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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Summarizing table of relevant applications and technologies with KPIs

Deliverable 2.2

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Topics	
Number	**Name**
1	Heating and burner technology; alternative heating methods; electrical heating
2	Modelling of entire furnace, model based predictive control (level 2)
3	Measurement and sensors, measurement-based furnace control (level 1); standards, regulations
4	Materials in the furnace and product quality
5	Heat transfer, heat recovery, productivity, economy

Technology readiness levels (TRL)	
TRL 1	basic principles observed
TRL 2	technology concept formulated
TRL 3	experimental proof of concept
TRL 4	technology validated in lab
TRL 5	technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	system prototype demonstration in operational environment
TRL 8	system complete and qualified
TRL 9	actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Source: Horizon 2020 programm (2014) - General Annex G

https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

Glossary		
Name	**Short definition**	**Definition**
Scope 1	A reporting organization's direct GHG emissions.	Direct GHG emissions occur from sources that are owned or controlled by the company, for example, emissions from combustion in owned or controlled boilers, furnaces, vehicles, etc.; emissions from chemical production in owned or controlled process equipment. Direct CO2 emissions from the combustion of biomass shall not be included in scope 1 but reported separately (see chapter 9). GHG emissions not covered by the Kyoto Protocol, e.g. CFCs, NOx, etc. shall not be included in scope 1 but may be reported separately
Scope 2	A reporting organization's emissions associated with the generation of electricity, heating/ cooling, or steam purchased for own consumption	Scope 2 accounts for GHG emissions from the generation of purchased electricity consumed by the company. Purchased electricity is defined as electricity that is purchased or otherwise brought into the organizational boundary of the company. Scope 2 emissions physically occur at the facility where electricity is generated.
Scope 3	A reporting organization's indirect emissions other than those covered in scope 2	Scope 3 is an optional reporting category that allows for the treatment of all other indirect emissions. Scope 3 emissions are a consequence of the activities of the company, but occur from sources not owned or controlled by the company. Some examples of scope 3 activities are extraction and production of purchased materials; transportation of purchased fuels; and use of sold products and services.

Source: The Greenhouse Gas Protocol - A corporate accounting and reporting standards, 2004

ghg-protocol-revised.pdf (ghgprotocol.org)

Overview of literature

RFCS projects			
Reference Number	Project full name or article name	Acronym	Link to report / publications / website
R1	Regenerative firing of low calorific value gas for high temperature processes, EUR N° 12093	-	https://op.europa.eu/en/publication-detail/-/publication/229f9888-e544-43cc-8d37-9fca6ea0fe87/language-en/format-PDF/source-259161951#
R2	Improved atmosphere control for product quality and combustion efficiency in reheating furnaces, EUR N° 19855	-	https://op.europa.eu/en/publication-detail/-/publication/2baa35c8-53bf-4e0d-98d5-e9874ae00404/language-en/format-PDF/source-266784811
R3	Optimization of beam reheating conditions in the reheating furnace, EUR N° 20194	-	https://op.europa.eu/en/publication-detail/-/publication/a5e4774d-cab1-49bb-9eb0-fcf3eb143909
R4	Integration of reheating furnaces with rolling conditions at the roughing mill, EUR N° 20196	-	https://op.europa.eu/en/publication-detail/-/publication/61ac72c9-7083-45fe-b030-617017782df9
R5	New continuous annealing technology with high speed induction heating followed by ultra fast cooling, EUR N° 20203	-	http://europa.eu.int/comm/research/rtdinfo.html
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	-	https://op.europa.eu/en/publication-detail/-/publication/217a1eda-1579-483c-ae3e-00362728151f
R7	Performance of reheating furnaces equipped with highly preheated air combustion technology, EUR N° 21147	HPAC	https://op.europa.eu/en/publication-detail/-/publication/d65a4234-7143-40ed-a7ff-69a7314faafa
R8	New ways to improve longitudinal temperature homogeneity of slabs in reheating furnaces, EUR N° 21334	-	https://op.europa.eu/en/publication-detail/-/publication/c07f2a65-ec7c-4709-8270-b309aec6e925
R9	Rules base systems for improved monitoring and guidance of reheating furnaces, EUR N° 21992	-	https://op.europa.eu/en/publication-detail/-/publication/4888df93-d44f-4582-90ae-9eae14eb5ddc
R10	Improved control of mechanical & geometrical properties of steel strips by thermal profile determination all along the annealing line, EUR N° 22034	-	https://op.europa.eu/en/publication-detail/-/publication/d89e4ce9-ec21-4760-ba9c-5900800fce28
R11	Adaptive mill pacing, EUR N° 22055	-	https://op.europa.eu/en/publication-detail/-/publication/f801a8d9-8bf6-46cf-b5bf-e40a051ae4f0
R12	Metallurgical aspects of the compact reheating treatment of hot rolled strips before coiling, EUR N° 22831	-	https://op.europa.eu/en/publication-detail/-/publication/649ace7e-98f7-44c9-800e-3a2e56b81d17
R13	Emissions reduction through analysis, modelling and control, EUR N° 23333	ERAMAC	https://op.europa.eu/en/publication-detail/-/publication/ae0B7ee7-fe81-46c2-bbc9-131653fcb80b
R14	Minimizing NOX emissions from reheating furnaces, EUR N° 23202	NOX-RF	https://op.europa.eu/en/publication-detail/-/publication/8a4b2301-b682-47e2-9dfd-344720ef3e53
R15	Investigations and measures to reduce emissions and energy consumption during the preheating of steel ladles, EUR N° 23175	ImSteelLad	https://op.europa.eu/en/publication-detail/-/publication/74b14123-0e3f-4c8c-b805-15ce4c85c8b4
R16	Improvement of top gas fired reheating and direct reduction furnaces for high temperature using innovative regenerative burners, EUR N° 24029	REGTGF	https://op.europa.eu/en/publication-detail/-/publication/14bac3a0-6d29-4712-88b1-7a51e60707fe
R17	Real-time intelligent diagnostics and optimisation of reheating furnace performance, EUR N° 24174	SMARTFIRE	https://op.europa.eu/en/publication-detail/-/publication/7b66b89c-4933-41db-b416-f2b3835dd035/language-en/format-PDF/source-277666065
R18	Optimization of stocks management and production scheduling by simulation of the continuous casting, rolling and finishing departments, EUR N° 24969	SIMUSTEEL	https://op.europa.eu/en/publication-detail/-/publication/6b8f59c8-0c11-4f72-8e7e-fc0f98c81548/language-en/format-PDF/source-277694916
R19	Quality improvement by metallurgical optimised stock temperature evolution in the reheating furnace including microstructure feedback from the rolling mill, EUR N° 25001	OPTHEAT	https://op.europa.eu/en/publication-detail/-/publication/1c701b87-4897-48ae-98dd-031817b1cabd/language-en/format-PDF/source-277693889
R20	CO2 reduction in reheating furnaces, EUR N° 25004	CO2RED	https://op.europa.eu/en/publication-detail/-/publication/feabfc3c-0f9a-49c6-9d63-2aaa7173533b
R21	Optimisation of the metallurgical structures and mechanical properties by improving the heat treatment processes in flat and long production lines with new setup and control methods, EUR N° 26174	ESTEP OPTIMET	https://op.europa.eu/en/publication-detail/-/publication/d85d2c24-7f3e-4366-9c9e-5d6d5c8eb2aa/language-en/format-PDF/source-277693833
R22	Hydrogen assessment in steel products and semi-products, EUR N° 26397	HYDRAS	https://op.europa.eu/en/publication-detail/-/publication/3e95e304-f755-4cea-b5ae-0086e519d513/language-en/format-PDF/source-277694543
R23	High emissivity annealing technique, EUR N° 27156	HEAT	https://op.europa.eu/en/publication-detail/-/publication/149B7fac-39c3-4daf-af07-3874f295c476/language-en/format-PDF/source-272040948
R24	Controlling flatness of strips in furnace of continuous annealing/galvanising lines	Flat strip control	https://op.europa.eu/en/publication-detail/-/publication/96d5a790-edb0-495b-9acf-eeaa7ddb2399/language-en/format-PDF/source-272132325
R25	Control of steel oxidation in reheating operations carried out with alternative fuels and new combustion technologies, EUR N° 27453	CONSTOX	https://op.europa.eu/en/publication-detail/-/publication/5db1c074-7666-11e5-86db-01aa75ed71a1/language-en/format-PDF/source-272149828
R26	Advanced measurements and dynamic modelling for improved furnace operation and control	DYNAMO	https://op.europa.eu/en/publication-detail/-/publication/de5068a7-03cd-11e7-8a35-01aa75ed71a1/language-en/format-PDF/source-272135637
R27	High efficiency low NOX BFG based combustion systems in steel reheating Furnaces	HELNOX-BFG	https://op.europa.eu/en/search-results?p_p_id=eu_europa_publications_portlet_search_executor_SearchExecutorPortlet_INSTANCE_q8EzsBteHybf&p_p_lifecycle=1&p_p_state=normal&queryText=High+efficiency+low+N
R28	Power generation from hot waste gases using thermoelectrics	PowGETEG	https://op.europa.eu/en/publication-detail/-/publication/9c33fec6-7587-11eb-9ac9-01aa75ed71a1/language-en/format-PDF/source-272143727
R29	Strategy to increase the hot strip rolling performance in terms of surface quality, final properties and reproducibility	INFIRE	sharepoint
R30	Non Sticking furnace Rolls to improve service life and product quality in continuous annealing and galvanizing lines	NoStickRolls	https://www.researchgate.net/publication/256906287_NON-STICKING_FURNACE_ROLLS_FOR_STEEL_PRODUCTS_TO_IMPROVE_SERVICE_LIFE_AND_PRODUCT_QUALITY_IN_CONTINUOUS_ANNEALING_AND_GALVANIZING_LINES_PRELIMINARY_STUD
R31	Automatic surveillance of hot rolling area against intentional attacks and faults	AutoSurveillance	https://www.researchgate.net/publication/354380548_Automatic_surveillance_of_hot_rolling_area_against_intentional_attacks_and_faults_AutoSurveillance_Overview_and_first_results_of_the_RFCS_funded_Project_Contact_data
R32	Advanced Coated Steels for new demanding Biomass Firing environment having a high recycling behaviour and an improved service life	BIOFIRE	No report, publication or website
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	https://burner40.nicepage.io/Home.html
R34	Acid dew point and corrosion sensors for dynamic waste heat recovery from steel mill flue gases	SafeDewPoint	https://www.bfi.de/en/projects/safedewpoint-acid-dew-point-and-corrosion-sensors-for-dynamic-waste-heat-recovery-from-steel-mill-flue-gases/
R35	Flexible Ladle Preheating Procedures using Plasma Heated Refractory	PlasmaPilot	https://www.mse.kth.se/process/projects/current-projects/flexible-ladle-preheating-procedures-using-plasma-heated-refractory-1.1069972
R36	Hydrogen Interaction with Retained Austenite Under Static and Cyclic Loading Conditions	HYDRO-REAL	https://www.mpie.de/4475082/HYDRO-REAL
R37	Green steel for Europe	-	https://www.estep.eu/green-steel-for-europe

HEU projects			
Reference Number	Project full name or article name	Acronym	Link to report / publications / website
H1	New Induction Wireless Manufacturing Efficient Process for Energy Intensive Industries	NIWE	http://niweproject.eu/
H2	SEWGS Technology Platform for cost effective CO2 reduction the in the Iron and Steel Industry	STEPWISE	https://www.stepwise.eu/
H3	Combustion for Low Emission Applications of Natural Gas	CLEAN-Gas	https://cordis.europa.eu/project/id/643134/results
H4	Development of a fuel flexible and highly efficient ultra low emission residential-scale boiler with coupled heat recuperation based on flue gas condensation	FlexiFuel-CHX	http://www.flexifuelchx.eu/
H5	Low Emissions Intensity Lime and Cement	LEILAC	https://www.project-leilac.eu/
H6	Renewable residential heating with fast pyrolysis bio-oil	Residue2Heat	https://www.residue2heat.eu/
H7	Intelligent Hot Dip Galvanizing furnace for better energy use, low environmental impact and extended kettle lifespan	e-Furnace	https://efurnace.gimeco.com/
H8	PROcess NeTwork Optimization for efficient and sustainable operation of Europe's process industries taking machinery condition and process performance into account	PRONTO	https://www.h2020pronto.eu/
H9	Green Industrial Hydrogen via Reversible High-Temperature Electrolysis	GrInHy	GrInHy2.0 | SALCOS® (salzgitter-ag.com)
H10	VAlidation driven DEvelopment of Modern and Efficient COMbustion technologies	VADEMECOM	https://cordis.europa.eu/project/id/714605 http://vademecom.eu/news/
H11	Novel integrated refurbishment solution as a key path towards creating eco-efficient and competitive furnaces	VULKANO	http://www.vulkano-h2020.eu/
H12	From residual steel gases to methanol	FreSMe	https://cordis.europa.eu/project/id/727504
H13	Hydrogen meeting future needs of low carbon manufacturing value chains	H2Future	https://www.h2future-project.eu/ https://cordis.europa.eu/project/id/735503
H14	Simulation-as-a-Service Tool for Industrial Furnaces Innovative Engineering Design	SaaStified	https://cordis.europa.eu/project/id/742183
H15	TORrefying wood with Ethanol as a Renewable Output: large-scale demonstration	TORERO	http://www.torero.eu/
H16	Energy Efficient Coil Coating Process	ECCO	https://www.aspire2050.eu/ecco
H17	The first 2500°C industrial furnace, for higher efficiency and up to 5 times higher strength materials	CARBIDE2500	https://www.cremer-polyfour.de/ovens/carbide2500_de/
H18	Significantly cheaper and cleaner energy from biomass combustion	DEBS	https://cordis.europa.eu/project/id/811529
H19	POLlution Know-how and Abatement	POLKA	https://www.polka-eu.org/
H20	Development of an Efficient Microwave System for Material Transformation in energy INtensive processes for an improved Yield	DESTINY	https://cordis.europa.eu/project/id/820783
H21	Simulation and Control of Renewable Combustion	SCIROCCO	https://cordis.europa.eu/project/id/832248
H22	Towards a full multi-scale understanding of zero-carbon metal fuel combustion	MetalFuel	https://cordis.europa.eu/project/id/884916
H23	Decarbonisation of carbon-intensive industries (Iron and Steel Industries) through Power to gas and Oxy-fuel combustion	DISIPO	https://cordis.europa.eu/project/id/887077
H24	Predictive tools for turbulent combustion of hydrogen-enriched natural gas through carefully reduced kinetic mechanisms	HYGAS	https://cordis.europa.eu/project/id/891173
H25	Developing Plasma-assisted ammonia technology for decarbonisation of power production	PlasNH3	https://cordis.europa.eu/project/id/101020492

Scientific articles			
Reference Number	Project full name or article name	Acronym	Journal
1	Toward CO2-neutral process heat generation for continuous reheating furnaces in steel hot rolling mills- A case study	-	Energy, Volume 224, 1 June 2021
2	Flameless combustion investigation of CH4 /H2 in the laboratory-scaled furnace"	-	International Journal of hydrogen energy 45, pp35208-35222, 2020
3	Power-to-gas and the consequences: impact of higher hydrogen concentrations in natural gas on industrial combustion processes	-	Energy Procedia 120, pp 96-103, 2017
4	Emissions and dynamic stability of the flameless combustion regime using hydrogen blends with natural gas" Intl journal of hydrogen energy 45, pp 1246-1258, 2021	-	Intl journal of hydrogen energy 45, pp 1246-1258, 2021
5	Hydrogen combustion as a thermal source";	-	9th International Conference on Applied Energy, ICAE2017, 21-24 August 2017, Cardiff, UK.
6	Feasibility study for the utilization of natural gas and hydrogen blends on industrial furnaces, paper presented at the workshop Hydrogen route for a green steel making process, online workshop, organized by ESTEP Focus Group Circular	-	Workshop Hydrogen route for a green steel making process, online workshop, organized by ESTEP Focus Group Circular Economy, June 2021
7	Tenova SmartBurners with 100% Hydrogen, paper presented at the workshop Hydrogen route for a green steel making process, online workshop, organized by ESTEP Focus Group Circular Economy, June 2021	-	Online workshop, organized by ESTEP Focus Group Circular Economy, June 2021
8	Development and testing of Flameless burner fed by NG/H2 mix, paper presented at the workshop Hydrogen route for a green steel making process	-	Online workshop, organized by ESTEP Focus Group Circular Economy, June 2021
9	Investigation of combustion characteristics of methane-hydrogen fuels"	-	Thermal Engineering, Volume 62, Issue 1, pp 64-67, 2015
10	Evaluation of a steady flamelet approach for use in oxy-fuel combustion";	-	Fuel, Volume 118, pp 55-68, 2014
11	11 A simplified approach for predicting NO formation in MILD combustion of CH4–H2 mixtures"	-	Proceedings of the Combustion Institute, pp 3343-3350, Volume 33, Issue 2, 2011
12	NOx formation in H2-CH4 blended flame under Mild condition";	-	7th Mediterranean Combustion Symposium – MCS 7 - Chia Laguna, Cagliari, Sardinia, Italy, September pp 11-15, 2011
13	13 Investigation of a pure hydrogen fueled gas turbine burner"; International Journal of Hydrogen Energy, Volume 42, Issue 15, pp 10513-10523 , April 2017	-	International Journal of Hydrogen Energy, Volume 42, Issue 15, pp 10513-10523 , April 2017
14	14 Laminar Combustion Characteristics and Mechanism of Hydrogen/Air Mixture diluted with N2 + H2O"; Journal of Hydrogen Energy; Volume 42, pp 4501-4507, 2017	-	Journal of Hydrogen Energy; Volume 42, pp 4501-4507, 2017
15	15 Low Single Digit NOx Emissions Catalytic Combustor for Advanced Hydrogen Turbines for Clean Coal Power Systems"; Proceedings of ASME Turbo Expo, Copenhagen, 2012	-	Proceedings of ASME Turbo Expo, Copenhagen, 2012
16	Hydrogen as burner fuel: modelling of hydrogen–hydrocarbon composite fuel combustion and NOx formation in a small burner", International journal of energy research, Volume 29, Issue11, pp 973-990, September 2005	-	International journal of energy research, Volume 29, Issue11, pp 973-990, September 2005
17	Technology Assessment of Hydrogen Firing of Process Heaters"; Energy Procedia", Volume 4, pp 1058-1065, 2011	-	Energy Procedia, Volume 4, pp 1058-1065, 2011
18	Tests by OVAKO Steel (https://www.ovako.com/en/newsevents/stories/first-in-the-world-to-heat-steel-using-hydrogen):	-	https://www.ovako.com/en/newsevents/stories/first-in-the-world-to-heatsteel-using-hydrogen
19	Plasma heating for the steel industry	-	Final report Swedish energy agency
20	Fossil-free heating furnaces	-	Final report Swedish energy agency
21	Numerical and Experimental Investigation of a MILD Combustion Burner, Combust. Flame Vol. 151 (2007) No. 4, 649-664	-	Combust. Flame Vol. 151 (2007) No. 4, 649-664
22	Flameless combustion modelling using detailed chemistry mechanism	-	European Combustion Meeting (ECM), Cardiff (UK), June 27 - July 1 2011
23	CO2 reduction in reheating furnaces,	-	Int. Symp. on High Temperature Air Combustion and Gasification (HiTACG), Poznan (Poland), July 5-7 2010
24	TenovaFlexyTech® TRGX burner modeling and testing	-	AISTech2010, Pittsburgh (USA), May 3-6 2010
25	25 9th Int. 6th European Rolling Conf. 2013	-	6th European Rolling Conf. 2013 - Venice (Italy) June 10-12 2013
26	Oxy-fuel flat flame burner with regenerative blast furnace gas preheating."	-	18th IFRF Members Conference. München, 2015
27	Einsatz von grünem H2 an Thermoprozessanlagen	-	BFI Kolloquium, 13.05.2020
28	Untersuchung eines Strahlrohrs für die hybride Beheizung von Industrieöfen mit Brenngasen und elektrischem Strom, bevorzugt aus erneuerbaren Energiequellen (HYBRIDSTRAHLROHR)	-	Final report, Grant agreement No: 34825/01, funded by DBU (Germany), 2021
29	Substitution von Erdgas durch H2 zur Vermeidung von CO2-Emmissionen, Potenziale und Hemmnisse	-	BFI-Kolloquium, 05.05.2021
30	Macroeconomic implications of switching to process-emission-free iron and steel production in Europé	-	Journal of cleaner production
31	Present and Projected Developments in Hydrogen Production: A Technological Review	-	
32	Hydrogen Production and distribution	-	
33	A mathematical model of a slab reheating furnace with radiative heat transfer and non-participating gaseous media	-	
34	Effects of hydrogen addition to methane on the thermal and ignition delay characteristics of fuel-air, oxygen-enriched and oxy-fuel MILD combustion	-	
35	Numerical study on a novel burner designed to improve MILD combustion behaviors at the oxygen enriched condition	-	
36	A novelty data mining approach for multi-influence factors on billet gas consumption in reheating furnace	-	
37	37 Energy savings in reheating furnaces through process modelling	-	Procedia Manufacturing 42 (2020) 205–210
38	Energy-Efficient Control of Continuous Reheating Furnaces	-	16th IFAC Symposium on Automation in Mining, Mineral and Metal Processing August 25-28, 2013. San Diego, California, USA
39	Reheating time optimization for metal products in batch-type furnaces	-	International Journal of Heat and Mass Transfer 186 (2022) 122474
40	Burners in the steel industry: utilization of by-product combustion gases in reheating furnaces and annealing lines	-	Energy Procedia 120 (2017) 20–27
41	A numerical analysis of the effect of heat recovery burners on the heattransfer and billet heating characteristics in a walking-beam typereheating furnace	-	International Journal of Heat and Mass Transfer 127 (2018) 1208–1222
42	Modelling and simulation of steel reheating processes under oxy-fuel combustion conditions e Technical and environmental perspectives	-	Energy 185 (2019) 730 – 743
43	Industrial reheating furnaces: A review of energy efficiency assessments, waste heat recovery potentials, heating process characteristics and perspectives for steel industry	-	Process Safety and Environmental Protection 147 (2021) 1209–1228
44	Influence analysis of the furnace wall emissivity on heating process	-	Infrared Physics & Technology, Volume 93, September 2018, Pages 326-334
45	Influence of nozzle design parameters on exhaust gas characteristics in practical-scale flameless hydrogen combustion	-	International Journal of Hydrogen Energy 47 (2022) 21287 – 21297
46	Laminar-burning velocities of hydrogen–air and hydrogen–methane–air mixtures: An experimental study	-	International Journal of Hydrogen Energy 31 (2006) 1768 – 1779
47	On the effective Lewis number formulations for lean hydrogen/hydrocarbon/air mixtures	-	International Journal of Hydrogen Energy 38 (2013) 5949 – 5960
48	Numerical simulation of slab heating process in a regenerative walking beam reheating furnace	-	International Journal of Heat and Mass Transfer 76 (2014) 405 – 410
49	Comparisons of different heat transfer models of a walking beam type reheat furnace	-	International Communications in Heat and Mass Transfer 47 (2013) 20 – 26
50	Numerical and experimental study on flameless oxy-fuel combustion in a pilot- scale and a real-size industrial furnace	-	Applied Thermal Engineering 141 (2018) 788 – 797

Literature review: Classification of literature and findings as well as determindes KPIs
Topic 1: Heating and burner technology; alternative heating methods; electrical heating

Classification Criteria								KPIs														
Reference number	Year	Related/identified Technology	Description of technology	Project full name or article name	Acronym	Short description of project	link to report / publications / website	success/ partial success/ failure	practical applications of results [yes/no; references]	follow-up projects	research gaps	TRL start [1-9]	TRL end [1-9]	Energy consumption [e.g. GJ/t; decrease in %]	Productivity [e.g. t/h; increase in %]	CAPEX increase/decrease	OPEX increase/decrease	Scale loss of product [e.g. g/m² or recution in %], yield increase	number of installations in industry	CO_2 emissions reduction scope 1 [e.g. kg/t or %]	CO_2 emissions reduction scope 2 [e.g. kg/t or %]	combustion efficiency
R7	2005	**Highly preheated air combustion burner**: Regemat 350 FLOX-Flame for NG (WS Wärmeprozesstechnik GmbH) and oiled fired HPAC Burner.	Burner designed to achieved both high thermal efficiency and low NOx emissions NOx-concentration 150ppm (4% O2 content in off gas)	Performance of reheating furnaces equipped with highly preheated air combustion technology	HPAC	The objectives of this project hwere to test the effectiveness and long-term reliability of HPAC burners and to determine the optimum conditions for installation of these burners in industrial furnaces (semi-industrial and full-scale tests and measurements in an oil-fired walking beam furnace).	https://op.europa.eu/en/publication-detail/-/publication/d65a4234-7143-40ed-a7ff-69a7314faafa	succes	yes, Regemat 350 is currently available at WS Wärmeprozesstechnik	no	experiments in different steel reheating furnaces	9	9	- 12 %	+ 2 %	-	Fuel costs: - 12%	-	-	- 12 %	-	+ 36.6 %
R27	2018	**BFG-air/oxy-burner** for steel reheating furnaces.	Burner designed and tested to burn blast furnace gas (BFG) with air or with oxyfuel and achieve high thermal efficiency and low NOx emissions. Three different breakthrough solutions have been designed, manufactured and tested at both pilot and long-term industrial scale, namely: (a) double regenerative BFG-air-burners (1.2 MW), (b) preheated BFG oxy-burner (1,2 MW) and (c) oxy-BFG-regenerative flat-flame burner (500 kW)	High efficiency low NO_x BFG based combustion systems in steel reheating Furnaces	HELNOX-BFG	The aim of the project is to develop a combustion system for the efficient utilization of blast furnace gas (BFG) (100%) in steel reheating furnaces by means of fuel preheating, in order to maintain the same production level of a high heating value fuel, reducing natural gas dependency, carbon footprint and nitrogen oxide emissions. The safety, performance, reliability and robustness of the technology have been assessed, proving that 100 % BFG can be fired in reheating furnaces, achieving typical furnace temperatures and keeping NOx emissions level below the European regulation threshold.	https://op.europa.eu/en/publication-detail/-/publication/878ee132-5335-11e8-be1d-01aa75ed71a1/language-en/format-PDF/source-272139306	success	yes, ArcelorMittal Spain: 150 t/h billet reheating furnace with 80% BFG	no	scale loss using regenerative burners	-	7, 8	-	-	+ 30 - 40M € per site	- 3-5 €/t_{steel}	-	at least 1	- 50-60 kg_{CO2}/t_{steel}	-	-
R2	2001	• Level 2 furnace control. • O_2-measurement by fixed zyrkon dioxid -probe. • **Combination of electrical and combustion heating for reheating furnaces**.	Furnace control of air-fuel ration and furnace atmosphere in multi zone furnace. Oxygen-measurement in furnace zones. Measurement point selected with the aid of CFD-simulation. Optimised furnace design and reduced leackage air by combination of electrical and combustion heating: optimized heating and surface quality. reduced high temperature oxidation.	Improved atmosphere control for product quality and combustion efficiency in reheating furnaces	-	Combination of air-fuel ratio and furnace atmosphere control with zone-wise O_2-measurement to reduce O_2 in furnace atmosphere: less heat loss in off gas and reduced high temperature oxidation (scale formation). Electrical heating in the 1st zone (soaking zone). Zone 2 and 3 of 3 with combustion heating.	https://op.europa.eu/en/publication-detail/-/publication/2baa35c8-53bf-4e0d-98d5-e9874ae00404	succes	yes: air-fuel ratio controler at walking beam furnace of "Neue Max Hütte" no: electrical heating	air fuel ratio controler: influence on scale formation. EGKS No. 7210-PA/019	electrical heating not demon-strated in practical application	4	6, 7	With electrical and combustion heating 6-7% energy saving	With electrical and combustion 25-35% productivity increase	-	-	-	at least 1	5 to 10 % (combustion heating subsidised by el. Heating)	-	-
R3	2002	• **Burner with flameless combustion** mode (mild combustion) combined with **on/off-mode operation**. • Measurement and control of air excess for burners in walking beam furnace.	Burner in flameless combustion mode is operating in on/off mode: high volume flow and mixing combustion and furnace gases while on-mode. Modified control system (level 1) by a new program in existing system.	Optimisation of the beam blanks' reheating conditions in the reheating furnace	-	Burner testing in the soaking zone (in zone 1 of 3) of a reheating furnace/walking beam furnace. Burner operation in on/off mode to improve furnace gas mixing and temperature uniformity. Control system (level 1) adapted to on/off mode and field instruments (valves connected to the control system are added to the piping system). Additionaly, an air flow control system is adapted in the control system. Temperature in blooms and furnace investigated: 15% increas in bloom temperature achieved. NO_X-emissions significantly reduced (about 50%) and energy consumption reduced.	https://op.europa.eu/en/publication-detail/-/publication/a5e4774d-cab1-49bb-9eb0-fcf3eb143909	Success: Product temperature increase of 15%. More temperature uniformity in the product. **The new heating and controlesystem alows to controle the temperature profile in the product.** Partial success: Existing temperature controle system is insufficient for well controled operation with new burner on/off operation.	yes, ProfilARBED Differdange (PADI) reheating furnace/walking beam furnace	-	-	-	6, 7	decrease, but only qualitative results	-	-	-	-	at least 1	-	-	-
R8	2005	• Wall cooling in the heating zone of reheating furnaces with an actuator to achieve controlled cooling at the sidewalls of the furnace. • Additional increased convective heat transfer by fan-mixing of furnace athmospher in the dark zone and controlled radiant heat transfer by burner on/off operation mode in the heating zone.	Cooling and increased convective heat transfer with fan tested in a pilot furnace , controlled radiant heat transfer to the product in the heating zone investigated in pilot furnace vaildation by thermocouple test in the slab (Schlepp-Versuch). At Rautaruukki´s walking beam furnace: radiant heat transfer to the product was investigated by on/off operation of top and bottom burners (level 1 and level 2 control aided by predictive CFD-simulation and vaildation by thermocouple test in the slab (Schlepp-Versuch)). Flame length tests to investigate the influence on heat transfer to the product: short and instabile flames have influence on heating slab ends (especially in zone 2 at low burner power). Controled burner on/off mode achieved **stable flames (!)** and temperature uniformity in the slabs. → bad burner opertation leads to non uniform product heating.	New ways to improve longitudinal temperature homogenity of slabs in reheating furnaces	-	The aim of the project is to achieve temperature uniformity in the slabs during the reheating process, especially to avoid hot ends of the slabs and cool spots on the slabs. An actuator for wall cooling in reheating furnaces was developed, tested in pilot scale furnace and slab heating was predicted by CFD simulation. Increased convection heat transfer was investigated by fans and burner on/off operation in dark and heating zone in a pilot furnace and by CFD simulation. Controled heat transfer to the product by level 1 and 2 burner controle of on/off operation aided by predictive CFD-simulation of heat transfer into the product.	https://op.europa.eu/en/publication-detail/-/publication/c07f2a65-ec7c-4709-8270-b309aec6e925	success		-	-	1	5, 7	increase because of cooling: + 0,5%	-	-	-	-	-	-	-	-
R14	2008	Findings: **1. Flameless technologies provide the best available technologies (BAT) for low Nox burners and primary Nox reductions.** **2.** Oxy-fuel combustion increases efficiency by reducing heat loss through the exhaust gas.	Flameless combustion with and without regenerative combustion air preheating. Air and oxy-fuel combustion. High Temperature Reduction (HTR): Mixing amonia in furnace exhaust to achieve SNCR. Experimental and theoretical investigation of combustion, reaction zone NOx formation and influence of NOx on the above mentioned reduction measures.	Minimising NOx emissions from reheating furnaces	NOX-RF	The aim of the project is to analyse existing low NOx-burner systems for air and oxy-fuel combustion to develop methods and give information and recommendations fro equipping reheating furnaces with burner systems to achieve low NOx emissions and increased efficiency: (1) Pilot testing of low NOX burners for air combustion including flameless combustion techniques with or without regenerative combustion. (2) Modelling of NOx formation in furnaces and from burners, validation with experiantal data. (3) Measurements in industrial furnaces and review of flue gas concentrations from NOx reduction technologies. (4) Trials of low NOx oxy-fuel combustion technology and air leakage control. (5) Investigation of NOx reduction method High Temperature Reduction (HTR) by mixing ammonia heat treatment-process exhaust gas in the exhaust of furnace to achieve SNCR. Experimental and theoretical investigations.	https://op.europa.eu/en/publication-detail/-/publication/8a4b2301-b682-47e2-9d6d-344720ef3e53	Success: techint burner BAT Failure: High temperature reduction works theoretically, but is not technically applicable in furnaces as NOx cannot be reduced.	-	no	well controled HTR to achieve NOx decease	9	9	Oxy-fuel combustion leads to decrease of energy consumption -9% to -14%	-	-	-	-	-	-	-	-
R15	2008	**Burner with regenerative combustion air preheating**.	Oxy-fuel burner in ladle preheating system (1st heating after a new refractory was built in the ladle) is replaced by a regenerative burner.	Investigations and measures to reduce emissions and energy consumption during the preheating of steel ladles	ImSteelLad	The objective of this project are (1) the heating of steel ladles with regenerative burners and preheated combustion air, (2) the temperature control of the ladle preheating process, (3) the combustion of aromatic compounds originating from the binding materials of new built refractory in steel ladles and (4) the construction of the suction hood to minimize air leakage.	https://op.europa.eu/en/publication-detail/-/publication/74b14123-0e3f-4c8c-b805-15ce4c85c8b4	Success: new burner with recuperator(!) and new hood reduces PAH emissions. failure: regenerative burner was not installed for ladle preheating (costs to high). partial success: regenerative system installed for ladle heating station.	yes, at DEW Siegen, Germany and Outokumpu Nirosta GmbH (TKS Nirosta Bochum)	-	-	7	8	-20% for ladle pre heating station with recuperator compared to oxy-fuel combustion	-	-	-	-	at least 2	-	-	-
R16	2009	**Burner with regenerative combustion air preheating**: modified burners (FBB-burner and GR8 Techint-burner) for highly preheated air were investigated.	The combustion of low calorific process gases from the steel mill lite top gas (BFG) or mixtures of these with regenerative preheated combustion air is used to heat reheating furnaces.	Improvement of top gas-fired reheating and direct reduction furnaces for high temperatures using innovative regenerative burners.	REGTGF	Experimental investigations at test plants, on-site measurements at industrial furnaces and numerical simulations of both show that regenerative heating combined with low calorific process gases is suitable to heat reheating furnaces. Furthermore a positive effect on product quality regarding scale formation and a more homogenous temperature distribution on product during heating process have been experimentally and theoretically determined.	https://op.europa.eu/en/publication-detail/-/publication/14bac3a0-6d29-4712-88b1-7a51e60707fe	success	no	-	-	4	6	-30% compared to natural gas or oil combustion with rekuperative preheated air	-	-	fuel costs decreas 300,000€/a per furnace (fuel costs 2006)	-	answer open	-	-	-
R20	2011	• Burner systems and heat recovery systems to: - increase heating efficiency - decrease NOx • Regenerative burner systems: - BFI burner with flame combustion and - Tenova TRGX burner with either flame as well as flameless combustion mode. Combustion of natural gas, COG, BFG, BOF. • Regenerator with ceramic honeycomb heat storage material • OXY-BF gas combustion; AGA REBOX concept Types S3 flameless combustion burner system.	Tenova: Flameless combustion of natural gas combined with regenerative preheated combustion air to reduce NOx emissions and increase furnace heating efficiency. BFI: Flat flame burner with tulip lime stone. Flame cooling at lime stone and by internal recircultion for NOx reduction in combination with highly preheated air. AGA: OXY-BFG flameless Combustion.	CO_2 reduction in reheating furnaces	CO2RED	Industrial heating tests in test and pilot-plants: Burner testing at CRM (Tenova burner) 1MW (natuaral gas), BFI (BFI burner) 90 -410 kW both with regenerativ preheated air and MEFOS (AGA burner) 400 kW non preheated air. - NOx-emissions significantly reduced by flameless combustion allthough regenerative preheated air. - NOx-emissions significantly reduced by flameless combustion of oxy-BFG combustion without preheated air. CFD- Simulation of Burner systems Field testing of one Tenova and one BFI burner each in different industrial furnace	https://op.europa.eu/en/publication-detail/-/publication/feabfc3c-0f9a-49c6-9d63-2aaa7173533b	success	In this project a BFI top firing burner system was installed at Feralpi in Lonato and tested for several months. In national projects (Germany) 3 batch type furnaces were fully equipped with burner systems and one of these furnaces with COG and BOF. Due to the good results, 300 burner systems for NG have been sold worldwide and are in operation, mainly in batch type furnaces.	no	No furnace fully equipped with burner; BFG-preheating (400°C): relevant technical challenge.	4	6, 7	Calculated in CFD simulation: Furnace fully equippded with **-Tenova TRXG compared to recuperator system: -10%** **- AGA-system with oxy-75%BFG/25%LPG compared to LPG-air recuperator system and if BFG is "non CO2 emission" : -70%**	AGA system oxy-100%BFG: -19% or if BFG is preheated 400°C: 0%	-	-	scale loss NG/Air compared to oxy-BFG no clear influence of fuel found	none in Project BFI-burner system: 300 systems world wide	-	-	-
R25	2015	• **Recuperative-, high speed-, flat flame burners.** • Influence on scaling by changing H_2O content in furnace atmosphere.	Alternative fuels (COG, BFG, BOF) and mixtures of these with NG to reduce H_2O content in the furnace atmosphere to influence scaling.	Control of steel oxidation in reheating operations carried out with alternative fuels and new combustion technologies, EUR N° 27453	CONSTOX	Influence of furnace atmoshpheres from combustion of process gases (COG, BFG, BOG and mixtures of those with NG) on scale characteristics. - lab and pilot scale experiments - CFD-modelling of oxygen condition, temperature and velocity on steel surface and scaling - simulation analysis and lab expeiment of surface structure and oxidation of heated materials	https://op.europa.eu/en/publication-detail/-/publication/5db1c074-7666-11e5-86db-01aa75ed71a1/language-en/format-PDF/source-272149828	partial success: fuels have no effect on scaling, but decreased H_2O content in furnace atmosphere decreases scale thickness and structure.	no	-	-	3	5	no	-	-	-	gain in yield 0,5% to 1%	-	no	no	-
R33	Project start 2018	Report not available yet	-	Development of a new burner concept: Industry 4.0 technologies applied to the best available combustion system for the Steel Industry	BURNER 4.0	Combustion systems and burners for the steel industry have been improved in the recent years focusing on energy saving, pollutant emissions reduction and process flexibility. Burner 4.0 Project is aimed to extend the present technological limits of the combustion systems concerning different areas (design, manufacturing, control & process optimization, operating life & maintenance) to new ones through a challenging combined application of the Industry 4.0 technologies. Additive manufacturing, Internet of Things, Smart Sensors, Big Data Analytics for process optimization and predictive maintenance will be introduced to the present burners leading to a break-through burner concept for the steel industry.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
H20	2022	**Microwave heating of particles for carbothermic reduction**. Relevant for iron oxid reduction in sinter process towards DRI.	Heating with microwave oven integrated in the feeding process of sinter reduction process cement, pigment or ceramic sector: Heating temperature 1000°C to 1400°C.	Development of an Efficient Microwave System for Material Transformation in energy	DESTINY	Microwave furnaces shall be developed for heating particles (cement, ceramics, pigments or sinter to reduce ferrous oxides). Demo furnaces for heating during feeding process up to MW-size shall be developed an investigated in i.e. pigment industry.	https://cordis.europa.eu/project/id/820783	As far as findable information: success in pigment industry	-	-	-	-	-	-	-	-	-	-	-	expected	-	-

H21	Project ongoing until 09/2024	• Storage of renewable energy such as H_2 • **Combustion of H2 injected parallely into furnace with methane combustion**	Experimental investigations of advanced H_2-combustion as well as DNS and LES-simulation of parallel burning of hydrogen air and methane air flames.	Simulation and Control of Renewable Combustion	SCIROCCO	SCIROCCO has two goals: provide effective storage for renewable energies and significantly improve existing combustionsystems. Objective (1) DOT Objective (2) is addressed by burningthe 'renewable' H2 in smart combustors with higher efficiencies and reduced emissions. Today, H2 is diluted in methane-lines ('drop-in' strategy) to burn in existing devices. This strategy ignores the exceptional properties of H2, which burns and ignites faster than all other fuels. We will exploit these properties in new chambers that (1) burn H2within a wide range of fossil fuel mixes and (2) use H2 as a powerful actuator to increase performance. Rather than diluting H2 in other fuels, we will inject H2 into the chamber separately. Research is needed to analyse the structure of these new dual-fuel flames that burn a fossil fuel and H2 simultaneously. This is a challenge for combustion science, requiring a re-think of chamber design and control. These fundamental issues will be addressed for two applications with fundamental societal impact: a) laminar gas-burning flames (stoves, heaters) b) swirled liquid fuel turbulent flames (aerospace and power gas turbines).	https://cordis.europa.eu/project/id/832248 https://cerfacs.fr/scirocco/	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	expected at least -65%	-	-
H22	2020 - 2025	Fundamental investigations in **combustion of metal powder oxides or metal powder hydroxides.**	Renewable energy is stored in powders of metal oxides or hydroxides. The powders are burned as a fuel and the reduced and seperated metal powders are reused as a oxygen carier.	Towards a full multi-scale understanding of zero-carbon metal fuel combustion	MetalFuel	In this project the solid fuel combustion of metal oxides (fuel source) is investigated on a fundamental level by a combined experimantal and theoretical/numerical approach.	https://cordis.europa.eu/project/id/884910 https://www.tandfonline.com/doi/full/10.1080/00102202.2022.2089030 https://doi.org/10.1016/j.proci.2022.07.044	-	-	-	-	-	2 - 3	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-
H23	2021-2023	Power-to-Gas integration in an oxygen blast furnace	Development of a new oxygen blast furnace model to assist the evaluation of Power to Gas integration cases . Best results where achieved for a PtG integration consuming treated blast furnace gas, applied to oxygen blast furnaces for coal replacement (PtG capacity of 490 MW).	Decarbonisation of carbon-intensive industries (Iron and Steel Industries) through Power to gas and Oxy-fuel combustion	DISPO	DISPO project covers the design and analysis of the integration of synthetic natural gas in iron and steel industry, as competitive alternative against renewable electrification. The project presents a novel concept that combines Power to Gas (PtG-energy storage) and oxy-fuel combustion (carbon capture) to decarbonise iron and steel industry. Power to Gas consumes renewable electricity to produce H2 (stored energy) and O2 (byproduct). This O2 is fed in the oxy-fuel furnace in the iron industry to obtain a high concentrated CO2 stream, thus avoiding the energy penalization of requiring an air separation unit. Besides, the stored H2 and the captured CO2 are combined via methanation to produce synthetic natural gas to be used in the industry or distributed through the gas network.	Manuel Ballera - DISPO project (mballera.es) https://cordis.europa.eu/project/id/887077	Success: Elaboration and validation of the blast furnace Project still in progress	-	-	-	-	Objectvie: 2	-	-	tbd	tbd	-	none	-21% (assuming a 500 tMt/h blast furnace)	-	-
H24	2022-2024	**Hydrogen enhanced combustion (HEC)** and safety issues for domestic combustion processes as well as for power generation.	HEC combustion of mixtures of hydrogen and natural gas.	Predictive tools for turbulent combustion of hydrogen-enriched natural gas through carefully reduced kinetic mechanisms	HYGAS	In this project HEC is investigated by fundamental research. Kinetic models and mechanisms are developed and integrated into CFD simulation modeling of HEC. The CFD models are validated by matl scale experimantal data. The CFD simulation is extended to medium and large scale applications as basis for applications. Developement of predictive tools for engineering HEC burners and heating.	https://cordis.europa.eu/project/id/891173	-	-	-	-	2 - 3	4	-	-	-	-	-	-	-	-	-	-	-	-	-
H25	2021-2023	**Amonia combustion** for gas turbine engines, plasma assisted combustion by blending amonia fuel with more reactive fuels (hydrocarbons, hydrogen,...)	Application of amonia as a fuel for gas turbine engines: enhance reactivity of amonia/air mixtures optimise existing burners	Developing Plasma-assisted ammonia technology for decarbonisation of power production	PlasNH3	In this project the amonia combustion in gasturbines is investigated. Experiments are conducted at the Gas Turbine Research Center (GTRC) at the University of Birmingham. Plasma assisted amonia combustion to increase reactivity is investigated with existing burners. The burners are optimised for amonia combustion. Furthermore detailed multi-scale numerical simulations of amonia combustion are performed to achieve findings and results to support the utilisation in marine and heavy load transportation engines, as well.	https://cordis.europa.eu/project/id/101020482	-	-	-	-	4	5	-	-	-	-	-	-	-	-	-	-	-	-	-
J1	2017	**HEC-with standard burners tested with H_2/NG mixture** at H_2-concentrations from 5% to 50%.	Lab test of Burner I: modular partially premixed jet burner. Burner II: forced-draught burner. Burner III: flameless oxidation burner at about 100 kW.	Power-to-gas and the consequences: impact of higher hydrogen concentrations in natural gas on industrial combustion processes	"H2-Substitution" by AiF (Grant No. IGF 18518 N/1)	3 Burners where tested in Lab Furnace with HEC combustion and H2-concentration up to 50%. Flamelength was investigated by CFD simulation. Conclusion: Burners have to be modified for HE-combustion. A fluctuation in H2-content in H2/NG-mixtures in German gas-net has to be to taken into account. Security-measures and risk-management for H_2/NG-mixtures are necessary to be prepared either in industria heating as well as households.	https://doi.org/10.1016/j.egypro.2017.07.157	-	-	-	-	4	5	-	-	-	-	-	-	-	-	-	-	-	-	-
J4	2021	Flameless combustion with HEC under subatmospheric conditions	• HEC combustion of mixtures of hydrogen and natural gas in flameless combustion mode. • H_2-concentration 0%, 25%, 45% and • Pressure in combustion chamber: 0,850 bar	Emissions and dynamic stability of the flameless combustion regime using hydrogen blends with natural gas"	-	Experimental investigation in lab scale test furnace with burner for flame and flameless mode at P = 28 kW and HEC at 0%, 25% and 45 % H2-concentration - pressure in furnace 0,850 bar - air ratio n = 1.17, 1.65, 2.0 (conventional flame) / parameter O2 - investigation in Emissions NOx, flame temperatures 2020 to 2120 K depending on n. - accoustic measurement to investigate flame stability - burning velocity is increased with increased H2- content	https://doi.org/10.1016/j.ijhydene.2020.09.196	-	-	-	-	4	4	-	-	-	-	-	-	-	-	-	-	-	-	-
J7	2021	Flameless burner HEC and 100% H2 fuel	Tenova SmartBurner technology: TSX recuperative flameless for reheating applications ready to use hydrogen as fuel (up to 100%), with nitric oxides reached in the operative range from 100% natural gas to 100% hydrogen — well below the next envisioned limits (80 mg/Nm3 at 5% of O_2, with furnace at 1250 °C).	Tenova SmartBurners with 100% Hydrogen	-		https://doi.org/10.1051/matecconf/202132512	-	-	-	-	7	8	-	-	-	-	-	-	-	-	-	-	-	-	-
J18	2021/2022	Linde **hydrogen burner** in reheating furnace at OVAKO rolling mill	-	-	-	Together with Linde Gas AB, Ovako have completed the world's first successful full-scale trial in a production environment of using hydrogen to heat steel before rolling. The use of hydrogen in combustion would have a great positive effect on the environment since the only emission generated is water vapor. The trial, in which steel was heated using hydrogen instead of LPG (liquefied petroleum gas) before rolling at the mill in Hofors, was successful and testing of the steel produced showed that heating with hydrogen does not affect the quality. Given the right conditions, Ovako could therefore introduce hydrogen heating for furnaces at all our rolling mills and thereby drastically reduce our already world-leading low carbon footprint from cradle to gate.	https://www.ovako.com/en/newsevents/stories/first-in-the-world-to-heat-steel-using-hydrogen/	success	yes	-	-	7	7	-	-	-	-	-	-	1	1	-	-

Literature review: Classification of literature and findings as well as determindes KPIs
Topic 2: Modelling of entire furnace, model based predictive control

Classification Criteria								KPIs													
Reference number	Year	Related/identified Technology	Description of technology	Project full name or article name	Acronym	Short description of project	link to report / publications / website	success/ partial success/ failure	practical applications of results [yes/no; references]	follow-up projects	research gaps	TRL start [1-9]	TRL end [1-9]	Energy consumption [e.g. GJ/t; decrease in %]	Productivity [e.g. t/h; increase in %]	CAPEX increase/decrease	OPEX increase/decrease	Scale loss of product [e.g. g/m² or recution in %], yield increase	number of installations in industry	CO_2 emissions reduction scope 1 [e.g. kg/t or %]	CO_2 emissions reduction scope 2 [e.g. kg/t or %]
R4	2002	Optimizing the slab distance in walking beam furnace to reduce temperature difference across the slab width.	System based on statistical evaluation of temperature maps provided by scanning pyrometer has been realized and implemented in the existing diagnostic system aiming at a periodic check of the correct distance between slabs in the walking beam furnace. Distance between slabs in the walking beam was set to 70-100 mm with a final results of a mean ΔT equal to 15-20°C between bar center and sides.	Integration of reheating furnaces with rolling conditions at the roughing mill, EUR N° 20196	Improheat	Investigations were made to integrate reheating furnaces with the roughing mill, focusing on the conditions to measure and control the temperature homogeneity of slabs. The measurmentes were used to improve heating models for the control of furnaces. The models consisted both of physical and neural network based varieties. Relationsships and conditions have been identified to not risk surface quality. Advisory systems have been developed to aid operators for avoidance of hazardous security limits.	https://op.europa.eu/en/publication-detail/-/publication/61ac72c9-7083-45fe-b030-617017782df9	sucess	yes, Acciai Speciali Terni Walking Beam furnace	-	-	-	7,8	-	-	-	-	-	at least 1	-	-
R7	2005	• CFD model of walking beam pilot-scale furnace • CFD model of existing ful-scale furnace with low NOx HPAC burners for NG	Prediction of O_2,CO_2, NOx concentrations in the furnace, gas temperature and velocity , furnace temperatures	Performance of reheating furnaces equipped with highly preheated air combustion technology, EUR N° 21147	HPAC	Burner using highly preheated air combustion (HPAC) technology and designed to produce low NOxemissions, have characteristics that are different to those of conventional burners. This has potential implications for the performance of steel reheating furnaces. The aims of this project have been to test the effectiveness and long-term reliability of HPAC burners and specify optimal conditions for installation of these burners in industrial furnaces. Taking a general case, the combustion efficiency of a furnace using natural gas with an exhaust gas temperature of 1200ºC and operating with 10% excess air at the burner preheated to 1000ºC, was calculated at 73.4% on a gross basis. If the combustion air is supplied at ambient temperature, the combustion efficiency reduces to 36.8%, almost doubling the fuel energy required to satisfy the heat released within the furnace. In modern furnaces with external recuperators the energy saving is less. The fuel savings can be translated into reductions in CO2 emissions and, with 'low NOx' HPAC technology, there are additional benefits from reduced NOx emissions.Although the economic justification for the application of HPAC technology can often be based on energy savings alone, other benefits can be realized. These include increased productivity, improved product quality and increased product yield (reduced scaling) but these are specific to each application and are difficult to quantify in general terms.	https://op.europa.eu/en/publication-detail/-/publication/d65a4234-7143-40ed-a7ff-69a7314faafa	**1.** pilot-scale furnace: failure: comparison with trial measurements deviate from prediction of the model, reaction rate was lower and entrainment was higher then prdicted (-> CO prediction higher and NOx lower) success: gas velocities prediction, trend in furnace roof, hearth and sidewall temperature **2.** full-scale furnace: sucess: model enabled a review of the furnace design to improve flow regime and thereby control and operation of the furnace	modelling of the dark (preheat) zone of a walking beam furnace No. 304 at SSAB (Tunnplat AB, Borlänge)		No validation of full scale furnace model	-	-	not specified	-	-	-	-	-	-	-
R9	2004	Management of the continuous reheating of slabs having varying size, steel grade and discharging temperature.	The utilisation of the operator experience and knowledge within a computer based control system might drastically increase the reheating process efficiency and productivity and the operational staff should be relieved.	Rules base systems for improved monitoring and guidance of reheating furnaces, EUR N° 21992	-	The overall objective of the project is the development and implementation of intelligent monitoring and guidance of reheating furnaces for optimised operation, based on artificial intelligence techniques, in terms of: 1. component and process on-line diagnosis (MEFOS, CSM); 2. estimation of the temperature and furnace atmosphere set points (BFI). System to prevent or to diagnose malfunctions in the furnace, and also to monitor the re-heating process according to different production ranges, providing the operator with guidance when deviating from correct behaviour. The innovative idea: Extend the conventional process control techniques by combining the results of on-line physical models calculations with expert system rules and statistical methods. Reconcile significant amount of data from a number of disparate sources, continuously apply expert rules and statistical methods to suupport operators for decision making and control.	https://op.europa.eu/en/publication-detail/-/publication/4888df93-d44f-4582-90ae-9eae14eb5ddc	Success: Two intelligent monitoring and guidance systems for the optimised operation of reheating furnaces, based on artificial intelligence techniques have been realised. That is: - component and process on-line diagnosis; - estimation of the temperature and furnace atmosphere set points. The systems are able not only to prevent or to diagnose malfunctions in the furnace, but also to monitor the re-heating process according to different production ranges, providing the operator with guidance when deviating from correct behaviour.	The developed rules based system for the guidance of reheating furnaces is working at the three industrial reheating furnaces at the hot strip mill of the Thyssen Krupp Steel AG in Bochum (Germany). The furnace rules based monitoring system has been developed and installed on the process control system of the furnace no. 301 of the hot strip mill at SSAB Tunnplat AB Works in Borlänge.	-	The innovative idea is to extend the conventional process control techniques by combining the results of on-line physical models calculations with expert system rules and statistical methods.	2	7	-	Improvement of the process efficiency (not quantified)	-	-	- Early detection of anomalies and timely identification of the possible causes (not quantified) - Predictive diagnosis preventing failures occurrence and avoiding failures propagation (not quantified) - Reduction of unplanned machines shut-downs and operator guidance during interventions phases (not quantified)	At least 1 for each of 2 system	-	-
R17	2008	Optimizing the operation of reheating furnaces, maintenance and product quality	Optimising is performed by providing furnace diagnostic tools for monitoring and controlling process parameters.	Real-time intelligent diagnostics and optimisation of reheating furnace performance, EUR N° 24174	SMARTFIRE	The objective is to identify ways of optimising the operation of reheating furnaces, maintenance and product quality by providing furnace diagnostic tools for monitoring and controlling process parameters. In one work stream, a technique was successfully developed to produce diagnostic signals from flame imaging. It also demonstrated for the first time that even nominally identical burners produce different characteristic signals. Without recalibration, this limits the transfer between burners, making furnace-wide application difficult. In another work stream, statistical and physical models of furnace features were developed and linked with furnace databases to form on-line real-time diagnostic systems, although the developed flame analysis system was not included in these diagnostic systems, as had originally been planned. The project was successful in developing a range of diagnostic techniques to help improve the operation of reheating furnaces as well as product quality.	https://op.europa.eu/en/publication-detail/-/publication/7b66b89c-4933-41db-b416-f2b3835dd035/language-en/format-PDF/source-277666065	Success: A flame analysis system has been developed that is capable of predicting burner characteristics, imbalances and fault conditions, and has also revealed new information about burners that will be of interest in the scientific community. Failure: The system requires further development before being fully applicable for furnace diagnostics	no It is considered that the work within this project can serve as a guide to all furnace operators and engineers on the considerations and possibilities of providing furnace diagnostics.	The flame monitoring system is being further developed as part of a new European Commission sponsored project (RFCR-CT-2008-00009) SMARTBURN – project RFCR-CT-2008-00009 is, in part, investigating the use of low cost flame monitoring systems for the optimisation of the combustion of power station utility boilers when co-firing coal and biomass.	A technique was successfully developed to produce diagnostic signals from flame imaging. It also demonstrated for the first time that even nominally identical burners produce different characteristic signals. Without recalibration, this limits the transfer between burners, making furnace-wide application difficult.	2	4	-	-	-	-	-	-	-	-
R19	2011	Tool for prediction and optimisation of the microstructure of hot rolled products (for rolling mills)	Development of several optimization algorithms: 1. furnace control system (FCS) for tracing the slab temperatures and the predefined reference heating curves 2. three new ideal heating curves for various steel grades and production routes (cold charging, hot charging and hot charging with soaking) developped 3. interface to help take the decision of rejecting decarburized billet and therefore minimize production of scrap 4. optimization of rolling schedules to improve mechanical propeties (yield strength)	Quality improvement by metallurgical optimised stock temperature evolution in the reheating furnace including microstructure feedback from the rolling mill, EUR N° 25001	OPTHEAT	The overall project aims are to optimise product quality, reheating furnace operation and material yield by improved monitoring and control of the reheating furnace and rolling mill. To achieve these objectives the dependence of the material properties on the heating in the furnace and the microstructure evolution inside the stock during rolling has to been considered. Sets of heuristic rules for control of the transient furnace operation and mill set up were estimated and operational strategies were developed. Mathematical modelling of the heating and rolling process with respect to microstructure, product quality, temperature and energy consumption was done and implemented. A user-friendly tool for prediction and optimisation of the microstructure was developed. The productivity of the rolling mill and material quality can be increased by using improved furnace strategies for handling stoppages in the rolling mill and changes from one lot of certain steel grade to another.	https://op.europa.eu/en/publication-detail/-/publication/1c701b87-4897-48ae-98dd-031817b1cabd/language-en/format-PDF/source-277693889	success: integrated hot rolling model and optimization tool has been successfully tested → leads to an improvement of material quality and productivity failure: online implementation of the hot rolling optimization tool (predictive+optimisation tool) was not feasible due to large computation time; only predictive tool online and use of a different optimization alfotirth	unmentioned		no common steel grades investigated by all partners	-	-	decrease through ideal heating curves	+ 2% for stainless steel reheating	-	-	-	-	-	-
R26	2017	Use of advanced furnace measurements technologies and **development of a real-time dynamic furnace model**	**1. Development and validation of various dynamic models** using a zonal modelling approach for: a pilot-scale furnace, a bloom walking beam reheating furnace, a bogie car reheating furnace and a billet walking beam reheating furnace	Advanced measurements and dynamic modelling for improved furnace operation and control	DYNAMO	The objective of this project is to improve furnace operation and control using advanced measurements and dynamic modelling. Specifications for different advanced furnace measurements and modelling were determined. Furthermore, advanced temperature equipment was put in operation on reheating furnaces and reviewed. The results were used to develop a real-time dynamic virtual furnace-models. These	https://op.europa.eu/en/publication-detail/-/publication/de5068a7-03cd-11e7-8a35-01aa75ed71a1/language-en/format-PDF/source-272135637	Models could be successfully validated with test cases or continous trials	Bogie car furnace (gerdau), Walking hearth reheating furnace (Mefos), Walking beam bloom reheating furnace (Tata), Walking beam billets reheating furnace (Saarstahl)	-	-		6	reduced gas comsumption: based on dynamic temperature control: - 4 to -12 % depending on production rate	-	-	-	-	at least 4	-	-
			2. Implementation of improved strategies and **improvements of furnace controller software**					success		-	-	-	-								
H3	2018	**Comprehensive kinetic mechanism to model combustion of natural gas.**	The scientific goal of the CLEAN-Gas project is to develop new experimental and numerical tools for improving natural gas combustion in innovative burners. Chemistry of pollutants species, soot particles, NOx	Combustion for Low Emission Applications of Natural Gas	CLEAN-Gas	The CLEAN-Gas EJD Programme aimed at improving and extending our scientific knowledge about new combustion processes for natural gas, including regenerative burners, flameless combustion, combustion of highly diluted mixtures or oxy-combustion. Those processes, despite already used in some industrial units, are still poorly understood and are very difficult to transpose from one industry to another. In order to reach this goal, the CLEAN-Gas EJD Programme proposed an innovative approach, based on the coupling between experiments and numerical simulations, including detailed chemistry and computational fluid dynamics applied to real complex geometries.	https://cordis.europa.eu/project/id/643134/results	The project partners worked on the development of detailed kinetic mechanism able to describe the combustion of natural gas in conventional and non conventional systems, including the formation of NOx and particulate emissions. The whole approach is based on a comprehensive investigation of different turbulent flames at different levels of complexity. The turbulent flames of increasing complexity vary in their nozzle design, fuel, and pressure conditions.	The numerical tools developed and validated inside the project were adopted for the simulation of industrial-scale combustion devices with the aim to improve the combustion process and reduce the formation of pollutant species.	-	-	2	4	-	-	-	-	-	-	-	-
H10	2022	**Investigation of modern and efficient combustion technologies** (MILD Combustion), by means of experimental, theoretical, and **numerical simulation** approaches.	The objective of VADEMECOM is to drive the development of modern and efficient combustion technologies, by means of accurate and adaptive models, allowing a detailed description of the phenomena only where necessary.	VAlidation driven DEvelopment of Modern and Efficient COMbustion technologies	VADEMECOM	Combustion science will play a major role in the future quest for sustainable, secure and environmentally friendly energy sources. Two thirds of the world energy supply rely on combustion of fossil and alternative fuels, and all scenarios forecast an increasing absolute energy supply through combustion, with an increasing share of renewables. Thus, combustion will remain the major actor in transportation and power generation as well as in manufacturing processes, like steel and glass. Nevertheless, combustion science will need profound innovation to meet future energy challenges, such as energy efficiency and fuel flexibility, and ensure future generations with affordable and sustainable energy and healthy environment. In this context, MILD combustion represents a very attractive solution for its fuel flexibility and capability to deliver very high combustion efficiency with virtually zero pollutant emissions. Such a combustion regime is the result of a very strong interaction between turbulent mixing and chemical kinetics. The fundamental mechanism of this interaction is not fully understood, thus justifying the need for experimental and numerical investigations. The overall objective of the present research proposal is to drive the development of modern and efficient combustion technologies, by means of experimental, theoretical, and numerical simulation approaches. New-generation simulation tools for MILD combustion will be developed, to reduce the dependence on sub-grid models and increase the fidelity of	https://cordis.europa.eu/project/id/714605	Success: Demonstrating the feasibility of MILD combustion with a variety of fuels (hydrogen, ammonia, methane and their mixtures). - Developing optimised and validated comprehensive chemical mechanisms for MILD combustion conditions and develop strategies for their reduction and inclusion in large scale simulation. - Developing models that can include realistic chemistry in the simulation of combustion systems, combining sate-space parameterisation, mechanism reduction, machine learning, efficient chemistry management. - Developing approaches to assess the confidence in the predictions from computational modelling, expanding our approaches for uncertainty quantification to realistic combustion systems.	no	-	-	2	3	-	-	-	-	-	-	-	-

Literature review: Classification of literature and findings as well as determindes KPIs
Topic 3: Measurement and sensors, measurement-based furnace control; standards, regulations

Classification Criteria									KPIs														
Reference number	Year	Related/identified Technology	Description of technology	Project full name or article name	Acronym	Short description of project	link to report / publications / website	Project partners	success/ partial success/ failure	practical applications of results [yes/no; references]	follow-up projects	research gaps	TRL start [1-9]	TRL end [1-9]	Energy consumption [e.g. GJ/t; decrease in %]	Productivity [e.g. t/h; increase in %]	CAPEX increase/decrease	OPEX increase/decrease	Scale loss of product [e.g. g/m² or recution in %], yield increase	number of installations in industry	CO_2 emissions reduction scope 1 [e.g. kg/t or %]	CO_2 emissions reduction scope 2 [e.g. kg/t or %]	Combusion efficiency
R2	2001	• Model aided control of air-fuel ratio in a multi zone furnace (level 2 furnace control). • **O_2-measurement by fixed zyrkon dioxid -probe.** • Combination of electrical and combustion heating for reheating furnaces.	Software controller on level 2 that can be implemented to already existing furnace control system. Based on PI-controller for each zone of the furnace and set of supervising rules; based on a flow model of the furnace and CO-measurements; based on the local estimation of the oxygen-content inside the furnace(recommended technology for O2 measurements: ZrO2-probes) + combination with numerical model for exhaust gas flow calculation to define optimum probe position for exhaust gas analysis	Improved atmosphere control for product quality and combustion efficiency in reheating furnaces, EUR N° 19855	-	Objective of the work 1) Improve surface quality of rolled products, 2) Increase capacity of existing reheating furnaces, 3) Reduce energy consumption in reheating furnaces. Modelling and experimental trials were performed to give insight into position of measurement points. Suitable sensors were testet for oxygen measurements. Based on these results a control strategy for the furnace atmosphere was made. Increase of furnace capacity was studied using supplemental electrical heaters in a pilot scale furnce. The dual heater setup increased the furnace capacity, and its potential application should be evaluated based on local energy prices. Reduced heating times were the main factor decreasing scale losses.	https://op.europa.eu/en/publication-detail/-/publication/2baa35c8-53bf-4e0d-98d5-e9874ae00404/language-en/format-PDF/source-266784811	BFI, IRSID (ArcelorMittal Maizières Research SA), MEFOS (Swerim), Rautaruuki (SSAB)	success	yes:walking beam furnace of "Neue Max Hütte	EGKS project (No. 7210-PA/019): air ratio controller, influence on scale loss	improvement possible by measuring the surface temperatur inside the furnace	-	6,7	decrease between 2.4 % and 6 %	-	-	-	reduction through O_2 reduction possible, but no estimations given	at least 2	yes (less energy consumption)	-	-
R3	2002	On/Off firing technique for burners in walking beam furnace	On/Off firing: firing carried out through several burners operated at full power for a limited cycle time.	Optimization of beam reheating conditions in the reheating furnace, EUR N° 20194	-	Work on optimising and improvement of the heating control of a reheating furnace focusing on large and complex shaped beam blanks. On-off control was investigated for the burners. A control algorithm was developed taking into account furnace position of the product, desired crosswide temperature distribution and type of product in the equalisation zone. Lead to the change of operation into on-off control in the lower equalisation zone. Operator can now control the transversal temperature profile, temperature unity was enhanced, fuel consumption and NOx emissions reduced.	https://op.europa.eu/en/publication-detail/-/publication/a5e4774d-cab1-49bb-9eb0-fcf3eb143909	ProfilARBED (today ArcelorMittal Belval) , Techint-Italimpianti (Tenova) and CSM (Rina)	success	yes, walking beam furnace ProfilARBED at Differdange (PADI)	-	-	-	9	decrease	-	-	-	-	Now State of the art	yes (less energy consumption)	-	-
		New regulation algorithm for lower equalization zones of the reheating furnace	Regulation algorithm: firing times depending on position of the product in the furnace, desired crosswide temperatur profile, type of charge in equalization zone						success		-	-	-	7 (today 9?)	decreaase	-	-	-	-	at least 1 at end of project		-	-
R4	2002	**Optimizing the slab distance in walking beam furnace** to reduce temperature difference across the slab width	System based on statistical evaluation of temperature maps provided by scanning pyrometer has been realized and implemented in the existing diagnostic system aiming at a periodic check of the correct distance between slabs in the walking beam furnace. Distance between slabs in the walking beam was set to 70-100 mm with a final results of a mean ΔT equal to 15-20°C between bar center and sides.	Integration of reheating furnaces with rolling conditions at the roughing mill, EUR N° 20196	Improheat	Investigations were made to integrate reheating furnaces with the roughing mill, focusing on the conditions to measure and control the temperature homogeneity of slabs. The measurmentes were used to improve heating models for the control of furnaces. The models consisted both of physical and neural network based varieties. Relationsships and conditions have been identified to not risk surface quality. Advisory systems have been developed to aid operators for avoidance of hazardous security limits.	https://op.europa.eu/en/publication-detail/-/publication/61ac72c9-7083-45fe-b030-617017782df9	CSM, British Steel, Mefos (Swerim), DDS (Duferco Danish Steel), Sidenor	sucess	yes, Acciai Speciali Terni Walking Beam furnace	-	-	-	7,8	-	-	-	-	-	at least 1	-	-	-
R6	2002	**Contactless measurements of radiation temperature** of technical hot surfaces and simultaneous spetroscopy of the thermal process	Using Fourier spectrometer (FTIR) to measure the whole thermal spectrum: collecting complete intensity profile of the thermal source, exploiting the special properties of interferometric measurements, which only work with a very small optical aperture (+ water-cool shield apparatus to prevent radiation of the furnace wall to reach pyrometer)	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	-	The target is to find a new and improved way to measure the true radiation temperature of hot surfaces. Also using spectroscopy for the thermal process. The method is to be used to measure hot strips in a cont furnace for thermal processes. The method is supported by modeling of the furnace.	https://op.europa.eu/en/publication-detail/-/publication/217a1eda-1579-483c-ae3e-00362728151f	EKO Stahl GmbH (ArcelorMittal), British Steel Strip Products, Corus RDT (Tata Steel), Aceralia (ArcelorMittal)	success: FTIR method works, annihilation of furnace wall radiation is possible with spectrometer failure: no validation of the spectrometer method (direct comparison between "new" and "classical" method under equal very well known conditions were performed but resultst are not reliable)	no, only tested in a pilot furnace (EKO Stahl at Port Talbot)	-	no comparison between "new method" with FTIR spectrometrand "old method" with classical pyrometer, no validation of measure temperatur with pyrometer	2	4,5	should decrese through better control of thermal process, knowing the true temperature	increase through better control and less disturbance	-	-	-	none mentioned	decrese with decreasing energy consumption	-	-
R26	2017	**Use of advanced furnace measurements** technologies and development of a real-time dynamic furnace model	**1. Test of advanced measurement technolgies**: - Gas temperature measurements: infrared gas temperature pyrometers,tunable diode laser absorption spectrometer (TDLAS), ultrasonic (accoustic) gas temperature measurement devices - Stock temperature measurements: billet prepared with shielded thermocouples to measure T at different positions in the billet - inner furnace temperature measurements: thermocouples + infrared systems (pyrometry and thermography) + radiometric temperature imaging (using Thermoteknix camera) - furnace atmosphere measurements at different locations in the furnace: gas analysing system (portable and continuous)	Advanced measurements and dynamic modelling for improved furnace operation and control	DYNAMO	The objective of this project is to improve furnace operation and control using advanced measurements and dynamic modelling. Specifications for different advanced furnace measurements and modelling were determined. Furthermore, advanced temperature equipment was put in operation on reheating furnaces and reviewed. The results were used to develop a real-time dynamic virtual furnace-models. These models were applied to the different furnaces of the consortium and used for the implementation of improved strategies and improvements of furnace controller software.	https://op.europa.eu/en/publication-detail/-/publication/de5068a7-03cd-11e7-8a35-01aa75ed71a1/language-en/format-PDF/source-272135637	BFI, TataSteel UK, Mefos (Swerim), Gerdau, University of South Wales (UoSW), Saarstahl	success: - response of pyrometer fast for transient condition - ultrasocnic gas temperature measurement partial success: - TC response slower then pyrometers - Thermoteknix camera (price, software, design of mounting)	Bogie car furnace (gerdau), Walking hearth reheating furnace (Mefos), Walking beam bloom reheating furnace (Tata), Walking beam billets reheating furnace (Saarstahl)	-	-	8	9	reduced gas comsumption: based on dynamic temperature control: -4 to -12 % depending on production rate	-	-	-	-	at least 4	-	-	increase through dynamic O2 control : no quantification
R31	2019-2023	**Solution for detecting anomalies** in re-heating furnaces, hot rolling mills and accelerated cooling	Solution that is capable of announcing a threat and in parallel **distinguishing between faults (i.e. sensoriel deficiencies, actuator malfunctioning, process perturbation)** and intentional attacks; focusses on the process-oriented treatment and not IT perspective	Automatic surveillance of hot rolling area against intentional attacks and faults	AutoSurveillance	AutoSurveillance will provide a solution for detecting anomalies in re-heating furnaces, hot-rolling mills and accelerated cooling, a solution that is capable of announcing a threat and in parallel distinguishing between faults and intentional attacks. To detect intentional sabotage, one must prior exclude things like drifts or errors in the measurements and unintentional process anomalies caused by the instability of process situations. Hence there is a need for monitoring control systems online, to detect any kind of abnormal behaviour. Sensorial deficiencies, actuator malfunctioning or process perturbations must be elemental part of a system that secures against intentional damages.	https://www.researchgate.net/publication/354380548_Automatic_surveillance_of_hot_rolling_area_against_intentional_attacks_and_faults_AutoSurveillance_Overview_and_first_results_of_the_RFCS_funded_Project_Contact_data	BFI, innoRIID, CETIC	no report yet	-	-	-	-	-	-	-	-	-	-	-	-	-	-
R34	2019-2022	Recover of waste heat from combustion of steel mill flue gases by dynamic adujstment of the flue gas temperature above the acid dew point (ADP) - develeopping inline monitoring of ADP temperature and inline corrosion monitoring - **novel inline ADP sensor** - inline corrosion probe for the protection of heat exchangers and chimneys during dynamic waste heat recovery	- ADP sensor: based on weighing of the condensing acid; installed in a bypass to the main gas duct, before heat exchanger - corrosion probe : based on measurement of resistance of a corroding element and reaching reaction time < 5min and lifetime >= 6 months; installed directly into the gas duct after heat exchangers, in the chimney - operational strategies and algorithm for dynamic waste heat recovery : based on measurements signals	Acid dew point and corrosion sensors for dynamic waste heat recovery from steel mill flue gases	SafeDewPoint	During combustion of steel mill gases acid dew point temperature varies strongly. SafeDewPoint aims to recover waste heat in hot blast stoves, power plants and reheating furnaces by dynamic adjustment of flue gas temperature above the acid dew point. This will be reached with a help of novel inline acid dew point sensor and corrosion probes. This system will enable direct reuse of up to 20% waste heat. The project addresses waste heat utilisation for the preheating of fuel gas, combustion air and boiler feed water. For EU it will result in a potential for savings of 107 million €/y or 3570 GWh/y and emission reduction of 720 ktCO2/y. It will support competitiveness and sustainability of European integrated steel plants.	https://www.bfi.de/en/projects/safedewpoint-acid-dew-point-and-corrosion-sensors-for-dynamic-waste-heat-recovery-from-steel-mill-flue-gases/	BFI, CENIM, Arcelor Mittal (AME), Salzgitter Flachsathl (SGFG)	failure: commercially available ADP sensor by Breen Energy Solutions (no reliable mensurement) partial success: novel acid dew point sensor tested under laboratory conditions with water vapor partial success: corrosion probe show responde <3min under laboratory conditions, minimal damage of probe	not yet	-	Further studies to increase the measurement accuracy of ADP sensor; operational tests of corrosion probe. Neither ADP nor corrosion rate monitoring has been applied in steel mill flue gases before.	2	4	- 3568 GWh/y	-	-	- 107 million €/y	-	0	- 720 kt CO2/y	-	-

Literature review: Classification of literature and findings as well as determindes KPIs
Topic 4: Materials in the furnace and product quality

Classification Criteria								KPIs											
Reference number	Year	Related/identified Technology	Description of technology	Project full name or article name	Acronym	Short description of project	link to report / publications / website	success/ partial success/ failure	practical applications of results [yes/no; references]	follow-up projects	research gaps	TRL start [1-9]	TRL end [1-9]	Energy consumption [e.g. GJ/t, decrease in %]	Productivity [e.g. t/h; increase in %]	CAPEX increase/decrease	OPEX increase/decrease	Scale-ups of product [e.g. g/m² or recution in %], yield increase	number of installations in industry	CO_2 emissions reduction scope 1 [e.g. kg/t or %]	CO_2 emissions reduction scope 2 [e.g. kg/t or %]
R30	2020	Furnace rolls working in continuous annealing and galvanizing lines	- Development of improved non-sticking coatings - Development of improved ceramic sleeves	Non Sticking furnace Rolls to improve service life and product quality in continuous annealing and galvanizing lines	NoStickRolls	The project aims to prolong the service life of furnace rolls working in continuous annealing and galvanizing lines, bringing reduction of maintenance costs and increase of productivity by lengthening time-to-maintenance, and to improve the quality of steel strips with respect to surface defects that arise as a consequence of wear and build-up of oxides from steel product picked up by roll's surface. The most challenging issues regarding pick-up formation have arisen since the need to increase strip's running speed and/or annealing temperature and the need to process critical steel products for automotive industry, such as advanced high strength steels containing elevated levels of Mn and/or Si.	https://www.researchgate.net/publication/356556287_NON-STICKING_FURNACE_ROLLS_FOR_STEEL_PRODUCTS_TO_IMPROVE_SERVICE_LIFE_AND_PRODUCT_QUALITY_IN_CONTINUOUS_ANNEALING_AND_GALVANIZING_LINES_PRELIMINARY_STUDY_ON_CHEMICAL_INTERACTIONS_AND_PICKUP_MECHANISM	The development of coating solutions with improved resistance to wear and pick-up formation was obtained by different approaches: i combination of new material compositions or new for the application; ii new for the application coating concepts (i.e. multiple layered); iii innovative or new in the field deposition technology able to achieve improved coating features.	A series of improved coating solutions were tried by different approaches. These included: a) a combination of new material compositions or new for the application; b) new for the application coating concepts (i.e., functionally graded coatings, multiple layered); c) innovative or new in the field deposition technology able to achieve improved coating features.	no	experiments in different coating solutions	3	6	-	-	-	Reduction of cost for coating is significantly lower (12 k€ vs 7 k€) The maintenance cost of rolls might be reduced by ~50 k€/year only by considering the coating cost	The industrial benefit is expected in terms of strip quality issues (50% reduction defect)	At least 1	-	-

Literature review: Classification of literature and findings as well as determindes KPIs
Topic 5: Heat transfer, heat recovery, productivity, economy

dissHEAT

Classification Criteria										KPIs															
Reference number	Year	Related/identified Technology	Scale	Description of technology	Project full name or article name	Acronym	Short description of project	link to report / publications / website	Comment	success/ partial success/ failure	practical applications of results [yes/no; references]	follow-up projects	research gaps	TRL start [1-9]	TRL end [1-9]	Energy consumption [e.g. GJ/t; decrease in %]	Productivity [e.g. t/h; increase in %]	CAPEX increase/decrease	OPEX increase/decrease	Scale loss of product [e.g. g/m² or redution in %], yield increase	number of installations in industry	CO_2 emissions reduction scope 1 [e.g. kg/t or %]	CO_2 emissions reduction scope 2 [e.g. kg/t or %]	Was heat transfer improved Yes/no (kW/m²)	Was heat transfer improved Yes/no (kW/m²)
R1	1989	Regenerative burner	Lab scale furnace	To enable use of very low calorific gas, both blast furnace gas and air is preheated using a combination of recuperator and regenerator	Regenerative firing of low calorific value gas for high temperature processes, EUR N° 12093	-	The report presents long term tests (1500 h) of a new type of regeneratie heater configuration in the reheating furnace to facilitate the combustion of low calorific gases (BFG). Different operation strategies were tested based on heat load and excess air. The concept worked well and a short section about the economical performance was included	https://op.europa.eu/en/publication-detail/-/publication/229f9888-e544-43cc-8d37-9fca6ea0fe87/language-en/format-PDF/source-259161951#	-	Sucess: sufficient combustion performance and temperatures were achieved in long term test using low calorific blast furnace gas	Yes - commercially available	-	-	3	4	Substantial if BFG can replace other higher quality fossil fuels but depends on system (>40 %)	-	Increase - requires purcase of new burner technology (payback ~2 years)	substantial decrease due to lower cost of BFG compared to typical fossil fuels	-	-	-	-	No	Depends on system - could result in increased heat recovery due to lower exit flue gas temperature (recuperator)
R2	2001	• Controll system • O2 sensor (ZrO2) • Dual heating setups (electric+burners) • Modelling (temperature, air fuel ratio, CFD)	Walking beam RHfurnace (90 ton/h, air, natural gas) Walking beam RH furnace (450 t/h, air) Pusher type RH furnace Walking beam RH furnace (3t/h, air,electric+oil)	Various controll or design improvements of the heating section in reheating furnaces to improve product quality, production and energy savings.	Improved atmosphere control for product quality and combustion efficiency in reheating furnaces, EUR N° 19855	-	The objective of the work was threefold: 1) Improve surface quality of rolled products, 2) Increase capacity of existing reheating furnaces, 3) Reduce energy consumption in reheating furnaces. Modelling and experimental trials were performed to give insight into position of measurement points. Suitable sensors were testet for oxygen measurements. Based on these results a control strategy for the furnace atmosphere was made. Increase of furnace capacity was studied using supplemental electrical heaters in a pilot scale furnce. The dual heater setup increased the furnace capacity, and its potential application should be evaluated based on local energy prices. Reduced heating times were the main factor decreasing scale losses.	https://op.europa.eu/en/publication-detail/-/publication/2baa35c8-53bf-4e0d-98d5-e9874ae00404/language-en/format-PDF/source-266784811	Electric boosting for hybrid reheating Several measures and furnaces were evaluated, with different outcomes	Overall sucess	Dual heating - No	-	-	Controll system: 3 ZrO2 probe: 9 Dual heating system: 3	Controll system: 7-8 ZrO2 probe: 9 Dual heating system: 6	air to fuel ratio optimization: 1-6 %, dual heating: 6-7%	Dual heating : 25-35%	Likely not relevant (2001 data) Electrical heater: 1.1 MSEK/MW Oil burner: 0.2 MSEK/MW	not relevant (2001 data) Energy cost: Electrical heater: 0.25 SEK/kWh Oil burner: 0.2 SEK/kWh	air to fuel ratio optimization: substantial, but not quantified Dual heating: improvement equivalent to the increase in productivity (20-24%)	-	Equivalent to the amount of fossil fuel replaces	Depends on electricity mix	Dual heating : Yes - Installation of heating in convection section of furnace significantly increased heat transfer	Dual heating: No - would likely result in reduced heat recovery from flue gas due to less convective heat transfer
R4	2002	• Controll system • Modelling (temperature)	Walking beam RH furnace (220 ton/h) Pusher RH furnace (Air) Walking beam furnace (natural gas) Walking beam furnace (70 ton/h, air, Natural gas)	Modelling and measurements was used to try and integrate/link the operation of reheating furnace and the roughing mill to improve surface quality	Integration of reheating furnaces with rolling conditions at the roughing mill, EUR N° 20196	Improheat	Investigations were made to integrate reheating furnaces with the roughing mill, focusing on the conditions to measure and control the temperature homogeneity of slabs. The measurmentes were used to improve heating models for the control of furnaces. The models consisted both of physical and neural network based varieties. Relationsships and conditions have been identified to not risk surface quality. Advisory systems have been developed to aid operators for avoidance of hazardous security limits	https://op.europa.eu/en/publication-detail/-/publication/61ac72c9-7083-45fe-b030-617017782df9	No useful data available	Partial sucess. some of the measures resulted in improved temperature homogeneity	-	-	-	-	-	-	-	-	-	-	-	-	-	no	no
R5	2002	• Transverse flux inductors • Modelling (inductive heating) • Quenching (water+additive)	Lab scale investigations	Continuous annealing/Galvanising of steel strips using transverse flux inductors (1-3 MW/m2) followed by cooling using water with added acids to prevent oxide scale growth	New continuous annealing technology with high speed induction heating followed by ultra fast cooling, EUR N° 20203	-	The objective of this project is to improve technologies for ultra fast heating and cooling of strips in continuous annealing process. IRSID's contribution is the improvement of the transverse flux induction technology by use of numerical tools. CRM's contribution is the development of a new cooling technology of carbon steel strips using a liquid as cooling medium. The following benefits are expected : to reach new mechanical characteristics for steels, to increase capacity and flexibility of the existing lines, and to built very compact lines	https://op.europa.eu/en/publication-detail/-/publication/35aadb9d-8b45-479d-af0f-14a203ac2117	-	Sucess: The aims of the project was achieved during during the project but needs to be tested in industrial scale	-	-	-	8	8	Depends on the efficiency of the method it replaces, induction energy efficiency ~75%	Substantial increase in productivity due to much higher heating rate (>x2)	decrease - 60% of conventional	Likely decrease, ~20-25% lower energy consumtion so depends on cost of electricuty vs fossil fuel	-	-	Equivalent to the amount of fossil fuel replaces	Depends on electricity mix	Yes - Several times higher than conventional heating methods (20 °C/s vs 500-1000 °C/s)	No
R7	2005	• Regemat 350 FLOX-Flame' regenerative burner (200 kW, natural gas) (low NOx burner) • Modelling (temperature, CFD)	Lab scale 'Walking beam RH Furnace (300 ton/h) using regenerative burner (heavy fuel oil+air)	High temperature preheating of combustion air (1000 °C) to improve performance of reheating furnaces and reduce NOx emissions	Performance of reheating furnaces equipped with highly preheated air combustion technology, EUR N° 21147	HPAC	Burner using highly preheated air combustion (HPAC) technology and designed to produce low NOxemissions, have characteristics that are different to those of conventional burners. This has potential implications for the performance of steel reheating furnaces. The aims of this project have been to test the effectiveness and long-term reliability of HPAC burners and specify optimal conditions for installation of these burners in industrial furnaces. Taking a general case, the combustion efficiency of a furnace using natural gas with an exhaust gas temperature of 1200ºC and operating with 10% excess air at the burner preheated to 1000ºC, was calculated at 73.4% on a gross basis. If the combustion air is supplied at ambient temperature, the combustion efficiency reduces to 36.8%, almost doubling the fuel energy required to satisfy the heat released within the furnace. In modern furnaces with external recuperators the energy saving is less. The fuel savings can be translated into reductions in CO2 emissions and, with 'low NOx' HPAC technology, there are additional benefits from reduced NOx emissions.Although the economic justification for the application of HPAC technology can often be based on energy savings alone, other benefits can be realized. These include increased productivity, improved product quality and increased product yield (reduced scaling) but these are specific to each application and are difficult to quantify in general terms.	https://op.europa.eu/en/publication-detail/-/publication/d65a4234-7143-40ed-a7ff-69a7314faafa	-	Sucess: the performance of the burner was verified in pilot and industrial settings	The burner technology is, and was commercially available	-	-	9 (new application of existing technology)	9	Fuel saving of about 12 % due to higher heat recovery ratio and efficiency	Theoretical increase of 2 %	Higher (requires more burners for given output)	Likely lower due to higher fuel efficiency	Not quantified, but should be reduced due to lower excess O2	-	Equivalent to fuel savings	-II-	No change compared to conventional burner	Heat recovery rate ~ 76-88%, no comparison made to conventional
R8	2005	• Controll system (burner) • Forced convection in dark zone of reheating furnace • Heating pipes (air) • Modelling (temperature, CFD)	Controll system: full scale walking beam furnace and pusher type furnace Forced convection: Walking beam furnace (3t/h)	controll system - improve the controll of burners thorugh additional information supplied by thermocopuples and/or CFD modelling Fans installed in the convection zone to increase convective heat transfer active cooling of slab ends to avoid overheating (heat pipes, combustion air preheating)	New ways to improve longitudinal temperature homogeneity of slabs in reheating furnaces, EUR N° 21334	-	The aim of the research has been to examine different technical solutions to minimise longitudinal temperature homogeneity of slabs and by that improve the performance of reheating furnaces and the quality of the product. The objective of the project is to develop new technical devices to avoid other-heating of slab ends and to improve the global longitudinal temperature homogeneity of slabs in reheating furnaces (apart from skid marks phenomena). The different solutions studied are : •local cooling devices near the slab-ends in heating and soaking zones for example, •additional fan in the dark entry zones, •new technologies to use alternatively left/right or top/bottom burners, •original design and location of exit sections of fumes. The benefits are an increased coil quality (dimensions, product quality) and better productivity of rolling mills (easier speed control in strip ends, reduced scrap).	https://op.europa.eu/en/publication-detail/-/publication/c07f2a65-ec7c-4709-8270-b309aec6e925	-	• Controll system: partial sucess : issues were identified but not resolved • Active convecton: Sucess: significant increase in heat transfer • Heat pipes: Sucess: temperature distribution significantly improved	-	-	-	Control system: 9 Forced convection: 3 Heat pipes: 3	Control system: 9 Forced convection: 6 Heat pipes: 6	Forced convection: Decreased due to higher heat transfer Heat pipes: 0.5% increase due to burner limitation (air had to be cooled before burner)	Forced convection: theoretically improved but not quantified	Forced convection and Heat pipes: Increase due to additional high temperature equipment	Forced convection: Lower due to increased heat transfer and productivity	Decreased due to higher production rate (lower residence time)	-	Equivalent to fuel savings	Depends on electricity mix	Forced convection: yes - 40% increase in convective heat transfer	Forced convection: Yes - increased due to lower exit flue gas temperature
R9	2006	• Control system (temperature setpoint rules) • Component and process on-line diagnosis modelling /temperature	1x pusher RH furnace (250 t/h) 2x walking beam furnace (310 t/h) 2x walking beam furnace (300 t/h)	Improve operator performance in controlling temperature of reheating furnaces with guidence from AI and statistical methods utilizing improved temperature diagnostics of the furnace	Rules base systems for improved monitoring and guidance of reheating furnaces, EUR N° 21992	-	The overall objective of the project is the development and implementation of intelligent monitoring and guidance of reheating furnaces for optimised operation, based on artificial intelligence techniques, in terms of: 1. component and process on-line diagnosis (MEFOS, CSM); 2. estimation of the temperature and furnace atmosphere set points (BFI). System to prevent or to diagnose malfunctions in the furnace, and also to monitor the re-heating process according to different production ranges, providing the operator with guidance when deviating from correct behaviour. The innovative idea: Extend the conventional process control techniques by combining the results of on-line physical models calculations with expert system rules and statistical methods. Reconcile significant amount of data from a number of disparate sources, continuously apply expert rules and statistical methods to suupport operators for decision making and control.	https://op.europa.eu/en/publication-detail/-/publication/4888df93-d44f-4582-90ae-9eae14eb5ddc	Upp to 10 °C better temperature controll compared to manual operation	Partial Sucess: initial implementation showed good result but it is not verrified long term	Steeltemp3D - no		Validation of results were not complete during project	Temperature setpoint rules: 3 component and process on-line diagnosis: 3	Burner controll: 7 component and process on-line diagnosis: 7	Not quantified	Not quantified	-	-	Not quantified	>1	-	-	no difference	no difference
R14		Findings: **1. Flameless technologies provide the best available technologies (BAT) for low Nox burners and primary Nox reductions.** **2.** Oxy-fuel combustion increases efficiency by reducing heat loss through the exhaust gas.	-	Flameless combustion with and without regenerative combustion air preheating. Air and oxy-fuel combustion. High Temperature Reduction (HTR): Mixing amonia in furnace exhaust to achieve SNCR. Experimental and theoretical investigation of combustion, reaction zone NOx formation and influence of NOx on the above mentioned reduction measures.	Minimising NOx emissions from reheating furnaces	NOX-RF	The objective of this project is investigate methods to reduce NOx emissions from steel reheating furnaces while maintaining good fuel efficiency and low CO levels for both air combustion and oxy-fuel combustion. - Give information an recomondations for NOx-burner systems when installation of new systems in reheating furnaces is necessary and planned; - investigate NOx reduction by evalusting new equipment and modification of existing equipment for air and oxy-fuel combustion; - experimental and theoretical (moddeling) investigations into methods to NOx reduction in industrial furnaces as well as in pilot furnaces.	https://op.europa.eu/en/publication-detail/-/publication/8a4b2301-b682-47e2-9d6d-344720ef3e53	Oxyfuel combustion technology could increase furnace productivity and oxygen supplies could arise from water electrolysis	Successful pilot trials proving the benefits of oxyfuel reheating and low NOx burner technology	-	-	-	Pilot trials therefore 7	Low NOx oxyfuel burners are used commercially	oxyfuel can give 25% lower fuel costs	6.5% in trials and up to 30% with oxyfuel	-	-	-	-	-	-	Higher HT with oxyfuel	-
R16	2009	• Regenerative burners with preheated HT air (>600 °C) and fuel • Modelling (CFD)	industrial scale furnace (2.5 MW)(NOx, CO vs preheat temp, natural gas) pilot scale furnace (300 kW) (same but low calorific gases) lab scale furnace	Combination of regenerative (air) burner and recuperative(fuel) with low calorific fuel to reduce flue gas losses (lower fuel consumtion)	Improvement of top gas fired reheating and direct reduction furnaces for high temperature using innovative regenerative burners, EUR N° 24029	REGTGF	The project was concerned with two main objectives: reduction of energy consumption and improvement of product quality in reheating and direct reduction furnaces. A regenerative burner system was investigated. High preheated combustion air leads to a decrease in fuel consumption and enables the substitution of valuable fuels like natural gas or oil by weak gases like top gas or other byproducts that often could not be used in a convenient way at present. Combustion of weak gases like top gas results in voluminous flame and high impulse of fields lead to a good mixing inside furnace atmosphere, product quality will improve.	https://op.europa.eu/en/publication-detail/-/publication/14bac3a0-6d29-4712-88b1-7a51e60707fe	Investigated reheating furnace had poor controll with high excess oxygen, typically five but up to 10 %	Partial sucess : reduction of energy consumtion was not shown experimentally	-	-	No comparison in efficiency with other modern burner technologies	9 (new application (low calorific fuels) of existing technology)	9	Theoretically up to 30% fuel savings possible compared to the current old burners in the measured furnace (old, low efficiency)	NA	-	ikely to decrease due to low price of low calorific gases	-	-	up to 30 % natural gas could be substituted (theoretical approximation)	-II-	NA	NA
R20	2012	• Burner systems and heat recovery systems to: - increase heating efficiency - decrease NOx • Regenerative burner systems: - BFI burner with flame combustion and - Tenova TRGX burner with either flame as well as flameless combustion mode. Combustion of natural gas, COG, BFG, BOF. • Regenerator with ceramic honeycomb heat storage material • OXY-BF gas combustion; AGA REBOX concept Types S3 flameless combustion burner system.	-	Tenova: Flameless combustion of natural gas combined with regenerative preheated combustion air to reduce NOx emissions and increase furnace heating efficiency. BFI: Flat flame burner with tulip lime stone. Flame cooling at lime stone and by internal recirculation for NOx reduction in combination with highly preheated air. AGA: OXY-BFG flameless Combustion.	CO2 reduction in reheating furnaces, EUR N° 25004	CO2RED	"The present project is focused on new generation of combustion devices. In fact the most efficient energy saving method in steel industrial furnaces has been and is either preheating combustion air by recovering flue gas heat or reducing the flue gas volume (removing/reducing the nitrogen ballast by oxygen enrichment) or combining both of them. On the contrary, direct use of these methods has led in the past to high NOx emission. The partnership of CO2RED allowed to approach the research project at different levels: - by pilot scale for single burner (CSM Combustion Station, BFI Pilot Plant, MEFOS Chamber Furnace) to obtain data about emissions of different combustion systems for different gaseous fuels in flameless and high efficiency condition; 16 - with Computational Fluid Dynamics (CFD) to support the design and optimisation of new combustion system for installation in the furnace; - by performing long period test (> 3 months) at industrial site to check the durability and reliability of the combustion systems working in a "real" industrial environment"	https://op.europa.eu/en/publication-detail/-/publication/feabfc3c-0f9a-49c6-9d63-2aaa7173533b	Oxyfuel combustion and/or regenerative burners can save fuel and reduce GHG emissions	Success: demonstration of both regenerative heat recovery and oxyfuel combustion	-	-	-	7 for prototype BFG-oxyfuel burner	8 - burner qualified in pilot furnace trials	Est. 48% savings with oxyfuel if BFG is flared as a waste gas	Option with LPG- oxyfuel or regenerative air preheating	5% reduction for regenerative combustion furnaces	Est. 7-10% less fuel for regenerative furnace	Less scale formation for BFG combustion for most steel alloys tested	-	Est. 48% savings with oxyfuel if BFG is flared as a waste gas	-	-	-
R28	2020	High temperature thermoelectric system	Full scale	High temperature (>550 °C) thermoelectric system (gas heat exchanger)	Power generation from hot waste gases using thermoelectrics	PowGETEG	The aim of the project was to determine possiblities of thermoelectric power generation using industrial gaseous waste heat at temperatur > 550°C. New solutions for control, power conversion, heat exchange and overheating protection of TEG (thermoelectric generators) were developed and investigated. A demonstrator (output of 800 Wel) was constructed and tested under industrial conditions. Expected conversion efficiency of TEG (~5%). Conclusions: generated power output was lower than expected after the lab trials, economic evaluation showed that TEG applications seem not to be profitable for large-scale electricity consumers which are subject to low electricity rates; Compared to other techniques (like ORC and SRC) the payback period of TE technology is currently clearly the highest.	https://op.europa.eu/en/publication-detail/-/publication/9c33fec6-7587-11eb-9ac9-01aa75ed71a1/language-en/format-PDF/source-272143727	Could be interesting in small industries as it is simpler to use and install than other competing technologies	Partial success: The technology works but is not cost competetive with other technologies. Longevity and maintainance may also be a problem	-	-	Long term studies. Significant fouling present after few weeks of test	4	6	NA	NA	Requires high electricity prices to have adequate payback times (3-5 years), but would still be worse than other technologies such as ORC or SRC)	-	-	-	-	-	-	Yes, additional energy was utilized after recuperator.

H2	2017-present	CCS (SEWGS-reactor) from blast furnace gas technoeconomic analysis	Pilot scale (10 ton CO_2 per day)	-	SEWGS Technology Platform for cost effective CO_2 reduction the in the Iron and Steel Industry	STEPWISE	STEPWISE is a project executed within the European H2020 LCE program. It has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 640769. The project aims at the demonstration of advanced pre-combustion CO_2 removal technology within the framework of the Iron and Steel industry, aiming at lowering the CO_2 footprint of steel production. Blast Furnace Gas is decarbonized and then intended for power production. The CO_2 removal is performed with an advanced CO_2 removal technology making use of regenerative solid adsorbents. The technology combines the conversion of the carbon monoxide into CO_2 and H_2 by reacting it with steam via the Water-gas shift reaction, with the adsorption of the CO_2 on a selective solid adsorbent at elevated temperature. This produces a hot H_2-rich stream at pressure, suitable for power production. Regeneration of the solid adsorbent by means of pressure swing results in a CO_2-rich product, suitable for transport and storage. In the Stepwise project, this process is demonstrated at a scale of 14 t/day CO_2 removal. The STEPWISE project represents the essential demonstration step within the research, development and demonstration trajectory of the Sorption Enhanced Water-Gas Shift technology (SEWGS). This project will further reduce the risks associated with scaling up of the technology.	https://www.stepwise.eu/	Very little data is shown from the experimental campaings CO_2 purity and H_2S removal only	Sucess: Majority of project goals were achieved	-	-	-	-	6	-	-	-	32.4 €/tCO_2 (theoretical)	-	-	Theoretical CO_2 avoidance rate of 37.2% to 74%	-	-	-
H9	2017-2019	High temperature electrolysis (Solid Oxide Electrolysis Cells, 750-850 °C steam)	Electrolyzer protptype (150 kW)	Upscaling and proof of concept for high temperature electrolysis which can also work as fuel cell (reversibel). Main focus is on upscaling and showing efficiency and reliability of the technology (>7000h operation time).	Green Industrial Hydrogen via Reversible High-Temperature Electrolysis	GrInHy	As a proof-of-concept, the GrInHy project includes designing, manufacturing and operation of a reversible generator based on the Solid Oxide Cell technology in a relevant industrial environment. Central element of GrInHy is the manufacturing, integration and operation of the worldwide most powerful reversible HTE prototype at an integrated iron-and-steel works. As a Research and Innovation Action, the project also focused on the improvement of robustness and durability of the HTE technology on cell and stack level. The project's main objectives were as follows: -Up-scaling of an HTE system (150 kWAC,EC) that can also be operated reversibly as fuel cell using either natural gas or hydrogen as fuels -Operation for at least 7,000 h meeting the hydrogen quality standards of the steel industry -Proof of reaching an overall electrical efficiency of at least 80 %LHV (ca. 95 %HHV) based on available steam from waste heat -Reaching a lifetime at stack level of greater than 10,000 h with a degradation rate below 1 %/1,000 h -Elaboration of a viable Exploitation Roadmap while showing the feasibility of future cost targets	GrInHy2.0 | SALCOS® (salzgitter-ag.com)	HTE efficiency 78 % LHV, EC Including hydrogen processing unit: 72.1 % Including alternative steam usage in steam generator: 67.4 % Fuel cell 48% efficiency with hydrogen	Sucess: all project's objectives and milestones were reached with only minor deviations	No	GrInHy2.0	No comparison to other renewable technologies such as electric heating, renewables solid or liquid fuels etc	4	5	approx. 25 % higher electrical efficiencies compared to low-temperature electrolysers	NA	From GrInHy2.0: economic objective: <4500 euro/Kg h2/d)	-	NA	0	-	Electrolysis had higher Climate impact than methane reformation unless very high share of renewables in electricity mix (> 75% renewable)	NA	NA
H16	~2019-2020	New furnace concept where the combustive zone is separated from the curing zone by a IR transmissive material. Thereby decreasing the size and increasing the energy efficiency by being able to run the curing under under-stochiometric conditions and increased solvent concentrations, with fuel-flexibility and low CO_2 footprint.	Pilot scale proof of concept, modeling	-	Energy Efficient Coil Coating Process	ECCO	ECCO proposes a novel solution for the curing oven operation, which can not only drastically increase the compactness and energetic efficiency of the system, but leads to an increased production flexibility due to a fuel-flexible, modular and potentially energetically self-sustainable process. The main idea is to heat the metal strip by IR-radiation and operate the curing oven well above the Upper Explosive Limit (UEL), thus, performing the drying and curing process in an atmosphere mainly consisting of the solvent vapours, which are used as fuel in IR radiant porous burners. This solution leads to a size/production capacity ratio reduction of 70% and a reduction of investment and operating costs of at least 40% each. Starting from previous activities at TRL 4, an interdisciplinary approach is foreseen, based on advanced-materials, combustion technology and prediction tools for system design/optimization, with active participation of key industrial stakeholders, to bring this technology to TRL 6 and realize a prototype furnace at industrially relevant size and environment.	https://www.aspire2050.eu/ecco	All results found relates to objectives and possible outcomes. I.e. reducing fuel consumption by 40% compared to existing advanced technologies and 50% compared to new installations, providing the same reduction in CO_2 emissions. CAPEX red 40%, OPEX red 40%. No outcomes from tests found.	-	-	-	-	4	aimed at 6 at the end	aimed at 40%	same capacity lower costs	aimed at 40%	aimed at 40%	-	-	-	aimed at 40%	-	-
H17	2019-2022	High temperature carburization to produce WC at very high emperatures, 2500C and comparing the properties of WC formed at 1600C up to 2500C	Demo scale (pilot)	Business project demonstrating a pusher type sintering furnace, lined with graphite, to acheive a new max temperature of 2500C during carburization of W to WC. the target is to achieve WC with higher hardness and wear resistance	The first 2500°C industrial furnace, for higher efficiency and up to 5 times higher strength materials	CARBIDE2500	The demand for higher strength materials(required for their longer use-life and higher overall performance) has significantly increased. One of the most common Carbide powders is the Tungsten Carbide (WC). WC powder is used in many different applications and across multiple large industrial sectors (automotive, Aerospace Manufacturing, Construction, Surface and Underground Mining,...). The global Tungsten Carbide powder market is expected to grow from 13.60 billion € in 2016 to 22.91 billion € in 2026, at a CAGR of 5.4%. Tests have proven that Tungsten Carbide (WC) powder produced at 2500°C is 3 to 5 times higher strength than the same material produced at 2200°C. The problem is that, at industrial scale, there are no such furnaces able to operate at 2500°C. CARBIDE 2500 is the first industrial furnace capable of operating at 2500°C, making it possible to produce the highly demanded higher strength Carbides.	https://www.cremer-polyfour.de/ovens/carbide2500_de/	-	success based on short description	yes	N7A		6	8	NA	NA. Target is to increase max temperature with goal to increase wear and hardness	NA	NA	NA	NA	electrical heated before and after	-	-	-
H20	2018-2022	Microwave applicator	Lab scale Pilot microwave kiln (installed in 2 relevant industries)	The target is to develop and demonstrate a new concept of firing granular feedstock for materials transformation using full microwave heating. Microwave energy entering this chamber reflects against the metallic walls and interacts with the material leading to an increase in its temperature	Development of an Efficient Microwave System for Material Transformation in energy INtensive processes for an improved Yield	DESTINY	The DESTINY project aims to realize a functional, green and energy saving, scalable and replicable solution, employing microwave energy for continuous material processing in energy intensive industries. The target is to develop and demonstrate a new concept of firing granular feedstock for materials transformation using full microwave heating as alternative and complement to the existing conventional production. The DESTINY system is conceived as cellular kilns in mobile modular plant, with significant advantages in terms of resource and energy efficiency, flexibility, replicability and scalability with reduced environmental footprint.	https://cordis.europa.eu/project/id/820783	~45 °C/min increase possible for stainless steel powders, however: If bulk metals are subjected to microwaves, a high degree of reflection is observed, accompanied by the induction of surface eddy currents and a high risk of arcing discharges. The penetration depth of microwaves on conductive metal surfaces is typically less than one micron (c.f. a typical penetration depth of 1–2 cm for organic matter). In addition to the well-documented safety issues, direct microwave heating of non-ferromagnetic bulk metals is very inefficient and best avoided (1).	Partial sucess: Project was validated in lab scale but results of pilot scale trials were not complete by the end of the last report	-	-	-	4	5 (6)	-	-	-	-	-	-	-	-	-	-
H23	2021-2023	P2G. Recycling the CO_2 from BF/BOF route and synthesizing it to synthetic NG	lab scale, planning the concept, economic and LCA analysis and modeling	ron and steel industries are among the most carbon-intensive consumers, requiring innovative programmes for their decarbonisation. An innovative proposal combines power to gas (PtG) technology that uses electrical power and oxy-fuel combustion to produce synthetic natural gas for the iron and steel industries.	Decarbonisation of carbon-intensive industries (Iron and Steel Industries) through Power to gas and Oxy-fuel combustion	DISIPO	Iron and steel industries are among the most carbon-intensive consumers, requiring innovative programmes for their decarbonisation. An innovative proposal combines power to gas (PtG) technology that uses electrical power and oxy-fuel combustion to produce synthetic natural gas for the iron and steel industries. The EU-funded DISIPO project intends to reach TRL 2 in the novel PtG-oxy-fuel-iron/steel concept through research objectives to design, simulate and optimise a complete plan of the concept, to estimate the maximum reduction of CO_2 related to the operation of the industries and availability of the renewable energy sources, and to conduct an economic and life-cycle analysis comparing the concept with existing operational concepts. In addition, the concept permits CO_2 recycling in carbon-intensive industries.	https://cordis.europa.eu/project/id/887077	Oxyfuel combustion is of interest	-	-	-	-	1	2	-	-	-	-	-	-	-	-	-	-
H25	2021-2023	plasma-assisted combustion of liquid ammonia	-	liquid ammonia as a carbon-free hydrogen alternative energy resource to replace hydrocarbon fuels in gas turbines for power production	Developing Plasma-assisted ammonia technology for decarbonisation of power production	PlasNH3	Climate change is a growing global threat. Harnessing green energy sources could mitigate the damaging impacts of climate change. Take for instance, the plasma-assisted combustion of liquid ammonia. This could prove to be an efficient, carbon-free alternative to hydrogen energy as well as hydrocarbon fuels for gas turbine engines used in energy and power production. The EU-funded PlasNH3 project aims to optimise the existing burner for pure ammonia while maintaining high fuel efficiency and low combustion emissions. It will also assist in overcoming current challenges that are slowing its introduction. The project is built on an ongoing project by the Gas Turbine Research Centre (GTRC) of Cardiff University, which has already started investigating ammonia flames.	https://cordis.europa.eu/project/id/101020492	No results are available currently - likely not applicable for reheating of steel "recent studies have shown that efficient and stable combustion of ammonia can be achieved using swirl combustors, thereby rekindling research interest in ammonia as a fuel for thermal power production.[36] The flammable range of ammonia in dry air is 15.15–27.35% and in 100% relative humidity	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
J1	2021	Steel reheating furnace using natural gas, electricity or hydrogen with either air or oxygen	Modelling, (simplified energy balance calculation based on the methodology of ISO 13579-1 [ref 39] and Pfeifer [ref 40])	Energy system analysis Case 1: State-of-the-art NG heating (reference case). Case 2: Fully electrical heating. Case 3: Hydrogen-air heating. Case 4: Hydrogen-oxygen heating.	Toward CO_2-neutral process heat generation for continuous reheating furnaces in steel hot rolling mills- A case study	-	The aim of a massive reduction of CO_2-emissions results in a move away from fossil fuels. In the hot stripproduction of steel, almost exclusively gas-fired furnaces are currently used due to the lower energycosts. On the contrary, it is imperative to convert existing fossil heated processes to CO_2-free (green)technologies in the context of the energy-transition. Obvious alternatives are electrical heating orhydrogen combustion, both strongly dependent on the specific electricity generation mix that de-termines the CO_2-emissions. In this case study, different process heat generation options for continuousreheating furnaces in steel hot rolling mills are discussed by a quantitative approach. A state-of-the-artreheating furnacefired with natural gas is used as reference case, while electrical heating, hydrogen-airheating and hydrogen-oxygen heating are the alternatives investigated. The energy balances, the primaryenergy consumption and the resulting CO_2-emissions are compared for the three countries of France,Poland and Germany with regard to the country-specific electricity generation mix. Additionally, thepossible development until 2050 is analysed. The results show the high impact of continuous reheatingfurnaces in steel hot rolling mills on the total CO_2-emissions of downstream steel processing. Further-more, the massive increase in electrical energy consumption of the whole steel production process ishighlighted. Each investigated alternative shows a significant potential to save CO_2-emissions, dependingon the country specific electricity generation mix and the future expansion of	10.1016/j.energy.2021.120155	Depending on electricity mix, electrification can lead to a significant increase in GHG emissions H_2 production efficiency: Current : 64.01% PEM: ~70.88% in 2030 SOEC: up to 84.5%	Sucess: all 3 cases show potential for a reduction of CO_2 compared to the reference case	No	-	Technical differences between technologies are not really explored	For electric heating (HT) is 3-4 Case 3-4: 4-8	Same	Reference case indicates an energy usage of 317.5 kWh/ton as BAT for air combustion of NG	-	NA	NA	NA	NA	Equivalent to replaced fossil fuel Direct electrification shows the largest reduction potential due to higher overall efficiency	High share of renewable in electricity mix is reqired, otherwise natural gas has lower climate impact than hydrogen or electric heating	NA	Higher furnace efficiency in electric heating due to no flue gas Total efficiency: Case 1: 57.78% Case 2: 74.06% case 3: 59.32% Case 4: 68.06%
J18		Heating with hydrogen in Ovako pit furnaces. Material investigations	Industry full scale tests	Hydrogen heating in industrial applications	Tests by OVAKO Steel (https://www.ovako.com/en/newsevents/stories/first-in-the-world-to-heat-steel-using-hydrogen):	-	Together with Linde Gas AB, Ovako have completed the world's first successful full-scale trial in a production environment of using hydrogen to heat steel before rolling. The use of hydrogen in combustion would have a great positive effect on the environment since the only emission generated is water vapor. The trial, in which steel was heated using hydrogen instead of LPG (liquefied petroleum gas) before rolling at the mill in Hofors, was successful and testing of the steel produced showed that heating with hydrogen does not affect the quality. Given the right conditions, Ovako could therefore introduce hydrogen heating for furnaces at all our rolling mills and thereby drastically reduce our already world-leading low carbon footprint from cradle to gate.	https://www.ovako.com/en/newsevents/stories/first-in-the-world-to-heatsteel-	Excellent	success	yes	Installation of electrolyser with a power of 17MW to generate 3500Nm3/h of H_2	Looking at more steel grades, oxide properties, descaling	9	9	-	-	-	-	-	-	1	-	-	-

J19	2021	-	-	-	Plasma heating for the steel industry	-	Electrification of steel industry heating furnaces can play a crucial role in achiev-ing the Swedish zero emission target. Thus, the PLATIS project has tested and evaluated plasma technology as an alternative heat source in the steel industry's furnaces. The project has built a pilot plant, performed tests, evaluated the process, analyzed heated material, and conducted a technical-economic analysis. The pilot experiments showed that it is both practical and functionally possible to heat steel with plasma technology. The tests demonstrated good process charact-eristics, even though the pilot plant was not fully optimized for the purpose. The experiments showed that the right choice of plasma gas and optimization of operating conditions has the potential to provide the steel industry with the desired steel quality after heating. For carbon steel, CO_2 produced less decarbonation compared to an N_2-atmosphere. Conversely, N_2 produced less oxide growth. In general, oxidation and decarbonization differed very little between the test samples. Some general challenges are the NOx-formation, system efficiency and mainten-ance costs, but also design and upscaling in the next step. Plasma technology has the potential to be implemented in both new and existing furnaces. The technology is best suited to heating processes where high temperatures >1000°C or certain atmospheres are required, such as heating furnaces or as heat source in powder and iron sponge production. A recirculation of gases is beneficial to minimize NOx emissions and reduce the cost of gas. The use of N_2 and CO_2 as energy carriers results in lower gas flows than LPG/air combustion, which should be considered in both new	http://www.energimyndigheten.se/forskning-och-innovation/projektdatabas/sokresultat/?projectid=30636	Excellent	Successful trials reheating steel with plasma burner technology	-	-	Prefer a longer electrode life and more gas tight furnaces to recycle gases	Plasma burners are available but not used in commercial reheating furnaces	7	Low TRL process but there is a possibility to someday reach similar furnace efficiences as existing combustion fired furnaces	Batch furnace trials	816 MSEK/MW for 673 kW system	´+ 63 SEK/ton or a 39% increase	-	0	1	-	See PLATIS Appendix 1 (not found on website)	-
J30		-	-	-	Macroeconomic implications of switching to process-emission-free iron and steel production in Europé	-	Deploying a recursive-dynamic multi-region multi-sector computable general equilibrium approach, we investigate switches from coke-to hydrogen-based iron and steel technologies in a scenario framework where industry decisions (technological choice and timing) and climate policies are misaligned. Overall, we find that the costs of industry transition are moderate, but still ones that may represent a barrier for implementation because the generation deciding on low-carbon technologies and bearing (macro)economic costs might not be the generation benefitting from it. Our macroeconomic assessment further indicates that anticipated bottom-up estimates of required additional domestic renewable electricity tend to be overestimated. Relative price changes in the economy induce electricity substitution effects and trigger increased electricity imports. Sectoral carbon leakage is an imminent risk and calls for aligned course of action of private and public actors.	-	Economic analysis	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
J33	2010	-	-	-	A mathematical model of a slab reheating furnace with radiative heat transfer and non-participating gaseous media	-	A mathematical model of the reheating process of steel slabs in industrial fuel-fired furnaces is developed. The transient temperature field inside the slabs is computed by means of the Galerkin method. Radiative heat transfer inside the furnace constitutes boundary conditions that couple the dynamic subsystems of the slabs. Constraining the heat fluxes to piecewise linear, discontinuous signals furnishes a discrete-time state-space system. Conditions for an exponential decrease of the open-loop control error are derived. easurements from an instrumented slab in the real system demonstrate the accuracy of the model. The simple and computationally inexpensive model is suitable for trajectory planning, optimization, and controller design.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
J34	2021	Mild oxyfuel combustion with CH_4/H_2 mixtures Modelling (CFD, Kinetics)	Lab scale (well stirred reactor) 10 kW, 15.6 kW, electrically heated combustion chamber	Kinetic and flow modelling of mild oxyfuel combustion varying concentration of CH_4, H_2, CO_2., N_2 and O_2. Models were validated against lab scale experiments. Main variables are temperature distribution and ignition delay time	Effects of hydrogen addition to methane on the thermal and ignition delay characteristics of fuel-air, oxygen-enriched and oxy-fuel MILD combustion	-	The present study investigated the effect of adding hydrogen to methane on the thermal characteristics and ignition delay in methane-air, oxygen-enriched and oxy-fuel MILD combustion. For this purpose, numerical simulation of MILD furnace is performed by k-ε turbulence, modified EDC combustion, and DO radiation models. Additionally, a well stirred reactor (WSR) analysis alongside with CFD simulations is used for getting the better insight of combustion process and numerical results. The results show that H_2 addition to CH_4 provides a more uniform temperature field with higher peak and average temperatures under a similar oxidizer atmosphere. Also, more ignition delay time (IDT) obtained by the replacement of CO_2 with N_2, can be compensated by consideration of H_2 in the fuel composition. This study implies that the use of H_2 as an additive to methane is an effective strategy for conversion of methane-air to oxy-fuel combustion system with almost identical thermal and ignition characteristics	https://reader.elsevier.com/reader/sd/pii/S0360319921027063?token=E738AA4689750BC65EE93814E88AA465916D36944D7FCA26EADE920A1DE15C36B4BCE84BD3E5FB3E2DA099B996F0689A&originRegion=eu-west-1&originCreation=20220930094333	Adding hydrogen to methane improves the temperature distribution and operational flexibility in maintaining a mild oxyfuel combustion of methane	NA	No			3	4	NA	NA	NA	NA	NA	0	NA	NA	NA	NA
J37	2019	Reheating furnaces in general	Tested in full scale furnace (120 ton/h)	The objective of the study is to define a model that represents all the main variables and parameters which influence the energy consumption during the heating. A lot of attention was focused was on how to load the furnace to optimize the production of the furnace towards the hot rolling process. One of the main variables was to reduce holding time after the slab had reached desired temperature due to process limitation in downstream processes	37 Energy savings in reheating furnaces through process modelling	-	Nowadays, energy efficiency is a crucial factor for the competitiveness of manufacturing firms, due to the rising of world energy prices and as a consequence of the environmental consciousness concerned with the consumption of non-renewable energy resources. The furnaces for steel reheating are responsible for a large amount of energy consumption, where less than 50% of the energy supplied to the furnace (mainly gaseous fuel) is net energy of steel heating, the remaining is lost. A consistent set of studies, which investigates energy reduction initiatives for the reheating furnaces, can be found in literature. However, almost all the studies are focused on technology alternatives (such as regenerative burners), whereas some others focus their attention on measurement and control action, mainly obtained by IT investments. This study aims at providing a mathematical model for a reheating furnace, by considering the efficiency-temperature relationships of the furnace. The model permits the user to identify the most proper optimization of the temperature-time relations, in the different productive situations, capable of guaranteeing the most energy-efficient reheating operations by preserving logistics performances. In order to make a cost-benefit analysis, different options for the furnace setting and related process operations have been considered with reference to a specific industrial case. The model highlights how improving the operating policies for controlling the key process parameters may lead to energy savings and, consequently, economic benefits, as well as pursuing environmental preservation thanks to the rational use of non-renewable	https://reader.elsevier.com/reader/sd/pii/S2351978920306351?token=D042FFAEA1B3AF40B32252A47BC664B4DE269B3C53F85890A99408751A8A68022A9B6F2821404648C3E9B82AB54B7949&originRegion=eu-west-1&originCreation=20221006085528	Not focused on the performance of the furnace itself, but the optimal loading sequence based on downstream requirements	Sucess: Implementation of the decission support system lead to significant improvements	Yes - italian steelmill (confidentiality)	-	Long term follow up	44960	7	14.07% compared to previous scheduling policy	Average residence time of the slabs was reduced by 14.28%	NA	NA	Should be lower due to lower residence time	-	Equivallent to fuel savings	-	No	No
J41	2018	-	Modeling	Modeling using regenerative burners in a WBF heating billets, using ANSYS fluent. Models describe the HT and billet heating, and results are validated by experimental data of the heating profile of the billets.	A numerical analysis of the effect of heat recovery burners on the heattransfer and billet heating characteristics in a walking-beam typereheating furnace	-	The present study presents a numerical simulation of the effects of using self-recuperative burners on theperformance of a walking-beam reheating furnace. The study was done using CFD (Computational FluidDynamics) simulations where a low computational cost method was implemented to simulate the billetheating as a steady state system. The preheating temperature of the air was defined as a function of theair mass flow and the flue gas temperature in each burner, using a UDF (User-Defined Function). Theresults of the billet heating profile were validated with experimental measurements in a furnace not uti-lizing heat recovery and showed good agreement with a maximum deviation of 54 K. Efficiency wasfound to increase from 32.7% to 48.5% with the use of self-recuperative burners. This result was reflectedin a fuel consumption decrease of 31.3%, or an increase in furnace production of 51.3%. The heat transferin the furnace and the billet heating characteristic were analyzed, which were observed to have changedwith the different burners. This effect was lesser when the thermal input was decreased, and greaterwhen the production was increased or when both remain constant. With and without heat recovery, radi-ation represents about 90% of the total heat flux on the billets. Due to the importance of radiation, solidand gas radiation were also analyzed. An improvement upon a methodology found in the literature wasproposed. Using this new methodology it was found that, for the furnace evaluated, around 25% of theradiation absorbed by the billets comes from the flue gases. The effect of defined a constant billet emis-sivity on the results of the simulation was also discussed	https://reader.elsevier.com/reader/sd/pii/S1876610217327182?token=A0EC716F777422A321BC5462D5C56FBA1FF706B477E27691F5B7049C17955BADB95070831C9CA3F54DBA59896F1EBC12&originRegion=eu-west-1&originCreation=20221006092012	-	success	-	-	-	-	-	fuel consumption could be lowered by 31% using regenerative burners, shown in modeling and verified by exp results	or productivity could be increased by 51%	-	-	-	-	31% reduction with same throughout	-	90% is accounted to by radiation, while this number decreased to 88% if production was increased. 25% of heat flux is from flue gases	heat recovery by using regenerative burners yes.
J42	2019	Walking beam furnace air combustion +recuperator(light fuel oil) Oxyfuel combustion+recuperator (propane) Modelling of flow and tempearture (zone model and CFD)	pilot scale 3 MW	Modelling (zone, CFD) and validation of differences between air combustion and oxyfuel combustion in a pilot scale walking beam furnace (slabs)	Modelling and simulation of steel reheating processes under oxy-fuel combustion conditions e Technical and environmental perspectives	-	This paper investigates the impact of flameless oxy-fuel combustion on the thermal performance of a pilot-scale steel reheating furnace. A comprehensive mathematical model, based on the zone method of radiation analysis, was developed, which takes into account the non-grey behaviour of the furnace atmosphere under oxy-fuel combustion conditions. The model was subsequently used to simulate the temperature profile of an instrumented slab used in the experiment. The results showed that the predicted slab temperature profile along the furnace is in good agreement with measurement. However the model over predicted the absolute slab temperatures due to the influence of formation of oxide scales on the slab surface, which was not taken into account in the current model. When compared to air-fuel combustion simulation, the results of oxy-fuel combustion also indicated a marked improvement in the furnace specific fuel consumption (approximately 16%). This was mainly due to the enhanced radiative properties of the furnace atmosphere and reduced exhaust energy losses as the result of less dilution effect from nitrogen. This resulted in reduction in the overall heating time by approximately 14 min. Furthermore, if the economics of carbon capture is taken into consideration, theoretically, the energy consumption per kilogram of CO_2 captured can be reduced from 3.5 to 4.2 MJ kg^{-1} to 0.96 MJ kg^{-1}.In conclusion, the current studies support the view that oxy-fuel combustion retrofitting to reheating furnaces is a promising option, both from a technical and from an environmental point of view.	https://reader.elsevier.com/reader/sd/pii/S0360544219313817?token=39006104AC6DA7E508F4D3055AFBC492B585E176D85D91C6F508DA300AC102D8569F54C9E14D3712029BD0CC8D830669&originRegion=eu-west-1&originCreation=20221006095241	-	Sucess: Significant improvement in using oxyfuel to air combustion and validation of modells	Yes - oxyfuel is installed in numerous furnaces	-	-	Oxyfuel: 9 Modelling: 2-3	Oxyfuel: 9 Modelling: 6-7	16% compared to air combustion, 1.13 to 0.94 GJ/kg 313 to 261 (very low) (+16 kWh for oxygen)	6 % increase	NA	NA	NA	100+	12.32 kg/ton or 16.9% 73.04 → 60.72	-	Yes - Based on the measurementsthis was due to higher gas temperatures in zone 2 with similar peak combustion temperatures	Yes, Due to lower ballast in flue gas (N_2) and lower flue gas exit velocity (due to lower flue gas volume, less convective heat transfer is required)
J44	2018	Modelling	Theoretical	Evaluating how wall emissivity affects heat transfer to the steel based on the emissivitivity and adsorbtivity of the flue gas.	Influence analysis of the furnace wall emissivity on heating process	-	High emissivity coating technology based on the improvement of the wall emissivity is an important heat transfer enhancement technology. However, the experimental results show that the influence of the wall emissivity on the heating process is uncertain. Therefore, the ternary model, which considers the non-gray radiation characteristic of the flue gas, is presented in this paper. Under such model, the analytical expression of the heat flow of the steel slab surface is derived. With the aid of such analytical expression, the influence of the wall emissivity on the heating process is analyzed. The results show that when α_{gw} is smaller than ε_g, the Q_s increases with the increase of ε_w. In this case, the high emissivity coatings will play a positive role in the furnace heating process. In contrast, when α_{gw} is larger than ε_g, the Q_s decreases when ε_w increases. At this point, the high emissivity coatings will hinder the furnace heat transfer. When the flue gas is simplified as a gray body, the change of furnace wall emissivity will cause no impact on the heat flow of steel slab surface. This also explains the reason why the Тимофеев formula makes no mention of furnace wall emissivity.	https://www.sciencedirect.com/science/article/abs/pii/S135044951830495X	With the assumtion that the wall is a grey body and gas is a non-grey The effect of wall emissivity on heat transfer to steel depends on the relative gas/wall adsorbance and the gas emissivity. If the gas is considered a grey body wall emissivity has no impact (grey body = adsorption is independent of temperature and wavelenght)	-	-	-	To make use of results, emissivity and adsorbtivity of the furnace wall, and furnace gas as a function of wavelengt and temperature must be known	-	-	-	If heat transfer is increased the productivity is also increased.	-	-	-	-	-	-	In theory yes - but must be evaluated experimentally as practical cases are hard to evaluate	-

J45	2022	Flameless air combustion	Lab scale combustion (232 kW)	Flameless air combustion of hydrogen or city gas (90% CH4, rest longer chain hydrocarbons) Burner configuration such as fuel gas velocity, combustion air velocity, and air nozzle pitch	Influence of nozzle design parameters on exhaust gas characteristics in practical-scale flameless hydrogen combustion	-	Considering the trend toward decarbonization, hydrogen is expected to be used as a fuel in industrial furnace burners. One of the challenges in using hydrogen as a fuel is the increase in thermal-NOx emission compared to hydrocarbon fuel owing to its high flame temperature. This study experimentally evaluated the combustion characteristics of flameless combustion, which is a low-NOx combustion technology, with hydrogen as a fuel in a practical-scale experimental furnace as well as the effect of nozzle design parameters on the combustion characteristics. Through comparative tests with city gas by considering parameters, such as the fuel gas velocity, combustion air velocity, and air nozzle pitch, the low-NOx effect of flameless combustion was confirmed in hydrogen combustion with appropriate nozzle design parameters. The optimal nozzle design parameters to achieve this effect differ from those for city gas, and the design guidelines are summarized.	https://reader.elsevier.com/reader/sd/pii/S0360319922018444?token=83E7B66899CE562D15613F8AA13FBCF0BD7E058141BD7DB8AED0FFDE3C8EC76111065F39C19376BE148AE1FDB99B438B&originRegion=eu-west-1&originCreation=20221007070135	Hydrogen combustion excess air lambda 1.2 → 4% excess oxygen Nox reduction of 80% was achieved with flameless hydrogen combustion compared to conventional Ingoing air and fuel velocity was very important, as well as temperature of air and the location of injection of air and fuel	Success. Significant NOx reduction was achieved without retrofitting the burner	-	-	-	3 to 4	5	NA	NA	NA	NA	NA	-	NA	NA	NA	NA
J48	2014	-	-	-	Numerical simulation of slab heating process in a regenerative walking beam reheating furnace	-	A simplified method is described to study the slab heating process in a regenerative walking beam reheating furnace. The boundary conditions of the furnace are matched with the burner properties in dif- ferent zones to simulate the slab heating process and consider both the regenerative reversing combustion process and the slab movement. The simulated results agree well with the experimental results. The predicted results show that the slab temperature increases rapidly in the furnace preheating and heating zones. The slab surface temperature rises faster than the central point of the slab. The section temperature difference of the slab increases until the maximum value is reached in the heating zone. The slab temperature along its length is distributed unevenly, which is slightly higher near the burner and lower near the center of the furnace. The slab charging temperature has a great influence on its heating process. An increase in charging temperature reduces the section temperature difference, and the slab whole heating time is significantly shortened for satisfying the emission conditions	https://reader.elsevier.com/reader/sd/pii/S0017931014003743?token=EB256AF5844D879D3ACCBAAFA798EA3533908F8D0550D6C417D82F02EA89D1B220E5EA0868A9F4AD98884DFDB884BA24&originRegion=eu-west-1&originCreation=20221007075119	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
J49	2013	-	-	-	Comparisons of different heat transfer models of a walking beam type reheat furnace	-	Four different heat transfer models (Model-1 to -4) for the prediction of temperature of the slabs of a walking beam type reheat furnace have been compared. The models are classified based on the solution methodology and simplifications. In the first three models (Model-1 to -3), the furnace is modelled as radiating medium with spatially varying known temperature. model-1 solves the 3D transient conduction in the slab and radiation in the furnace separately and is coupled via the boundary condition. In the second model, both radiation in the furnace and conduction in the slab are solved simultaneously. A user defined function (UDF) programme has been developed to process the movement of the slabs.Model-3 is similar to Model-2 but it includes additionally the skid support systems for the slabs. In the Model-4, convection in the furnace has been included in addition to all the features considered in Model-3. The convection has been modelled with the consideration of flow of hot gas through the inlet of the burners. All the models have been compared for their performance and computational time. Model-1 has been found to be quite economical and accurate. The inclusion of skid supporting system has little effect in the temperature distribution in the slab.	https://reader.elsevier.com/reader/sd/pii/S0735193313001292?token=780CD37945AE9858C934D470F513E1BDE5AEA51B810B633C4B6799724AA2C94EB06B7AB111A6BE7B57A94F76636F8C79&originRegion=eu-west-1&originCreation=20221007075818	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
J61	2020	Flameless oxyfuel combustion (full or partial, REBOX)	Full scale (upp to 300 t/h)	Review of sucessfull flameless oxyfyel combustion (full or partial) installations by Linde (REBOX). Includes comparison between air, partial oxyfuel and oxyfuel combustion in terms of scale losses, productivity, emissions and and energy savings	Successful use of flameless oxyfuel in steel reheating	-	Using oxyfuel combustion in steel reheating provides higher throughput and substantial fuel savings.Accordingly, oxyfuel has many benefits, but also some drawbacks like hot spots in furnaces and thermal NOx generation. However, by making the combustion "Flameless" by creating a 'volume combustion', these issues can be overcome, and additional advantages can be achieved. This paper describes different solutions, both fully flameless and semi flameless, which have been developed and implemented in steel reheating and annealing furnaces.Over the past three decades, Linde has made more than 160 oxyfuel installations in all types of reheating furnaces, both batch and continuous, and for production of all different steel grades. Since 2003, focus has been on using Flameless Oxyfuel, hitherto resulting in 112 successful installations, 90 of these operating fully with 100% Flameless Oxyfuel. This paper describes results from these installations, which includefuel savings of up to 60%,increased throughput by up to 50%,substantial reductions of CO2and NOx emissions,much improved temperature uniformity of the heated steel,reduction of scale losses by up to 50%. Cases with conversion from air-fuel to Flameless Oxyfuel will are described. These examples comprise installations in soaking pit furnaces, rotary hearth furnaces, roller hearth furnaces, and walking beam furnaces with up to 300 t/h nominal capacity, and for production of carbon steel, engineering steel, and stainless steel grades at companies in USA, Europe, and Asia	https://doi.org/10.37904/metal.2020.3460	Note that all comparisons is made with respect to air combustion of solid, liquid or gaseous fuels Due to high CO2 concentration in off gas, it is well suited for CO2 separation Preliminary results indicate it works well with hydrogen	Sucess: Improvements across the board with numerous sucessfull installations	Yes, see number of installations	-	-	9	9	Energy savings of >25% compared to air combustion	20-60% compared to air combustion	NA	NA	scale losses reduction as high as 50%	Flameless oxyfuel: 90 Partial: 22	Equivalent to fuel savings	Even higher due to material savings and iand increased productivity	Yes - large increase in radiative heat transfer due to higher adiabatic flame temperature and removal of gas ballast (N2)	Yes - Substantial reduction in exchaust gas volyme, resulting in much lower off gas losses
J65	2021	Oxyfuel combustion Modelling (CFD) Technoeconomic analysis	Theoretical	technoeconomic modelling of oxyfyel combustion (natural gas) including LCA and GHG emissions	Oxygen enrichment combustion to reduce fossil energy consumption and emissions in hot rolling steel production	-	The reheating furnace operation in the hot mill is natural gas- and electricity-intensive. Oxygen enrichment combustion for reheating furnaces has been proposed to curb and replace natural gas use. In this study, heat transfer in steel slabs in the combustion environment of a push-type reheating furnace was simulated using a computational fluid dynamics (CFD) model. Two oxygen enrichment methods that optimized for performance were selected— a medium oxygen enrichment (MOE) case and an oxy-fuel (OF) case. A life cycle analysis (LCA) characterized the energy and emission profiles of an integrated iron and steel manufacturing process using the two oxygen enrichment cases for the hot mill. These conditions were evaluated for energy use and carbon in-tensity and compared with a baseline case. Results show that with oxygen enrichment, natural gas consumption can decrease by 19.6%–26.8%, total energy consumption (natural gas and electricity) can decrease by 15.1%– 20.7% in the hot mill. Emissions of greenhouse gases can decrease by 11.1%–15.2% in the two optimized cases with 14%–27% reductions in regulated criteria pollutants (nitrogen oxides, carbon monoxide, particulate matter, volatile organic compounds, black carbon, organic carbon, and volatile organic carbons). There is a tradeoff between reducing natural gas consumption and increasing electricity demand from a life cycle perspective. Although the OF case resulted in higher energy- and emissions-related benefits, the MOE case showed the more desirable heat flux uniformity, which is key to maintaining product quality. The analysis suggests that oxygen enrichment in the reheating	https://doi.org/10.1016/j.jclepro.2021.128714	Does not consider flameless combustion! Unit is cradle to grate for hot rolled steel 21.7 MJ/kg (4.7 % is hot rolling) 1.9-6.9 kg CO2 equivalent/kg	NA	Yes	-	-	9	9	26.8 % decrease compared to air combustion	-	-	-	-	-	~15% compared to air combustion	-	-	-
J67	2022	Alternate renewable fuels	Theoretical for reheating furnace, but higher TLR in other applications such as transportation	H2 is added to NH3 to increase the combustability of NH3. NH3 is easier to produce and stora than H2 and can be produced without any GHG emissions and has a well established market already (235 million tones annually)	Characteristics of NH3/H2 blend as carbon-free fuels: A review	-	In the pursue of a carbon-free economy, the utilization of fuels with low or zero carbon footprint account for only 1% of global final energy demand, a share that is predicted to follow a dramatic growth to 20% by 2050. Ammonia (NH3) has become dominant in the international transportation and storage of low-carbon alternative fuels. NH3 is regarded as an alternative fuel, as a carbon-free fuel, and renewable hydrogen (H2) carrier with high energy density, and its production and distribution infrastructure are well established. However, a current challenge is that NH3 has a lower burning velocity and a narrow flammability limit. Thus, the use of NH3 has numerous limitations in practical combustion applications. Blending NH3 with H2 is considered a solution that has been proposed to enhance NH3 combustion by improving ignition, flammability, and H2 safety issue. Using NH3 blended with H2 as a fuel in combustion systems is a practical approach to decarbonizing the energy sector. Thus, this review highlights the existing influential studies and ongoing research on NH3/H2 blended fuels. The review covers NH3 assists the safety behaviour of H2 use, in-situ NH3 dissociation, NH3 and H2 properties, NH3/H2 combustion characterization, techniques for low NOx NH3/H2 combustion, and challenges for NH3/H2 combustion. Finally, recommendations for future studies are provided for further developing the utilization of NH3/H2 as blended fuel.	10.1016/j.jclepro.2021.128714	Could be interesting as a fuel or co-combustion fuel with H2, this study focuses in ammonia as a transportation fuel Currently investigated in reheating by linde, Oxyfyuel combustion seems to resolve a lot of the issues with reactivity of NH3	-	-	-	-	2	2	-	-	-	-	-	-	-	-	-	-
J64	2021	Alternate renewable fuels Heat recovery Kalina cycle (water/ammonia) CO2 separation H2 from electrolysis Methanol via CO2 hydrogenation (70bar)	Theoretical	Combined CO2 capture and waste heat recovery (electricity and heat) from steel industry to produce methanol. includes economic performance	Thermodynamic and economic analysis of a synthetic fuel production plant via CO2 hydrogenation using waste heat from an iron-steel facility	-	This study aims to investigate thermodynamic and economic feasibility of utilizing medium temperature waste heat from an iron-steel facility to produce synthetic fuel via captured CO2 hydrogeneration. First, waste heat from reheating and blast furnace of an iron-steel facility is used as heat resource for a regenerative Kalina cycle (KC) to generate electrical power and to heat the reboiler of an amine-based Carbon capture plant (CCP). Later, generated electricity from the KC is used for the PEM electrolyser and other power consuming devices through the plant. Generated hydrogen and captured CO2 are utilized in the methanol production plant (MPP). KC showed highest efficiency at a maximum temperature of 488 K with an ammonia fraction of 65% while the optimal current density of the PEM electrolyser is 2.2 kA/m2. Under optimal conditions, plant fuel production efficiency reached up to 19% with a methanol cost of $532 ton-1 for a daily methanol capacity of 3.69 tons. Present plant is competitive to those of other clean synthetic fuel production facilities. Such configurations can be scaled up for large amounts of carbon capture and utilization.	https://doi.org/10.1016/j.enconman.2021.114074	Overall plant efficiency is calculated as 19.47% by considering the lover heating value of methanol vs total input of energy	NA	NA	-	real world application	2	2	NA	NA	NA	NA	-	0	Methanol produced could substitute some fossil fuel	-	no	Yes - system could be used in place of recuperator or waste heat boiler to recover waste heat from flue gas (Tin ~600 °C, Tout 140 °C)
J57	2018	Energy apportionment model	Theoretical	Modelling based on real world data	Bottleneck of slab thermal efficiency in reheating furnace based on energy apportionment model	-	To reveal distribution of slab thermal efficiency (STE) and its bottlenecks, a slab region thermal efficiency(SRTE) model and an STE model were established based on the energy apportionment model of areheating furnace in this paper. The bottleneck index of the slab thermal efficiency (BISTE), which couldbe used to assess the influence of SRTE on STE in a particular region, was proposed. First, the regionalenergy balance equation was listed based on reheating furnace region division. Next, the SRTE and STEmodels were established. Second, the bottleneck of slab thermal efficiency (BSTE) was achieved througha partial correlation analysis (PCA) of billet samples, which were obtained according to the differencebetween billet loading temperature and its residence time in the reheating furnace. Next, the BISTE wasadvanced to accurately determine the BSTE. Finally, several suggestions or measures, that could improveSRTE, were proposed. The case study has demonstrated the validation of these models, and the BISTE was42% (Preheating), 19% (Heating II), 18% (Soaking), 11% (Heating I) and 10% (Preheating&Heating),respectively. Therefore, the preheating zone is the key region used to improve STE.	Bottleneck of slab thermal efficiency in reheating furnace based on energy apportionment model	Modelling indicated major savings could be made by decreasing exit flue gas temperature Not sure it is relevant for more modern reheating furnaces due to the increased heat recovery using recuperators or oxyfuel combustion (or electric)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
J53	2017	Organic rankine cycle with HT phase changing materials modelling	Pilot scale (3 Mw)	Modelling and evaluation of a ORC heat recovery system	Improving energy recovery efficiency by retrofitting a PCM-based technology to an ORC system operating under thermal power fluctuations	-	-	https://doi.org/10.1016/j.apenergy.2017.09.054	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

J68	2017	Reheating of steel slabs using electricity (resistive) or natural gas+Air	Theoretical comparison between different industrial scale applications using industrial data and norms	Comparison between steel, high strenght steel, high strenght aluminum alloys and carbon fiber reinforced plastics in their production and heat treatment. Comparison between conventional natural gas combustion with air and state of the art resistive heaters in terms of efficiency and capacity Good information regarding BAT on CO2 emissions and data related to it from Germany	Industrial Furnaces - Status and Research Challenges	-	The modern Industrial Furnace Technology is characterized by the design of new furnaces for high strength metals and carbon fibers for the light weight construction concepts in automotive industry. The furnaces for the annealing of modern high strength metals (steel, Al), are characterized by innovative cooling sections, with high cooling rates and a concomitant homogeneity, which are controllable for different steel or aluminum grades, variable widths and thicknesses for high productivity strips plants for products used in automotive industry. Resulting from this intensive research and development concerning the improvement of the local heat transfer knowledge for extremely high heat fluxes with gas, mist and/or water cooling is necessary. This research is driven by a competitive situation between steel and aluminum and since a few years also carbon fiber reinforced plastic (CFRP). On the other hand steels with a cheap alloying concept are used successfully in combination with the press hardening technology. The furnaces for the different applications in light weight design are very different between the materials (steel, Al, CFRP) due to different temperature ranges, principles of heat transfer and thermal operations.The environmental aspect of industrial furnaces requires the reduction of the specific CO2-Emissions which can be realized with advanced technologies improving the energy efficiency of fuel heated furnaces (high temperature air preheating with recuperative and regenerative burner concepts). For the overall CO2-emission reduction of 90 % up to 2050 related to 1990 actually no proved concepts are available	10.1016/j.egypro.2017.07.153	-	NA	No	-	Theoretical	NA	NA	Lower than natural gas electricity is ~85% efficiency compared to 58-65 % for natural gas Does not account for efficiency of producing electricity	with BAT of electrical heating the capacity in surface load is still 2-4 times lower than natural gas+air in the 1100-1300 °C range	NA	NA	Lower productivity increases scale growth but also depends on the O2 content of the protective gas (air vs inert gas)	-	-	No proven concepts available which can show a 90% reduction in CO2	No, heat transfer is significantly lower for electrical heating above 1000 °C compared to conventional burner setups	Yes, total heat recovery is improved in electrical heating due to lack of flue gas
J69	2022	Numerous	Full scale	-	Best available techniques (BAT) reference document for the ferrous metals processing industry	-	The Best Available Techniques (BAT) Reference Document (BREF) for the Ferrous Metals Processing Industry is part of a series of documents presenting the results of an exchange of information between EU Member States, the industries concerned, non-governmental organisations promoting environmental protection, and the Commission, to draw up, review and – where necessary – update BAT reference documents as required by Article 13(1) of Directive 2010/75/EU on Industrial Emissions (the Directive). This document is published by the European Commission pursuant to Article 13(6) of the Directive. The BREF on Ferrous Metals Processing Industry covers the operation of hot rolling mills with a capacity exceeding 20 tonnes of crude steel per hour, the application of protective fused metal coats with an input exceeding 2 tonnes of crude steel per hour (this includes hot dip coating and batch galvanising), the surface treatment of ferrous metals using electrolytic or chemical processes where the volume of the treatment vats exceeds 30 m3 (when it is carried out in cold rolling, wire drawing or batch galvanising), as specified in Points 2.3 (a), 2.3 (c) and 2.6 of Annex I to Directive 2010/75/EU, respectively. This BREF also concerns independently operated treatment of waste water that are not covered by Directive 91/271/EEC as specified in point 6.11 of Annex I to Directive 2010/75/EU, provided that the main pollutant load originates from the activities covered in this BREF	https://op.europa.eu/en/publication-detail/-/publication/0923f1e0-751f-11ed-9887-01aa75ed71a1	-	-	-	-	-	-	-	Optimized furnace door design:5% reduction Regenerative burner:~40-50 % reduction Recuperative burner:~25-30 % reduction 100% oxyfuel:40-65% reduction oxygen enrichment:29 % reduction Oxygen lancing:5-16% reduction Flameless combustion:25 65% reduction Pulse fired burner:up to 10% reduction Flue gas recirculation:1-10% increase Optimized skid design:1% reduction Heat recovery from skids:7% reduction Heat conservation during transfer of feedstock:0.33 GJ/ton ~10% reduction Hot/direct charging:39% reduction	Regenerative burner:10-15 % increase 100% oxyfuel:Increased Flameless combustion:40 50% increase Flue gas recirculation:Lower Heat conservation during transfer of feedstock: increase Hot/direct charging:25% increase	-	-	-	-	-	-	-	-