Journal of Physics:
Conference Series



**PAPER** • **OPEN ACCESS**

# High-temperature electrolysis for industrial decarbonisation: a real-scale demonstration in the steel sector

To cite this article: Martina Fantini *et al* 2025 *J. Phys.: Conf. Ser.* **3143** 012073

# High-temperature electrolysis for industrial decarbonisation: a real-scale demonstration in the steel sector

**Martina Fantini[1*], Elena Crespi[2], Andrei Denissenko[3], Minna Toivola[4], Claudio Leoncini[5], Felix Kaiser[6], Silvia Rossetti[7], Stephen J. McPhail[8], Giovanni Camarda[9], Giulio Guandalini[10], Paolo Colbertaldo[10] and Stefano Campanari[10]**

[1] EU CORE Consulting, Via XX Settembre 98/E, 00187 Rome, Italy
[2] FONDAZIONE BRUNO KESSLER, Via Santa Croce 77, 38122 Trento, Italy
[3] AKTSIASELTS ELCOGEN, Valukoja 23, 11415 Tallinn, Estonia
[4] ELCOGEN OY, Niittyvillankuja 4, 01510 Vantaa, Finland
[5] TENOVA, Via Gerenzano, 58, 21053 Castellanza (Varese), Italy
[6] RWTH-AACHEN IOB, Kopernikusstraße 10, 52074 Aachen, Germany
[7] ACCIAI SPECIALI TERNI, Viale Benedetto Brin 218, 05100 Terni, Itlay
[8] KIWA Corporation, Sir Winston Churchilllaan 273, 2288 EA Rijswijk, Netherlands
[9] Baker Hughes, Via Felice Matteucci 2, 50127 Firenze, Italy
[10] Politecnico di Milano, Energy Department, via Lambruschini 4A, 20156, Milano

*E-mail: fantini@eucore.eu

**Abstract.** The decarbonisation of energy-intensive industries is a crucial step towards achieving climate neutrality. Among these, the steel sector remains one of the largest $CO_2$ emitters, requiring innovative solutions to reduce fossil fuel dependency while maintaining efficiency and product quality. This study gives an overview and presents objectives and early progresses of SYRIUS project (*SOEC hydrogen integration and circular use in steelmaking process*), a Horizon Europe Innovation Action supported by the Clean Hydrogen Partnership. The main goal of SYRIUS is to integrate a 4.2 $MW_{el}$ Solid Oxide Electrolyser (SOEC) into the process line of an operational electric arc furnace (EAF) steel plant, enabling on-site hydrogen production with waste heat recovery and circular integration of process by-products.

The proposed system addresses key technological challenges in hydrogen production and utilization for industrial applications. The SOEC electrolyser, operating at high temperature with high electrical efficiency (specific consumption below 37 $kWh_{el}/kg_{H2}$), utilizes steam recovered from the steel reheating process, significantly reducing electricity demand compared to low-temperature electrolysis technologies. This approach not only lowers operational costs but also optimises energy use within the steelwork, demonstrating a cost-effective and scalable hydrogen production model.

Hydrogen produced on-site will be directly fed into a high-efficiency, fuel-flexible slab reheating furnace, designed for progressive decarbonisation through hydrogen combustion. The furnace can operate with variable $H_2$-natural gas mixtures, reducing $CO_2$ emissions by 5,600 tonnes per year during the project and up to 35,700 tonnes per year with future expansion. Additionally, the oxygen by-product from electrolysis is recovered and reintegrated into the process, further optimizing combustion efficiency and contributing to additional fuel savings.

A full-scale demonstration in operational environment of this system will be conducted over 5,000 operational hours, validating the feasibility of integrating the SOEC technology within a complex industrial environment. The study also includes techno-economic assessments to evaluate the potential for cost reductions in hydrogen production, as well as life cycle and sustainability analyses to quantify environmental benefits.

This paper addresses advancements achieved in the first months of the project on (i) definition of system modelling and preliminary process simulation, ensuring that the integration of the SOEC is optimized for efficiency and performance, (ii) engineering and permitting activities to establish the necessary regulatory framework for installation, (iii) early-stage SOEC stack development, focusing on material validation and component design, and (iv) waste heat recovery strategies, exploring how steam from the reheating furnace can be efficiently redirected to support electrolysis.

*Keywords*: SYRIUS, steel industry, decarbonisation, Solid Oxide electrolysis

## 1. Introduction

The steel industry is one of the largest energy consumers, with an average of 5.2 MWh of primary energy per tonne of steel produced. In terms of emissions, this results in 9% of all anthropogenic $CO_2$ emissions worldwide [1], showing an increasing tendency since steel production is expected to grow by more than a third within 2050 [2].

Of the total current steel production, 78% is attributed to the “primary route”, which utilizes iron ore as feedstock to produce virgin steel. Within this segment, 70% of the output is generated through the Blast Furnace-Basic Oxygen Furnace (BF-BOF) technology, using coal as main fuel and being responsible for the majority of steel output and related global $CO_2$ emissions. The remaining nearly 8% of steel within this primary route category is produced using Direct Reduced Iron (DRI) technology (followed by Electric Arc Furnace (EAF) processing), using natural gas as main fuel. The “secondary route”, based on EAF and using scrap steel as main feedstock, has lower energy demand and carbon footprint [3] and it currently covers the remaining 22% of world steel production (41.5% in the EU, with peaks of 81% in Italy and 61% in Spain). Producing 1 tonne of steel with EAF results in the emission of approx. 0.3-0.6 $t_{CO2}$ per tonne of steel, vs. the typical 2.2 $t_{CO2}$ per tonne of steel for the BF-BOF route, including both the direct emissions from fossil fuels use and the indirect emissions deriving from electricity consumption at average grid carbon intensity [2, 4].

There are several technological pathways towards a lower carbon intensity for the steel industry that, in the most considered options, relate to the upstream crude steel production [5], (i) employ different approaches for iron ore reduction, such as the DRI route, and (ii) increasingly integrate the use of renewable electricity and green hydrogen as input energy vectors or implement $CO_2$ capture and storage (CCS) options. Independently from the crude steel production pathways, significant $CO_2$ emissions are related to the hot rolling mill processes occurring downstream the cast steel production [6].

Among the most important sources of direct $CO_2$ emissions at this stage there are high-temperature processes, such as the steel slab reheating or the heat treatment (e.g. annealing) of steel products. Steel reheating, in particular, is adopted for most crude steel processing, apart from the few productions employing a continuous casting and rolling approach. A typical steel reheating furnace consumes nearly 32 $Nm^3_{NG}$ per tonne of steel [7] (or other fossil fuel such as syngas from BF-BOF plants) to reach steel slab temperatures above 1,200°C prior to the hot rolling lamination process. The resulting $CO_2$ emissions (61 $kg_{CO2}$/t of steel) are therefore present in nearly all crude steel processing routes and are among the most important direct emissions (Scope 1) in the case of EAF steelmaking. Decarbonization of such processes entails the introduction of electrification (e.g. induction heating, currently feasible only for certain sizes and limited maximum temperatures) or the use of clean fuels such as hydrogen. Hydrogen is, in fact, considered the first candidate to replace fossil fuels in steelmaking, both in primary production (substituting coal as a reducing agent) and in secondary steelmaking [8].

The urgency to integrate hydrogen-based methods in sustainable steel production routes is not without challenges. While the production of renewable-based green hydrogen through low-temperature water electrolysis already offers relatively low specific capital costs and demonstrated durability, high-temperature Solid Oxide Electrolysis (SOEC) technology may offer unmatched conversion efficiency and lower electricity consumptions, especially when coupled with heat recovery from the industrial process for supplying steam to the electrolyser. However, current state-of-the-art SOEC systems struggle with producing hydrogen at the necessary rate and cost, and they are not yet compatible for coupling with the demand of industrial processes at the required scale and with a sufficiently demonstrated reliability (e.g., tens kW of SOEC electrolyser are required to supply hydrogen to a DRI plant vs several tens MW for a single slab reheating furnace and vs several hundred MW scale electrolysis for a full-scale DRI installation).

Within this framework, the SYRIUS project [9] aims to address such challenges by integrating a 4.2-$MW_{el}$ SOEC at the existing EAF-based steel production plant in Terni, Italy (Figure 1), to produce 100 kg/h of green hydrogen. This hydrogen will supply an 84 $MW_{th}$ slab reheating furnace (WBF, walking beam furnace), showing the potential to reduce $CO_2$ emissions of the steel reheating production step process by: (i) 5,600 t/y or 4.3% of furnace emissions during the project; (ii) up to 35,700 t/y or 27% of furnace emissions in a future expansion at larger scale (25 MW SOEC with maximum heat recovery from the furnace); (iii) or up to 100% in case of full hydrogen feeding of the furnace, combined with heat recovery from other waste heat sources in the steelwork processes, such as directly from the EAF. By generating steam through furnace off-gas heat recovery, implementing by-product oxygen recovery in the furnace (allowing additional savings of 430 $t_{CO2}$/year in SYRIUS and of 2% fuel input in future expansion) and analysing options for water recycle, SYRIUS seeks to minimize external energy consumption and sets industrial circularity at the project core.

The purpose of the following work is to present an overview of the project and the progress of the first six months of SYRIUS activities.

**Figure 1.** Acciai Speciali Terni plant in Italy

## 2. SYRIUS: concept and methodology

*2.1 Concept*

SYRIUS is an innovation action supported by the Clean Hydrogen Partnership and co-funded under the Horizon Europe research programme, that, spanning 54 months, aims at tackling the most polluting phase of the steel-making process, steel heating, by simultaneously advancing innovative stack and module designs of high-temperature electrolysis (SOEC) and demonstrating its integration for more than 5,000 working hours at a relevant scale in operational environment (TRL7) – namely at the Acciai Speciali Terni SPA (AST) steel plant in Terni, Italy – including a full recovery of the produced oxygen and its utilization, together with hydrogen, in a fuel-flexible slab reheating furnace.

The partnership consists of three research organizations and nine industrial partners which include two leading European universities, one research center, major players in steel production and hydrogen certification, as well as several technology providers. Figure 2 shows the various partners and the location within Europe.

Journal of Physics: Conference Series **3143** (2025) 012073 doi:10.1088/1742-6596/3143/1/012073


**Figure 2.** SYRIUS Consortium

Significant effort is being directed towards the integration of the SYRIUS concept in the pilot plant and demonstration activities to achieve ambitious targets. Figure3 illustrates the basic concept of SYRIUS when integrated in the AST steel plant in Terni, Italy, one of the most important integrated steelmaking sites in Europe in the stainless-steel sector with more than 1 million tonnes of stainless and specialty steel produced per year. The integrated system is constitued by individual units at different maturity level (TRLs):

i) a high-temperature SOEC: it offers high electrical efficiency for hydrogen production, especially when integrated with waste heat recovery from external sources, such as industrial processes. While the core materials and stack architecture are robust, the operation in electrolysis mode still faces key challenges in particular in long-duration performance, current density optimisation, and cost reduction. Currently, the technology is positioned at TRL5 with previous experiences validating performance but not yet demonstrating full system reliability at scale. SYRIUS will advance SOEC technology to TRL7 by developing a multi-stack 4.2 MW system with improved current density (from 0.5 to 0.75 $A/cm^2$), optimized hot balance-of-plant, and long-term testing under real industrial load profiles. CAPEX will be reduced through modularisation and design-for-manufacturing strategies, positioning the SOEC as a scalable building block for industrial hydrogen deployment;

ii) a flexible hydrogen and oxygen-enriched air burner: modern steel furnaces increasingly adopt flameless combustion to reduce $NO_x$ and $CO_2$ emissions, and hydrogen-ready burners have reached TRL8-9. However, challenges remain in process integration, control of combustion atmospheres, and safe, continuous hydrogen supply. SYRIUS will advance the state of the art by demonstrating a flexible burner coupled with a high-temperature SOEC at multi-MW scale in a real production environment. The burner will operate with variable

$H_2$/NG ratios, enriched with oxygen recovered from the SOEC, offering both fuel and oxidant flexibility. The system will be tested in an operational furnace, assessing impacts on combustion stability, emissions, and material treatment outcomes. This full-scale integration (combining on-site hydrogen and oxygen use) will bring the overall solution to TRL8 and deliver key insights into infrastructure, safety, optimized combustion efficiency and process control requirements for future hydrogen-based industrial furnaces;

iii) a heat recovery integration with SOEC: heat recovery systems in steel plants are mature (TRL9), but their integration with high-temperature electrolysers is untested. In SYRIUS, a key innovation lies in adapting the conventional steam recovery infrastructures of the AST steel plant to support the SOEC. This requires the design and control of a dual-loop system, where thermal energy from the reheating furnace is used to generate high-purity steam for electrolysis. Specific attention will be given to ensuring stable steam supply at adequate temperature during partial load or transient furnace operation. Advanced control logic will manage the interaction between the furnace, the heat exchanger, and the electrolyser to guarantee operational reliability. In addition, SYRIUS will explore the recovery of low-grade heat and condensation water for purification and reuse, contributing to circularity. This demonstration will represent a first-of-a-kind application, raising the TRL of heat recovery-SOEC integration from TRL7 to TRL8 within a fully industrial context.

iv) a process integration including Energy Management System (EMS): currently, SOEC systems are operated as steady-state, base-load units, controlled by relatively simple PID logic. This approach overlooks opportunities for cost and emissions optimisation in response to fluctuating electricity prices and renewable generation. SYRIUS will introduce a major innovation by integrating an advanced EMS, based on model predictive control, capable of dynamically optimizing SOEC operation when integrated with PV plants and batteries to form a Virtual Power Plant. The EMS will take into account of the forecasts of PV production profiles, Battery operational constraints and SOEC part-load efficiency curve, operational constraints (e.g., start-up and ramp-up limits) and operating costs (including those associated to the degradation) to determine the cost-optimal management solution for the virtual power plant. The EMS, developed over the last 10 years by Politecnico di Milano (POLIMI), is based on a detailed Mixed Integer Linear Programming (MILP) model of the virtually aggregated plant. Demonstration in an industrial setting will bring the EMS and SOEC integration from TRL5 to TRL7. Additionally, Politecnico di Milano will explore the optimal long-term design of fully renewable energy systems powering hydrogen production, using advanced Mixed Integer Linear Program (MILP)-based planning tools. This comprehensive integration aims at positioning the SOEC not as a stand-alone device, but as a responsive, optimised asset within a smart industrial energy ecosystem.

Through the set of demonstration activities in relevant environment planned in SYRIUS, the system will reach TRL7 for the core part (the electrolysis plant) and TRL8-9 for the other plant and project components.

The project aligns with the broader ambition of the steelmaking sector to identify and implement the most effective combination between all the available technologies and fuels, with the purpose of producing high-quality products at the lowest achievable carbon footprint, without giving up competitiveness.

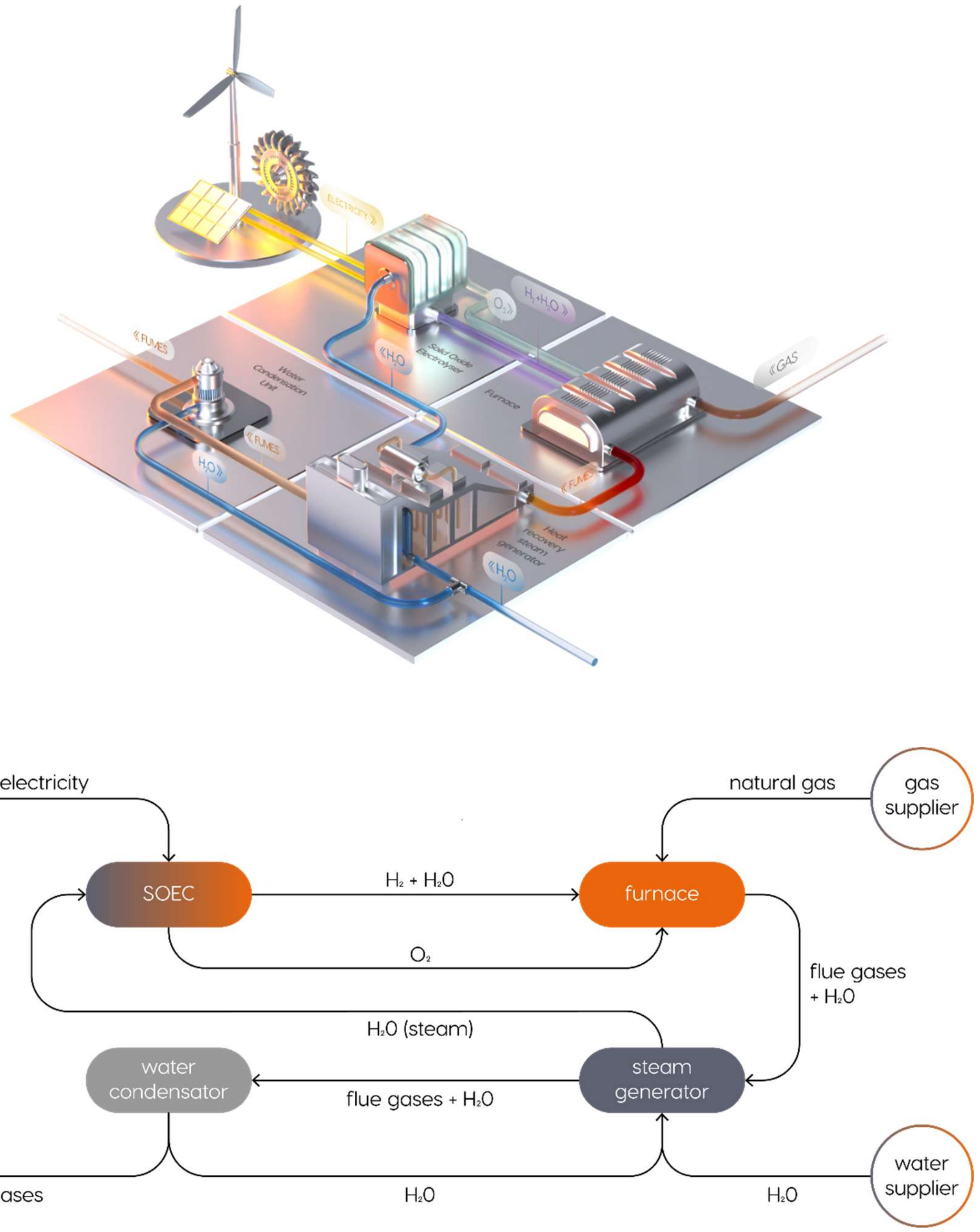


**Figure 3.** SYRIUS Concept and plant integration.

*2.2 Methodology*

To integrate the SOEC in the real electric arc furnace steelmaking environment, SYRIUS follows a structured and progressive implementation strategy. The methodology is articulated in five main phases: 1. analysis, 2. development, 3. integration, 4. demonstration, and 5. impact assessment. Each phase builds upon the results of the previous one, ensuring technical continuity and readiness for real-scale deployment.

In the first 18 months, the project focuses on the analysis and preparatory work required to adapt the existing infrastructure at the AST steel plant in Terni. This involves defining the design parameters and operational requirements for integrating the 4.2 MW SOEC plant, performing a comprehensive risk and safety assessment, and addressing permitting and regulatory compliance. During this phase, significant effort is dedicated, in particular by Politecnico di Milano and Fondazione Bruno Kessler (FBK), to the co-design of interfaces between the SOEC and the reheating furnace, including the modelling of the steam loop that will feed the electrolyser with process heat recovered from flue gases.

Parallel to this, the project will initiate the detailed engineering of the SOEC multi-stack module and its associated systems. Key aspects include the optimisation of stack layout for thermal stability and maintenance, carried out by ELCOGEN, the development of a larger scale SOEC module, carried out by Baker Hughes (BH), and the pre-certification of the system for safe industrial deployment under the scope of Kiwa and its affiliated Vinçotte. Before scaling up to the 4.2 MW plant, a smaller prototype module, around 100 kW, will be tested under controlled conditions at Baker Huges's facilities in Florence. This intermediate step will enable early validation of performance targets, safety aspects, and component integration, reducing risks prior to the full-scale implementation.

In terms of control architecture, the early phases will involve the definition of a smart EMS, capable of coordinating hydrogen production, storage, and usage. This EMS, joint effort of Politecnico di Milano and Fondazione Bruno Kessler, will be designed to optimise operations in response to dynamic electricity prices and variable renewable availability, leveraging virtual aggregation schemes as allowed by the Italian regulatory framework. The EMS development will follow a hybrid modelling approach combining long-term planning and real-time optimisation.

From a plant integration point of view, the SYRIUS methodology foresees the design of dedicated interconnections for steam, electricity, and gas flows between the SOEC system and the steel plant infrastructure. Wherever possible, existing components at the Acciai Speciali Terni site will be reused and adapted to minimise disruptions and facilitate integration. The heat recovery system will be designed to ensure the generation of steam with suitable pressure and temperature levels for the electrolyser, even under variable furnace operating conditions.

A central element of this integration is the new slab reheating furnace developed and provided by Tenova, designed for full industrial operation with hydrogen-natural gas blends up to 100% $H_2$. This furnace will receive both hydrogen and oxygen-enriched air produced by the SOEC and will serve as the main testbed for evaluating thermal efficiency, emissions reduction, and impacts on steel quality. Additionally, as depicted in Figure 3, the flue gases from this furnace will be used as the primary heat source for the steam feeding the SOEC, creating a highly efficient circular system. Tenova also contributes to the design and optimisation of the heat recovery and flue gas handling infrastructure to ensure stable and safe operation under real load conditions.

To support the whole process anlysis and integration, dedicated simulation activities will be conducted starting from the early phases of the project. These will include a process model in Aspen Plus®, enriched with a specific SOEC component, and a dynamic model developed in Modelica. These tools will help predict system behaviour under steady-state and transient scenarios, support the design of the EMS, and enable the definition of robust control and optimisation strategies.

In the final phase, Aachen University will play a key role by leading the life cycle assessment (LCA) of the SYRIUS system, applying internationally recognised standards to quantify the environmental impacts and circularity potential of the integrated process, thus providing robust evidence of its sustainability for future industrial uptake.

Journal of Physics: Conference Series **3143** (2025) 012073 doi:10.1088/1742-6596/3143/1/012073

Currently, the project is in the first phase, which is dedicated to modeling and designing the main units that will be integrated in Terni.

## 3. Activity progresses

SYRIUS kicked off in January 2025. In its early phase, significant progress has been made in defining the system architecture and performing a preliminary simulation-based design. In particular, the consortium completed a revised analysis of the plant specifications, outlining the expected layout and functional connections between the SOEC system, the steel slab reheating furnace, the heat recovery steam generator and the associated utility infrastructures at the Acciai Speciali Terni site. Multiple configuration options were explored and compared, leading to the selection of a reference configuration in which the SOEC receives steam generated through a waste heat recovery loop from the flue gases of a new Heat Recovery Steam Generator connected downstream of the Tenova's WBF slab reheating furnace, as depicted in Figure 4.

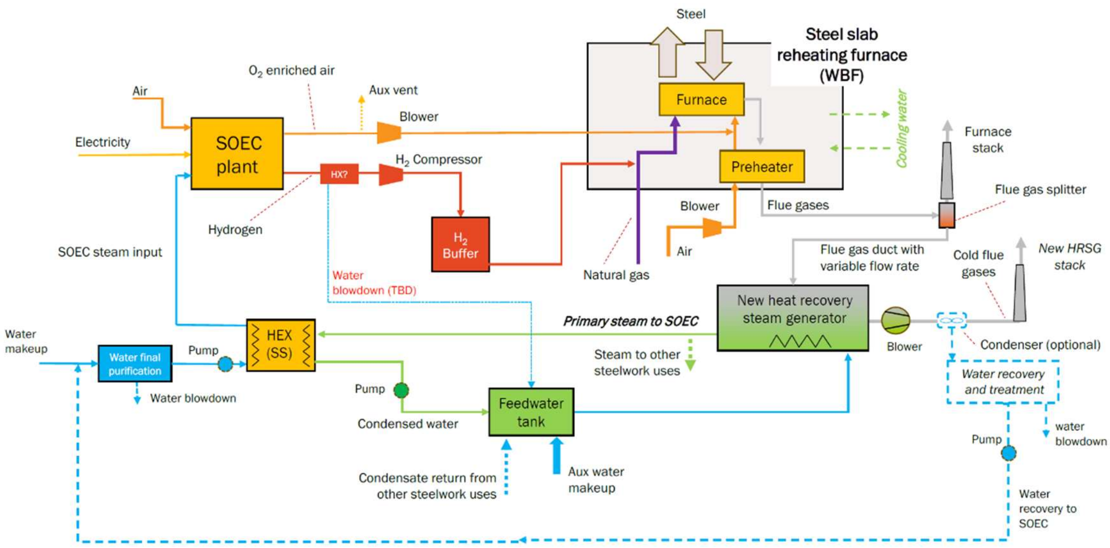


**Figure 4.** Indicative layout of SYRIUS plant.

Initial modelling assumptions, system capacities (e.g., the 4.2 $MW_{el}$ SOEC pilot producing 100 kg/h of hydrogen), and interconnection requirements have been defined and they are now being used to inform engineering and permitting strategies. Moreover, during an operational workshop held at Acciai Speciali Terni in February, dedicated attention has been given to interface specifications, defining inputs and outputs for each subsystem (including electrical power requirements, hydrogen and oxygen flows, water make-up and purge, and flue gas conditions) and spatial allocation within the plant's constraints. Key parameters such as the SOEC operational load (expected to operate mainly full-load) and its thermal integration with the furnace were analysed to define expected working profiles. Similarly, the furnace is described under different fuel feeding conditions (from NG-only to full hydrogen) and oxygen-enriched air feeding, identifying how combustion atmosphere, flue gas temperature, and heat availability may vary and influence the steam production rate for electrolysis.

As reflected in Figure 4, regarding early-stage SOEC development, initial efforts have focused on defining the stack module configuration and integration in the real system. Baker Hughes is working on two main technical areas of the project: the design of the SOEC multi-stack module and the integration of the electrolyzer prototype into the AST plant. In this initial phase of the project, efforts are focused on defining the configuration of the multi-stack module and developing the preliminary design of the 100 kW-scale demonstrator, which will be used to validate the technology at TRL6. The design also includes the development of the Balance of Plant (BoP) and the integration of the demonstrator into BH's testing facility in Florence, where it will undergo testing. A key aspect of this phase is safety, which is already being addressed with the involvement of KIWA, Vinçotte and BH' subject matter experts. Additionally, this design phase involves close collaboration with ELCOGEN, which will manufacture and supply the solid oxide cells. In parallel, BH is collaborating with AST and TENOVA to assess the integration of the SYRIUS prototype into the AST plant located in Terni, Italy. Current studies are focused on defining all BoP components, optimizing the system footprint to fit the available space, establishing interconnection parameters with the steam supply and the furnace, and initiating discussions on safety and component certification.Once these initial studies are completed, a preliminary bill of materials for all major components will be available. This will enable an initial assessment of the overall system integration costs and support the finalization of the detailed design. The 4.2 MW SYRIUS prototype will be based on the multi-stack module currently under development for the demonstrator. A 5,000-hour test campaign will validate the technology at TRL7, assessing both system performance and degradation over time. The design of the prototype and its integration into the AST plant will strongly leverage the analytical model being developed by Politecnico di Milano and Fondazione Bruno Kesler.

Preliminary modelling activities have also been initiated, including a high-level process simulation using Aspen Plus®. At the same time, the main elements to be included in the Modelica dynamic model and their main features have been identifies, allowing to collect all the data required to simulate the plant dynamic behaviour and support the definition of the control loops and of the EMS.

In parallel, preparatory work on permitting has started, with an initial alignment on the scope of the new versus legacy installations, the available permits and corresponding authorities. As the design of the new installation approaches more tangible forms, this activity will initiate the due analyses and interactions to run successfully through the permitting process.

## Acknowledgements

The SYRIUS project is supported by the Clean Hydrogen Partnership and its members under Grant Agreement 101192534. Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Clean Hydrogen Partnership. Neither the European Union nor the granting authority can be held responsible for them.

## Acronyms

| | |
|---|---|
| BF-BOF | Blast Furnace-Basic Oxygen Furnace |
| DRI | Direct Reduced Iron |
| EAF | Electric Arc Furnace |
| EMS | Energy Management System |
| NG | Natural Gas |
| SOEC | Solid Oxide Electrolyzer or Electrolysis |
| SYRIUS | SOEC hydrogen integration and circular use in steelmaking process |
| WBF | Walking Beam Furnace (for steel slab reheating) |

## References

[1] Lopez G., Farfan J., Breyer C, 2022, Journal of Cleaner Production. 375 (2022) 134184. https://doi.org/10.1016/j.jclepro.2022.134182.
[2] https://www.iea.org/reports/iron-and-steel-technology-roadmap – IEA. Iron and Steel Technology Roadmap. Consulted on 17/03/2024.
[3] Devlin, A., Kossen, J., Goldie-Jones, H. et al., 2023, Nat Commun 14, 2578 (2023). https://doi.org/10.1038/s41467-023-38123-2.
[4] Y. Qian et al., 2024, Carbon Research (2024), Springer, DOI:10.1007/s44246-024-00118-z.
[5] M. Shahabuddin et al., 2023, J. of Cleaner Production, 2023, DOI:10.1016/j.jclepro.2023.136391
[6] EUROFER, "Determination of greenhouse gas (GHG) emissions in energy-intensive industries", www.eurofer.eu/publications/reference-documents/excel-tool-for-european-standard-en-19694-2/, accessed in March 2024.
[7] Astesiano D. et al., 2023, Mat. & Tech. 111, 203 (2023) doi:10.1051/mattech/2023018.
[8] https://www.estep.eu/assets/CleanSteelMembersection/CSP-SRIA-Oct2021-clean.pdf ESTEP, Clean Steel Partnership Strategic Research and Innovation agenda, 2021, Consulted on 7/04/2024
[9] https://syrius-project.eu/, Accessed on 3rd of May, 2025