La Metallurgia Italiana
International Journal of the Italian Association for Metallurgy
DOI: 10.36146/2025_05_30

Coke breeze combustion and COG dry reforming pilot plant development for the production of hot hydrogen-rich syngas in integrated plants for injection in the blast furnace and CO_2 mitigation (ProSynteg)

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The iron and steel sector contributes 2.6 gigatonnes of carbon dioxide (Gt CO_2) annually, accounting for 7% of the global energy system's total emissions. Currently the steel sector is the largest industrial consumer of coal, from which it takes around 75% of its energy input. Blast Furnace-Basic Oxygen Furnace (BF-BOF) is the main route for the world steel production, with an overall of 70% of the total amount of steel produced. This route has a strong impact on carbon dioxide (CO_2) production generating about 2.15 tonnes of CO_2 for 1 tonne of crude steel. In this frame the main objective of the ProSynteg project is to reduce the coke rate and associated CO_2 emissions from Blast Furnace (BF) by means of the set-up of process to produce hot H_2-rich syngas, which can be directly injected into the BF. The H2-rich syngas is produced by dry-reforming of coke oven gas and/or natural gas with hot CO_2 from oxy-combustion of coke breeze or alternative solid circular C sources. The alternative utilization of the coke breeze is a fundamental aspect because it could progressively lose its current valorisation in the steel production cycle due to the progressive closure of the sintering plants. The pilot tests will be integrated with experimental laboratory tests for the characterization of the coke breeze and simulations to setup process conditions.

KEYWORDS: SYNGAS, CO_2, COG, COKE BREEZE

INTRODUCTION

The injection of reducing gases in the Blast Furnace (BF) to reduce coke consumption has been studied and tested on pilot and even industrial scale over the last 50 years in Russia [1], USA, Japan [2,3,4] and now China. Important experiments were notably performed in Tula (industrial scale, Russia, 1970's), in Seraing (pilot and industrial tests, Belgium, 1970-1980's, operated by partner CRM), in the frame of the EU-wide ULCOS project [5,6,7].

Along with these projects and tests, reducing gas injections have been performed at different levels in the BF: in the existing tuyeres or through new injection ports at shaft level or even higher on the BF shell.

The injection of reducing gas in the BF shaft is one of the most promising methods of reducing CO_2 emissions from steel works. Shaft injections do not limit the furnace operation in terms of raceway adiabatic flame temperature (RAFT) and improve the top gas temperature due to

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increase in shaft gas volume. In case of reformed Coke Oven Gas (COG) injection at BF shaft, the temperature of the COG should be equivalent to the temperature of the lower shaft (900 - 1000 °C), to not cool or overheat the shaft zone.

The main objective of the ProSynteg project is to set up a pilot plant to test the dry reforming of hydrocarbons present in the coke oven gas (or natural gas), into hydrogen and carbon monoxide exploiting the heat and CO_2 coming from coke breeze oxy-combustion. The resulting reformed gas (syngas) can be injected into the BF as a reducing agent, thus reducing the quantity of coke and consequently the emissions of carbon dioxide. Currently, coke breeze is used as a fuel in the sinter plant. However, with the anticipated progressive shutdown of lot of sinter plants, the use of coke breeze could become difficulty on the external market, since it is classified as a waste material. This project proposes an innovative route to internally reuse coke breeze within the steel shop, reducing the overall coke production for the BF and contributing to lower CO_2 emissions.

OVERVIEW OF THE PILOT PLANT CONCEPT

The ProSynteg project addresses the challenge of reducing CO_2 emissions in the steelmaking sector through an innovative approach that integrates coke breeze valorization and gas reforming processes. The core concept consists of utilizing the thermal energy and carbon dioxide generated by coke breeze oxy-combustion to perform the dry reforming of hydrocarbons from COG into a synthesis gas (syngas) rich in hydrogen (H_2) and carbon monoxide (CO).

This syngas is valuable for injection into the shaft of a BF as a reducing agent, thus decreasing the utilization of metallurgical coke and subsequently lowering CO_2 emissions. A key element of the project is the design and operation of a pilot plant capable of demonstrating the feasibility of this concept under industrially relevant conditions. The pilot plant is composed of two main subsystems:

1. A combustion zone, that enables controlled oxy-combustion of coke breeze, generating high-temperature flue gases containing CO_2.
2. A dry reforming reactor zone, where hydrocarbons and CO_2 react at high temperatures to produce syngas.

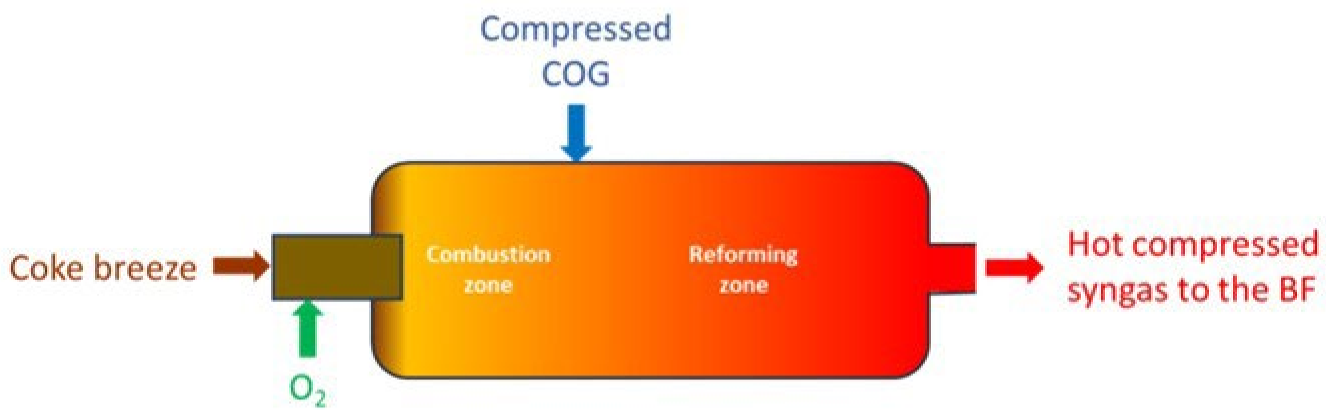

Fig.1 - ProSynteg project concept scheme.

The first zone is mainly characterized by a solid fuel burner, which is designed to perform coke breeze combustion. After that, the produced CO_2-rich flue gases are properly combined with the compressed COG, to start the dry reforming process. Generally, dry reforming is an advanced gas treatment process at high temperature (around 1000 °C) that converts methane and high hydrocarbons into a mixture of CO and H_2 which is suitable for BF shaft injections. The dry reforming process offers a secondary benefit: the thermal decomposition and removal of heavy hydrocarbons, such as tar, benzol, and other condensable compounds commonly found in COG. This thermal decomposition enhances the quality and usability of the gas downstream by increasing the amount of H_2 and CO produced.

This integrated system permits not only to valorize coke breeze material but also supports a circular and sustainable approach to steel production. The following sections describe the pilot plant design, the reformer modelling activities, the detailed engineering and the adaptation of the pilot plant and its components.

PREPARATION OF THE SITE FOR THE EXPERIMENTAL TRIALS

The coke breeze burner with nominal power of 1 MW will be tested at RINA-CSM combustion station in Dalmine (Italy). The following preliminary activities to perform the oxy-combustion tests have been carried out:

1) Design of the combustion chamber and coke breeze injection system

2) Installation of the cryogenic oxygen tank and oxygen ramp

<u>Design of the combustion chamber and coke breeze injection system</u>

The combustion chamber is constituted by a combustion section with a length of 2850 mm and internal section of 850mm and a cooling section with a length of 2525 mm and internal section of 1150 mm.

The combustion section comprises a horizontal cylindrical outer casing with a conical outlet of carbon steel sheet (S275JR) and internally lined with multiple layers of refractory and insulating bricks designed for high-temperature applications

The cooling section consists of a heat exchanger with a double concentric cylindrical chamber. The com-bustion gases pass through the inner chamber, while the water for the gas cooling flows through the outer chamber.

Fig. 2 shows the drawing of the combustion chamber (left) and expected temperature profile along the combustion chamber (right).

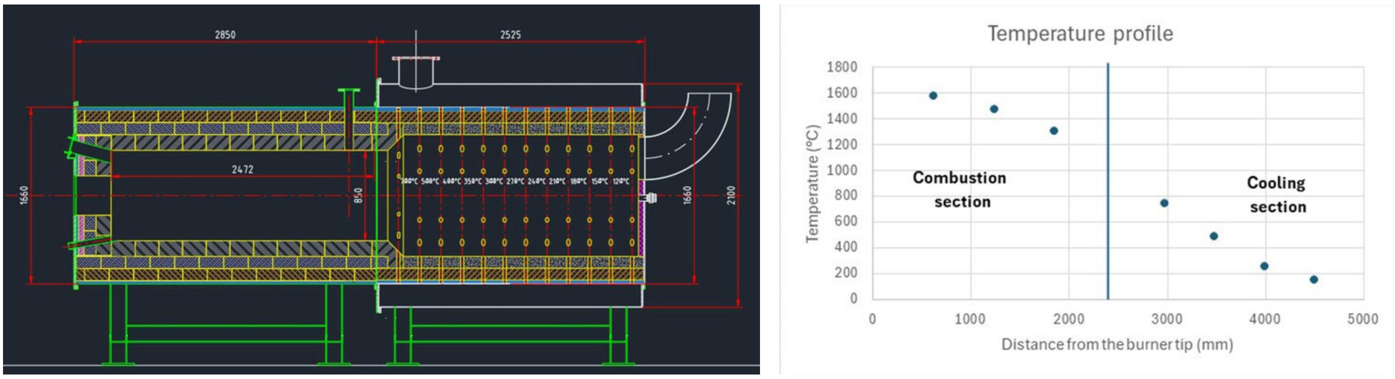

Fig.2 -Combustion chamber characteristics.

The combustion section can work up to a temperature of 1600 °C. The cooling section is equipped with 6 lances, inserted in the body of the reactor, to guarantee a gas temperature at the exit of the cooling section of 150 °C. In order to monitor the combustion process, several holes are developed in both sections to allow the introduction of thermocouples or other probes. The cooling section is also equipped with an inlet pipe to inject dilution air to cool the combustion gas and the off-gas evacuation duct.

For the transportation and injection of the coke breeze to the burner a pneumatic system has been designed. This pneumatic system can inject up to 100 kg/h of coke bree-ze with a grain size in the range of 50-100 micron.

A cryogenic tank with the capacity of 10.000 liters at the pressure of 9 barG and an atmospheric vaporizer to con-vert the liquid oxygen into gaseous state has been instal-led in RINA-CSM Dalmine yard.

In order to supply the oxygen at proper pressure and flow rate an oxygen regulation unit has been developed and installed in the RINA-CSM Dalmine yard, the oxygen re-gulation unit has been created in stainless steel frame, it is equipped with electrical panel with integrated PLC.

The oxygen ramp provides a maximum flow rate of 800 Nm³/h at the proper pressure. The oxygen ramp is constituted by:
1) Oxygen line: it is equipped with pressure reduction group to reduce the inlet pressure from 18 barG to 2.5 barG.
2) Nitrogen line: it provides the inert gas for the pneumatic actuators of the instrumentations.
Fig. 3 shows the final location of the oxygen ramp at RINA-CSM Dalmine yard.

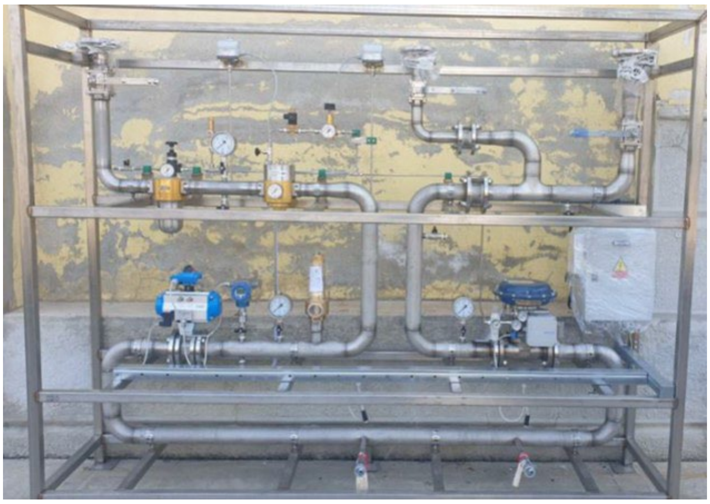

Fig.3 - Final location of the oxygen ramp at RINA-CSM Dalmine yard.

REFORMING MODEL
In order to analyse the influence of the reforming process parameters on the syngas characteristics, a combined CSTR-plug flow reactor model has been developed. The model evaluates equilibrium and kinetical compositions by using a detailed kinetics scheme, which has been developed for COG application. Analysis has been focused on the influence of process conditions (temperature, pressure, fuels composi-tion), on syngas flowrate, temperature and composition as well as soot production.

The target syngas will be defined by the following figures of merits values:

- CH_4 mole fraction < 5%;
- H_2O mole fraction < 7%;
- $(CO+H_2) / (CO_2+H_2O) > 7$;
- Syngas temperature <1100°C (optimum) - Syngas temperature <1300°C (acceptable);
- Soot weight per cubic meter of syngas (as minimum as possible).

The kinetics scheme was developed by Politecnico di Milano (PoliMi) for COG evaluations, including the detailed analysis of heavy hydrocarbon evolution during partial oxidation and prediction of soot precursor.

To simulate both combustion of the coke breeze and reforming process of the COG the following conditions have been used:

- Working pressure: 1.1 bar
- COG characteristics:
  - Temperature: 25 °C (environment temperature)
  - Flowrate: 200 Nm³/h
  - Composition: as reported in Tab. 1.
- Coke Breeze characteristics: as reported in Tab. 2.

Tab.1 - Composition of COG (%vol/vol).

CH_4	C_2H_6	C_2H_4	C_6H_6	O_2	H_2	H_2O	CO	CO_2	N_2
22,61	0,81	1,67	1,23	0,42	45,61	1,6	4,77	2,46	18,82

Tab.2 - Coke Breeze characteristics.

Value	Unit	Coke breeze
Bulk density	kg/m^3	854
Volatile matter	% (db)	2,2
Ash	%(db)	11,8
Fixed carbon	%(db)	86,0
Carbon	% (db)	96,2
Hydrogen	% (db)	0,3
Nitrogen	% (db)	1,5
Sulphur	% (db)	0,8
Oxygen	% (db)	1,2

Fig. 4 shows the trend of CH_4, H_2O, yield and temperature for various coke flowrate calculated by the reforming model at the outlet of the reactor. In Fig. 4 is also reported the trend of thermodynamic equilibrium (which is the limit of the conversion and production of chemical species) and the figure of merit thresholds that must be respected.

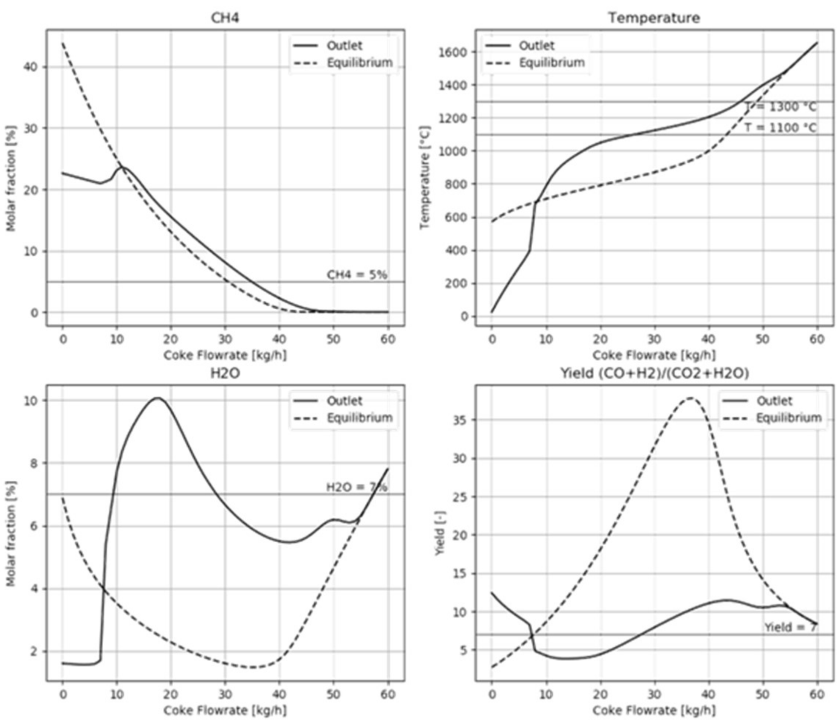

Fig.4 - Syngas gas characteristics. Model results (continuous black line), Thermodynamic equilibrium (dashed line) and figure of merit

Based on the data reported in Fig. 4, to satisfy all figures of merit, the desired working point for the coke breeze flow rate must be in the range of 35-45 kg/h.

DETAILED ENGINEERING AND ADAPTATION OF THE PILOT PLANT

The detailed engineering of the adaptation of the pilot plant for coke breeze use has been carried out.

Market and technological studies have also been conducted to define specific technical solutions and to identify potential equipment suppliers for the plant's design and adaptation.

The pilot plant consists of the following main components:

1. combustion chamber equipped with oxygen burner (oxy-coke breeze);
2. dry reforming reactor;
3. post-combustion chamber for the complete oxidation of the syngas produced before discharge into the atmosphere;
4. dilutor;
5. filter;
6. chimney (i.e. fume stack);
7. coke breeze storage, transportation, and injection system.

Test campaigns are planned on the above-described pilot plant, to collect a suitable set of process data for the analysis and validation of the H_2-rich syngas production process by means of COG dry reforming via coke breeze oxy-combustion.

The oxy-burner, fed with coke breeze, is located in the combustion chamber; the hot flue gas (mainly CO_2) produced in the combustion chamber flows to the reforming reactor, in which it is mixed with the methane containing gas (compressed COG) supplied through a radial distributor. The objective of the reforming section is to obtain at the reactor output, a gas having the lowest possible concentration of methane and other hydrocarbons, and the maximum possible concentration of hydrogen and carbon monoxide (45-65% of H_2 against 25-50% CO).

After sufficient residence time, the reforming process is completed, and the resulting syngas is produced. In the pilot plant configuration, this gas cannot be directly discharged into the atmosphere due to its elevated temperature (above 1000 °C) and high hydrogen content. Consequently, after undergoing continuous chemical analysis via dedicated sampling lines, the syngas is routed to a post-combustion chamber, where it is fully oxidized through the controlled injection of air—an operation made efficient by the high reactivity of the gas mixture.

The resulting flue gases, free from residual combustibles, are subsequently conveyed to a dilution unit (see Fig. 5), where air is introduced to reduce the gas temperature below 350 °C. This temperature reduction step is essential for protecting the downstream filtration unit. The cooled gases are then passed through a high temperature filter (see Fig. 5), which serves to capture any particulate matter potentially generated during the reforming process. The use of dilution air ensures thermal stability and functional integrity of the filtration system. Finally, the treated gases are discharged into the atmosphere via the chimney.

In future industrial scale applications, the produced syngas is intended to be directly injected into the blast furnace (BF) shaft as a reducing agent, thereby eliminating the need for post-combustion and subsequent gas treatment stages employed in the pilot plant setup.

The pilot plant has been designed considering the following main characteristics:

- Producing 500 Nm^3/h of reformed gas at > 1000 °C and atmospheric pressure
- Followed by combustion of the gas (with secondary air)
- Gaseous feed: coke oven gas or natural gas (200 Nm^3/h max)
- Solid circular C feed: coke breeze (90 kg/h max)
- Oxygen feed (190 Nm^3/h max)

Fig. 5 shows the rendering of the pilot plant with the coke-breeze configuration with the indication of both of main components and main section.

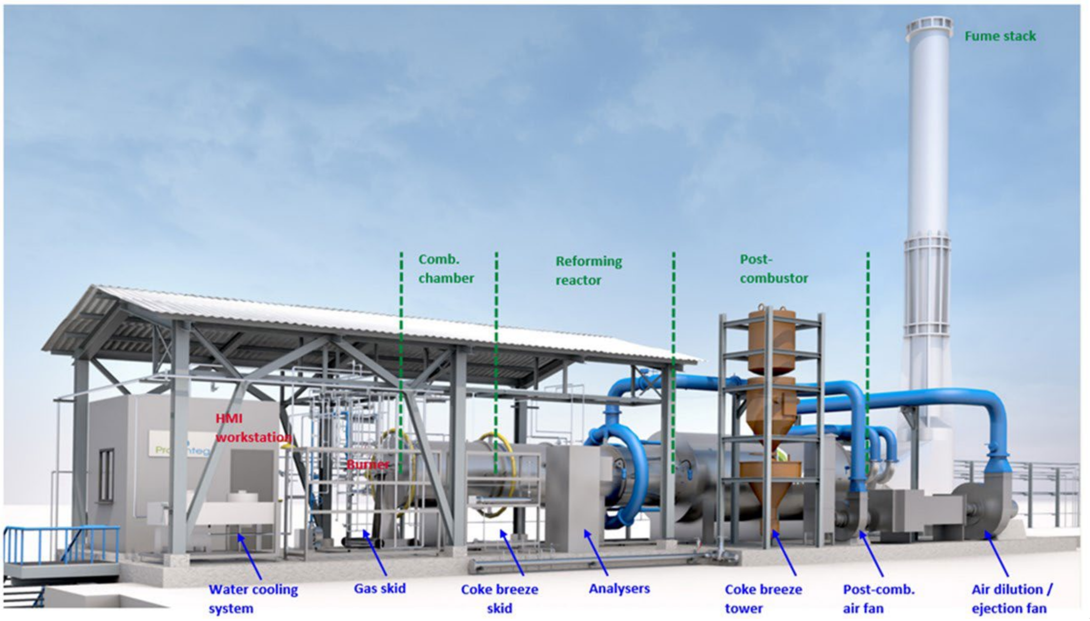

Fig.5 - Rendering of the pilot plant "coke-breeze configuration".

CONCLUSIONS

This work presented the conceptual development and implementation of an innovative pilot plant designed to support the decarbonization of the steel industry. The proposed system enables the production of a H_2-rich syngas for BF shaft injection by integrating coke breeze oxy-combustion with the dry reforming of coke oven gas.
The design of the combustion chamber has been finalized, and the main bids have been evaluated. The combustion chamber is constituted by a combustion section with a length of 2850 mm and internal section of 850 mm and cooling section with a length of 2525 mm and internal section of 1150 mm and it is able to test burned up 1 MW. The cryogenic oxygen tank of 10.000 L and the oxygen ramp able to provide flow rate of 800 Nm3/h at the maximum pressure of 5 barG has been installed and set up and tested in RINA-CSM Dalmine yard.
A combined CSTR-plug flow reactor model has been developed to analyze the influence of the reforming process parameters on the syngas. The results of the model show that to produce a syngas that can be directly injected in the BF the desired working point for the coke breeze flow rate must be in the range of 35-45 kg/h.
The detailed engineering of the adaptation of the pilot plant for coke breeze use has been carried out. Market and technological studies have been also conducted to define specific technical solutions and to identify potential equipment suppliers for the pilot plant's design and adaptation.
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ACKNOWLEDGMENTS

This work was carried out with support from the European Union's Research Fund for Coal and Steel (RFCS) research program under the ongoing project: Production of hot hydrogen-rich syngas in integrated plants for efficient injection in the blast furnace and CO2 mitigation – ProSynteg- GA number: 101057965.

REFERENCES

[1] Tseitllin et al.; A Flow-chart for Iron Making on the Basis of 100% Usage of Process Oxygen and Hot Reducing Gases Injection; ISIJ International, Vol. 34, 1994, No. 7, p. 570–573.

[2] Miwa, T., Okuda, H.; CO2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50 (COURSE50) ; J.Jpn.Inst Energ. 2010, 89:28 35

[3] Ueno, H. et al.; Outline of CO2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50 (COURSE50 Project); J. Jpn. Inst. Energy, 2015, 94:1277 1283

[4] Shigeaki Tonomura et al.; CO2 Ultimate Reduction in Steelmaking Process (COURSE50 Project), ICSTI 2018

[5] ULCOS, Ultra Low CO2 Carbon Steelmaking, project number FP6-NMP-515960, 6th EU Framework Programme for Research and Technological Development (FP6). The consortium worked on 15 subprojects (some of them were partially funded within the RFCS programme), including SP1 New blast furnace (RFSR-CT-2004-00005), SP4 Hydrogen steel production, SP10 New C-based steel production (RFSR-CT-2009-00002), SP15 IDEOGAS (RFSP-CT-2006-00001).

[6] Birat, J.P. et al.; ULCOS program: a progress report in the Spring of 2008, SCANMET III, 3rd International Conference on Process Development in Iron and Steelmaking, 8–11 June 2008, Luleå, Sweden

[7] Birat, J.P.: CO2-lean steelmaking: ULCOS, other international programs and emerging concepts; 1st International Conference on Energy Efficiency and CO2 Reduction in the Steel Industry, 27 June – 1 July 2011, Düsseldorf

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