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Gradual integration of REnewable non-fossil ENergy sources and modular HEATing technologies in EAF for progressive CO2 decrease

Transferability Guidelines

Deliverable D5.3

Delphine Snaet (ESTEP)
Valentina Colla, Ismael Matino, Orlando Toscanelli (SSSA)
Oliver Hatzfeld, Thorsten Hauck, Tolga Eroglu, Emanuel Thienpont, Kersten Marx (BFI)
Marianne Magnelov (SWERIM)
Asier Zubero Lombardia (Sidenor Aceros Especiales SL)
Aintzane Soto Larzabal (Sidenor I+D)
Pascal Kwaschny, Esin Iplik (LINDE)
Carl Allertz, Niklas Kojola (SSAB)

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1. Introduction

1.1 Purpose and scope of the present document

The GreenHeatEAF Consortium is keen to ensure the transferability of project results across the European steel sector and beyond, to contribute to improving sustainability and resilience of the European steel industry.

The outcomes of the project GreenHeatEAF are conceived as technologies and process revamping methodologies, which can fit the demand of the steel companies related to:

- integration of non-fossil gases flows in Electric Arc Furnace (EAF) processes with different charge materials and configurations;
- modular regenerative and alternative heating technologies for increasing in-process heat recovery from off-gases and for valorising slag latent heat;
- exploitation of biomass, biochar, and other renewable C-carriers for the supply of non-fossil energy and carbon in the EAF process.

Therefore, it is of utmost importance that such results are made exploitable by European industries beyond the project lifetime by fostering their transferability and favouring creation of multiple market opportunities.

To this aim the Consortium is committed to interacting with stakeholders and collect their feedback on project development and foreseen outcomes, to steer as much as possible the research activities in a way that the outcomes meet as much as possible their demands.

The present document describes some initial guidelines to ensure transferability of project outcomes, which have been developed based on the first stage of stakeholder consultation and on the suggestions provided by the Advisory Board (AB) nominated by the Consortium.

To collect suggestions and feedback, a first survey was organised focused on the part of the research outcomes (modelling and simulation) which already showcased some preliminary outcomes in the first year of the project, which were also presented in a few workshops. This helped raising interest, awareness and curiosity toward the project and the implemented methodologies and, consequently, also raised interest toward the survey and willingness to complete it.

Moreover, the Consortium organised a meeting and a series of interviews with the members of the AB, which was focused on foreseen barriers for transferability of the foreseen Key Exploitable Results (KER) of the project, such as identified at the proposal stage, which is considered still valid at the time of compilation of the present document.

The consortium will continuously revise the developed guidelines during the project, as long as the different solutions which compose the GreenHeatEAF portfolio will be developed, to verify that the main indications are followed, but also to refine such guidelines based on further stakeholders' consultation which will include some showcasing of project results as well as on future suggestions provided by the AB. To this aim, ad-hoc meetings and further interviews are planned with the AB.

1.2 Structure of the document

This rest of the document is divided into 4 main sections:

- Section 2 presents the AB members.
- Section 3 describes the first stakeholders' survey which was launched through ESTEP to get feedback on the use of modelling and simulation tools in the context of the topics treated by GreenHeatEAF.

- Section 4 shortly introduces the previously identified KERs of the project, discusses the potential barriers to and intensifiers for their transferability as emerged from an internal analysis and the indications provided by the AB.
- Section 5 provides some concluding remarks and indications for future work especially concerning interactions with stakeholders.

2. The Advisory Board

The members of the AB were selected based on their competencies on the different topics treated in the project, ensuring an appropriate blend of competencies coming from both the academic and the industrial field.

Six members where selected, among which four from industries and two from Academia. Among the four industrial members, two experts (Mr. Haase and Mr. Abraham) work in other companies belonging to the same multinational group of two beneficiaries of GreenHeatEAF, Mr. Chini works at Ferriere Nord, an Italian electric steelwork external to the project Consortium and Dr. Pietrosanti represents the perspective of the plant builders, being a consultant of Danieli Automation S.p.A.

Please find below a synthetic description of the profiles of the AB members.

Mr. Björn Haase

Mr. Haase is Manager “Non Metal Products” at Höganäs Sweden AB. He holds a long-term competence in metallurgy, both in a research perspective but also from a production management view. This includes close cooperation with the academia, both in general projects but also in bi-lateral activities. The metallurgical work has covered many things from use of raw material, process control, energy efficiency, etc. and, in the recent years, with much focus on reducing the carbon footprint. Mr. Haase also holds a long term experience in handling of side-stream materials (residual materials) and by-products from iron and steel industry. This work covers utilization of the various side-stream materials both internally and externally including productifying of the materials. This also includes being chairman for the group focusing on side-stream products at Jernkontoret (the Swedish steel producers association).

Mr. Sunday O. Abraham

Dr. Sunday Abraham received his MSc. (6 year program) degree and PhD in metallurgy and steelmaking from Moscow State Institute of Steel and Alloys in 1996. In 1999 he joined the former IPSCO Inc. in their research and development facility in Regina, Saskatchewan, as research engineer. In 2004, he became the manager of the research and development facility and then in 2008, he was promoted to director of technical services. In 2010, he joined SSAB Americas in their research and development facility as principal research engineer. In 2019, he became the director of the research and development facility. Dr. Abraham has developed numerous algorithms for process modelling for optimization of the electric arc furnace scrap melting, ladle refining and continuous casting processes, product quality improvement, and production cost savings. He is the author of over 20 publications; and the recipient of AIST Hunt-Kelly Outstanding Paper Award in 2012 and AISI Medal in 2014. He is one of the inventors of the “Methods and Systems for the Quantitative Measurement of Internal Defects” - US patent #s 10,031,087 B2, 10,782,244 B2, and 11,635,389 B2.

Mr. Matteo Chini

Matteo Chini obtained His master's degree in the field of Computer and Information Technology in 2016. Following his graduation, he developed a keen interest in the steel industry collaborating with the Pittini Group, a prominent manufacturer of long steels. Since 2019, he has served as the R&D Assistant at Compagnia Siderurgica Italiana S.r.l., the holding company of the Pittini Group. In this role, he has had the opportunity to coordinate and manage various technical aspects of RFCS, Horizon 2020, and Horizon Europe-funded projects. These responsibilities have engaged him in the day-to-day operations of the steel sector, particularly in areas such as Digital Industry, Decarbonization, and Circular Economy. This experience has exposed him to the challenges and dynamism of the industry's intense focus on innovation. Matteo Chini is an expert in steelworks processes and in the implementation of modeling and simulation systems within the steel industry for control purposes.

Dr. Costanzo Pietrosanti

Dr. Pietrosanti started his career at Centro Sviluppo Materiali S.p.A. in 1979, becoming department manager and director in 1992. He has significant experience in the fields of finite element analysis and modelling, fracture mechanics, and plant erection management and quality control. He holds a very relevant experience in organization, management and performance assessment for Research, Development and Innovation in industrial companies as well as in digitalisation of complex systems; Digital Maturity Assessment and implementation of Capability, Maturity Models and management by Key Performance Indicators-based systems. Dr. Pietrosanti is currently a research and development project evaluator at the Research Fund for Coal and Steel (RFCS). Until 2023 He was chairman of the Smart Factory Focus Group of the European Steel Technology Platform (ESTEP). He is member of the task force and the implementation group of the Clean Steel Partnership (CSP). Since May 2015, he holds the position of senior consultant in the steelmaking sector for Danieli Automation.

Dr. Thomas Echterhof

Dr.-Ing. Thomas Echterhof is academic director at the Department for Industrial Furnaces and Heat Engineering at RWTH Aachen University, Germany. He studied metallurgical and materials engineering at RWTH Aachen University and received his diploma in 2005 and his doctorate in engineering science in 2010. Since 2009 he is leading the research group on mass and energy balances with a special emphasis on the resource and energy efficiency of electric arc furnace and heat treatment processes. Since 2011 he is deputy head and since 2019 academic director at the department. Dr. Echterhof was project manager in charge of the RWTH contribution to seven EU RFCS projects related to EAF steelmaking and was coordinator in four of them. He was also responsible for several other national funded research projects. His main research interests include the optimisation of energy and resource efficiency and environmental impact of energy and resource intensive processes like the EAF steelmaking. Thomas has authored or co-authored more than 70 journal and conference papers as well as numerous industrial project reports, poster and conference presentations. He is also involved in teaching and is giving a lecture on electric arc furnace technology at RWTH Aachen University. In 2015 he established the European Academic Symposium on EAF Steelmaking - EASES and organized it regularly since then.

Prof. Caisa Samuelsson

Caisa Samuelsson is Professor in Process Metallurgy at Luleå University of Technology. Her research competence concerns the research area of Process Metallurgy with a focus on pyrometallurgy. Her research experience covers base metals metallurgy, recycling, and utilization of residues from iron and steel production and base metals extraction as well as recycling of consumer goods. In recent years research experience also covers use of bio coal in metallurgical processes.

3. First stakeholders' survey

The GreenHeatEAF Consortium is committed to gathering primary data and information, collecting feedback, increasing ownership of results, and ensuring industrial interest and commitment towards the project results throughout the whole European steel community. To this aim, an integrated consultation of the stakeholders is planned, which will accompany the project development and will focus mainly on target groups of the business concepts, steel producers, plant providers, hydrogen, and biomass suppliers.

As an initial step in this direction, a first survey was launched in November 2023 to collect the stakeholders feedback on some of the expected outcomes of the project. To encourage participation, the decision was made to keep the survey very compact, with a compilation time of about 5 minutes, and to focus it on the sub-set of results/technologies which was already presented in some dissemination events, namely the modelling and simulation tools.

The survey was spread out by ESTEP as well as by the coordinator and the partners through their own network of contacts.

3.1 Structure of the survey

The main purpose of the survey was to collect feedback on the general interest of the audience in the adoption of renewable non-fossil energy and Carbon sources and heating technologies as well as on the perceived usefulness and knowledge on the use of modelling and simulation tools in this context.

The survey, that is reported in **Appendix I**, is composed by a total of 12 questions and is organised into the following four main sections:

1. The first section entitled "Premise" does not contain any question but shortly introduces the project and the purpose of the survey.
2. The second section entitled "Basic information on the respondent" contains 2 questions collecting in an anonymous form a few personal data on the respondent, i.e. the country and type of company/institution where He/She works.
3. The third section entitled "Modelling and simulation on GreenHeatEAF topics" contains 8 questions aimed at assessing the general interest of the respondent in the adoption of renewable non-fossil energy and Carbon sources and heating technologies, the current and potential interest in the company/institution of the respondent in using modelling and simulation tools to investigate this topic, the main perceived intensifiers for and barriers to the adoption of modelling and simulation tools and the professional experience of the respondent on this topic.
4. The fourth section entitled "Intensifiers and barriers for any kind of model" conveys 2 final general questions concerning the main perceivers factor which can amplify or hamper the transferability of any kind of modelling tool.

3.2 Outcomes of the survey

At the time of delivery of the present document, 103 respondents from a quite wide range of countries compiled the questionnaire. The geographical distribution of the respondents is shown in **Figure 1**. Italy, Sweden, Germany and Spain are the most represented countries, as these countries hold a relevant steel sector but also because they are highly represented in the project consortium.

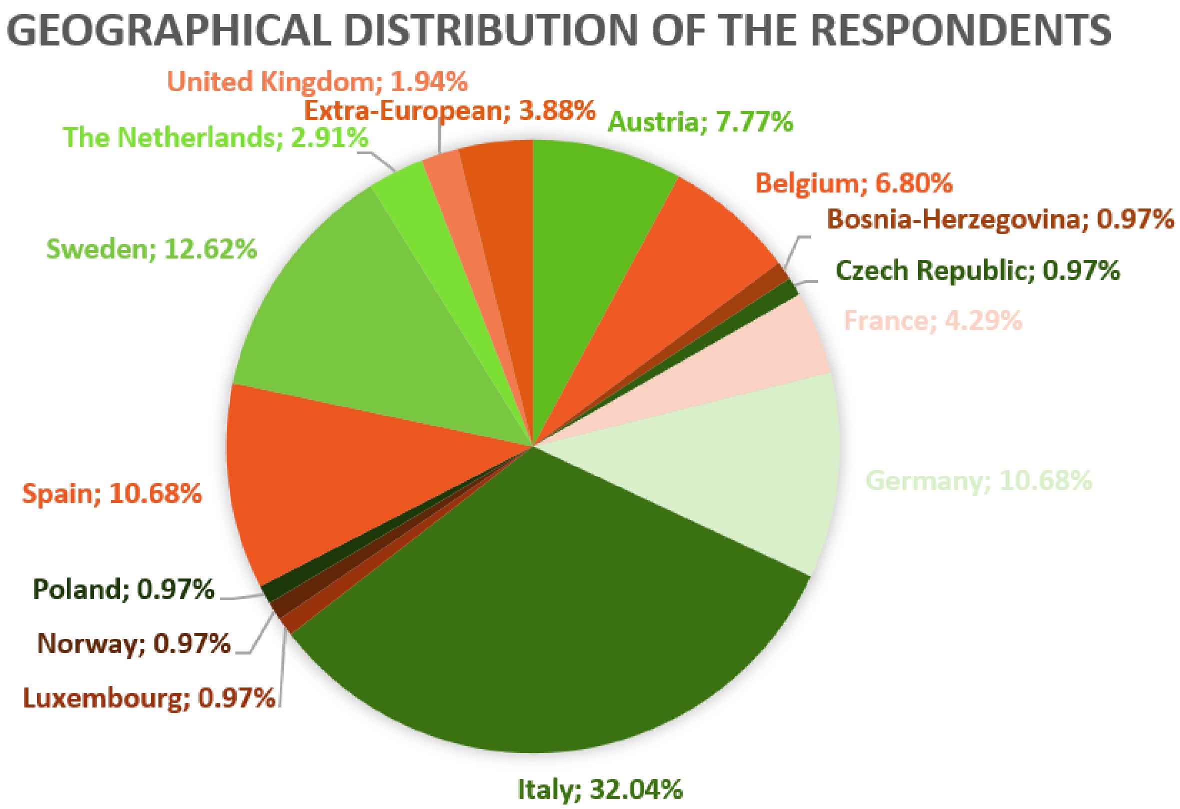


Figure 1. Distribution of the countries of the respondents (question 2 of the survey).

Such as largely expected, almost half of the respondents work in a large company (see **Figure 2**), as the survey was spread in the steel community and most steelworks belong to such category. However, also the academic community working in the steel sector actively participated, with more than 20% of the respondents. Respondents belonging to other kind of company work mostly in consultancy companies but also in trade unions and institutions of the European Union (EU).

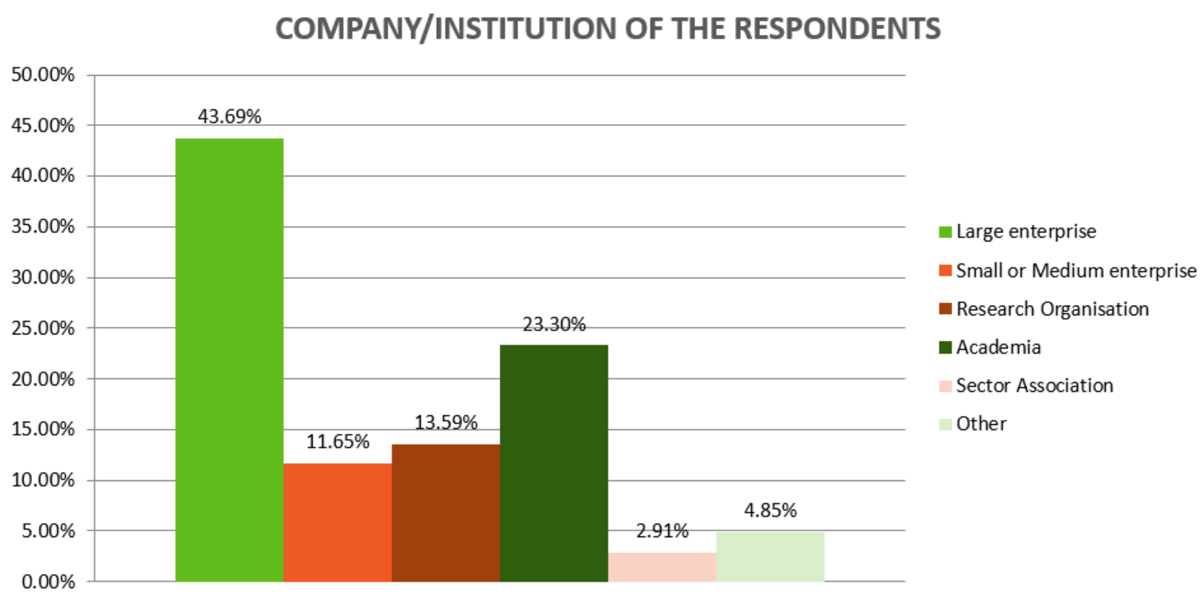


Figure 2. Distribution of the company/institution of the respondents (question 1 of the survey).

Such as shown in **Figure 3**, more than 90% of the respondents belong to companies or institutions that are investigating or planning to investigate the adoption of renewable non-fossil energy and C sources and heating technologies.

Figure 3. Ongoing activity or plans of the respondents' companies or institutions concerning the topics treated by GreenHeatEAF (question 3 of the survey).

According to the collected outcomes of the survey, modelling and simulation tools are used more frequently to investigate the adoption of renewable energy sources and heating technologies rather than the use of renewable C-sources, such as shown in **Figure 4**.

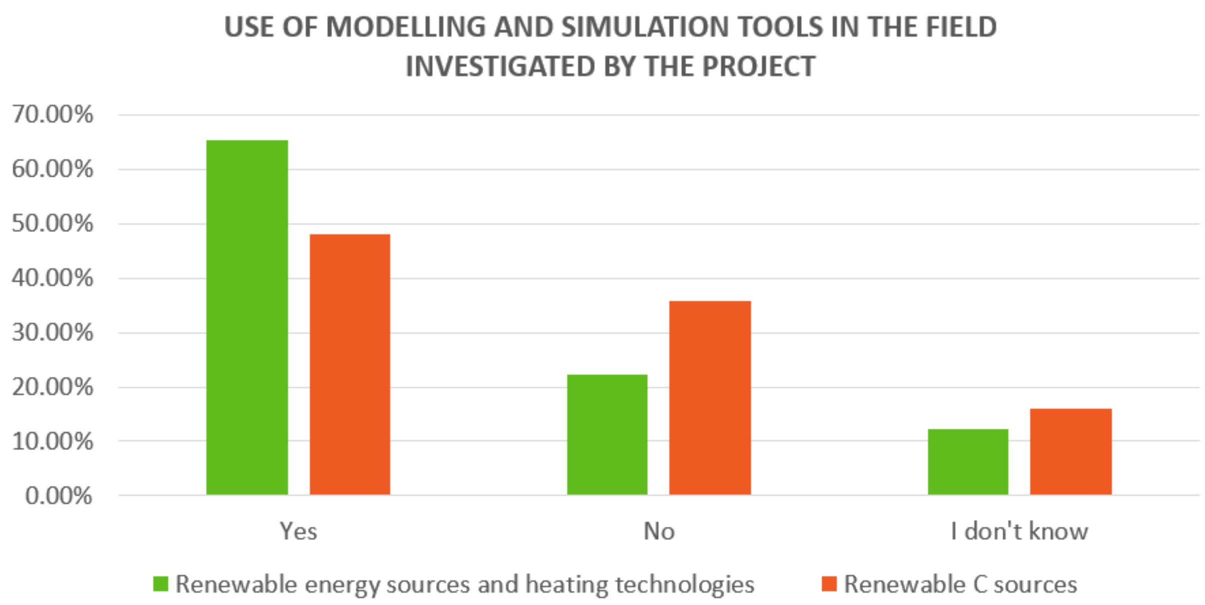


Figure 4. Use of modelling and simulation tools on the topics investigated in GreenHeatEAF (questions 4 and 6 of the survey).

Among the respondents Who indicated an ongoing use of modelling and simulation tools to investigate the adoption of renewable energy sources and heating technologies, 96% indicate that internal solutions are developed to this purpose mostly in Python, Matlab, Simulink, Excel and C, such as schematically depicted by the word clouds reported in **Figure 5,** (Julia, C++ , C#, Fortran and Delphi are also mentioned by a few respondents), while 58% indicate the use of commercial tools, mostly Aspen Plus, Ansys Fluent and Comsol (see **Figure 5**), but gPROMS, OpenFOAM, ThermoCalc and SimuCalc are also mentioned by a few respondents.

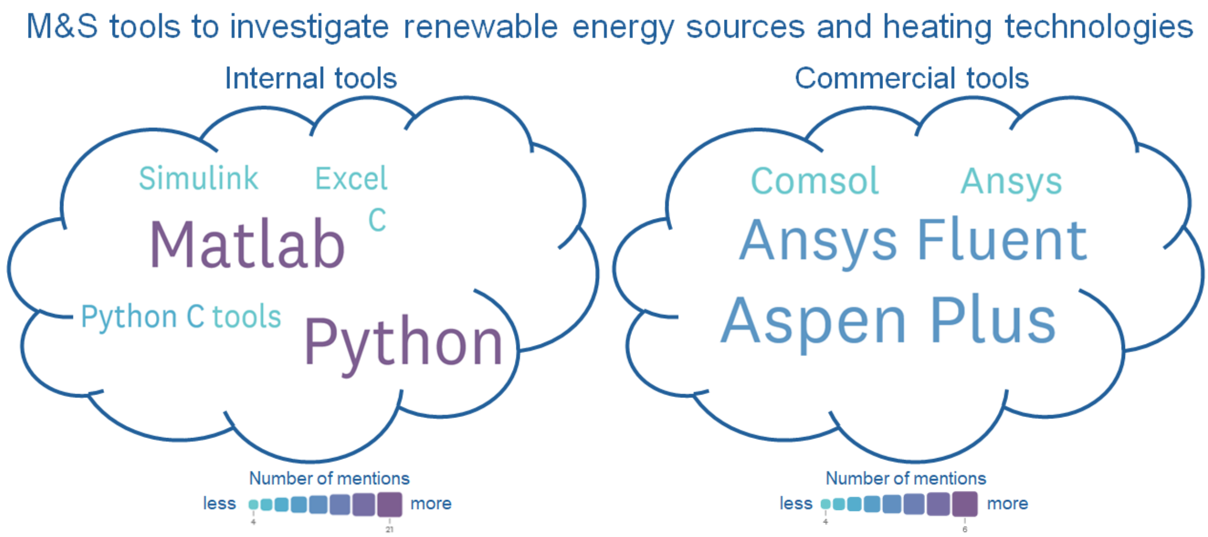


Figure 5. Word clouds depicting the tools adopted to develop models and simulations to investigate renewable energy sources and heating technologies (question 5 of the survey).

Similarly, although in smaller numbers, among the respondents Who indicated an ongoing use of modelling and simulation tools to investigate the adoption of renewable C sources, 82% indicate that internal solutions are developed mostly in Python, Matlab, Simulink and C, such as schematically depicted by the word clouds reported in **Figure 6,** with C++, C# and Delphi mentioned by a few respondents, while 62% indicate the use of commercial tools, mostly Aspen Plus, Ansys and Fluent (see **Figure 6**) but gProms, FactSage, Comsol, ThermoCalc and OpenFOAM are also mentioned by a few respondents.

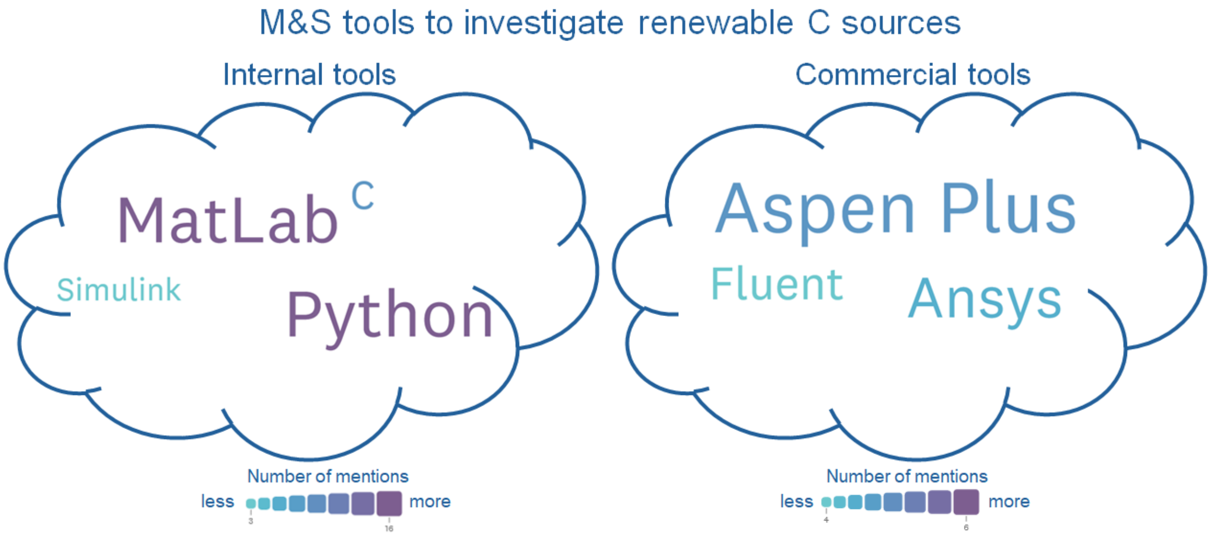


Figure 6. Word clouds depicting the tools adopted to develop models and simulations to investigate the adoption of renewable C sources (question 6 of the survey).

About 78% of the respondents declare a potential interest of their company/institution in modelling and simulation tools to investigate or implement the adoption of renewable non-fossil Carbon and energy sources and heating technologies, such as shown in **Figure 7**.

Among the barriers to the use of modelling and simulation tools to investigate or implement the adoption of renewable non-fossil C and energy sources and heating technologies, the most relevant ones are the uncertainty in the return of investment and the lack of adequate skills in the company, such as shown in **Figure 8**. Other identified barriers are:

- lack of credible roadmaps and plans imposed by governments;
- unclear path towards reaching the goals;
- poor model reliability in complex applications;
- difficulties in the validation of the model outcomes due to lack of relevant plant/process data;
- difficulties in modelling, foreseeing and elaborating all the anomalous events and/or deviations that happens during the production process;
- poor representativity of the process complexity and limited cases definition;
- poor capability to represent many aspects, such as market availability.

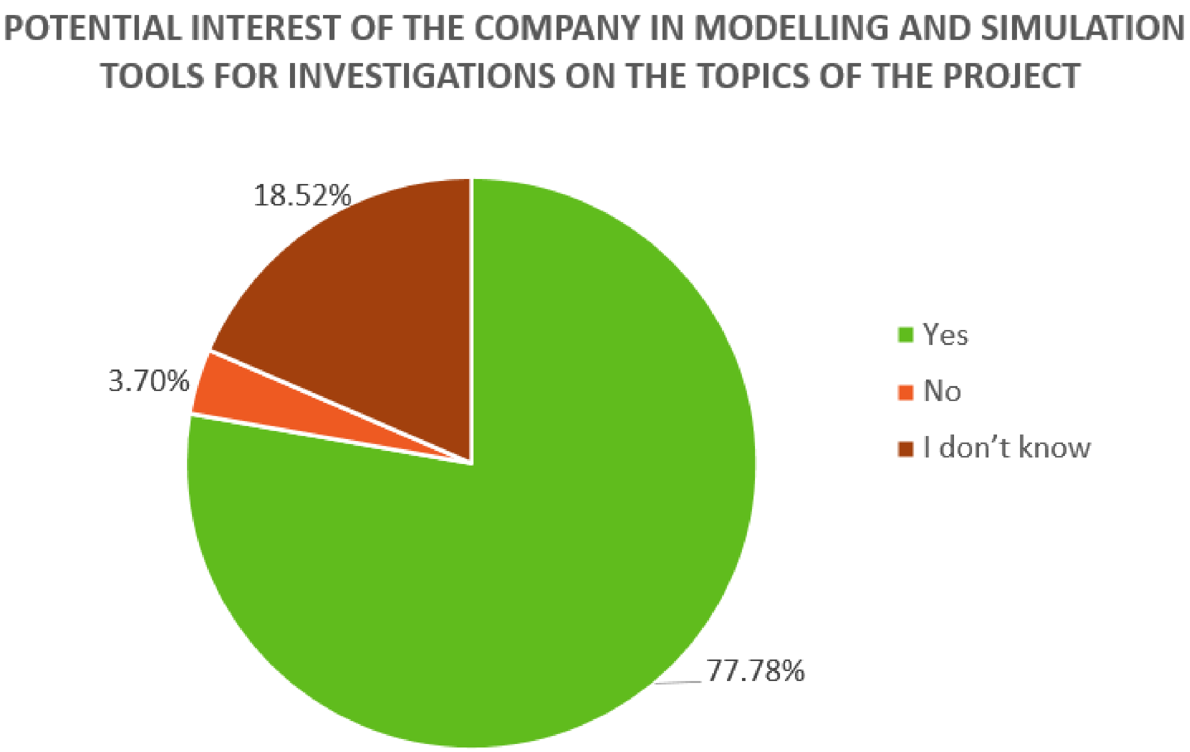


Figure 7. Potential interest perceived by the respondents within their company/institution to apply modelling and simulation tools to investigate or implement the adoption of renewable non-fossil Carbon and energy sources and heating technologies (question 8 of the survey).

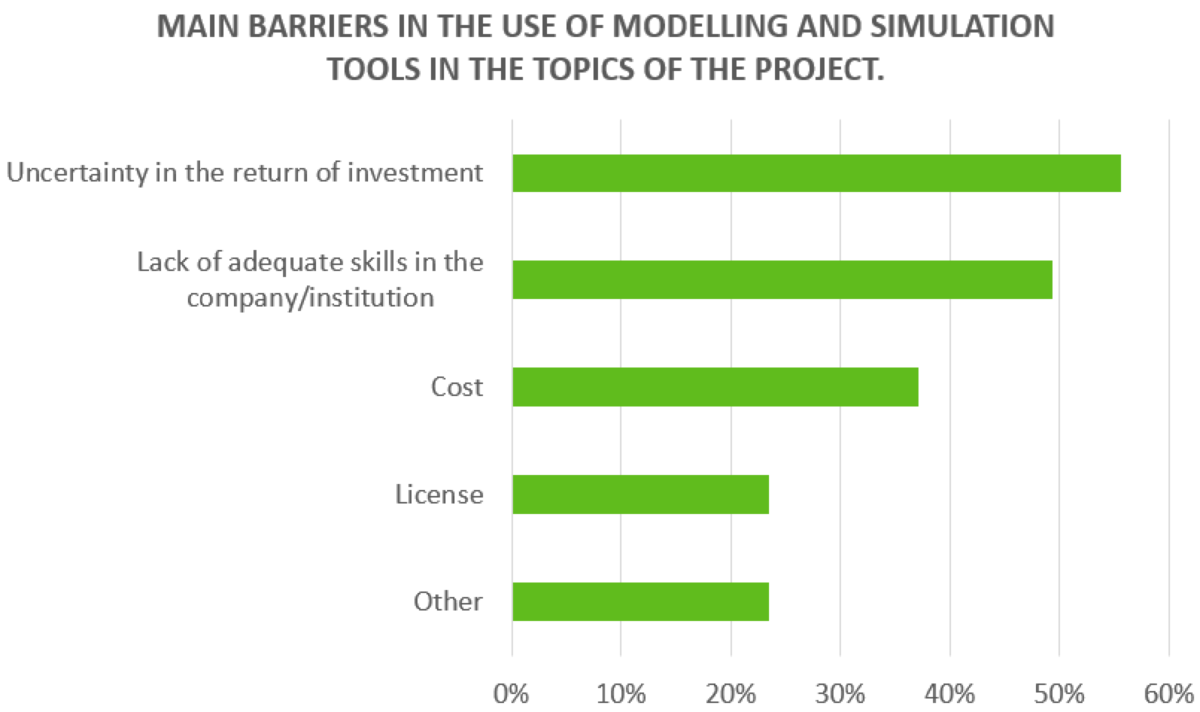


Figure 8. Main barriers in the use of modelling and simulation tools in the topics treated within GreenHeatEAF (question 9 of the survey).

Figure 9 shows that almost half of the respondents never applied models for investigations related to renewable non-fossil C and energy sources management and optimization.

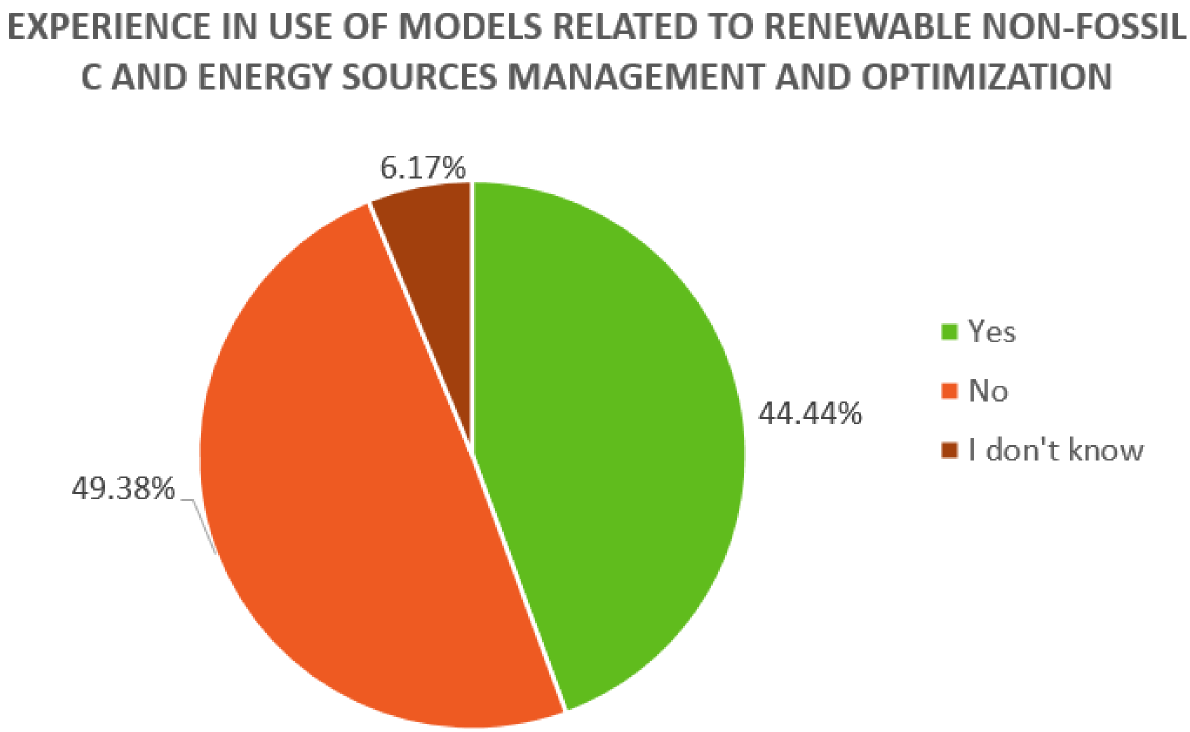


Figure 9. Experience of the respondents in the use of models related to the management and the optimization of renewable C and energy sources (question 10 of the survey).

The main factors that can favour transferability of any kind of model (i.e. a model for any purpose, also not dealing with the topics treated by GreenHeatEAF) are identified in the evident benefits in savings of resources, materials, energy and emissions reduction, model simplicity and usability, as well as evident benefits for product quality and increased yield, such as shown in **Figure 10**. Other enablers are identified in model maintainability and availability of documentation to ensure a reliable long-term use of the model.

On the other hand, the main barriers to model transferability are identified in the difficulty to gather internal data for model tuning and customization, in the lack of adequate skills to run the model and interpret its results and the cost of purchasing the modelling environment, such as depicted by **Figure 11**. Other barriers are identified in:

- lack of adequate documentation accompanying the model and ensuring its maintainability and long-term use;
- excessive time needed to adapt the model and achieve an adequate accuracy;
- lack of internal resources dedicated to models' usage and adaptation;
- lack of trust in models that were initially developed in or for other companies.

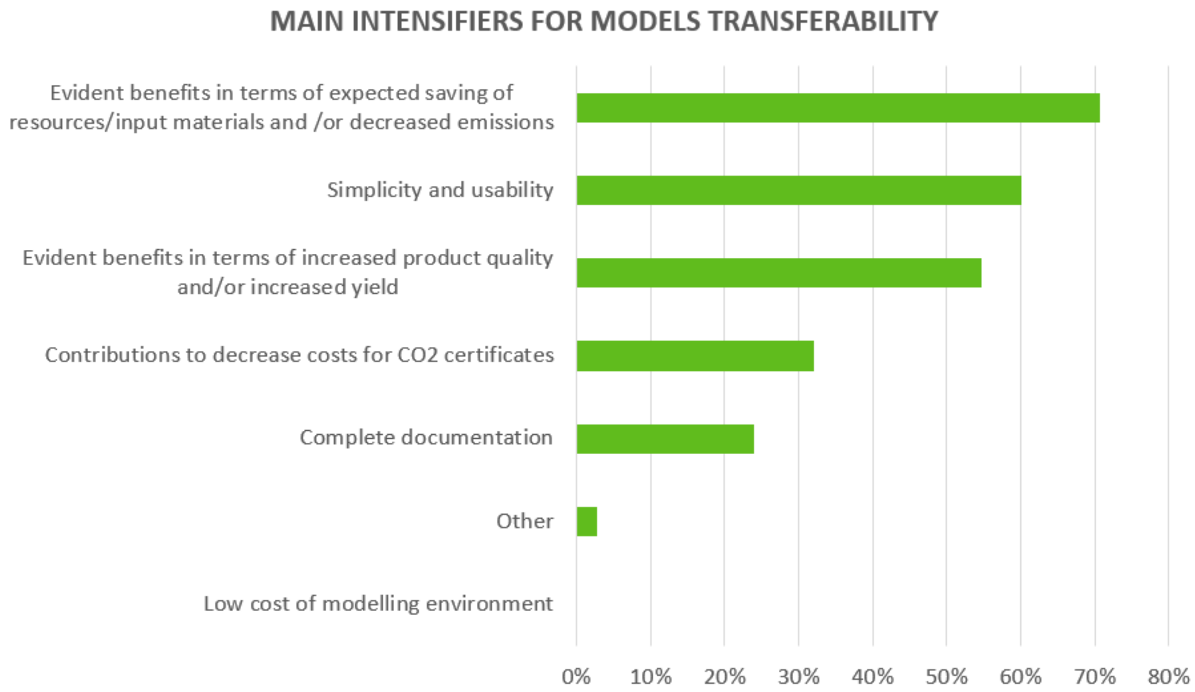


Figure 10. Main intensifiers for the transferability of any kind of model (question 11 of the survey).

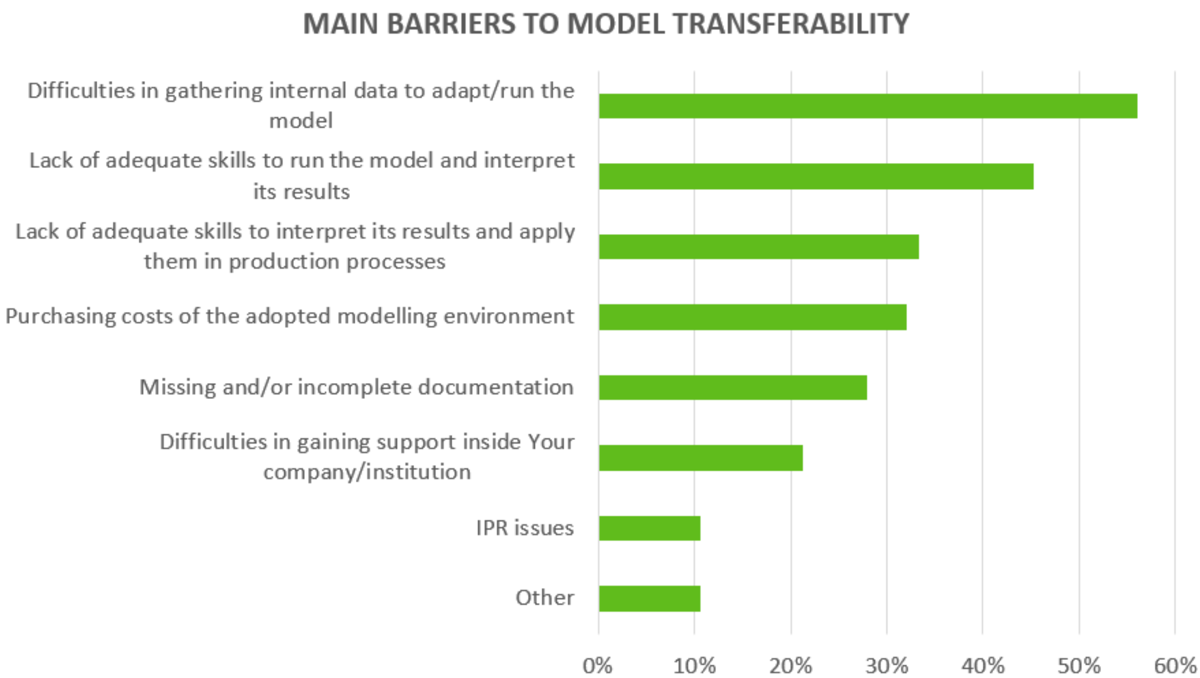


Figure 11. Main intensifiers for the transferability of any kind of model (question 12 of the survey).

3.3 Main lessons learnt from the survey

Although almost half of the respondents of the survey state to have no or very limited experience in the use of modelling and simulation tools on the topics treated by GreenHeatEAF, most of them declare a potential interest of their company/institution in this field, which means that this component of the project activity contributes to fill a gap within the steel community, especially for the adoption of non-fossil and renewable C-sources, where investigations in this direction appear to be less frequent, according to the collected answers. Moreover, the modelling and simulation tools that are being used in the project are among the most cited ones, which confirms the goodness of the selection made by the Consortium. The fact that some of these tools have a not negligible cost apparently does not represent a relevant problem, as cost does not rank high among barriers and low cost does not represent an intensifier for the transferability.

On the other hand, people are encouraged to use modelling and simulation tools when their environmental benefits clearly show up, thus the GreenHeatEAF Consortium is committed to highlight as much as possible the direct positive pitfalls that might derive from the developed tools. This can be achieved, for instance, by developing some even simple add-ons enabling an even rough calculation (for instance, based on averaged data that the user can easily provide) of the potential gains and savings with respect to the standard operating practice.

Noticeably, the most relevant barriers perceived by the respondents is the difficulty in gathering the data required to run the model. Consequently, transferability for the models developed in GreenHeatEAF can be enhanced if the models use “standard” data, i.e. data that are normally collected and easy to find/input by the user and if the model come equipped with some simple tools (e.g. an Excel sheet) that facilitate data collection. However, the survey also highlights a major problem of the steel sector, which refers to an existing gap on data “standardization” especially for assessments related to environmental sustainability of technologies and solution. This issue goes far beyond the scope of the project, as it probably deserves a project on its own, but it is clear that models’ transferability also passes through a clear definition of the meaning of the data required and input and provided as output by the model and a straightforward and not ambiguous interpretation of the results of simulations. Therefore, a sort of “manual for use” should be provided together with the models to facilitate its usage. This also meets another demand clearly highlighted by the survey, i.e. the availability of an adequate documentation which enhances model usability and provide clear guidelines for its adaptation, fine-tuning and maintenance also beyond the project lifespan.

Lack of skills is a further major obstacle to transferability of modelling and simulation tools. Although a good documentation can mitigate the difficulties, the outcome of the survey clearly demonstrate that simplicity of usage needs to be considered since the design stage to enhance transferability of modelling and simulation tools. Moreover, training tools and measures should be provided to help new users at any level. GreenHeatEAF foresees the development of training material, although mostly dealing with security measures to avoid issues on the usage of hydrogen as well as best practices to manage hydrogen. Therefore, a possible solution to support transferability of modelling and simulation tools developed within the project is to include in documentation some training material, such as slides and examples supporting new users in practicing and getting familiar with some of the developed tools.

On the other hand, workforce upskilling and attraction of new talents especially related to digital and “green” skills for the steel sector has been the focus of some past and ongoing EU-funded projects, such as, for instance, the two Erasmus Plus projects entitled “*Blueprint New Skills Agenda Steel: Industry-driven sustainable European Steel Skills Agenda and Strategy*” (ESSA) and “*Skills Alliance for Industrial Symbiosis – (SAIS) A Cross-sectoral Blueprint for a Sustainable Process Industry (SPIRE)*” (SPIRE-SAIS). SSSA and SIDENOR participated to both projects, thus can promote the use of some of the tools derived by these projects to better identify the required skills and promote upskilling measures that provide the main notions for the simulation tools and solutions developed within the project. Moreover, the establishment of a connection with the ongoing project SPIRE-SAIS and with any further follow up of both projects can be a way to amplify the dissemination of projects results and gather hints and feedback to enhance transferability of project outcomes.

4. The Key Exploitable Results of the project

At the proposal stage, 9 KERs have been identified for the project that are summarised in **Table 1**.

Table 1. Summary of the KERs of the project.

KER No	Short description	KER type	Exploitation path	Owner	Other partners involved
KER1	Off-line CFD model for EAF	Know-how	Use	BFI	Sidenor, CELSA, DEW
KER2	Industrial demonstration of biomass use and continuous charging of DRI	Process	Use	Sidenor, CELSA, Hoganas	BFI, SSSA, SWERIM
KER3	Holistic and modular off-line simulation models of EAF-based route including exploitation of non-fossil fuels and materials, comprehensive of auxiliary units	Know-how	Use	SSSA	Sidenor, CELSA, DEW
KER4	Control system for management of heat capacities	Product	Use, license	SSSA	Sidenor, CELSA, AGA
KER5	Use of hydrogen in COJET technology for EAF	Know-how	Use	LINDE	SWERIM, SSAB, CELSA, Hoganas
KER6	Gas and heat recovery monitoring system	Product	license	BFI	Hoganas, B&D
KER7	Hydrogen Enhanced oxy-fuel Combustion for existing EAF burners	Process	Use	BFI	DEW
KER8	Test-bed for heat recovery from off-gas	Process	Other	SWERIM	BFI, Hoganas, SSAB
KER9	Recovery of heat from EAF slag	Process	Use	SSAB	SWERIM, Cementa, Hoganas, CELSA

In the present section the potential barriers to the transferability of each KER are analysed, based on an internal analysis as well as on the indications provided by the AB in two meetings and interviews that were carried out in 2023.

The proposed analysis will be a starting point for the development of the different KERs, but will also be regularly updated and revamped, also based on further stakeholder consultations, with the twofold aim of checking whether the present transferability guidelines are followed for all the KERs and of identifying new barriers that might arise during the development of the project due to internal (e.g. particular features of the KERs which are not yet defined at the present stage) or external factors (e.g. market evolutions, new standards or regulations). Moreover, new KERs might also be generated by the project, which were not considered at the proposal stage, for which the analysis needs to be repeated.

4.1 KER1: off-line CFD model for EAF

4.1.1 Short description of KER1

The scope of KER1 is CFD simulations to optimise EAF heating with main focus on the gas phase. The analyses have two sub-scopes: i) the combustion near a single burner, and ii) the macroscopic scope to optimise resulting overall conditions in the EAF (maximise primary EAF energy efficiency, and secondary heat recovery). A CFD simulation model of the combustion from actual EAF burners is set up. A first simulation calculates the combustion in demonstration scale and is verified using the results of trials with different degrees of H_2 enrichment. In a second simulation the combustion in the EAF burner is calculated at full scale also taking the operational conditions of industrial plants into account. In these CFD investigations, the influence of different degrees of Hydrogen Enhanced Combustion (HEC) on flame (ignition, length, shape, depletion, volume flow rates, gas velocities, temperature field and concentration distribution), thermal stress on the burner are of main concern. Results will be analysed and discussed with industrial partners regarding safe and maximum possible H_2 substitution in the fuel and regarding the optimisation of EAF energy efficiency, heat recovery and dust abatement.

For investigation focused on the HEC influences on the overall EAF process and the off-gas conditions, an existing macroscopic CFD model from previous research projects for the complete EAF gas phase is adapted to the industrial EAF and extended to enable HEC analyses. Studies are performed to investigate the influence of alternative burner gas composition on the 3D temperature, concentration, and velocity field for different boundary conditions regarding decarbonisation by use of H_2 and biogas. **Figure 12** depicts exemplary the temperature distribution inside an EAF during burner operation at the flat bath phase. Results are validated using operational data and results from off-gas temperature and composition measurements and are discussed to derive optimisations of burner configuration, process parameters, process efficiency, suction flow rate of the primary dedusting system and off-gas heat recovery. This will consider the current state as well as future boundary conditions with decarbonisation. Basing on these model results different off gas scenarios can be developed to analyse how to optimise heat recovery.

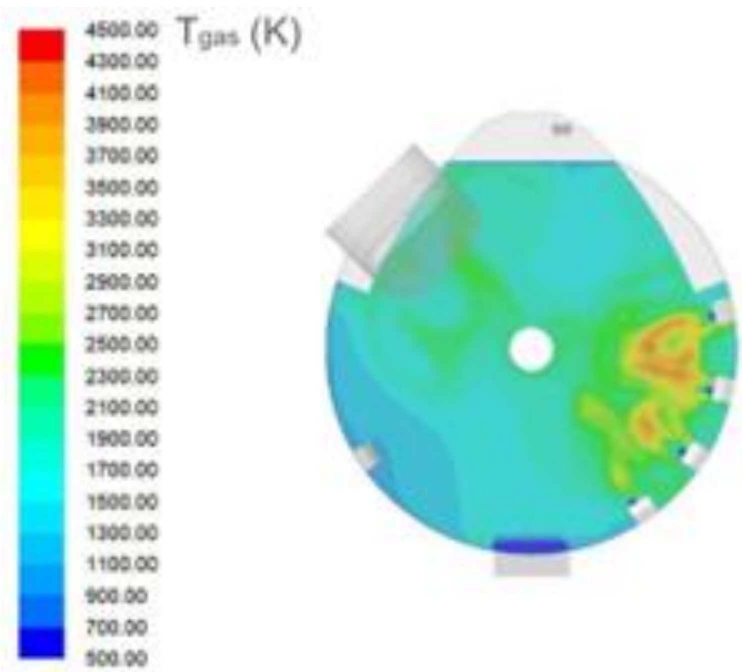


Figure 12. Exemplary temperature distribution during flat bath phase inside EAF during burner operation.

4.1.2 Identified intensifiers for and barriers to transferability of KER1

The CFD results are highly influenced by the individual geometry of the EAF and all-involved parts (burner, lances, etc.). Also, the process parameter (volume flow, energy rate, materials, etc), which are set as Boundary Conditions (BC) to the model, have an impact to the results of e.g., temperature- and flow-distribution and gas concentration. Consequently, the CFD model has to be individually adapted to the plant in order to supply accurate results.

Since CFD simulations are generally an approximation based on several BC, the quality of the results can vary even for the same model. In addition, in daily practice, certain BC are unknown or difficult to measure and have to be considered using assumptions. In the case of transient conditions/process states, this effect is made even stronger and requires also a higher computational effort. However, all these factors come at the expense of accuracy. Inhomogeneous distribution and process states can lower accuracy and make it too complex and complicate to simulate.

Furthermore, external BC may influence the degree of freedom for system optimisation individually corresponding to the respective industrial plant conditions. A typical example are the parameters and conditions of the suction system like volume flow and dust load.

4.1.3 Identified measures to enhance transferability of KER1

To enhance the transferability of the outcome of KER1, operational measuring campaigns for determination of the values and range of temperature, gas concentrations, dust load at different furnace (processes) states should be carried out. This should enhance the validity and the transferability of the outcome in KER1. Comparison by overall energetic balance of the EAF can also help to classify comparable EAF.

In general, the modelling of steady-state conditions/process phases, should be preferred due to accuracy reasons and should be only extended by optional transient simulation for unsteady EAF conditions for cases with well-known BC.

Table 2 summarises the identified potential intensifiers for and barriers to transferability of KER1 and related actions that will be put in place during the project to favour such intensifiers as well as to overcome and/or avoid the materialisation of such barriers.

Table 2. Summary of potential intensifiers for and barriers to transferability of KER1 and related actions.

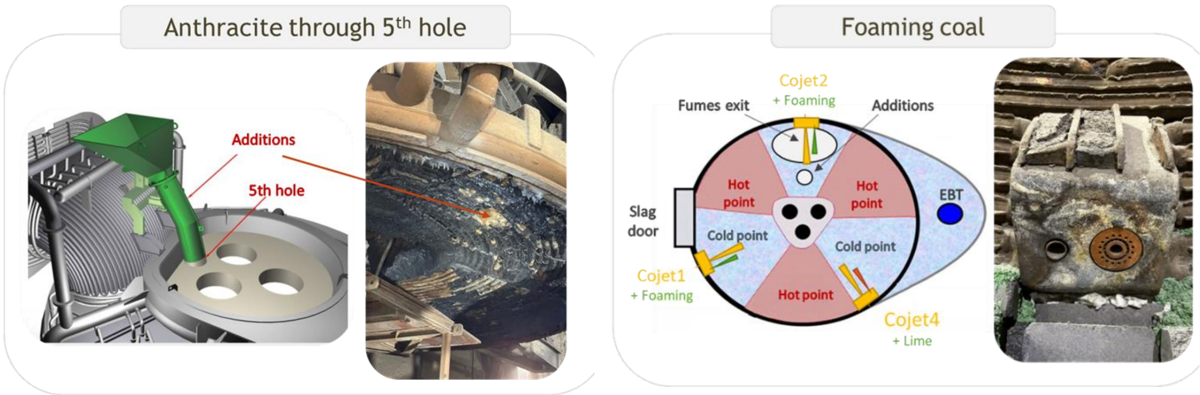
Intensifier for transferability	Enablers
Well-known BC	Temperature, gas concentration, mass flow
Identical EAF type and process parameter	Geometry, EAF type
Steady-state furnace cases/states	Low fluctuations of target values
Separate examination of the individual furnace conditions/states	Definition of characteristic furnace conditions
Barrier to transferability	**Countermeasure**
Unknown BC	Additional measurements
Different EAF type & process parameter	Definition of valid value range
Transient furnace conditions	Well known BC & validation of values

4.2 KER2: Industrial demonstration of biomass use and continuous charging of DRI

4.2.1 Short description of KER2

With the aim to avoid CO_2 emissions in the melting process for the steel production, specifically in the EAF, one option is to substitute the fossil fuels by other renewable organic materials based on carbon like biomass/biochar. Depending on the C-content and other chemical characteristics, such as sulphur, Higher Heating Value (HHV), volatile, ashes, moisture and particle size, this material could directly substitute the anthracite and coal that are used during the process.

Three industrial partners (Sidenor, CELSA and Höganas) will conduct industrial trials substituting different C-sources during the melting process in the EAF. Carbon can be introduced in the EAF in different shapes and ways. In the case of anthracite, due to the higher size of the material, it can be added in the scrap basket or through the 5th hole (a hole in the EAF roof, **Figure 13.a**). On the other hand, foaming coal requires finer grain size and is added through injectors (**Figure 13.b**).



(a) (b)

Figure 13. Main applications of biomass/biochar at the EAF.

Moreover, trials at Swerim pilot EAF will be conducted with injection of bio-carbon (reference case with anthracite) for a selection of use cases for raw materials and processes.

1. Scrap bucket charging
2. Continuous feeding of:
   i. Hot Briquetted Iron (HBI)
   ii. Scrap
   iii. Direct Reduced Iron (DRI)

At first, for the study of the available biomass/biochar, market research has been carried out contacting a total of 20 companies specialised in biomass, identifying 24 different materials from 9 countries. The materials with higher potential were analysed and compared with the technical properties that are required in mentioned applications in the EAF.

4.2.2 Identified intensifiers for and barriers to transferability of KER2

Since different EAF and produced steel grades are considered within the project, the work developed in KER 2 would be easily transferable between most of the steelmakers that work with the EAF route. The similar geometry of the facility as well as the process itself, make it easier to directly use these materials in other companies.

The market research of the available biomass/biochar, and the characterisation of their technical properties can be directly transferred to other companies willing to substitute the carbon sources in their processes, regardless their kind of industry.

In the case of other steelmakers, despite the steel grades and metallurgical processes can be different, it will be reflected in the specific biomass that is selected by each of them, and the amounts to be consumed. The information generated in this project is also valuable for them.

On the other hand, two EAF process models, developed in previous European projects, are being adapted to the new conditions required when using biomass. The use of these models is not directly transferable to other steelmakers, since it should be adapted with specific information about the process itself, employed raw materials, operation variables, etc. Nevertheless, with new data, models could be easily adapted.

However, the main barrier to the transferability is related to the availability in the market of the biomass, in terms of amount, quality and price. There are very few biomass suppliers with a production capacity big enough to provide the amount of material that is required for the total substitution of C-sources in the EAF in continuous operation. In addition, most of them are still working in small-scale and the absence of the economies of large-scale production make prices unaffordable for most of the consumers.

4.2.3 Identified measures to enhance transferability of KER2

To enhance the transferability of the results of KER2, a very detailed monitoring of the process during the industrial trials using different kinds of biomass/biochar will be carried out. The performance of these materials will be evaluated considering some features like the foaming quality (EAF operators' perception, on-site acoustic measurements, total harmonic distortion, general electric data), the amount of slag generated (slag pot weight), the lime consumption due to higher ash content, the steel quality in terms of composition, the changes in productivity due to the electrical energy efficiency, the time of dephosphorizing, the dust generation and the events of violent reactions due to the higher volatile content.

These features that are common to other steelmakers will be used to explain the performance of the biomass/biochar during the transferability of the results activities.

Table 3 summarises the identified potential intensifiers for and barriers to transferability of KER2 and related actions that will be put in place during the project favour such intensifiers as well as to overcome and/or avoid the materialisation of such barriers.

Table 3. Summary of potential intensifiers for and barriers to transferability of KER2 and related actions.

Intensifier for transferability	Enablers
Market research of available biomass/biochar	Suppliers are common for every industry using biomass/biochar
Characterisation of the available biomass/biochar in the market	Information about the technical properties of these sustainable materials
Same EAF process and steel grades	Requirements about Carbon and sulphur content. Volatile, ashes, HHV and moisture
Use of already tested models	Developed in previous projects and adapted to the use of biomass, HBI and DRI
Barrier to transferability	**Countermeasure**
Availability of biomass/biochar	The insufficient supply capacity in terms of quality, amount, and price will make it more difficult a total decarbonisation of the EAF process via biomass. Other renewable materials should be considered to complement the biomass.
Different EAF process and steel grades	Requirements should be analysed in each case and the models adapted to the new BC
Internal constraints about the use of biomass in EAF	The performance of these materials should be studied and tested before implementing them in the routine.
High variability in the features of biomass, biochar, and other alternative C-sources, such as polymers	The effects of a few pre-conditioning processes (pyrolysis and torrefaction) are included in the investigation that is developed with the support of the simulations. The volume of the input material is usually very limited compared to the scrap, which is by itself a highly variable material, thus the features variability can normally be masked by the scrap variability. However, limit values for the main properties of the alternative materials will be identified via simulation.
Relevant cost of polymers and other biomass/biochar	In the final analysis for economic viability, the real cost of such material will be computed considering not only the purchase cost but the achievable savings in terms of emission. Moreover, normally when using material extracted from end-of-life products, such as tyres, the portion of material derived from biogenic source is not considered in the emission computation, while it should be. This will be taken into account in the project.

4.3 KER3: Holistic and modular off-line simulation models of EAF-based route including exploitation of non-fossil fuels and materials, comprehensive of auxiliary units

4.3.1 Short description of KER3

An existing model of the EAF developed in Aspen Plus (see **Figure 14**) is being adapted to consider injection and charge of renewable non fossil C-bearing and alternative Fe-bearing materials, as well as non-fossil fuels. All the considered materials are being modelled and the possibility to use them in EAF process is being implemented. This adaptation is implemented in a more complex simulation model for the whole EAF route that is presently being used for scenario analyses investigating the effects of the injection and charge of different materials and fuels and related ratios e.g., on steel and by-product composition, energy consumption, electric energy efficiency, CO_2 emissions.

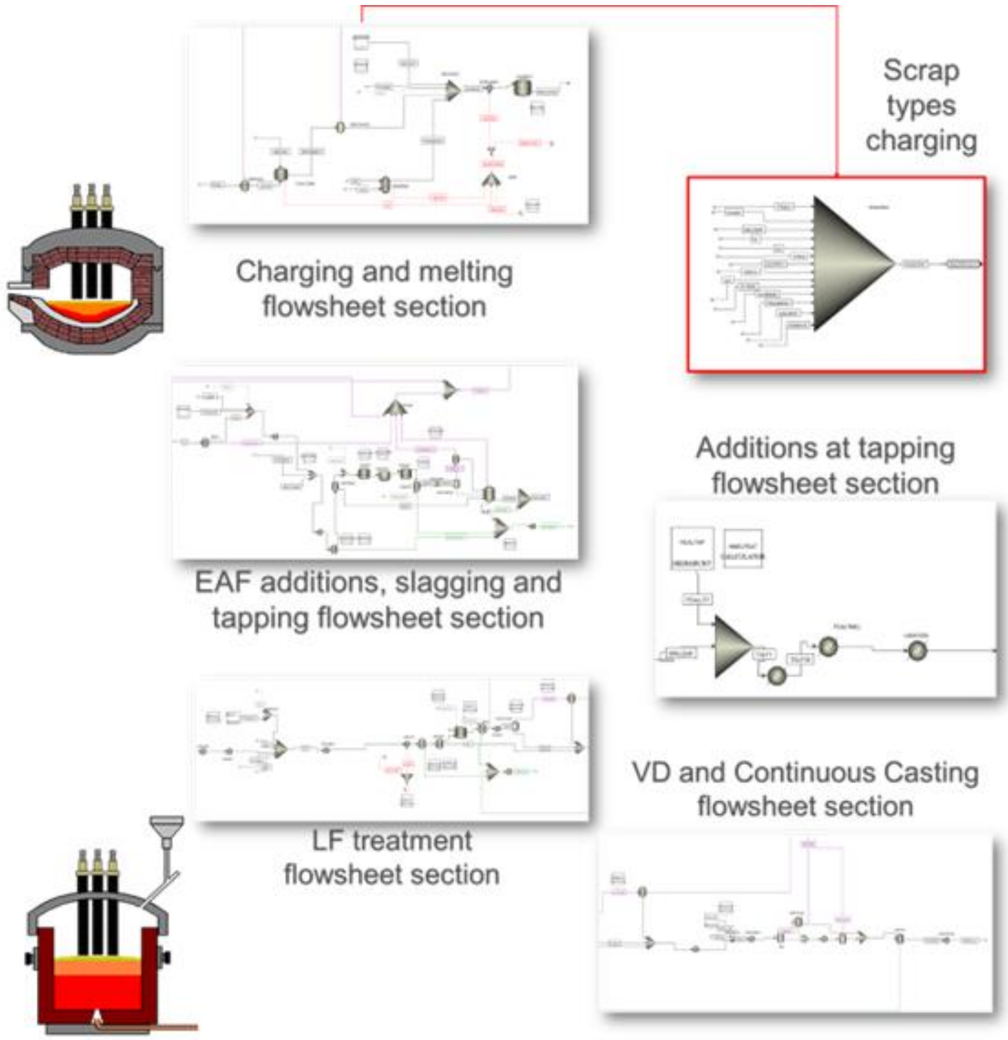


Figure 14. Schematic overview of the Aspen Plus model of the EAF process route.

4.3.2 Identified intensifiers for and barriers to transferability of KER3

Availability of a good set of data to tune the model is indeed a critical factor for its transferability to other electric steelworks.

Moreover, the model is implemented in Aspen Plus, which is a commercial software to be acquired by the companies in perpetual or annual license. The cost can represent a barrier. On the other hand, if the model enables relevant savings in terms of energy and materials costs, CO_2 emissions and continuous process and product quality improvements, such savings can even pay back the cost for a yearly licence,

Lack of suitable know-how inside a company is a further barrier to transfer the model in the industrial context.

4.3.3 Identified measures to enhance transferability of KER3

The Aspen plus-based model is fed with data that are normally found in steelworks; thus, no special sampling campaigns are needed to transfer the model. Moreover, the model is being validated and tuned for different "families" of steels (i.e., groups of steel grades showing similar features), and a procedure is already established to iterate the tuning procedure for further families, the overall model and tuning procedure being the result of a study started almost one decade ago and supported by cooperations with different steelworks producing quite different steel grades.

When the model is used off-line for scenario analyses, normally the analyses have a limited duration, as they are done to drive some strategic choice or investigate the possibility to modify operating practices, therefore, these analyses do not necessary require a perpetual licence.

Moreover, once the model is tuned, surrogate models or reduced order model could be developed using data that are generated by the model together with new experimental data. Therefore, thanks to the possibility to enlarge the data basis, which is enabled by the model, a wide variety of data-driven approaches can be adopted jointly or alternatively with respect to merely physics-based or heuristic models. This is also the approach to be followed when on-line version of the model is required for optimization purposes, such as planned within the project for the implementation of Model Predictive Control approaches to optimize the management of heat capacities. In effects, this also helps reducing the computational burden and time.

Finally, to favour transferability of project results, the models will come equipped with a detailed documentation that supports understanding of their main principles and basic assumptions.

Table 4 summarises the identified potential intensifiers for and barriers to transferability of KER3 and related actions that will be put in place during the project favouring such intensifiers as well as to overcome and/or avoid the materialisation of such barriers.

Table 4. Summary of potential intensifiers for and barriers to transferability of KER3 and related actions.

Intensifier for transferability	Enablers
Data availability for model tuning.	No need for special "sampling campaigns": the model is fed with data that are usually collected in most steelworks.
Simplicity in model tuning and adaptation	A consolidate procedure for model tuning is available.
Gaining economical support for model maintenance	Achievable savings in terms of energy and materials costs, CO_2 emissions and continuous process and product quality improvements
Barrier to transferability	**Countermeasure**
License cost for the simulation environment	Possibility to develop surrogate/simplified models using data generated by the model
Computational cost and time	Possibility to develop surrogate/simplified models using data generated by the model
Lack of know-how in the company to use and maintain the model	Production of detailed documentation on the developed models.
Limited capability to represent dynamic phenomena	Although Aspen Plus is not the best tool to represent some dynamic phenomena such as dust diffusion phenomena, dusts contents in fumes and dust composition are evaluated, and a finer tuning can be developed provided that data are available.

4.4 KER4: Control system for management of heat capacities

4.4.1 Short description of KER4

Efficient control systems need to be designed to manage heat capacities and flows by supporting process operators through ad hoc designed Decision Support Systems (DSS). In such context, Model Predictive Control (MPC) and in general real-time optimization systems, already proved to be effective in power system balancing and in managing energy streams in the context of traditional steelmaking routes in compliance with a set of complex constraints.

The basic idea behind MPC is to exploit dynamic models of the process, which can be described by data-driven models (e.g. standard system identification, linear empirical, Machine Learning (ML), etc.) or physic-based ones, to optimise the current timeslot while considering also future ones. This is achieved by optimizing, for a finite prediction horizon, an ad-hoc objective function that describes the plant behaviour from a specific point of view (economic balance, energy consumption, etc.). The controller closes the loop with the controlled plant by implementing only the current control action on the system and measuring the actual behaviour, before optimizing again, repeatedly.

Within GreenHeatEAF, MPC will be applied to manage heat capacities in electric steelmaking, which is a complete novelty with respect to the state of the art, and to provide optimized control suggestions to improve alternative C-sources and non-fossil fuel usage at optimal process performance while reducing resource and energy consumptions.

4.4.2 Identified intensifiers for and barriers to transferability of KER4

With respect to more traditional control and optimization approaches, MPC shows the capability to anticipate future events and can suggest control actions accordingly, in particular when the future disturbances or future scheduling of the processes is known in advance. Therefore, it is particularly powerful in managing complex interacting processes which exchange streams for which the time trends of the flows depend also on external conditions (e.g., market, weather parameters, etc.) that can be forecasted, although with limited accuracy. Within a MPC approach, models' accuracy could be a key factor, but not all the system components play the same role in achieving a reliable result of the optimization procedure. On the other hand, the control system's transferability heavily depends on maintainability and transferability of forecasting and plant models, which should be carefully considered since the design stage.

Moreover, a suitable infrastructure to collect the data that are needed to tune and run the model "almost" in real time should be available, which has a cost that should be paid back by the savings achievable through the optimization.

Additionally, the complexity of control strategy and the approach for its design and implementation heavily depend on the modelling complexity (e.g. non-linearities, mixed logical dynamics, etc.). For this reason, the design approach for models and control systems must balance accuracy requirements for the modelling and computational burden of control system that must operate in real-time. Implementing and operating complex control systems based on MPC could require expensive commercial libraries for solving the optimization strategy in real-time. Also in this case, the cost related to commercial libraries and software should be paid back by the economic feasibility of the proposed approach.

4.4.3 Identified measures to enhance transferability of KER4

A suitable trade-off needs to be achieved between models' accuracy and complexity in view not only of their computational cost but also of their maintainability and transferability, considering the impact that the different components can have on the optimization results. In other words, the basic principle of “as simple as possible, as complex as needed” should be followed. Within the project, at the very beginning a *Minimum Viable Product* (MVP) will be developed exploiting very simple models, whose accuracy might be initially not very high, but which are simple to set-up and tune. Completeness (i.e., coverage of all the required components) will be prioritised with respect to accuracy in such initial stage. Afterwards, complexity will be gradually enhanced only for those models which show a relevant impact on the optimisation performance.

The transferability of the control approach can be enhanced by balancing its complexity and computational burden. For achieving this scope, several techniques can be applied to simplify the control approach (e.g., linearization, simplification of the problem, etc.). In the case that the optimization of plant operations can only be guaranteed through sufficiently complex control systems, in some development environments and languages (such as Python and C#) several sufficiently stable and reliable open-source libraries can be used for deploying the solutions identified.

As far as data availability is concern, the possibility to partly rely on the existing IT system, by duplicating the data in a local data repository (remotely accessible to the developers), detached from the one used for standard process control, and the availability of an on-site virtual machine to setup, test, and run the models and the optimization solution can be a safe and cost-effective way to overcome criticalities related to the need to preserve normal process operating conditions while developing and testing the optimization solution exploiting real data.

Table 5 summarises the identified potential intensifiers for and barriers to transferability of KER4 and related actions that will be put in place during the project favouring such intensifiers as well as to overcome and/or avoid the materialisation of such barriers.

Table 5. Summary of potential intensifiers for and barriers to transferability of KER4 and related actions.

Intensifier for transferability	Enablers
Data availability for model tuning.	Availability of a suitable infrastructure for real-time data collection
Simplicity in model tuning and adaptation	Keeping the models as simple as possible, also by sometimes sacrificing accuracy, as the optimisation algorithm can partly compensate for less impactful processes. Formalising a simple procedure for model tuning.
Gaining economical support for system maintenance	Achievable savings in terms of energy and materials costs, CO_2 emissions and continuous process and product quality improvements
Barrier to transferability	**Countermeasure**
Models used in MPC do not fit to a different steelwork.	Starting with simple models, easy to transfer and understand and increase model complexity only when it is “paid back” by a significant improvement of the optimization results.
Computational cost, time and complexity	Starting with simple models and simple optimization formulation, and gradually enhance complexity only for the most impactful processes/components.
Cost of control strategy design and implementation	Open-source libraries (in python and C#) can be exploited for developing and deploying the identified control solution
Cost of the infrastructure establishment, system development, test, and maintenance	Establish a local data repository and a virtual machine to set-up, fine tune and test the system

4.5 KER5: Use of hydrogen in COJET technology for EAF

4.5.1 Short description of KER5

The use of CoJet burners in EAF steel production is common practice. The burners operate in two basic modes. During the melting phase the burners are designed to support the melting process and during the refining phase they are designed to inject oxygen (see **Figure 15**).

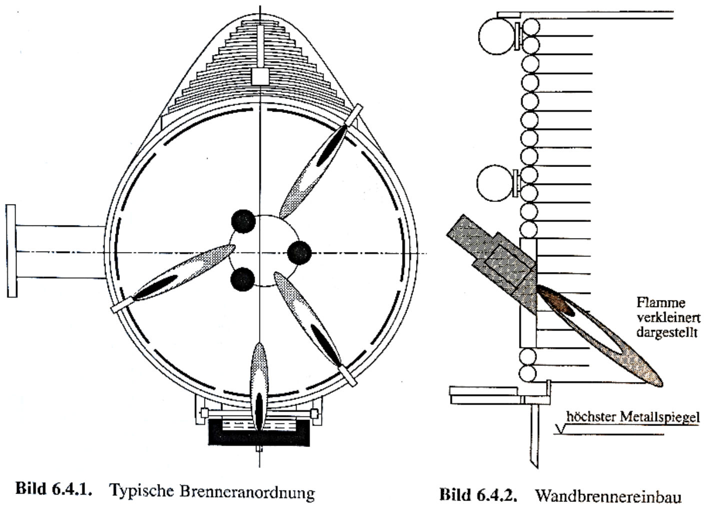


Figure 15. Scheme of a CoJet burner (source: Elektrostahl Erzeugung, Karl-Heinz-Heine. 6.4.1 Zusatzbrenner).

The burners are operated with fossil fuels such as natural gas.

Depending on the furnace diameter and different production, the burners are arranged and operated differently. A distinction can be made between different metallic feeds such as scrap, HBI, DRI or liquid feed. Different scrap preheating methods, like ConSteel or different shafts, can also be used for preheating scrap.

The burners are arranged in the furnace to avoid cold spots in the furnace. In AC furnaces, this means between the electrodes, where the arcs contribute little energy. Depending on the diameter of the vessel, different numbers of burners can be used. For example, 3 CoJet burners are usually installed in a common 120 t EAF. For larger diameters, more burners are used to ensure even energy distribution and oxygen input.

During the melting phase, the CoJet burners are operated as pure oxygen/fuel burners in which case the melting process is supported. Oxygen is then blown into the furnace during refining phase.

During the charging or tapping phase, the burners are set to pilot mode in to ensure rapid raising of power after closing the lid.

The purpose of KER5 is the replacement of fossil fuels for CoJet burners with hydrogen as a fuel. Assuming that the electrical energy for the electric arc of the EAF is green, another major part of CO_2 emissions at the furnace can be eliminated. That will bring the CO_2 emissions at the EAF on the lowest technical possible level.

4.5.2 Identified intensifiers for and barriers to transferability of KER5

Linde has more than 138 CoJet installations worldwide. Hydrogen combustion itself is known topic. Hydrogen flames have a higher temperature than fossil fuel-based flames that's why hydrogen for the scrap melting phase can be an advantage. It could reduce the Tap-to-Tap time or if a productivity increases in not needed the electrical demand during the melting phase. During refining the CoJet is run in lance mode. Linde made trials at Tonawanda lab in the USA with different fuels for coherent jet. It was shown that the length of the coherent jet (in air) was significantly increased in length. That will increase the penetration depth of the jet and increases its efficiency. If this behaviour is the same into the melt will be seen during the trial at SWERIM.

EU Emissions Trading System (ETS) prices increases over the last years significantly. Before the energy crises the price per tonne of CO_2 was about €30. Excluding the peak in summer 2022, the prices are still rising (current price: above €80/tonne of CO_2). In addition, the free certificates for heavy industries are decreased what leads to increased production costed based on CO_2.

The situation on the natural gas market and other fossil fuels is also much more difficult compared to the past. Also, here the prices for natural gas (on spot market) are double as high as a few years ago. The availability of natural gas is on top much more difficult compared to before the energy crises.

Summarized, the advantages of use of hydrogen as a fuel is an intensifier for the installation of a hydrogen based CoJet burner.

In many cases experience with hydrogen are rather lower compared to fossil fuels. That's why it could be needed to educate people working at the furnace/ maintenance for the furnace and responsible for hydrogen supply.

Hydrogen is a still a rare product. The availability of hydrogen is based on different factors. If the colour of hydrogen (grey or green) is not the question the availability of green electricity for green hydrogen and natural gas for grey hydrogen is the key factor. Therefore, the installation of hydrogen supply in the range that its suitable to convert a fossil fuel based CoJet to a hydrogen based CoJet, is based on the availability of the needed energy source (natural gas or green electricity).

Based on the this the hydrogen price will be varying on the location where it is produced. To be compatible for steel producers the question needs to be answered if a higher product price for a CO_2 reduced steel product will be paid by the end customer, or if a higher price for hydrogen compared to fossil fuel will just increase the production cost.

All in all, the decision for hydrogen for CoJet burner will be based on the availability of hydrogen and its price.

4.5.3 Identified measures to enhance transferability of KER5

The measure to increase CO_2 prices like EU-ETS will increase the cost for the use of fossil fuels and make the use of hydrogen (if available), more and more attractive. Especially in regions where green electricity is in suitable amounts available the use of green hydrogen is an advantage for the steel producers.

If the availability is once given, the supply situation and the on-site pipeline network as well as the flow skids needs to be checked. Based on studies, in many cases the existing natural gas pipelines can be used to the supply of hydrogen. Valves, gaskets, flowmeter etc. needs to be checked individually. That counts for pipeline and flow skids. If the revamp of the current installation to hydrogen ready is possible the transition costs are manageable.

The European Union is currently offering different fundings for the transition to a green industry, which is helpful for the business case. Once the installation is done the running costs are expected to be reduced in the future when hydrogen is available in big amounts.

As a soft key, if the advantages of using hydrogen in the EAF steelmaking process are high enough to reduce the additional cost compared to a fossil fuel, this mid increases the transition to use of hydrogen for CoJet.

Table 6 summarises the identified potential intensifiers for and barriers to transferability of KER5 and related actions that will be put in place during the project favour such intensifiers as well as to overcome and/or avoid the materialisation of such barriers.

Table 6. Summary of potential intensifiers for and barriers to transferability of KER5 and related actions.

Intensifier for transferability	Enablers
Rising CO_2 prices (EU-ETS)	Reduces cost gap between hydrogen and fossil fuel
Rising prices for fossil fuels	Reduces cost gap between hydrogen and fossil fuel
Higher flame temperature with hydrogen	Reduced melting time (increased productivity or reduction in electrical energy demand)
Deeper bath penetration	Increased efficiency during refining (increased productivity or reduction in electrical energy demand)
Barrier to transferability	**Countermeasure**
Availability of (green) hydrogen	Increase in hydrogen facilities and its production
Higher price for hydrogen than fossil fuel	Higher availability of hydrogen will reduce the price
High transition cost for hydrogen ready system	Funding from different authorities (like EU)/ usage of existing equipment and revamp
Lack of experience with hydrogen	Creating awareness and provide trainings

4.6 KER6: Gas and heat recovery monitoring system

4.6.1 Short description of KER6

One current problem of the process is that a large part of the EAF energy input leaves the process with dusty exhaust gas. In order to find an optimum compromise between adequate dedusting and minimum energy losses more knowledge regarding the boundary conditions is needed. The EAF process has different steps and the amount of dust produced depending on the different steps is unknown. Generally, the dust tends to settle down near the EAF and in the duct causing maintenance issues if suction and flow velocities are too low. KER6 includes the optimisation of the exhaust gas extraction basing on new measurement data. The existing process measurement system will be extended with a fast and continuous Acoustic GAs temperature Measurement (AGAM) in the non-cooled area of the duct and thermocouples in the cooled area close to the EAF will be installed. Further detailed information about the off-gas will be acquired by a measurement campaign. New and existing data will be analysed by mathematical methods and a concept for a support system for the operators will be developed. Main aim is to optimize the suction flow rate of the primary dedusting system to increase energy efficiency of the EAF. To optimize the exhaust system BFI will analyse three different points. Point 1 is the point where the flue gas and the false air where mixed. Point 2 defines the complete combustion. Point 3 is where the off-gas is cooled down in the exhaust duct. **Figure 16** shows the described concept.

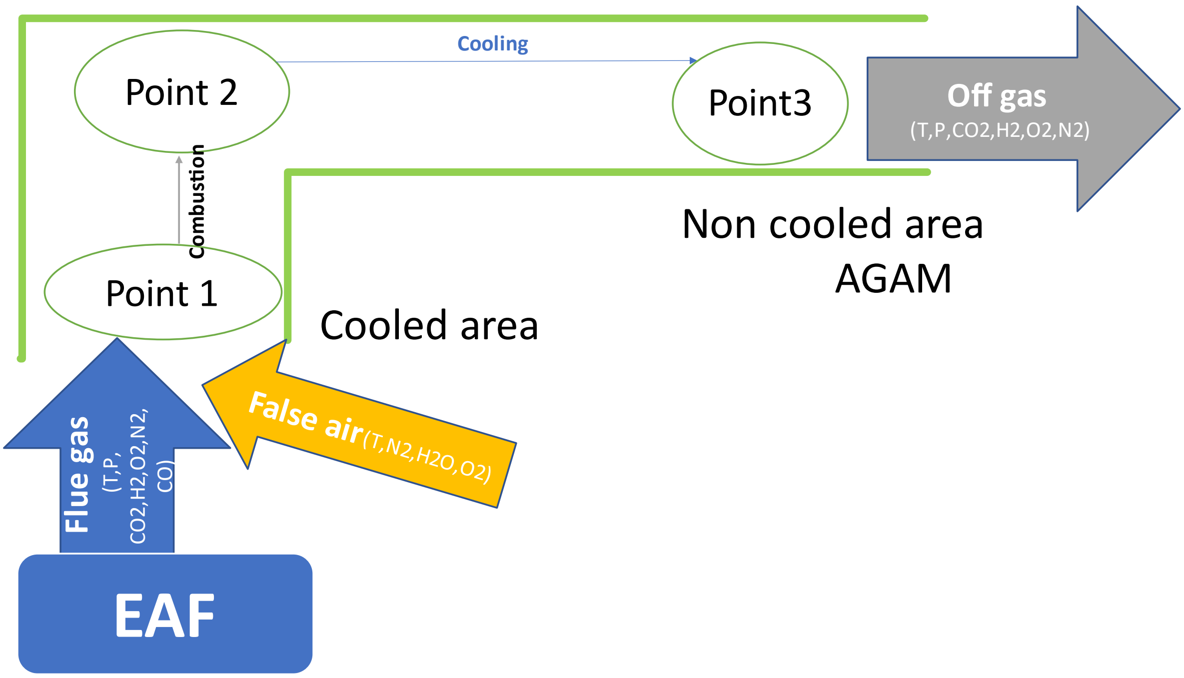


Figure 16. Schematic representation of the flue gas duct to calculate the heat recovery potential.

4.6.2 Identified intensifiers for and barriers to transferability of KER6

One difficult point of this work is to reach a trade-off between using the heat energy in the EAF and a sufficient dedusting, as a high exhaust rate reduces the usable heat energy in the EAF. Another aspect is the unknown dust generation depending on the different process steps. Therefore, a measurement campaign is needed to get more information about this aspect. The new gas monitoring system based on AGAM delivers very fast information about gas temperature and indications about the flow velocity. The drafted support system exploits all information for more efficient gas handling and EAF operation.

4.6.3 Identified measures to enhance transferability of KER6

To enhance the transferability of the outcome of KER6, operational measuring of the temperature, gas concentration, EAF process parameters and fan power should be carried out. An energy balance would also make clear how much energy is lost in the process and how much is used for the process or recovered.

Table 7 summarises the identified potential intensifiers for and barriers to transferability of KER6 and related actions that will be put in place during the project favour such intensifiers as well as to overcome and/or avoid the materialisation of such barriers.

Table 7. Summary of potential intensifiers for and barriers to transferability of KER6 and related actions.

Intensifier for transferability	Enablers
Well- known process parameters	Temperature, gas concentration, fan power
Steady-state furnace cases/states	Low fluctuations of target values
Separate examination of the individual furnace conditions/states	Definition of characteristic furnace conditions
Barrier to transferability	**Countermeasure**
Unknown process stability	Additional measurements, measurement campaign
Different EAF type	Definition of valid value range
Transient furnace conditions	Validation of values

4.7 KER7: Hydrogen Enhanced Combustion and enhanced ambient air for existing EAF burners

4.7.1 Short description of KER7

An oxy-fuel EAF natural gas burner operating at the EAF of Deutsche Edelstahlwerke (DEW) was downscaled and hydrogen enhanced combustion (HEC) at 300 kW will be investigated with this burner at a pilot test facility. The test facility is currently in preparation and the burner is being manufactured (see **Figure 17**). The tests of combustion characteristics, flame shape and size, temperature and concentration field deliver the basic and validation data to set up the simulation model of this burner. The simulation model is needed for the simulative investigation of the EAF heating process with HEC to substitute the fossil fuels for steel production.

The technology for HEC with existing EAF burner will be at TRL 5. The results from simulation of EAF heating are the basis to operate the full scale EAF burner with HEC. With the exploitation of HEC with existing EAF burners at full scale TRL 7 is reached. This exploitation is foreseen to be performed after the project.

Relevant results and findings from burner simulation and EAF heating with HEC are the prediction of flame size, heat input into the melt as well as the thermal stress on the burner as an issue for the secure operation.

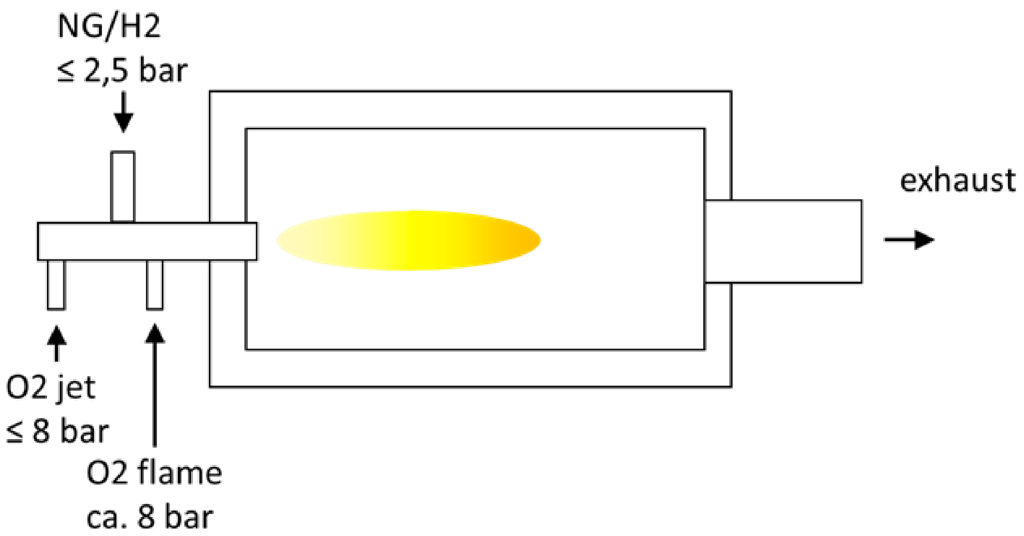


Figure 17. Schematic sketch of test setup for burner trials at BFI pilot test facility.

4.7.2 Identified intensifiers for and barriers to transferability of KER7

The outcome of these investigations are findings and results regarding the possibility to operate the existing burner at DEW with a mixture of hydrogen and natural gas. The highest ratio of hydrogen to natural gas in this fuel-mixture for a safe burner operation as well as the EAF heating predicted by simulative investigations (KER1) are the most important results for operators. With these results the operator has information from the technical side to if HEC is an option for the EAF heating or not.

The decrease of CO_2 emissions by substituting natural gas proportional by hydrogen as a fuel is an intensifier for transferability. Additional fuel prices as well as the availability of hydrogen can be an intensifier as well as a barrier for transferability. Costs for investigations for the hydrogen supply can be barrier, safety issues and the regulations for i.e., NO_x emissions and safety related to hydrogen use can be a barrier as well.

4.7.3 Identified measures to enhance transferability of KER7

The existing regulations must be modified regarding NO_x for Hydrogen combustion. Energy balancing and calculating the required energy for the use of either HEC as well es electric power as energy input in the EAF process gives important information for decisions to apply this technology at current EAF. The security in hydrogen and natural gas supply enforces the transferability as well.

Table 8 summarises the identified potential intensifiers for and barriers to transferability of KER7 and related actions that will be put in place during the project favour such intensifiers as well as to overcome and/or avoid the materialisation of such barriers.

Table 8. Summary of potential intensifiers for and barriers to transferability of KER7 and related actions.

Intensifier for transferability	Enablers
Technical results and findings of necessary operation conditions	Safe burner operation, high proportion of hydrogen in fuel mixture
Decrease of CO_2 emissions and cost for CO_2 certificates	Reduces cost gap between hydrogen and fossil fuel
Safe supply of hydrogen	Increased and safe use of hydrogen
Increasing prices for fossil fuels	Reduces cost gap between hydrogen and fossil fuel
Barrier to transferability	**Countermeasure**
Missing hydrogen supply affords hydrolysers. Additional investment costs for hydrolysers are necessary.	Efficient operation and strategic hydrogen generation at periods with low electricity prices.
Missing regulations for NO_x emissions for hydrogen combustion as (1) emission limits are only formulated for natural gas and “other fuels” in BEF FMP and (2) given definitions of NO_x limits do not allow a fair comparison between different fuels and oxidizers. The calculation methods in regulations and measuring methods are moist based. This leads to higher NO_x emissions at H_2/O_2 combustion for hydrogen combustion compared to natural gas.	Revision of NO_x limit definitions for flexible fuel operation.

4.8 KER8: Test-bed for heat recovery from off-gas

4.8.1 Short description of KER8

A testbed for heat-recovery will be designed and constructed to demonstrate the concept of modular regenerative heating of gases from future EAF off-gas. Tests on pilot scale will be carried out where heat will be transferred to carrier gases through 50 kW ceramic recuperator with synthetic EAF off-gas doped with dust.

The technology is currently at TRL 4-5. The ceramic recuperator was manufactured of SiSiC, tested, and validated at pilot scale in previous investigations. Heat transfer of about 50kW sensitive heat from off gas at 1.200°C from natural gas combustion to preheat air from ambient temperature to about 800°C was achieved in these tests. The pressure loss in the ceramic recuperator is low and it is operated at ambient pressure.

During the trials in this project the recuperator will be investigated regarding heat resistance, thermal stress, deposits on recuperator surface and efficiency.

4.8.2 Identified intensifiers for and barriers to transferability of KER8

The energy efficiency of the EAF can be increased by in-process heat recovery from its off-gases by using the ceramic recuperator that is under development. As already proved, the heat from off-gases during natural gas combustion has preheated air to about 800°C, which can be used in the EAF for example to heat the iron carrier, or in other processes.

A barrier to the transferability is the high dust load and fluctuation of gas temperature during the different process steps during batch/continuous feeding. Therefore, trials with synthetic EAF off-gas doped with dust will be conducted to investigate the performance of the recuperator regarding heat resistance, thermal stress, deposits on recuperator surface and efficiency (test bed planning see **Figure 18**).

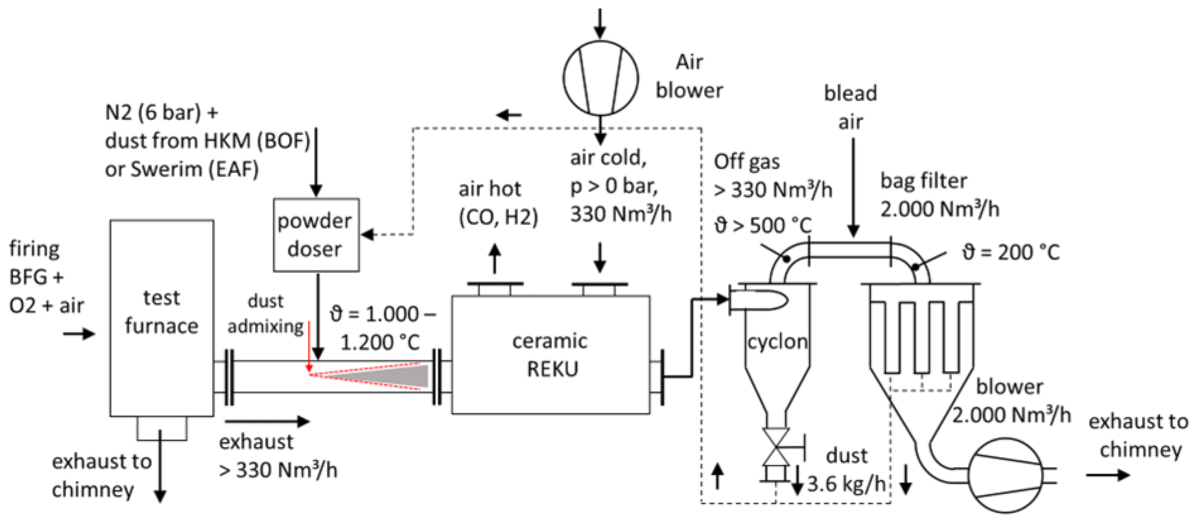


Figure 18. Sketch of planned test bed for heat recovery test from synthetic off gas with ceramic recuperator.

The technology is new, TRL 4-5, and successful results in pilot trials, will bring the recuperator to a higher TRL. To increase the awareness of the new technology, pilot results need to be communicated and further, to bring the recuperator from pilot scale to industrial scale, long term trials under industrial conditions should be carried out.

The use of the recuperator in industrial scale will lead to investment costs but on the other hand cost saving in fuels etc will decrease in the long term.

4.8.3 Identified measures to enhance transferability of KER8

To enhance the transferability of the results of KER8, a detailed monitoring of the process and the recuperator during the pilot trials will be carried out. The performance of the recuperator will be investigated regarding heat resistance, thermal stress, deposits on recuperator surface and efficiency. This should enhance the validity and the transferability of the outcome in KER8 and bring it to a higher TRL.

Table 9 summarises the identified potential intensifiers for and barriers to transferability of KER8 and related actions that will be put in place during the project favour such intensifiers as well as to overcome and/or avoid the materialisation of such barriers.

Table 9. Summary of potential intensifiers for and barriers to transferability of KER8 and related actions.

Intensifier for transferability	Enablers
New technology	Pilot trials, from TRL 4-5 to higher TRL
Heat recovery/utilisation	Energy savings, reduced costs.
Barrier to transferability	**Countermeasure**
Dust load and fluctuations of gas temperature	During trials, the recuperator will be investigated regarding heat resistance, thermal stress, deposits on recuperator surface and efficiency.
Low TRL	Pilot trials conducted in the project. Create awareness. Long term trials in industrial scale.
Investment cost	Savings in fuels etc in long term.

4.9 KER9: Recovery of heat from EAF slag

4.9.1 Short description of KER9

In the green transition of the steel industry, EAF furnaces will replace the conventional blast furnace steelmaking route. Today, granulated blast furnace slag is used as a raw material in the cement industry. With the closing of blast furnaces, this raw material flow needs to be replaced. The EAF slag cannot readily replace the granulated blast furnace slag as a cement raw material due to the different properties. However, the EAF slag can be chemically modified to fit the requirements for cement production.

Trials in pilot scale will be carried out where the slag chemistry is modified during tapping into the slag pot, by some reducing agent such as FeSi. The heat of the slag is recovered by tapping the liquid EAF slag into the slag pot where the reduction agents are added. The slag modification reactions, mainly the reduction of iron oxides, takes place in the slag pot. The chemistry may be further adjusted by the addition of slag formers such as aluminium oxide.

After the reactions have finished, the slag is cooled rapidly via water granulation or other method for achieving a glassy slag.

4.9.2 Identified intensifiers for and barriers to transferability of KER9

The trials are carried out for different user cases with scrap and DRI charging, which enhance the possibility of the developed KER9 to be transferred to other steelmakers. The process of modifying the slag in the slag pot is adapted to the size of the furnace, meaning that the process can readily be scaled up to an industrial case. Even though the slag properties will vary between different steelmakers, the modification of slag chemistry can be tailored to the specific case so that the finished slag product is suitable for use in the cement industry. Even different cement producers might have different requirements and specifications for their production setup.

One of the main intensifiers is that in the coming years and decades, it is likely that blast furnaces in Europe will be replaced with EAFs. This means that the granulated blast furnace slag that is used in the cement industry today to reduce the CO_2 emissions will disappear. This creates a demand to replace the blast furnace slag, which could be done with modified EAF slag.

The use of metallic elements for modifying the slag, such as FeSi, will have a large impact on the processing cost and this could be a barrier for transferability. The process of modifying the liquid slag in the slag pot is not an industrial matured process. Uncertainties of process instability as well as yield of reduction agents could act as barriers as well.

4.9.3 Identified measures to enhance transferability of KER9

To enhance the transferability of the results of KER9, a detailed observation and monitoring of the process during the pilot trials will be carried out. A detailed analysis of the process will be carried out. The weight of slag, reduction agents, temperature at different intervals, sampling and analysis of final slag composition as well as investigation of the cementitious properties will be carried out. The process will be tested for different user cases, that is with scrap charging and DRI charging, which will set the results in a broader perspective.

The cost of reduction agent will have a large impact on the processing cost and can act as a barrier for transferability. A more cost-effective process could be the reduction of the iron oxide in the EAF furnace with carbon prior to tapping. This lowers the required amount of reduction agent to be added during tapping. In the pilot trials, this method will be tested for some of the trials.

Table 10 summarises the identified potential intensifiers for and barriers to transferability of KER9 and related actions that will be put in place during the project favour such intensifiers as well as to overcome and/or avoid the materialisation of such barriers.

Table 10. Summary of potential intensifiers for and barriers to transferability of KER9 and related actions.

Intensifier for transferability	Enablers
Slag modification process tested for different steelmaking processes	User cases with both scrap and DRI charging
Transition from blast furnace route to EAF route in Europe	Granulated blast furnace slag will disappear from the European market which will create a large demand for a replacement product. Modified EAF slag can replace the GBF slag without increasing emissions.
The process can be tailored to the specific process/production setup	Investigation on the cementitious properties will be carried out which will aid in finding the future requirements on EAF slag as a cement raw material.
Barrier to transferability	**Countermeasure**
Cost of reduction agents used in the slag pot	Trials with reducing the iron oxide content of the slag prior to tapping
Uncertainty on the process stability	Trials with reducing the iron oxide content of the slag prior to tapping

5. Conclusions

In order to derive some guidelines to be followed during the project for ensuring a wide transferability of projects outcomes throughout the EU steel sector, the GreenHeatEAF Consortium is implementing a strategy based on a thorough analysis of intensifier for and barriers to transferability of each KER of the project, with the support of stakeholders' consultations and a carefully selected and well assorted AB.

In the first year of the project, as a first step of the interaction with the stakeholders, a survey was launched, which focused on the part of the research outcomes (modelling and simulation) which already showcased some preliminary outcomes in the first year of the project, which were also presented in a few workshops. This helped raising interest and curiosity and, consequently, also interest and willingness to complete the survey. Of course, further surveys and consultations are planned throughout the project referring to other aspects of the developed research activity, that will also be reported in a dedicated deliverable (Deliverable D5.4 Summary of Stakeholder Consultations) to be delivered at the end of the project. All the indications gained in such consultations that can be useful to enhance transferability of the project outcomes will be also considered, although not reported in the present document.

Moreover, two meetings and interviews with the AB members were organised, where each KER foreseen at the proposal stage was presented, analysed and discussed and questions were addressed to the AB members particularly dealing with the factors which can favour or prevent transferability of the identified KERs. As a result of such consultations as well as of internal discussions on the KERs themselves, a detailed analysis of intensifiers for and barriers to transferability of each KER has been developed, which is presented in this document.

Such analysis will be periodically reviewed by the Consortium and kept updated along with the progress of the project activities, to both check whether the present transferability guidelines are followed and identify new barriers that might arise to internal (e.g. particular features of the KERs which are not yet defined at the present stage) or external factors (e.g. market evolutions, new standards or regulations). If new KERs are generated by the project that are not considered here, the analysis will be repeated.

Moreover, further meetings are planned with the AB members during the project, to both present the ongoing activities and the progresses in the development of each KER and discuss on possible measures to enforce its transferability across the EU steel sector. The outcomes of these will also contribute to the update of the transferability analysis.

6. List of Figures

7. List of Tables

8. List of acronyms and abbreviations

Acronym	Full Name
AB	Advisory Board
AC	Alternating Current
AGAM	Acoustic GAs temperature Measurement
BC	Boundary Conditions
BFI	VDEh Betriebsforschungsinstitut GmbH
CFD	Computational Fluid Dynamics
CSP	Clean Steel Partnership
DEW	Deutsche Edelstahlwerke
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EASES	European Academic Symposium on EAF Steelmaking
ESTEP	European Steel Technology Platform
ETS	Emissions Trading System
EU	European Union
GBF	Granulated Blast Furnace (referred to slag)
HBI	Hot Briquetted Iron
HEC	Hydrogen Enhanced Combustion
HHV	Higher Heating Value
IT	Information Technology
KER	Key Exploitable Result
ML	Machine Learning
MPC	Model Predictive Control
MVP	Minimum Viable Product
RFCS	Research Fund for Coal and Steel
SSSA	Scuola Superiore Sant'Anna
TRL	Technology Readiness Level
USA	United States of America

Appendix I: First stakeholders' survey

GreenHeatEAF

Gradual integration of REnewable non-fossil ENergy sources
and modular HEATing technologies in EAF for progressive CO2 decrease

GreenHeatEAF survey on Modelling and Simulation tools

Premise

The project entitled "Gradual integration of REnewable non-fossil ENergy sources and modular HEATing technologies in EAF for progressive CO_2 decrease" (GreenHeatEAF) is a Research and Innovation Action funded by the European Union through the Horizon Europe framework, which aims at demonstrating the integration of non-fossil fuels and renewable C-sources in EAF process to decrease CO_2 emissions and dependence from fossil energy and C-sources markets.
As its name suggest, GreenHeatEAF focuses also on improvement of heat recovery solutions both from off-gases and slag considering the changes of their features with the introduction of H_2 and/or biomass and considering different charge materials and modes. Technologies and processes for heat recovery are being tested and ad-hoc control approaches will be developed.
GreenHeatEAF addresses the challenges linked with the above-described objectives by combining pilot, on field and simulation investigations.
Transferability of GreenHeatEAF solutions is tackled through different business cases belonging to the industrial partners. Moreover, the Consortium is committed to be continuously connected to the main stakeholders in the steel sector to gather indications and suggestions on how to enhance the transferability of the expected outcomes throughout the steel sector and possibly beyond, For instance in the metal industry.
The present survey refers to modelling and simulation tools, which are developed and exploited especially in the first stages of the project but are also one of the projects' first outcomes. The survey aims at collecting feedback on the most relevant barriers which hamper transferability of modelling and simulation tools in the context. It takes about 5 minutes and not all the questions are mandatory.
The data provided are protected by confidentiality and will be processed according to GDPR (General Data Protection Regulation). Data will remain within the consortium and will be published anonymously for statistical purposes only. Sending the survey, You give Your consent for the data processing. You have the right to withdraw the consent in any time.
The GreenHeatEAF Consortium gratefully acknowledges all participants for their valuable inputs.

Gradual integration of REnewable non-fossil ENergy sources
and modular HEATing technologies in EAF for progressive CO2 decrease

GreenHeatEAF survey on Modelling and Simulation tools

Basic information on respondent

* 1. How can Your company/institution be classified?

- ◯ Large enterprise
- ◯ Small or Medium enterprise
- ◯ Research Organisation
- ◯ Academia
- ◯ Sector Association
- ◯ Other (please specify)

* 2. Where is Your company located?

Other (please specify)

GreenHeatEAF

Gradual integration of REnewable non-fossil ENergy sources
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GreenHeatEAF survey on Modelling and Simulation tools

Modelling and simulation on GreenHeatEAF topics

* 3. Is Your company already investigating and/or implementing the **adoption of renewable non-fossil energy and Carbon sources and heating technologies** or planning to do this in the incoming 3-5 years?

- ○ Yes
- ○ No
- ○ I don't know

* 4. Is Your company exploiting modelling and simulation tools to investigate or implement the **adoption of renewable energy sources and heating technologies**?

- ○ Yes
- ○ No
- ○ I don't know

5. If You answered Yes to the previous question, which are the main simulation tools adopted in Your company/institution to investigate or implement the **adoption of renewable energy sources and heating technologies**?

Internal tools developed within the company (please specify the development environment, e.g., MatLab/Simulink, Python, C++, C#, etc.)

Commercial specific simulation tools (please specify)

* 6. Is Your company exploiting modelling and simulation tools to investigate or implement the **use of renewable Carbon sources**?

- Yes
- No
- I don't know

7. If You answered Yes to the previous question, which are the main simulation tools adopted in Your company/institution to investigate or implement the **use of renewable Carbon sources**?

Internal tools developed within the company (please specify the development environment, e.g., MatLab/Simulink, Python, C++, C#, etc.)

Commercial specific simulation tools (please specify)

* 8. Is there a potential interest in Your company/institution in modelling and simulation tools to investigate or implement the **adoption of renewable non-fossil Carbon and energy sources and heating technologies**?

◯ Yes

◯ No

◯ I don't know

* 9. Which are, in Your opinion, the main barriers in the use of modelling and simulation tools to investigate or implement the **adoption of renewable non-fossil C and energy sources and heating technologies**? Please select up to 3 options

☐ Cost

☐ License

☐ Lack of adequate skills in the company/institution

☐ Uncertainty in the return of investment

☐ Other (please specify)

* 10. Did You in Your professional activity ever exploited or tried to exploit models **related to renewable non-fossil C and energy sources management and optimization**?

◯ Yes

◯ No

◯ I don't know

GreenHeatEAF

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GreenHeatEAF survey on Modelling and Simulation tools

Intensifiers and barriers for any kind of model

* 11. Which are, in your opinion, the main intensifiers to transfer/customise a model developed **for any purpose** in a different context to the demand of your company/institution? Please select up to 3 options 0

- [ ] Simplicity and usability
- [ ] Complete documentation
- [ ] Evident benefits in terms of increased product quality and/or increased yield
- [ ] Evident benefits in terms of expected saving of resources/input materials and /or decreased emissions
- [ ] Contributions to decrease costs for CO_2 certificates
- [ ] Other (please specify)

* 12. Which are, in Your opinion, the main barriers to transfer/customise a model developed for any purpose in a different context to the demand of Your company/institution? Please select up to 3 options 0

- [ ] Missing and/or incomplete documentation
- [ ] Lack of adequate skills to run the model and interpret its results
- [ ] Difficulties in gathering internal data to adapt/run the model
- [ ] Lack of adequate skills to interpret its results and apply them in production processes
- [ ] Purchasing costs of the adopted modelling environment
- [ ] Difficulties in gaining support inside Your company/institution
- [ ] IPR issues
- [ ] Other (please specify)