0% (0)

17 responses

Do you have experience with in-situ gas analysers?

○ Yes
○ No

Yes	47% (8)
No	52% (9)

17 responses

Are you currently planning any of the following furnace conversions?

☐ Yes, to any fuel other than natural gas such as hydrogen, a...
☐ Yes, to oxy-fuel or oxygen enriched air
☐ Yes, to a flexible fuel solution
☐ Yes, to electrical heating
☐ No, not currently

Yes, to any fuel other than natural gas such as hydrogen, ammonia, biogas	32% (10)
Yes, to oxy-fuel or oxygen enriched air	32% (10)
Yes, to a flexible fuel solution	12% (4)
Yes, to electrical heating	22% (7)
No, not currently	0% (0)

14 responses

Figure 18: Feedback on questions during the poll, webinar nr 5.

2.5.3 Task 4.3 Holding a workshop on the roadmap (CSM, all)

There was an opportunity to hold a workshop on the preliminary roadmap and at the same time present the DissHeat project at the ESTAD/METEC conference and fair in Dusseldorf. Thanks to the organizing committee we could hold the workshop during the fourth day between 9am-1pm.

The schedule consists of:

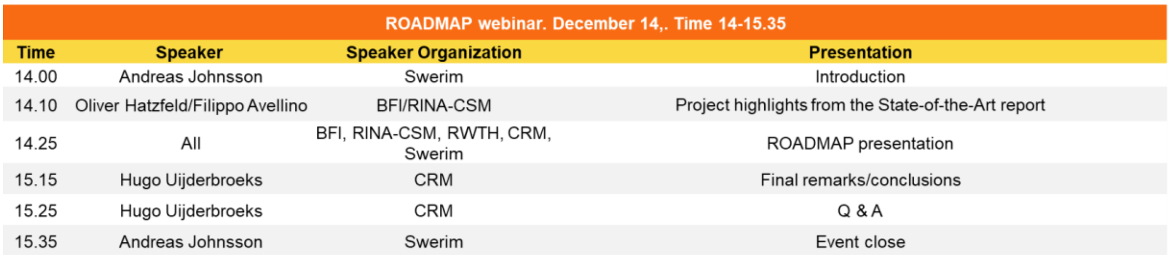
- Introduction by the DissHeat coordinator (Swerim)
- Technical presentations per topic
    - Heating and burner technology (BFI)
    - Modeling and control (level 2) of entire furnaces (RINA CSM)

  - Sensors and control (level 1), standards and regulations (RWTH)
  - Materials in the furnace and product quality (CRM)
  - Heat transfer, heat recovery, productivity and economy (Swerim)
- DissHeat draft roadmap for future research (CRM)
- Guest presentations relating to current questions in research on industrial heating and outlook
  - Sustainable blast furnace gas firing in reheating furnaces by Victor Cuervo (Arcelor Mittal)
  - Upcoming requirements and needs for heating from a Scandinavian perspective by Jonas Lagergren (senior expert at SSAB and chairman of the Swedish iron and steelmaking association Jernkontoret´s focus area TO51- Energy and furnace technology)
  - Sustainable heating technologies for today and tomorrows metal industry Enrico Malfa (Tenova)
- A panel discussion with guest speakers and Thomas Echterhof of RWTH with topics led by Swerim and BFI
  - Future research
  - Research gaps in industrial heating
  - Questions from DissHeat and audience
- Internal summary and wrap-up (CRM)

The name of the workshop event is: Workshop for future research roadmap in industrial heating. https://metec-estad2023.com/program/DissHeat-workshop.html

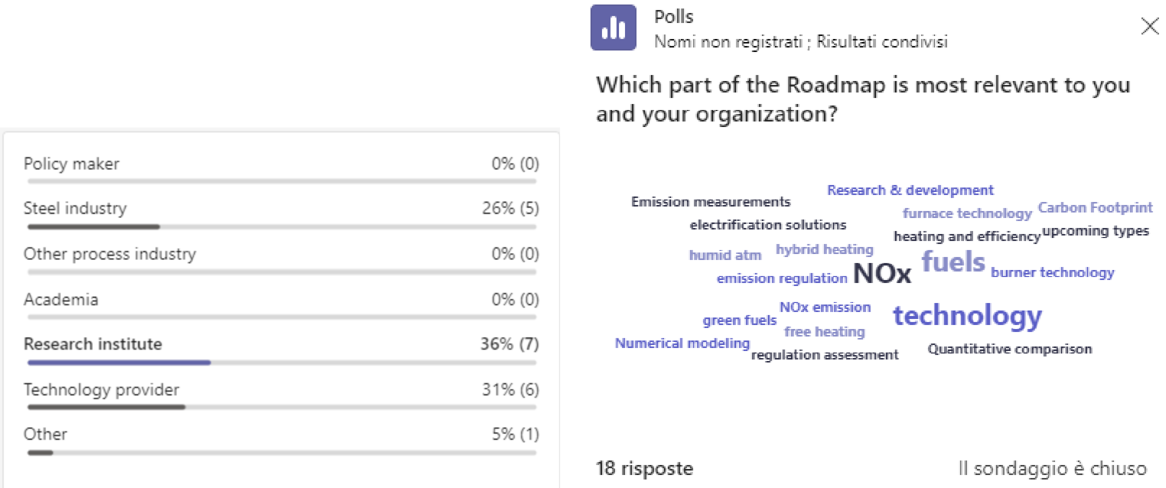
The day was productive and interesting, and held according to the schedule except that there was a change of speaker from SSAB´s side. Jonas Lagergren, SSAB, who were attaining the conference held their presentation. There were about 50 guests, but since it was quite a long event lasting 4 full hours, visitors were coming and going, and it was hard to keep track of the exact number of attendees. However, many of the pre-registered attendees didn't show up and others joined. With facts at hand it was probably a bad idea to have pre-registration, with a fully booked session, which may have prevented other guests from showing up thinking it was non accessible.

A webinar on the final roadmap was held on dec 14 at 14-15.35. The event was promoted via the respective project partners channels and via LinkedIn. The agenda for the final roadmap can be seen in figure 15. Besides the introduction and roadmap presentation, the content from D3.3, presentation for dissemination was presented including main findings from the State-of-the-Art report. The webinar had an attendance of about 30 persons and the areas they represented can be seen in *figure 19*, as well as the feedback on the poll question in, *figure 20*, we launched at the end of this webinar.



ROADMAP webinar. December 14,. Time 14-15.35			
Time	**Speaker**	**Speaker Organization**	**Presentation**
14.00	Andreas Johnsson	Swerim	Introduction
14.10	Oliver Hatzfeld/Filippo Avellino	BFI/RINA-CSM	Project highlights from the State-of-the-Art report
14.25	All	BFI, RINA-CSM, RWTH, CRM, Swerim	ROADMAP presentation
15.15	Hugo Uijderbroeks	CRM	Final remarks/conclusions
15.25	Hugo Uijderbroeks	CRM	Q & A
15.35	Andreas Johnsson	Swerim	Event close

Figure 19: Final roadmap webinar agenda.



Policy maker	0% (0)
Steel industry	26% (5)
Other process industry	0% (0)
Academia	0% (0)
Research institute	36% (7)
Technology provider	31% (6)
Other	5% (1)

Polls
Nomi non registrati ; Risultati condivisi

Which part of the Roadmap is most relevant to you and your organization?

18 risposte

Il sondaggio è chiuso

Figure 20: Poll replies received during the future roadmap presentation.

2.6 Work package 5 – Future research and roadmap (CRM)

2.6.1 Task 5.1 Current practices in conventional mills (CRM)

In conventional rolling mills one to even four reheating furnaces, *figure 21*, are installed to reheat programmed slabs fast, homogeneous and in an economical way up to the target temperature. The economical way is focussed on the lowest energy consumption. A homogenous reheating is important for technical reasons related to rolling, but also to assure the control of the thickness of the product.

Figure 21: Reheating furnace in a hot strip mill

The typical reheating furnace has the following characteristics:

- Typically 450 ton of steel are reheated in per hour
- A typical width of a furnace is 11.5 meters and a length of 60 meters. Hereby the maximum slab length is 11 meters.
- The length of a furnace varies from 30 to 70 meters.
- The width can be up to 15 meters.
- The minimum time of a slab inside the furnace is 130 to 140 minutes in an oxidised atmosphere, which means a substantial amount of scale is being formed.
- The reheating temperature depends on the grade and varies between 1100 and 1250°C.

A typical layout of a reheating furnace is presented in *figure 22*. Slabs are first charged in a pre-heating zone, with no burners installed. The slabs move than to the heating zone and are heated up to the required temperature, about 90% of the energy is applied in this zone. The heating zone is followed by a soaking zone also equipped with burners with about 10% of the power. Important is the evacuation of emission gasses, mostly in contra-flow of the hot rolled product. A heat exchanger is used to preheat the air to the burners.

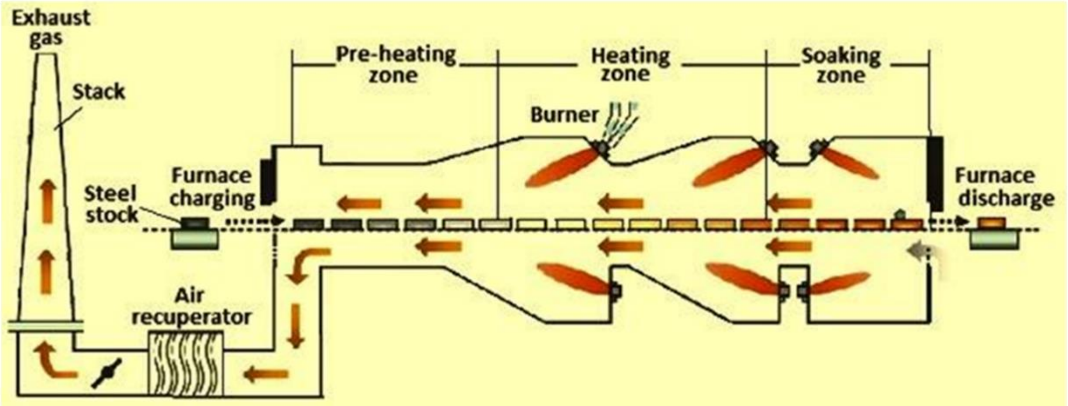


Figure 22: Typical layout of a reheating furnace

Inside a walking beam furnace for slabs about 150 to 200 burners are installed, see *figure 23* and 19. Most burners are installed at the sides, but additional burners can also be mounted on the top side of the furnace.

Figure 23: Installation of burners

Reheating furnaces are also equipped with different systems to recover the heat of the gas flow and to preheat the air to the burners. Heat recuperation is performed by a batch of heat exchangers or recuperators installed on the gas exhaust channels of the furnace, *figure 24*. In the recuperators the entry gasses of about 675°C are cooled to 300°C at the exit. The air to the burners is preheated up to 500°C.

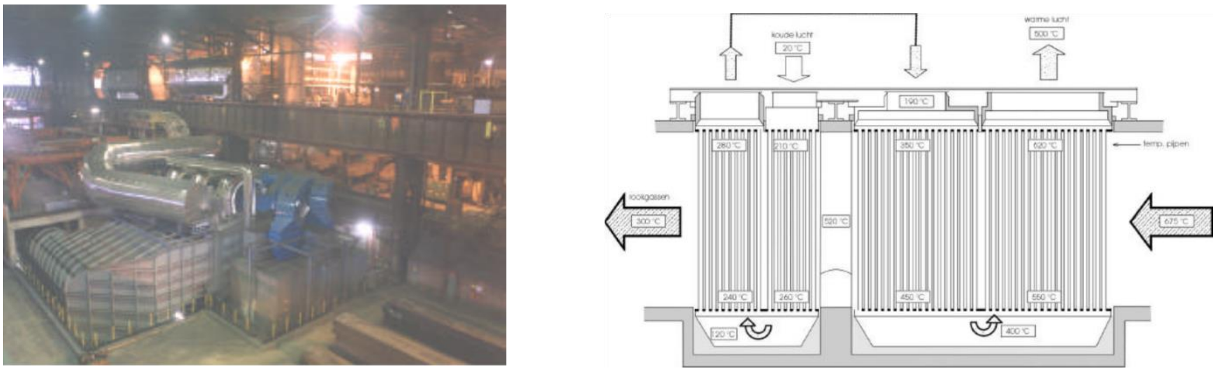


Figure 24: Heat recuperators

The average consumption of a reheating furnace is illustrated in *table 6*.

Table 6: The average consumption of a reheating furnace.

Parameter	Unit	Average
Natural Gas	MJ/ton	739.9
Converter Gas	MJ/ton	142.8
Coke Gas	MJ/ton	499.9
BF Gas	MJ/ton	15.9
Total Technological Fuels	**MJ/ton**	1,398.4
Oxygen	Nm³/ton	0.0
Nitrogen	Nm³/ton	0.6
Compressed Air	Nm³/ton	16.7
Industrial Water	Nm³/ton	3.9
Electricity	kWh/ton	78.1
Steam	kg/ton	4.8

The best practices for a reheating furnace are:

- A total fuel consumption of 1150 MJ/ton. Steckel mills or compact mills even up to 1000 to 900 MJ/ton.
- To apply hot charging: some mills apply hot charging up to 60%, at temperatures up to 750°C. Hot charging is limited mainly by the slab yard management, the maximum temperature of cranes and scarfing requirements.
- Heat loss during storage in the slab yard can be reduced by heat retention boxes
- A transfer bar thickness of 40mm, to limit heat losses. The transfer thickness is limited by the strength of the crop shear and the reduction of the finishing mill.
- Burner technology:
    - Two main types of burners are used in reheating furnaces:
        - Jet-flame burners (long flame), used in frontal and side walls (typically 1 MW-8 MW)
        - Flat-flame burners, used on the roof (typically 200 kW – 1 MW)
    - Normally, burners are operated with preheated air (~500°C, central recuperator) to partially recover the energy content of the flue gases (~800ºC at furnace outlet).
    - To increase the burner efficiency, preheated air temperature can be increased by:
        - Self-recuperative burners (power limited to about 300 kW). Each burner exhausts flues through an air recuperator (air preheated at 600-700°C).

    Normally used in tunnel furnaces (CSP), and heat treatment furnaces (direct and indirect firing).

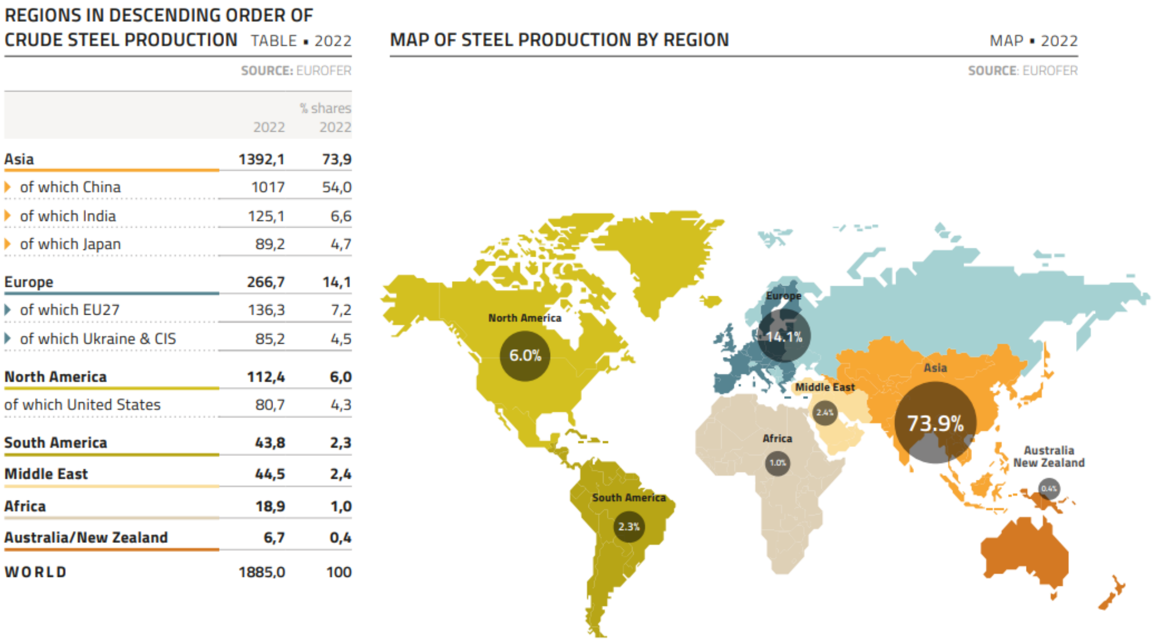
  - Regenerative burners. Air and flue gases are sequentially flown through a ceramic regenerator, achieving preheated air temperatures of ~1000ºC.

- On the other hand, to increase the efficiency (and to enhance productivity), oxygen-enhanced combustion can be used:
  - Oxygen can be injected in standard air-fuel burners to increase the O_2 level of oxidizer from 21% O_2 to about 25% O_2
  - Oxygen lancing can be used to upgrade standard air-fuel burners, so that global O2 level in oxidizer is increased to about 50% O_2
  - Oxyfuel burners using 100% O_2 (no air)
  - Hybrid air-oxy-fuel burners. Used e.g. in ladle heaters (air-fuel refractory drying and oxy-fuel heating).
- Regarding fuel flexibility, burners can be operated with a certain range of fuel gas (the Wobbe index is an usual metric for gas interchangeability). Also, in dual-fuel burners, two types of fuel gases can be used (e.g. NG and BOFG) by separate gas lances. In some cases, gas blend is done upstream (mixing station), and depending on the blend one or the other lance is used.
- Regarding NOx level:
  - Standard burners. High NOx level, especially with high air temperature.
  - Low NOx burners: staged air-fuel burners or flameless burners (aiming to delay air-fuel mixture and to enhance the flue gas recirculation so that peak flame temperature is reduced).
- Two types of burners are advised:
  - Flat-flame air-fuel burners, flexible fuel operation, low NOx. Already validated for 100% H_2.
  - Jet-flame air-fuel burners, flexible fuel operation, low NOx. Validated for 65% H_2.

2.6.2 Task 5.2 Market needs an overview (CRM)

The aim is to define the market needs regarding reheating furnaces also taking into account hot charging practices, import of hot rolled products and slabs and mini-mills.

The crude steel production in Europe in 2023 reached 128.2 Mton (136.3 Mton in 2022, *Figure 25*. The demand of steel in EU was 132.2 Mton in 2023.



REGIONS IN DESCENDING ORDER OF CRUDE STEEL PRODUCTION TABLE ▪ 2022

SOURCE: EUROFER

	2022	% shares 2022
Asia	**1392,1**	**73,9**
of which China	1017	54,0
of which India	125,1	6,6
of which Japan	89,2	4,7
Europe	**266,7**	**14,1**
of which EU27	136,3	7,2
of which Ukraine & CIS	85,2	4,5
North America	**112,4**	**6,0**
of which United States	80,7	4,3
South America	**43,8**	**2,3**
Middle East	**44,5**	**2,4**
Africa	**18,9**	**1,0**
Australia/New Zealand	**6,7**	**0,4**
WORLD	1885,0	100

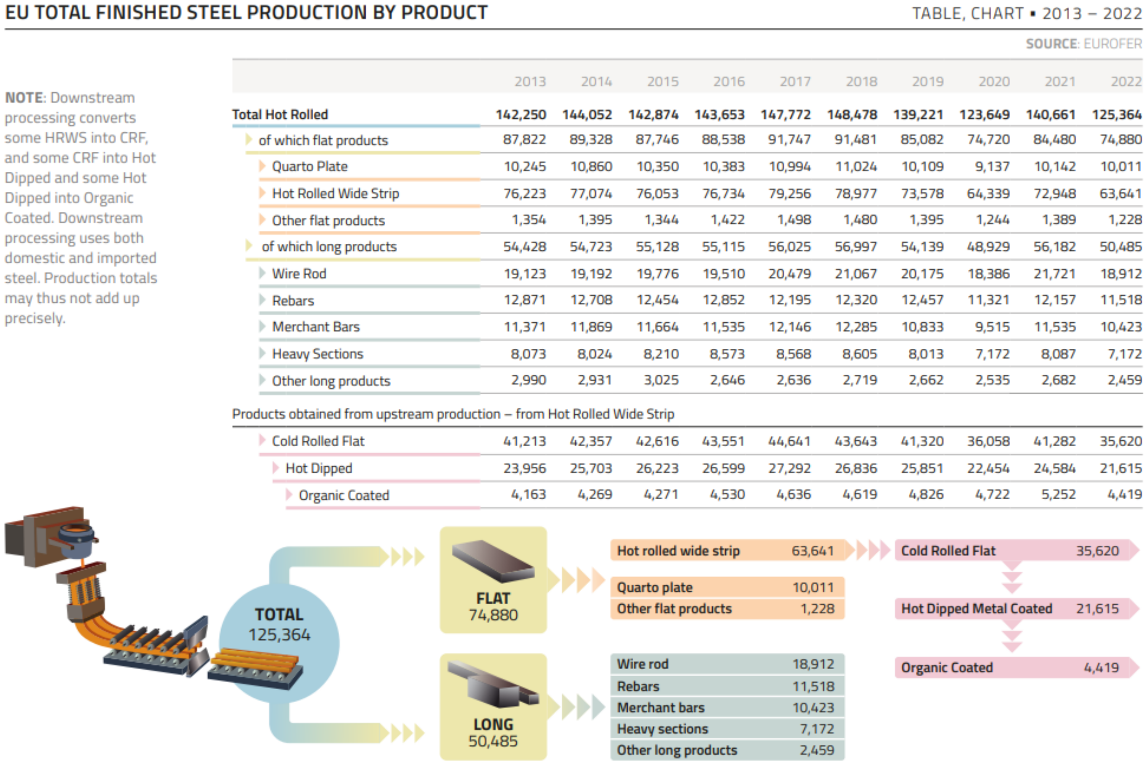
MAP OF STEEL PRODUCTION BY REGION MAP ▪ 2022

SOURCE: EUROFER

Figure 25: Steel production by region (EUROFER)

By product quality, in can be observed in *figure 25* and *Figure 26* that the total number of hot rolled wide strips in 2022 was 63 Mton, of which 35 Mton was cold rolled.

EU strip mill products are mainly sold directly to end-users, 53.8%. 36.7% is sold to steel service centers and 9.5% to merchants. The biggest market in EU is the “Automotive sector”, 40 to 50%. This also illustrates the strength of the EU steel industry. In many applications a product is developed together with the customer, resulting in long term constructs of 5 to 6 years, related to specific model types of cars. The other markets are “Audio, video and domestic appliances”, “Construction”, “Mechanical engineering”, ”Sanitary facilities” and “Packaging material”.



EU TOTAL FINISHED STEEL PRODUCTION BY PRODUCT TABLE, CHART ▪ 2013 – 2022

SOURCE: EUROFER

NOTE: Downstream processing converts some HRWS into CRF, and some CRF into Hot Dipped and some Hot Dipped into Organic Coated. Downstream processing uses both domestic and imported steel. Production totals may thus not add up precisely.

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Total Hot Rolled	**142,250**	**144,052**	**142,874**	**143,653**	**147,772**	**148,478**	**139,221**	**123,649**	**140,661**	**125,364**
of which flat products	87,822	89,328	87,746	88,538	91,747	91,481	85,082	74,720	84,480	74,880
Quarto Plate	10,245	10,860	10,350	10,383	10,994	11,024	10,109	9,137	10,142	10,011
Hot Rolled Wide Strip	76,223	77,074	76,053	76,734	79,256	78,977	73,578	64,339	72,948	63,641
Other flat products	1,354	1,395	1,344	1,422	1,498	1,480	1,395	1,244	1,389	1,228
of which long products	54,428	54,723	55,128	55,115	56,025	56,997	54,139	48,929	56,182	50,485
Wire Rod	19,123	19,192	19,776	19,510	20,479	21,067	20,175	18,386	21,721	18,912
Rebars	12,871	12,708	12,454	12,852	12,195	12,320	12,457	11,321	12,157	11,518
Merchant Bars	11,371	11,869	11,664	11,535	12,146	12,285	10,833	9,515	11,535	10,423
Heavy Sections	8,073	8,024	8,210	8,573	8,568	8,605	8,013	7,172	8,087	7,172
Other long products	2,990	2,931	3,025	2,646	2,636	2,719	2,662	2,535	2,682	2,459
Products obtained from upstream production – from Hot Rolled Wide Strip										
Cold Rolled Flat	41,213	42,357	42,616	43,551	44,641	43,643	41,320	36,058	41,282	35,620
Hot Dipped	23,956	25,703	26,223	26,599	27,292	26,836	25,851	22,454	24,584	21,615
Organic Coated	4,163	4,269	4,271	4,530	4,636	4,619	4,826	4,722	5,252	4,419

Figure 26: EU total finished steel production by product

The grades being rolled in each plant can strongly vary. An analysis of the grades being roll in different mills resulted in an average value of product families being produced in a European hot strip mill, *table 7*. The contribution are deep drawing grades followed by HSLA and structural steels.

Table 7: Typical product families being rolled in a HSM

Product family	**%**	**Mton/year**
Drawing/Isotropic	26	16,38
IF Drawing	17	10,71
HSLA	15	9,45
Structural steels	11	6,93
Packaging	9	5,67
IF High Strenght	4	2,52
BH	4	2,52
Dual Phase	2,3	1,449
API tubes	2	1,26
Plates	2	1,26
Ferrite Bainite	1,8	1,134
TRIP	1,8	1,134
High Carbon	1,4	0,882
Enameling	1,2	0,756
Electrical steels	1	0,63
Multiphased steel	0,5	0,315
Total	**100**	**63**

Considering an average consumption of 1.4 GJ/ton, the market need regarding reheating furnaces is 88,000,000 GJ.

The best method to reduce the market need regarding reheating furnaces is hot charging. Hot charging practices strongly vary between the different European hot strip mills depending on the layout of the mill and the product mix. In some mills, such as ArcelorMittal Florange, hot charging is even not possible as all slabs are imported from other facilities. Today, in average 9% of the slabs are hot charged at a temperature of about 150°C.

Today some mills already apply hot charging for 60% of their product mix even at temperatures up to 750°C.

Hot charging of all slabs is however not realistic (e.g. orders, slab production, slab import, mill productivity, slab yard management).

In 2022 about 5.3 Mton of slabs were imported to Europe. The European steel market was significantly dependent on the import of slabs from Ukraine and Russia. As a result of the war, the supply structure changed significantly: Russia reduced the shipment of slabs, Ukrainian exports collapsed due to the loss of production capacity. Russian exports of slabs to the EU in 2022 amounted to 3.36 million tons. Several European consumers have partially switched to slabs from China (336 kton), India (207 kton), as well as from Brazil (463 kton). In the future, the share of Brazilian slabs in European markets could increase as ArcelorMittal acquired the Brazilian slab producer CSP. Major increases are however not expected. Some slab grades can also not be imported as the temperature of the slab between casting and rolling cannot go below 150°C, so they must be warm charged. The rules of the plants are different but in general it concerns grades with a $C \geq 0.4\%$ or $C \geq 0.3\% + Mn > 1.0\%$ or $Si > 1\%$. So, this accounts for some C-Mn grades, AHSS or high Mn grades, or high Si/ high Al grades. In average about 3% of the product mix.

So, considering all constraints (e.g. orders, slab production, slab import, mill productivity, slab yard management) it could be viable to hot charge about 60% of the slabs at 500°C. The average energy consumption could be reduced to 1 GJ/ton, and by this lower the market need for energy regarding reheating furnaces to 63,000,000 GJ, or a reduction by almost 30%.

Another factor that could reduce the market need regarding reheating furnaces is of course the import of hot rolled flat products.

The import of flat hot rolled strips in 2022 in the EU was about 9 Mton, see *figure 27*. The main import countries are Turkey, India, South Korea and Taiwan. The export from the EU of flat hot rolled products in 2022 was about 2 Mton, *figure 28,* resulting in a difference of 7 Mton. Compared to a production of flat hot rolled strips in EU of 63 Mton, means about 11% is imported. If import would increase with a factor 2, it would lead to a reduction of market need regarding reheating furnaces of 10%. So, 79,000,000 to 56,000,000 GJ if hot charged. Major increases are however not expected taking into account the client relationship and if necessary, Europe could also protect his market.

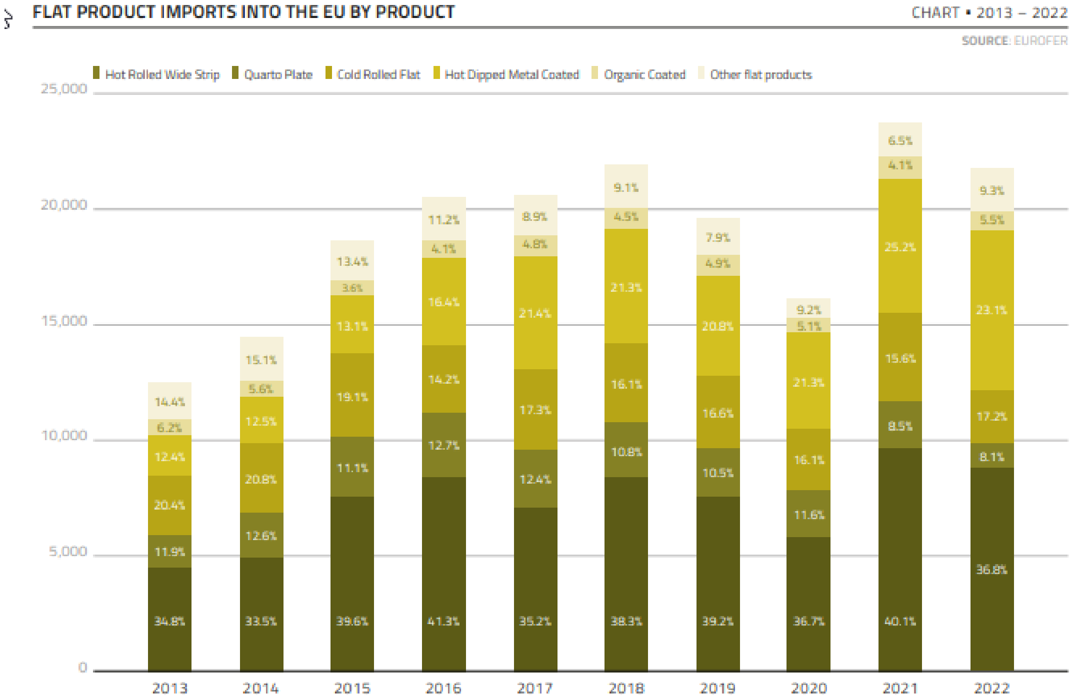


Figure 27: Import of flat products into the EU

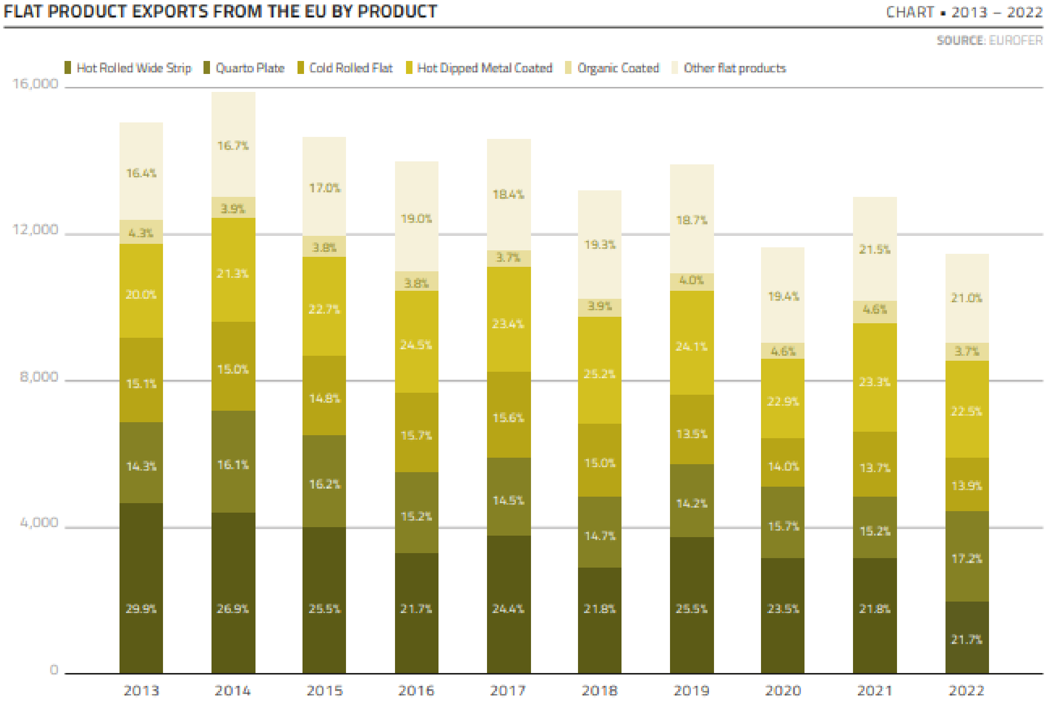


Figure 28: Export of flat products form the EU.

A third option to reduce the requirement of reheating furnaces is the increase of mini-mills in EU. The energy consumption in a mini-mill is about 0.9 GJ/ton. In 2022 about 7 Mton of hot rolled strip has been rolled on mini-mills, about 11%. The main mini-mills are the ESP (Endless Strip Production) plants of Arvedi, the CSP (Compact Strip Production) plant of TKSE, the CSP plant of ArcelorMittal in Sestao and the DSP (Direct Sheet Plant) of Tata Steel NL. An increase of mini-mills in EU is however not expected as some companies already intended to close their operation. In 2023, only 0.2 Mton was produced at the CSP plant of ArcelorMittal Sestao.

The main limiting factors are:

- The investment cost in new plants
- Only production gains for thin products (<2mm)
- The mixed scheduling
- Limited number of grades that can be rolled. On a mini-mill it is possible to produce low carbon, high-strength low alloy (HSLA), electrical steel grades, ferritic bainite steels, and some multi-phase and Si grades.
- The secondary cooling configuration during casting (edge cracks)
- Surface quality (high reductions, high roll wear)
- Limited cooling power and length on the runout table

Mini-mills are especially of interest for local markets with the availability of steel scrap. By EAF a low capex is required. With the transition in Europe to DRI-EAF route perhaps the interest of mini mills will increase.

If the current mills would produce at their maximum capacity, the volume could increase to 13 Mton, so 20% of the market needs. If investment capital and time to market is not a problem in theory 75% of all hot rolled strips could be produced on mini-mills. It is however not expected that their share will increase higher than 25%, so an additional 15%. By this the market need regarding reheating furnaces could reduce to 83,000,000 GJ, or a reduction 5%.

2.6.3 Task 5.3 New reheating technologies (CRM)

Discussions were constantly ongoing with steel industry delegates, and the outcomes of these discussions are included in the presented material on current practices as well as the future road map.

2.6.4 Task 5.4 Future roadmaps and task 5.5 Future research needs (CRM, all)

During the timeline describing the project duration, the work has involved three main phases:

- Looking back at research already performed under the two big research pillars RFCS and Horizon Europe, previous Horizon 2020. The project results and publicized final reports have been analysed to bring forward outcomes which were classified and summarized. The analysis also included what has been going on in the international arena, with emphasis on the last 5 years and with particular focus on low CO2 heating.
- State of the art collected and analysed based on BREF documentation.
- A roadmap, looking towards what is required going forward.

The roadmap is a report available on the DissHeat homepage (DissHeat.eu) and lists per topic what is required to achieve a low carbon emission future in the field of furnace technology for steel reheating furnaces.

Global focus of the roadmap for future research

Global focus of the roadmap for future research is reducing CO_2 emissions by 35% by 2030, and of achieving carbon-neutral steelmaking by 2050. The global roadmap of one of the major steel producers, ArcelorMittal, is presented below, *figure 29*. The main focus regarding reheating furnaces is the sourcing of clean electricity (Key D). At this moment mainly studies and industrial trials are being performed. Industrial changes are expected after 2030 in order to be carbon neutral by 2050.

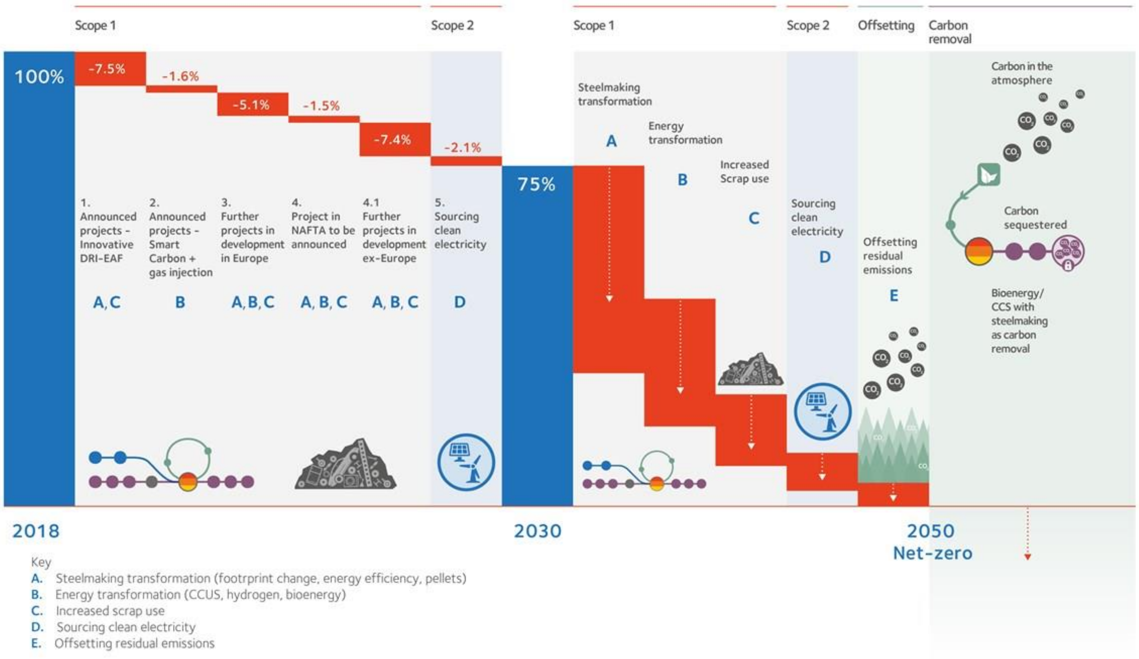


Figure 29 : Decarbonization of the steel industry

To achieve the net-zero target in 2050 the project DISSHEAT has defined several research needs in the field of:

- ”Heating and burner technology”
- ”Modelling and control (level 2) of entire furnaces”
- ”Sensors and control (level 1), standards, regulations”
- ”Materials in the furnace and product quality”
- ”Heat transfer, heat recovery, productivity economy

The results will be presented in the following paragraphs.

Topic 1- heating and burner technology and Topic 5- heat transfer, heat recovery, productivity, economy

The report covers the opportunities and challenges for the five subtopics, however topic 1 and five are closely linked and it is convenient to handle them together. Below is the topics points that have to be addressed:

Burner technology

Technology impact and integration research on:

- Combustion heating with flexible fuel burners for fuels including.
    - Hydrogen, biofuels, NH_3, with the oxidizers air, OEC, oxyfuel and NOx emissions have to be handled and options are flameless and ultra-low NOx burners

  - The impact on product heating such as: the flame temperature and flame shape and the effect on radiative heat transfer, efficiency with the flue gases (% H_2O, %N_2, %CO_2 etc) that exist, *figure 30*.

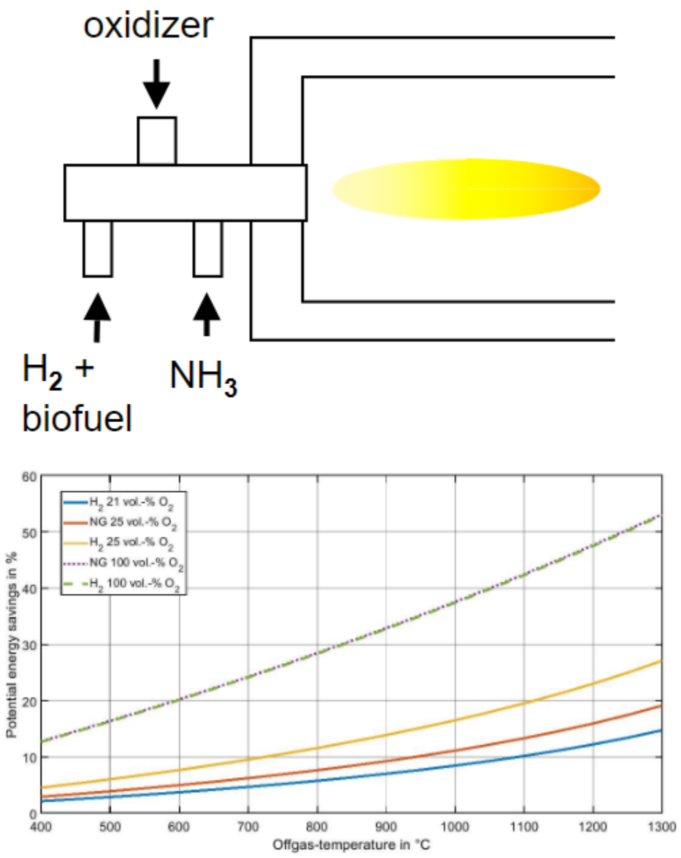


Figure 30: Impact on heating.

- Efficiency and efficient heating with new technologies by heat recovery from exhaust gases to preheat:
  - The oxidizer, future fuels or mixtures with exhaust gases
  - The products in the dark zone, *figure 31*, and the effect the new fuels, hybrid heating alternatives and flexifuel heating has on the exhaust gases.
  - How the specific use case/plant efficiency is affected.

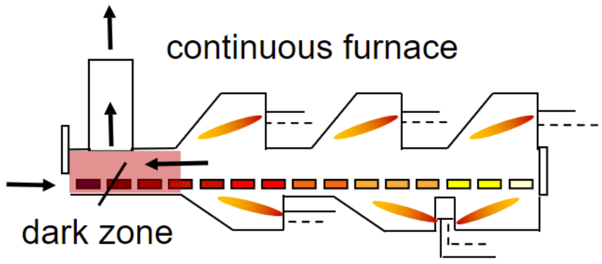


Figure 31: Heating of products in the dark zone of the reheating furnace.

- The impact on the product and the plant by hydrogen combustion, electrical heating or flexifuel combinations on:
  - The product/material, the temperature uniformity, and the oxide formation

  - The effect on the furnace (lining, refractories) and auxiliaries related to the new technological solutions, i.e. high H_2O content in the exhaust gases and its effect on resistive heating elements and refractories and insulation, lining.
  - The safety related to new solutions, such as pure H_2 combustion.
- Specific combinations such as hybrid heating between combustion and electrical heating driven by:
  - Availability of future fuels and renewable energy and the impact on use of H2 produced by electricity (green H2) or the direct use of electricity for heating and how the local availability of biofuels is for the region or plant.
  - The effect on the material and if it has limitations on the dimensions that can be produced, i.e. high efficiency induction heating has limitations for broad format ranges related to where the induction heating technology development is currently. Also, the impact the specific heating method has on the material/product and the entire hot rolling process.
- For hydrogen combustion and the adjustment for the plant there are some prerequisites on a plant level that can be identified, see *figure 32*:
  - The installed reheating furnaces can in most cases be retrofitted and the current infrastructure can be preserved to a large degree.
  - There will be needs for investments in electrolysers, or if there are options to buy H_2 on the market where the most convenient option would be if there would be an access to a H_2 gas grid. Already today the electrolysers production capacities are being upscaled to levels matching the need for reheating furnaces. If a gas grid is installed, a gas grid by itself would be a possible H_2 storage.

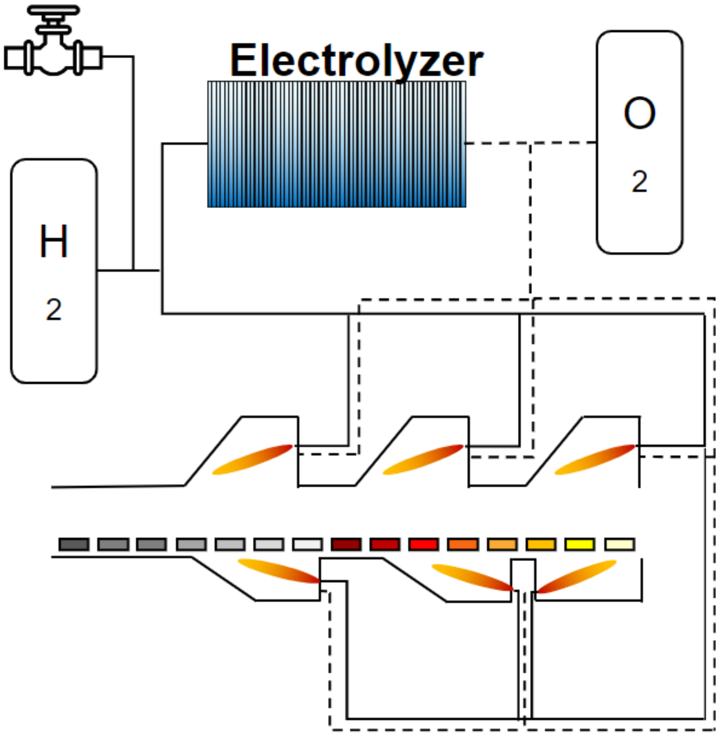


Figure 32: Solution with an electrolyser.

- Electrical heating solutions from an industrial point of view and considering the two options of new greenfield installations or retrofitting options.

  - Greenfield installations could offer a completely and adapted electrical furnace solution. Inductive heating can be used for pre-heating offering high productivity but with a drawback on flexibility in geometric variations if energy efficiency and productivity is to be on the high end. Resistive heating can be utilized for soaking offering high energy efficiency and high control while there is a possibility to introduce a protective atmosphere to suppress oxide scale formation.
  - Retrofitting options can also introduce inductive heating, but keeping the current product variations can lead to high losses in efficiency. Resistive heating can be used, but if existing furnace volumes are used there are limitations in the power density that can be provided in a volumetric sense. There are emerging technologies like rotodynamic heating which possibly can provide higher power density in a future perspective.
- On the topic of flexifuel solutions, there is a great opportunity to investigate the hybrid solution which could include an flexifuel option, which would require an investigation of how this solution could be optimized (H2/NG with O2 + electrical solutions) and this can be addressed through technology integration research on hybrid furnace operation interactions (induction, combustion (various fuels), electrical heating and whether this solution would benefit from a retrofit or a greenfield installation, *figure 33*.

As a last point related to topics 1 and 5, there is also a need to make an overhaul on the system level, *figure 34*, and it would be beneficial to make research on the system level relating to:

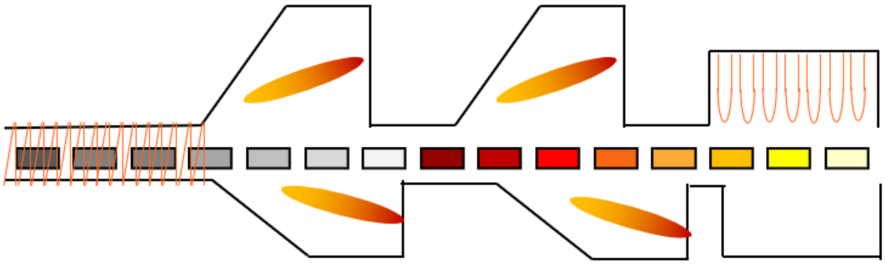


Figure 33: One hybrid furnace solution.

  - The internal integration within the steel mill
  - Are there options to include CCS/CCU technologies.
  - Is there a possibility for flexible interactions with the gas and power grid.
  - How should the oxygen for the combustion be applied to make the most efficient process?
  - Is there a possibility to integrate the steel plant with chemical industries for synthetic fuel production.

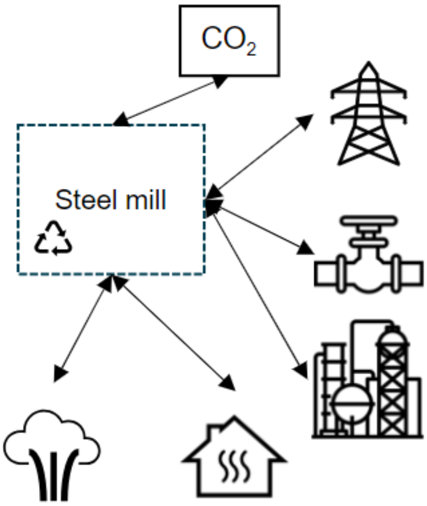


Figure 34: System level

  - Can the process heat not currently used to be further integrated with steam or hot water production or to produce electricity via solutions like Rankine cycle.
  - Can the logistics be improved and adapted for hot or warm charging?

Topic 2- Modelling and control of the entire furnace

There are constantly evolving new opportunities to improve the control of the furnace:

- There are possibilities to improve the kinetics schemes and how the chemical dynamics are happening that would increase the understanding, see *figure 35.*
- The way the pollutants are being formed, including NOx and particulate emissions.
- New and improved ways to monitor the flame.
- Different tools will be applied such as Kinetic scheme interpreters (CHEMKIN, Cantera), CFD software (Fluent, OpenFOAM, …) and increased CPU calculation power (clusters, servers)

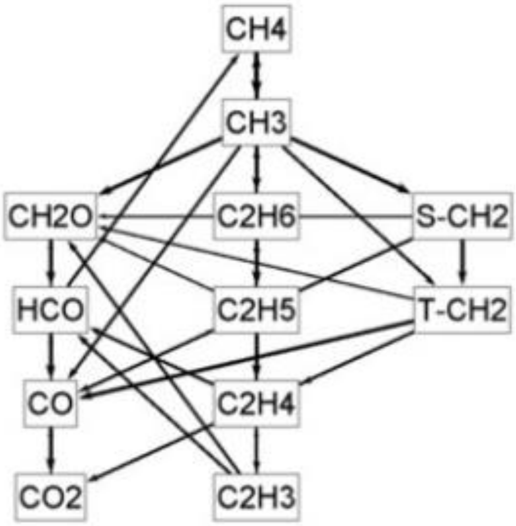


Figure 35: Kinetic scheme modelling.

The statistical approaches can be extended and approved, and field that offer the most rapid progress are AI (artificial intelligence) and ML (machine learning) solutions which can include physical injected neural networks and use dynamic and/or auto-adaptive modelling for improved process control, *figure 36.*

New possibilities to store and analyse big data and the tools to use this possibility is presented in *figure 37*. These tools can be used for extended statistical approaches based on observation, formulating a hypothesis to explain observations, hypothesis testing, data analysis and conclusions.

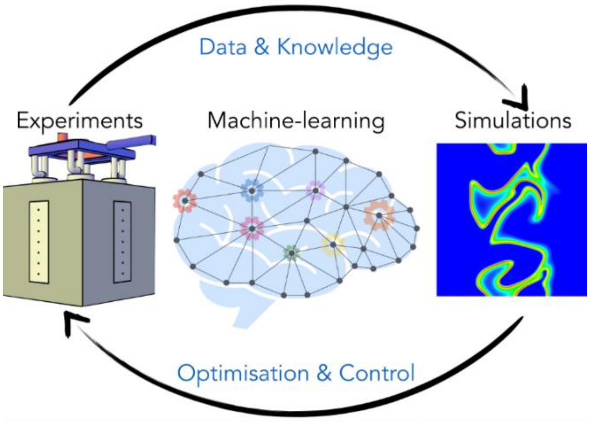
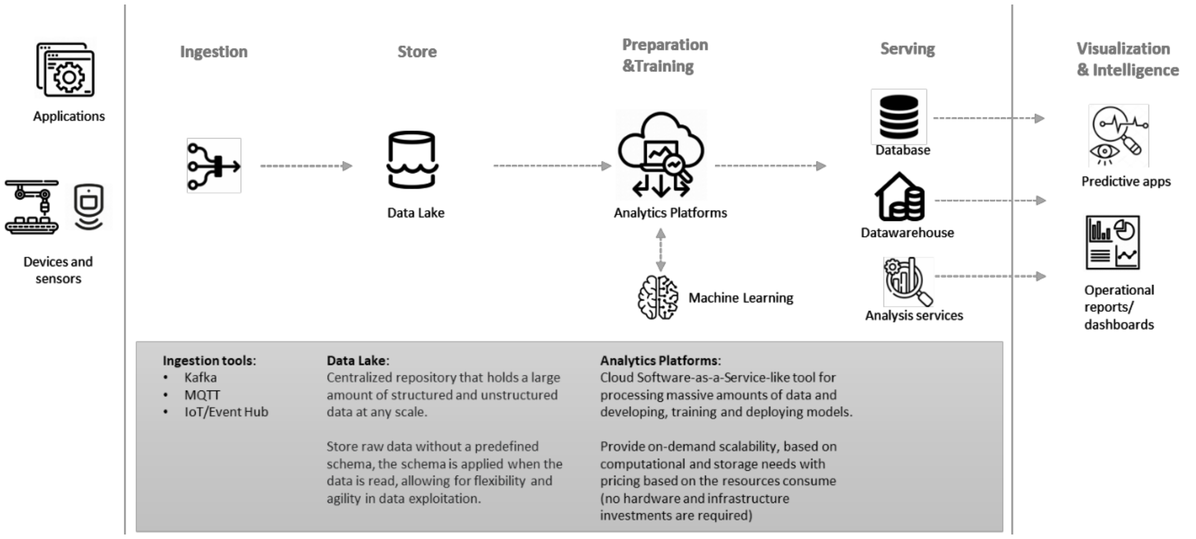


Figure 36: Process control.



Ingestion tools:
- Kafka
- MQTT
- IoT/Event Hub

Data Lake:
Centralized repository that holds a large amount of structured and unstructured data at any scale.

Store raw data without a predefined schema, the schema is applied when the data is read, allowing for flexibility and agility in data exploitation.

Analytics Platforms:
Cloud Software-as-a-Service-like tool for processing massive amounts of data and developing, training and deploying models.

Provide on-demand scalability, based on computational and storage needs with pricing based on the resources consume (no hardware and infrastructure investments are required)

Figure 37: Big data storage and analysis and some of the tools available.

Topic 3- Sensors and control, standards and regulations

The future research needs related to fuel switches can be summarized in *figure 38*. This figure describes the impact of alternative heating systems on the furnace control, level 1, system. And considers multi-fuel burners and the need for adaptive burner control systems for smooth furnace operation.

- The impact on fuel quality is considered compared to two Natural gas sources, H-gas which is originating from Russia and has a methane content of about 87-99%, costs more than L-gas and has a higher low calorific value (LHV) and lower levels of nitrogen and CO_2. L-gas originates from Northern Germany and the Netherlands, has lower LHV and more nitrogen and CO_2. 100% natural gas (H-gas) has a LHV of ~11 kWh/m^3, 100% H_2 has a LHV of ~3 kWh/m^3, and NH_3 a LHV of ~5 kWh/m^3.
- The Wobbe index (WI) indicates the gas interchangeability or whether they can be combined. WI of H-gas is 13.6-15.7 kWh/m^3, WI of L-gas is 11-13 kWh/m^3 and the levels of H2 that is interchangeable with H-gas is 100% H_2 or below levels of about 30% H_2. Intermediate levels of H_2 (50-90%) is better suited to be mixed with L-gas.
- The right part of the figure indicates the change in power output with L-gas and H-gas with level of H_2 used between 0-100% and the relative air consumption during the combustion, showing that the lambda value is increased, as the H_2 content is increased from 0% compared to the pure natural gas case (stochiometric conditions and lambda =1) under constant gas and air partial pressures.

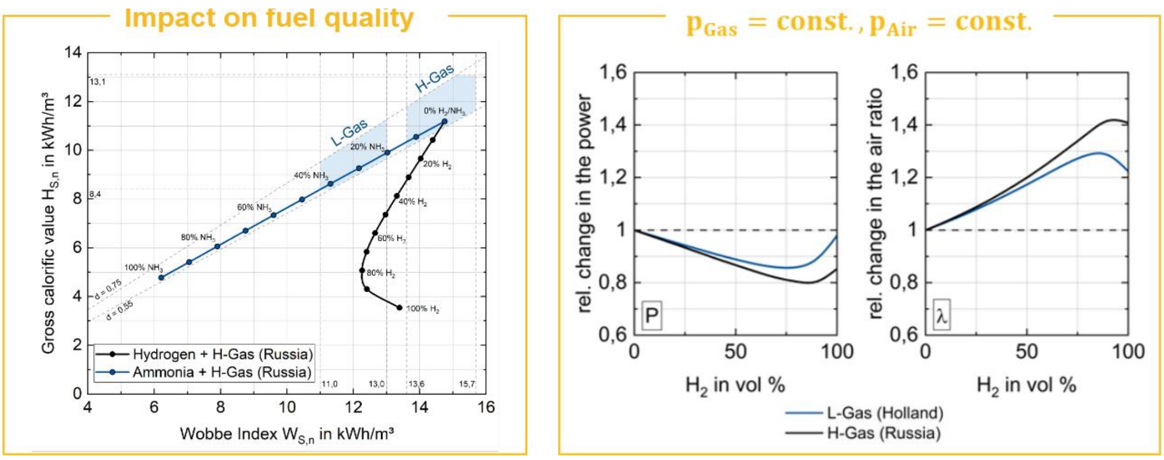
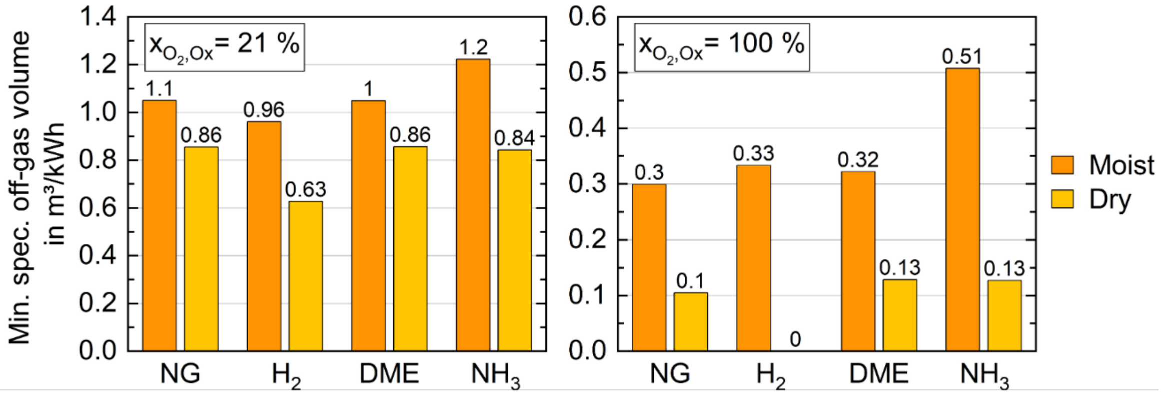


Figure 38: Impact of fuel quality.

The impact of alternative heating systems on off-gas measurements can be seen in *figure 39*. The figure shows the water content in the off-gases using alternative fuels and pure oxygen or air combustion.

- In air, left part of the figure, there is nitrogen from the air, only 21% oxygen, and for the case of natural gas, the moist off-gas content after combustion is 1.1 m^3/kWh and dry content is 0.86 m^3/kWh, the moist containing H_2O, CO_2 and N_2 mainly. For the same case with pure O_2 combustion, there is no N_2, and the moist off-gas contains 0.3 m^3/kWh, and dry 0.1 m^3/kWh, meaning 2/3 of the content is H_2O.
- For the other cases there is no CO_2 and the difference between moist and dry for air is resulting from N_2 and H_2O, where the H_2O is removed in dry conditions. The off-gas volumes in m^3/kWh from H2, DME and NH_3 can be seen for each case.
- For pure oxygen combustion, lacking N_2, the differences are larger as no CO_2 is present for DME, H_2 and NH_3.
- For the case of H_2/O_2 combustion, there is only H_2O, meaning no dry remaining when the sample condensate. This poses a special challenge as for instance the NOx levels measured is performed in dry conditions.



For a fair comparison of NO_x emission, measurement on moist basis is recommended

Figure 39: Water content in off-gases under air and pure O_2 combustion of various fuels.

This means there is a need for a revision of emission measurement standards for measurements on moist basis when we are talking about CO_2 free fuels and off-gases with low or no levels of dry remaining after condensation and to make fair comparisons new standards with measurements on moist basis is recommended. The following standards are affected, see *figure 40*.

EN 14792

Stationary source emissions – Determination of mass concentration of nitrogen oxides – Standard reference method: chemiluminescence

EN 14181

Stationary source emissions — Quality assurance of automated measuring systems

EN 15267-3/-4

Assessment of air quality monitoring equipment –Part 4: Performance criteria and test procedures for stationary/portable automated measuring systems for periodic measurements of emissions from stationary sources

Figure 40: Standards subject to suggested revisions.

- Revision of NOx limit definitions for flexible operation
    - for flexible fuel operation
    - for hybrid heating operation (electric & gas)
- Revision of BREF Ferrous Metals Processing to include new BAT-AELs definitions
    - To date, BAT AELs for the heating of feedstock in hot rolling are only defined for two fuel categories: "100% natural gas" and "other fuels“

Use of alternative fuels according to ISO 13577-2 “Industrial furnaces and associated processing equipment - Safety - Part 2: Combustion and fuel handling systems”:

- “When other fuels like e.g. hydrogen are used additional risk assessment is conducted to prove suitability of components”
- “Where fuel gas with a volume fraction of more than 80 % hydrogen (H_2) is used additional risk assessment shall prove suitability of components etc. and procedures”
- “In case of hydrogen and fuel gases with a volume fraction of more than 80 % hydrogen the safety time for ignition shall be limited to 3 s”
- “In case of gaseous fuels with a volume fraction of more than 80 % hydrogen or acetylene (C_2H_2) residual fuel from the automatic shut-off valves to the burners shall be safely discharged or burned”

Topic 4- Materials in the furnace and product quality

Technology impact and integration research will focus on:

a. New insulation materials for reheating furnaces to limit heat loss

b. Application of reflective coatings on the furnace walls

c. New ceramic materials with improved resistance for humidity and different scale layers.

d. Study of the impact of residuals on product quality and reheating strategy. By moving from the blast furnace route to the DRI-EAF more residual elements are expected with could have an impact on the product quality during reheating. For instance:

    - Cu will diffuse quickly leading to segregation, roughening of the interface and intergranular oxidation.

    - Mo above 0.25% will increase scale adhesion.

e. A full screening of all grades, with all different hybrid reheating configuration related to scale growth, scale composition, descaling, decarbonization and hydrogen embrittlement. For instance, with 100% hydrogen firing scale growth is increased by 20 to 35% but also a different scale layer can be observed on a dual phase steel, *figure 41*. Scale spalling took place in a different location for NG and H_2 firing. A separate phase is observed containing Si and Al.

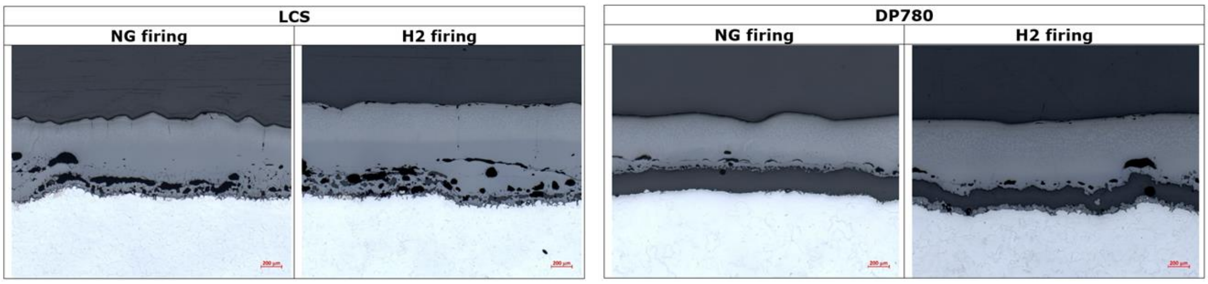


Figure 41: Impact of 100% hydrogen firing on scale growth and composition

f. Application of protective coatings, *figure 42*.

Figure 42: Application of protective coatings

g. Alternative metallurgical compositions to improve product quality.

h. Wear of new hybrid reheating components:
    - Burner nozzle wear by hydrogen flame
    - wear of electrical resistances

3 Exploitation and impact

The project was presented during the CSP Cluster event – Decarbonization of reheating and treatment furnaces, October 27 by BFI.

RWTH presented a summary of the ESTAD workshop and the overall project at AOTK (Aachener Ofenbau und Thermoprozess-Kolloquium) on the 17.-18.10.2023: “ DissHeat - Analysis of the best available technologies and outlook on future developments for heating furnaces in the steel industry

The project was presented during the annual TGA2 Downstream steel processing meeting on October 17, Swerim.

The two abstracts were:

Abstract 1: Electrification of reheating furnaces: state of the art and future research needs

Downstream industrial furnaces on the metalworking side must be de-fossilized to achieve the target of CO2-neutral steel production. This work aims to promote measures to reduce the carbon footprint of reheating furnaces gathered from the literature, EU/RFCS/ECSC projects and EU-BAT documents and promote state-of-the-art technology to a wider audience, and finally develop a roadmap for future research activities. This paper aims at promoting measures that improve the efficiency and productivity of reheating furnaces, electrical heating, or carbon-neutral fuels.

The work comprises a critical review of relevant EU-projects and literature from the last 25 years, which was compiled and tabulated based on key performance indicators related to efficiency, productivity, heat transfer, heat recovery and scope 1 and 2 greenhouse gas emissions. The findings were disseminated to stakeholders from the steel industry, technology providers, policymakers, and researchers through workshops and webinars. This provided feedback and insights to formulate a roadmap for technological development, research activities and priorities. In this work, findings relevant for electrification was considered and elucidated. Recent developments of electric heating technologies, inductive heating or radiative resistive heating are better suited to provide efficient, carbon-neutral heating in reheating furnaces. However, the cost of electrical heating presents a major hurdle for large-scale implementation due to the requirement of greenfield installations, larger retrofits and basic electric infrastructure, and a supply of fossil-free power production.

Due to the long lifespan of reheating furnaces, research into low CO_2 technologies applicable in existing furnaces can be applied and is required in the short and mid-term. This includes indirect electrification through hydrogen and other electro fuels together with direct electrification through resistance and induction heating. Long term, further development is needed towards electrification, electric heating technologies and hybrid heating. We also identified research opportunities for new integration possibilities within steel mills, and potential synergies with other industries.

Abstract 2: *Dissemination and future research road map on heating and burner technology in industrial heating in the European steel industry*

This article deals with the analysis of research conducted in Europe on industrial heating in the steel industry and future research needs for fossil free heating. The European steel industry consumes enormous amounts of fossil fuels for the production and processing of steel and is therefore responsible for a large share of industrial CO_2 emissions. The steel industry has therefore taken measures under the European Green Deal to reduce these emissions. However, the focus of new developments has so far been on steel production due to the particularly high demand for fossil fuels for pig iron production.

Almost half of the industrial energy demand in Europe is required for thermal processing equipment such as industrial furnaces, whose energy consumption amounts to 1,650 TWh/a [6]. Industrial furnaces for metal processing in Europe are responsible for about 8 % of the total consumption of all European industrial furnaces, accounting for 99 to 132 TWh/a.

In the dissemination project „DissHeat“, funded by the Research Fund for Coal and Steel (RFCS), research projects and international research of the last 25 years, the State of the Art (SoA) and best available technologies, on industrial heating in steel industry, where analysed, classified and evaluated. The CO_2 reduction potentials of the SoA and new technologies as well as their readiness for implementation for current industrial furnaces and in particular reheating furnaces in rolling mills were determined and evaluated. Based on these findings and results, a future research roadmap was developed in cooperation with stakeholders from research, plant operators and suppliers. Therein the future research needs in the topic of heating and burner technology for a CO_2 free industrial heating on the pathway to green steel have been defined.

4 Conclusions

The results of the work have been many, and since this is an action under accompanying measures, a dissemination project under the RFCS, a major part of the work are in the form of collected and analysed material, compiled in reports of what has been previously done over the last 25 years under the project areas RFCS and HEU, but also on the international scene in the form of international literature. Another important outcome or results of this project is the many dissemination and communication actions.

To evaluate the performed work in a broad interdisciplinary subject has been rewarding but also a lot of work. Fortunately, the researchers involved in the project are highly skilled and experienced within the field and the competences required to carry out this task. The same accounts for the future roadmap, where experience and knowledge is paramount to see what is coming.

5 List of figures

6 List of tables

7 List of acronyms and abbreviations

ADP	Acid Dew Point
BAT	Best Available Technology
BREF	Best Available Technology reference documentation
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
CSP	Compact strip production
DME	Dimethylether
GHG	Greenhouse gas emissions
HEC	Hydrogen enhanced combustion
HEU	Horizon Europe projects
IR	Infrared
LHV	Lower heating value
LPG	Liquefied Petroleum Gas
NG	Natural gas
NH3	Ammoniac
NO_X	Nitrogen Oxide in Exhaust from combustion as mixture of NO, NO_2 (N_2O here neglectable)
OEC	Oxygen enhanced combustion
OPEX	Operational Expenditures
ORC	Organic Rankine Cycle
RANS	Reynolds-Averaged Navier–Stokes equations
RFCS	Research fund for coal and steel
SNG	Synthetic natural gas
SoA	Statement of Applicability
TRL	Technology readiness level

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