E-ECO DOWNSTREAM

Development of Heating Technologies for the Efficient Renewable Energy Consumption of CO_2-Neutral Downstream-Processes

Initial exploitation strategy with transferability analysis to drive project development

Deliverable 6.7

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E-ECO Downstream

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1 Abstract

This deliverable presents the Initial Exploitation Strategy and Transferability Analysis for the E-ECO Downstream project, outlining how the project's Key Exploitable Results (KERs) will be leveraged to maximize industrial, environmental, and societal impact. The document defines the strategic framework for transforming research outcomes into practical applications that accelerate the decarbonization of downstream steelmaking and other energy-intensive sectors.

It details the methodology applied to identify, analyze, and evaluate each KER in terms of its exploitation potential, market relevance, and cross-sector applicability. The analysis draws on partner inputs gathered through structured questionnaires, ensuring a consistent and comprehensive assessment across all results.

The report emphasizes the alignment of exploitation and transferability activities with the project's overall objectives—reducing CO_2 emissions, enhancing energy efficiency, and promoting sustainable industrial transformation. It also highlights synergies between KERs, notably between heat recovery and hybrid heating solutions, and defines engagement pathways with key stakeholders including industry, policy makers, and technology platforms.

Finally, the deliverable sets the foundation for the Final Exploitation and Transferability Strategy, which will integrate pilot-scale validation outcomes, business models, and market feedback to ensure the long-term sustainability and scalability of E-ECO Downstream innovations.

2 Introduction

This deliverable presents the Initial Exploitation Strategy and Transferability Analysis for the E-ECO Downstream project. Its goal is to define how the project's Key Exploitable Results (KERs) can be transformed into tangible, sustainable outcomes that support the decarbonization of downstream steelmaking and related energy-intensive sectors.

The exploitation strategy outlines how results will be commercialized, disseminated, and scaled to ensure continuity beyond the project's lifetime, while the Transferability Analysis identifies cross-sector opportunities and assesses their applicability in other industrial domains. Together, they strengthen the project's long-term impact, market relevance, and sustainability.

These activities are conducted within Work Package 6 (WP6) – Dissemination, Exploitation and Communication, led by BFI with contributions from all partners. The exploitation strategy and IPR Management task runs from M1 to M42, producing two reports:

- D6.7 – Initial Exploitation Strategy with Transferability Analysis (M12) [Current report]
- D6.8 – Final Exploitation Strategy and Transferability Guidelines (M42)

The strategy identifies industrial applications, policy implications, and cross-sector use cases, while addressing IPR management, stakeholder engagement, and alignment with market and policy frameworks. It links closely with :

- WPs 1–4, which generate the exploitable innovations such as fuel-flexible burners, hybrid heating, logistics optimization, and heat recovery.
- WP5, Integration and Assessment, which provides technical, economic, and ecological evaluation.
- WP6, which ensures coherence between exploitation, dissemination, and communication activities.

This document is structured as follows:

- The following section provides an overview of the project, including a summary of the project context, the main exploitation outcomes, and the methodology applied to develop this deliverable.
- The subsequent section presents a detailed analysis of each KER, based on the questionnaires completed by the project partners. Each KER is described following a consistent structure and format to ensure comparability and coherence across all results.
- Finally, the document concludes with a summary of the key findings, conclusions, and next steps for the continued development and implementation of the project's exploitation and transferability strategy.

3 Overview of the Project

The E-ECO Downstream project addresses the urgent need to decarbonize the steel industry, one of the most energy- and CO_2-intensive sectors in Europe. While previous efforts have focused primarily on upstream processes, this project targets the downstream stages—such as reheating and heat treatment—where significant potential remains for reducing emissions.

Aligned with the EU's Green Deal objectives of a 55% reduction in greenhouse gas emissions by 2030 and full climate neutrality by 2050, E-ECO Downstream aims to replace fossil-based fuels with hydrogen, biogas, and electricity, enabling a transition to low- or zero-carbon heating technologies. The project is structured around six key objectives (Fig 1):

- Fuel-flexible burners – Developing retrofittable, 3D-printed burner components to enable the use of green fuels in existing furnaces.
- Hybrid heating concepts – Combining hydrogen combustion and electric heating in pilot-scale tests to demonstrate energy efficiency and emission reduction.
- Improved logistics – Introducing hot and warm charging solutions to minimize heat loss between casting and rolling stages.
- Advanced heat recovery – Adapting recuperator and regenerator systems for new fuel conditions to maximize waste heat utilization.
- Implementation roadmap – Creating a European-level roadmap and timeline for the deployment of decarbonization technologies in downstream steelmaking.
- Dissemination and exploitation – Engaging industrial stakeholders, policymakers, and technology developers to ensure broad impact and replication.

The methodology combines computational simulations, laboratory studies, and pilot-scale experiments using real industrial data. Key research activities include thermal and combustion modeling, hybrid furnace testing, and system-level analyses of logistics and heat recovery.

Ultimately, E-ECO Downstream will deliver validated technologies, best-practice guidelines, and an implementation roadmap to guide the steel industry's transition to fossil-free heating. The results will contribute not only to emission reductions but also to energy efficiency, process flexibility, and competitiveness across European steel production and related process industries.

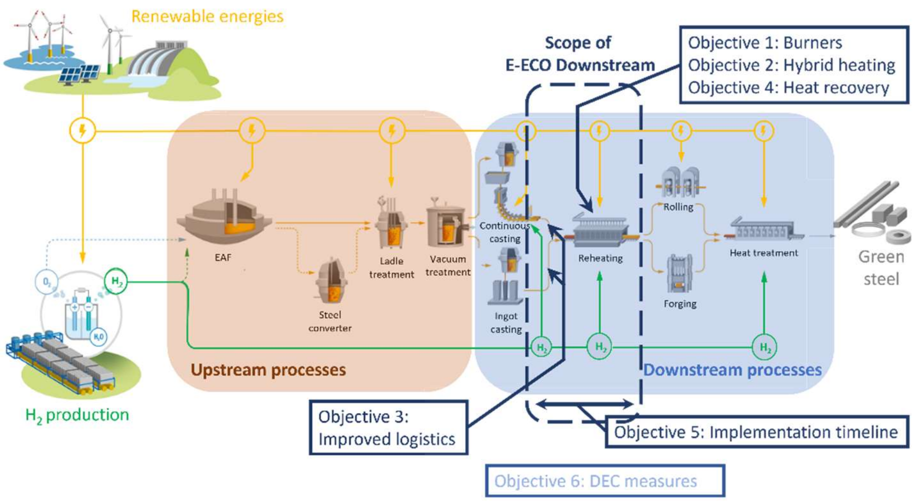

Fig 1: Exemplary production route of green steel with the intervention point of E-ECO Down-stream.

In order to define the exploitation strategy, the starting points were the KERs as defined in the E-ECO-Downstream project.Table 1 reports the identified KERs.

TABLE 1: E-ECO-DOWNSTREAM KERS

KER No.	Short description	KER Type (Process, product, know-how)	Exploitation path (Manuf, Use, Licence, Other)	Owner	Other partners involved
KER 1	Experimental results from retrofitted burner operation at pilot scale when exploiting new fuels	Know-how	Use	All	
KER 2	Concepts for heat recovery from off-gases and from other sensible heat sources considering future downstream processes	Know-how	Use	SSSA, BFI, KUP	ADI, FER
KER 3	Modified and efficient recuperator for preheating fuel and oxidizers	Product	Use	KUP, BFI, VDM	ADI, FER
KER 4	Model of warm/hot charging solutions.	Know-how	Use	All	
KER 5	CFD furnace model for heat transfer due to electrical heating	Know-how	Use	KAN	
KER 6	Economic and ecological impact assessment for decision making	Know-how	Use	SSSA, BFI	All
KER 7	Roadmap and implementation timeline for future technologies	Know-how	Use	All	
KER 8	Hybrid heating concepts	Know-how, product	Use	SWE, KAN, FER, ADI	BFI, SSSA

The methodology applied to develop the initial exploitation strategy and transferability analysis followed a structured multi-step process:

- Definition of guiding questions addressing gap analysis, exploitation planning, and transferability aspects for each KER.
- Collection of inputs from project partners responsible for individual KERs through questionnaires and structured interviews.
- Analysis and synthesis of the collected information to identify key exploitation pathways, market potential, and cross-sector opportunities.
- Integration of preliminary business insights to outline potential commercialization and sustainability approaches.

This process was complemented by three analytical dimensions: a market and user analysis to determine relevant stakeholders and adoption conditions; a preliminary exploitation strategy to define industrial uptake pathways, and sustainability measures; and a transferability assessment to explore the applicability of KERs beyond the steel sector, including potential barriers, enablers, and required adaptations.

4 Detailed Analysis for Each KER

4.1 KER1 – Experimental results from retrofitted burner operation at pilot scale when exploiting new fuels

4.1.1 Overview

KER1 aims to retrofit existing reheating furnace burners to enable flexible use of renewable and carbon-free (C-free) fuels such as biogas, hydrogen and its mixtures. It demonstrates a low-cost solution that ensures stable combustion, low NOx emissions, and high efficiency at pilot scale, validating its industrial feasibility. This KER supports the decarbonization of downstream steel processes, offering a cost-effective alternative to full burner replacement.

4.1.2 Technical Innovation and Development

Conventional furnace burners are optimized for a narrow operating range e.g., natural gas (NG). When operating conditions or fuel types change, their efficiency, emissions, and lifespan deteriorate significantly. To adapt to new fuels, industries usually need to replace entire burner systems (high CAPEX and downtime) or build new furnaces altogether. Existing hydrogen burner solutions on the market also present limitations. They require full system replacement, lack flexibility for transitional fuel mixtures (NG/H_2 blends), have not been validated at pilot or industrial scale, and often rely on ceramic materials that are incompatible with metallic furnace structures and susceptible to mechanical stress.

KER1 bridges this gap by :

- Developing retrofit-compatible burner components that can be installed as spare parts in current systems.
- Providing validated pilot-scale data on performance, efficiency, and emissions.
- Demonstrating a low-cost, low-interruption path to decarbonization.
- Enabling incremental adoption of C-free fuels without disrupting production lines.

The development of KER1 is a collaborative effort, with SSSA contributing data analysis, hydrogen embrittlement evaluation, and combustion modelling for process optimization. BFI and KUP are responsible for the design and testing of retrofitted burner parts, while the industrial partners FER provides and ADI together with BFI provide burners and support experimental testing.

KER1 is currently at Technology Readiness Level 4 (TRL4), with components like additive manufacturing (AM) and NG/H_2 burners already at TRL 9. After pilot testing at BFI, it is expected to reach TRL 6 by 2028. The innovation lies in combining these mature technologies into a validated retrofit solution through simulation and pilot-scale testing.

4.1.3 Market and Users

KER1 targets industrial users operating NG burners, where reheating furnaces are central to production. It enables cost-effective decarbonization by retrofitting existing burners for hydrogen and fuel mixtures, reducing costs and downtime while maintaining current furnace setups and meeting future emission goals.

Potential users and customers are:

- Steel producers and processors – primary users operating reheating furnaces with NG burners.

- Other industrial sectors – including glass, ceramics, and chemical processing, where combustion systems are essential for heating.
- Industrial operators – seeking cost-effective decarbonization solutions.
- Burner and furnace Original Equipment Manufacturers (OEMs) – potential customers who can integrate the retrofit concept into their service portfolios.

The key stakeholders include industrial operators, OEMs, AM companies, and research partners involved in simulation and material development. Broader stakeholders comprise industrial associations, regulators, and hydrogen suppliers, who play vital roles in enabling infrastructure readiness, ensuring compliance with safety and environmental standards, and supporting market adoption.

The initial market lies in the EU steel industry, with over 400 reheating furnaces needing decarbonization. Early adoption is expected in Germany, Italy, and Sweden, driven by strong steel production, active pilot projects, and national hydrogen strategies.

4.1.4 Exploitation Strategy and Sustainability

The exploitable results include guidelines for developing and 3D-printing burner components, along with pilot-scale validation using NG/H_2mixtures.

Adoption requires only partial component replacement and infrastructure readiness for hydrogen supply — not full system rebuilding — and implement updated safety measures.

The main challenges to exploitation include limited hydrogen infrastructure, regulatory constraints, and financial hesitation within the steel industry. These barriers will be addressed through early engagement with regulators, transparent safety and performance documentation, and demonstrations of economic viability to strengthen confidence in adoption.

The exploitation routes will include:

- Consultancy services and licensing of retrofit designs to burner manufacturers and plant operators.
- Collaboration with OEMs and industrial associations (e.g., ESTEP, Hydrogen Europe) to promote knowledge transfer and market visibility.
- Integration into sustainable business models based on the adaptation of existing technologies for long-term, low-emission operation.

Through partner cooperation, KER1 will follow a sustainable business model that extends the life of existing technologies while enabling decarbonization and cost reduction. Data protection, worker safety, and emission reduction are key priorities, ensuring responsible contribution to climate and industrial sustainability.

4.1.5 Transferability and Cross-Sector Potential

KER1 can be transferred to other high-temperature and emission-intensive industries such as glass, ceramics, cement, and petrochemical sectors, where fuel flexibility and decarbonization are essential. These industries would benefit from the cost reduction, improved efficiency, and sustainability achieved through retrofitting existing burners instead of replacing entire systems.

To enable transfer, target sectors must have access to hydrogen, suitable high-temperature furnace infrastructure, and regulatory approval for their use. Minor modifications — such as adapting burner geometry, materials, and safety protocols — would be required to meet sector-specific process conditions.

The main barriers include the limited availability and high cost of hydrogen, the need for sector-specific burner designs, and regulatory constraints. These can be addressed through policy support, operator training, standardization of retrofit methods, and close engagement with regulators to ensure safe and economically viable adoption.

4.2 KER2 – Concepts for heat recovery from off-gases and from other sensible heat sources considering future downstream processes

4.2.1 Overview

KER2 focuses on developing and adapting heat recovery concepts for downstream steelmaking processes such as recuperators and regenerators capable of operating efficiently with future fuels like hydrogen and biofuels. The aim is to preheat fuels and oxidizers by utilizing off-gases and other sensible heat sources within steel production processes, particularly in reheating and heat treatment furnaces.

The concepts are not standalone but designed to be integrated into downstream processes within the steel industry, offering potential for improved energy efficiency and reduced emissions through advanced heat recovery.

4.2.2 Technical Innovation and Development

Currently available recuperators and regenerators are designed mainly for NG-based furnaces and are not optimized for hydrogen combustion or varying fuel mixtures. These conventional systems face several technical gaps, including limited resistance to high H_2O content and reactive exhaust gases, lack of flexibility for changing fuel compositions, and incompatibility with AM and advanced high-temperature materials.

The E-ECO Downstream technologies overcome these limitations by:

- Introducing 3D-printed recuperators with optimized design for enhanced heat exchange.
- Applying Ni-based high-performance alloys to ensure durability under extreme temperature and reactive conditions.
- Enabling adaptation to future fuels, including hydrogen and biofuels.
- Scenario-based modeling to evaluate performance in various decarbonization routes.

The main contributors are BFI and KUP, developing heat recovery concepts, with KUP also designing and 3D-printing recuperators. SSSA leads process analysis and CO_2 assessments, while ADI and FER provide industrial data, modeling support, and pilot testing.

By the end of the project in 2028, KER2 is expected to reach TRL 4 – 6, with the developed concepts pilot-tested and validated in a relevant industrial environment.

4.2.3 Market and Users

KER2 targets energy-intensive industries seeking to reduce CO_2-emissions and improve energy efficiency through advanced heat recovery technologies adaptable to hydrogen and biofuel operation. It provides a cost-effective efficiency solution enabling 10 – 30% energy savings and allowing retrofitting of existing furnaces without full replacement.

Potential users include:

- Steel and metal,
- Foundries, forging companies,
- Non-ferrous metal manufacturers and
- Furnace and burner manufacturers.

Key stakeholders for KER2 include steel producers as end-users, OEMs for technology integration, and hydrogen suppliers supporting fuel transition. Policy makers drive regulatory incentives, while research platforms such as ESTEP and EUROFER facilitate knowledge exchange and promote wider industrial adoption.

The initial market focus lies in Germany, Italy, and Sweden, supported by national hydrogen and decarbonization initiatives. Across the EU, the potential market encompasses over 400 downstream steel plants and related facilities, representing an annual market potential exceeding €100 million.

4.2.4 Exploitation Strategy and Sustainability

The KER2 exploitable results encompass know-how on heat recovery integration, pilot-tested component designs, material data for high-temperature environments, and validated scenario studies supporting large-scale industrial deployment.

The value proposition of KER2 is its ability to retrofit existing furnaces cost-effectively with fuel-flexible heat recovery systems, delivering higher energy efficiency and lower CO_2 emissions without requiring full system replacement.

To adopt the solution, industrial users will primarily need to integrate modified recuperators, adapt fuel and oxidizer supply systems, and ensure compliance with evolving safety and regulatory standards related to hydrogen and high-temperature operation.

Barriers to exploitation include safety challenges with hydrogen, limited fuel standardization, investment hesitancy, and restricted hydrogen availability. These will be mitigated through pilot demonstrations, stakeholder engagement, development of implementation roadmaps, and close cooperation with regulatory bodies.

Key exploitation pathways include:

- Licensing of designs and technical know-how to OEMs and industrial partners.
- Integration into existing furnace designs and applying retrofit services.
- Joint commercialization through collaboration among consortium partners
- Policy and standardization support through active engagement with ESTEP, EUROFER, and A.SPIRE.

The concept will be validated through pilot installations and technical assessments, leading to the creation of best-practice guidelines and ensuring industrial readiness.

The exploitation strategies for KER2 and KER3 are closely aligned, as both focus on advancing heat recovery and energy efficiency in downstream steel processes. While KER2 provides the conceptual and analytical framework for utilizing off-gases and other sensible heat sources, KER3 translates these concepts into validated recuperator designs for preheating fuel and oxidizers under future hydrogen and biofuel conditions.

4.2.5 Transferability and Cross-Sector Potential

KER2 is transferable to energy-intensive sectors such as non-ferrous metals, glass, cement, ceramics, and chemical processing. Its applicability depends on combustion-based heating systems, hydrogen or biofuel availability, and decarbonization policies. When adopted, it offers higher energy efficiency, lower emissions, and greater operational flexibility, delivering clear ecological and economic benefits.

Minor adaptations — such as sector-specific material selection, integration with local control systems, and compliance with safety and emission standards — may be needed. Key barriers include high investment costs, limited hydrogen infrastructure, and insufficient technical expertise. These can be mitigated through training, pilot demonstrations, and collaboration with industry associations to establish sector-specific standards and best practices.

4.3 KER3 – Modified and Efficient Recuperator for Preheating Fuel and Oxidizers

4.3.1 Overview

KER3 is a key technological outcome of the E-ECO Downstream project, designed to enhance industrial heat recovery by preheating both fuels and oxidizers using waste exhaust heat. This hydrogen-ready recuperator operates up to 1,200 °C and adapts to variable gas compositions, ensuring safe and efficient operation in hydrogen-rich and oxygen-enriched environments.

By improving thermal efficiency and enabling the use of low-carbon fuels, KER3 contributes directly to industrial decarbonization, energy cost reduction, and EU Green Deal objectives.

4.3.2 Technical Innovation and Development

Traditional industrial recuperators — such as Trymax counter-flow units[1] (100 – 600 °C), TSB Energy smoke-tube recuperators[2] (flue gas cooling to 50 °C), and Saint-Gobain SiC recuperators[3] — perform well in conventional fossil-fuel systems but lack the flexibility, durability, and efficiency required for hydrogen combustion and dual-stream heat recovery.

KER3 bridges this technological gap by integrating:

- Advanced nickel-based alloys for superior thermal and chemical resistance,
- AM and optimized 3D geometries for high heat-transfer efficiency,
- Dual-preheating capability for fuel and oxidizer streams, and
- Enhanced mechanical robustness and adaptability to variable combustion atmospheres.

The development combines the expertise of BFI (thermal testing and integration), VDM Metals (alloy development), and KUP (3D printing and design optimization).

Currently at TRL 4, the technology will advance to TRL 5 – 6 through pilot-scale validation by 2027. Designed for integration into furnaces and process heaters, KER3 provides a future-proof, hydrogen-compatible solution for sustainable industrial heating.

4.3.3 Market and Users

KER3 targets energy-intensive industries transitioning to low-carbon and hydrogen-based energy systems. It enhances productivity, energy efficiency, and emission reduction across:

- Steel and metal production,
- Glass and ceramics manufacturing,
- Chemical and petrochemical industries, and
- Energy and aerospace sectors using high-temperature furnaces or turbines.

Potential users include plant operators, equipment manufacturers, and engineering companies seeking hydrogen-ready, high-efficiency solutions.

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[1] https://trymaxfurnace.com/product/industrial-recuperator

[2] https://tsbenergy.com/en/recuperator

[3] https://www.ceramicsrefractories.saint-gobain.com/de/produkte/produkte-nach-anwendung/waermebehandlung/heatcor-und-silit-rekuperatoren

KER3 involves stakeholders across the industrial heating and decarbonization value chain. Key actors include steel and metal producers as end-users, technology suppliers for system integration, and policy bodies supporting deployment through energy efficiency initiatives. Research partners, investors, and industrial clusters further drive validation, commercialization, and market uptake.

Initial market focus lies in Germany, Italy, Sweden, Spain, and France, where strong industrial bases and national hydrogen strategies support adoption. Manufacturing will involve high-temperature component suppliers, AM specialists, and alloy producers.

4.3.4 Exploitation Strategy and Sustainability

The exploitation strategy for KER3 aims to validate, demonstrate, and commercialize a high-performance recuperator technology through joint exploitation by BFI, VDM, and KUP, supported by industrial partners across the value chain.

Key exploitable results include a validated recuperator design, pilot-scale performance data under hydrogen-rich conditions, and simulation tools for efficient system integration. Deployment opportunities exist for both retrofitting existing combustion systems and integrating the technology into new industrial installations.

Adoption of the KER3 technology will require only limited adaptations, such as adjustments to furnace infrastructure, integration with process control systems, safety compliance measures, and staff training.

Exploitation challenges are expected to arise from operational integration complexities, market hesitation due to cost and reliability concerns, and regulatory hurdles related to hydrogen safety and material certification. These barriers will be addressed through pilot testing under real industrial conditions, close collaboration with industry partners, and early engagement with certification bodies. Moreover, detailed cost–benefit analyses and targeted stakeholder engagement activities will be conducted to build trust, demonstrate economic feasibility, and ensure regulatory compliance.

The main exploitation routes include:

- Service expansion: material testing, process simulation, and system optimization services.
- Technology licensing: transfer of recuperator designs and know-how to OEMs and industrial partners.
- Collaborative demonstration projects: Pilot-scale installations with industrial end users.
- Consulting and training: Support for hydrogen transition readiness and efficient heat recovery integration.

Throughout and beyond the project, partners will:

- Conduct pilot testing and material validation to confirm TRL 6 readiness.
- Optimize AM and alloy parameters for industrial scalability.
- Disseminate technical knowledge through workshops, conferences, and publications.
- Develop commercialization frameworks including licensing agreements and industrial collaborations.

Through this coordinated strategy, KER3 will progress from pilot validation to industrial deployment, ensuring measurable technological, environmental, and economic impact while contributing to Europe's sustainable industrial transformation.

4.3.5 Transferability and Cross-Sector Potential

KER3 demonstrates strong potential for transfer across industries that operate high-temperature processes and generate recoverable exhaust heat. Target sectors include non-ferrous metals (aluminium, copper), glass and ceramics, refractories, pulp and paper, and energy or aerospace applications involving turbines and combustion systems.

Successful cross-sector adoption depends on:

- High-temperature environments with stable exhaust gas conditions,
- Access to hydrogen or oxygen-enriched fuels, and
- Advanced process control and monitoring capabilities.

To fit different industrial contexts, KER3 may require adaptations such as material selection, geometry scaling, and customized integration interfaces.

The expected benefits of cross-sector deployment include higher thermal efficiency, reduced fuel costs, improved durability, and lower CO_2 emissions, supporting operational and environmental objectives.

Potential barriers — such as infrastructure compatibility, investment costs, and certification requirements — can be mitigated through technical training, standardization efforts, and collaboration with regulatory bodies.

Overall, KER3 represents a scalable, transferable, and future-ready innovation, leveraging advanced materials, AM, and high-efficiency thermal recovery to support Europe's transition toward climate-neutral industrial production.

4.4 KER4 – Model of warm/hot charging solutions

4.4.1 Overview

KER4 focuses on the development of a predictive heat-transfer and process model that estimates how much energy, fuel, and CO_2 emissions can be saved when cast slabs, billets, or bars are reheated with minimized heat loss between casting and rolling. By enabling warm and hot charging, the model supports significant decarbonization potential, with CO_2 savings estimated between 0.6 $MtCO_2$ and 2.4 $MtCO_2$ per year across EU BOF-based production. For EU EAF based production estimated CO_2 savings are calculated between 0,53 $MTCO_2$ and 2,11 $MtCO_2$ per year in case of applying hot and warm charging. The model can be used either as a standalone decision-support tool or integrated with other fuel-saving technologies developed within the project.

4.4.2 Technical Innovation and Development

Conventional downstream steel plants typically rely on reheating slabs, billets, or bars after they have cooled down in slab yards. While this setup historically offered operational flexibility and lower investment costs, it leads to substantial heat loss and high energy demand during reheating. Existing warm or hot charging practices are mainly available in fully integrated, newly built plants where continuous casting and continuous rolling are physically connected. In contrast, most European mills lack the spatial layout, insulated storage, and production planning systems required to implement warm or hot charging. These limitations create major gaps—high heat losses, increased reheating fuel consumption, higher CO_2 emissions, and additional material scaling.

KER4 addresses these structural and operational gaps by :

- Supporting efficient production planning in downstream steel mills by improving the management of slab/billet reheating programmes.
- Reducing energy losses between casting and rolling by enabling warm and hot charging strategies.
- Decreasing of reheating energy demand by 10–40%, directly addressing the high energy consumption of current cold-charging practices.
- Reducing the demand for future fuels (e.g., hydrogen, biofuels) and reduces electrical power use in hybrid heating setups.
- Contributing to decarbonization through reduced CO_2 emissions and lower CO_2-related costs.
- Mitigating scaling and material loss by enabling faster reheating when warm/hot charging is applied.

The technical development is carried out jointly by the partners : BFI leads the KER, performing heat-flow measurements and developing energy and emission models for cold, warm, and hot charging; SSSA contributes complementary heating simulations and saving assessments; and ADI and FER provide the industrial data, specifications, and plant constraints needed to ensure realistic modelling.

KER4 is currently at TRL 4, supported by theoretical analyses and calculated fuel-saving scenarios; by the end of the project, it is expected to progress toward TRL 5 as the modelling framework is refined and validated with industrial data.

4.4.3 Market and Users

KER4 targets steel producers operating reheating furnaces, particularly those with discontinuous production in EAF and BOF plants. Potential benefits for users include improved energy efficiency, reduced CO_2 emissions, lower fuel consumption, and cost savings achieved by minimizing heat loss before reheating.

Primary users include :

- Steel producers
- Foundries and forging companies
- Non-ferrous metal industries requiring reheatin
- Furnace, insulation, and plant-design suppliers
- Suppliers and manufacturers include OEMs producing industrial heating systems, furnace components, insulation technologies, transport systems, and process-management solutions.

The potential market comprises over 400 downstream steel processing plants in the EU, with additional opportunities in non-ferrous and high-temperature industries.

Key stakeholders span steel producers, OEMs, policy makers and regulators, as well as research platforms such as ESTEP, EUROFER, VDEh, AIM, and Jernkontoret. Engagement will be promoted through advisory boards, conferences, trade fairs, webinars, and demonstrator visits.

4.4.4 Exploitation Strategy and Sustainability

The exploitation strategy for KER4 focuses on delivering process, production, and logistics concepts that enable warm and hot charging, complemented by insulation designs to minimize heat loss prior to reheating.

Key exploitable results include calculated energy-saving potentials, scenario analyses, and plant-specific data that serve as decision-support tools for industrial investment and planning. The results support deployment in steel, non-ferrous, and other high-temperature industries, offering guidance for decisions such as direct hot charging or implementing insulation strategies, as well as integration into hybrid heating concepts.

Industrial end-users adopting KER4 will need to install hot- or direct-charging configurations or apply insulation solutions, while ensuring compatibility with production workflows, safety protocols, and regulatory standards.

Exploitation challenges relate to high CAPEX requirements, production-organisational constraints such as space, scheduling, and storage of semi-hot materials, and material limitations at elevated temperatures. These will be addressed through simplified insulation concepts, minimisation of space demand, scenario-based roadmap development, and targeted stakeholder engagement.

Primary exploitation routes consist of:

- Use in industrial processes to support planning and optimisation of warm/hot charging strategies.
- Integration into OEM offerings, enabling incorporation of the model into furnace, insulation, or process-management solutions.
- Licensing of know-how to industrial partners for implementation and further development.

Ethical and environmental considerations are positive, as the KER promotes sustainability, efficient resource use, and low-carbon production pathways.

4.4.5 Transferability and Cross-Sector Potential

KER4 can be transferred to other high-temperature processing industries such as non-ferrous metal sectors (e.g., aluminium and copper), where maintaining elevated product temperatures between process steps is crucial for efficiency and quality. These industries would benefit from the same advantages demonstrated in steel production—reduced fuel consumption, lower CO_2 certificate costs, improved heating efficiency, and potential quality improvements resulting from minimized thermal losses.

To enable transfer, target sectors must operate high-temperature heating processes in which products require sustained heat between production stages, but where breaks in production or intermediate storage lead to unavoidable heat loss. Successful adaptation requires integrating the KER4 heat-retention and modelling concepts into sector-specific production procedures, adjusting boundary conditions to match different product geometries, thermal properties, and operational constraints.

The main barriers to transfer include capital investment requirements, uncertainties around return on investment, and limited available space in existing plants for insulated storage or modified logistics. These challenges can be addressed through demonstration and pilot projects, engagement with industry associations and regulators, and the dissemination of technical documentation and open-access publications that build confidence and support informed decision-making.

4.5 KER5 – CFD furnace model for heat transfer due to electrical heating

4.5.1 Overview

KER5 aims to deliver a Computational Fluid Dynamics (CFD) model for simulating heat transfer in electrically heated reheating furnaces, with a particular focus on hybrid configurations that combine hydrogen combustion and electric heating.

The tool is being developed to function as a standalone simulation environment and is intended for integration into the design and optimization workflow of hybrid reheating furnaces, with the goal of supporting future industrial decarbonization efforts.

4.5.2 Technical Innovation and Development

Conventional CFD tools, such as ANSYS Fluent, provide general simulation capabilities for heat transfer but do not include validated models specifically designed for hybrid (H_2 + electric) reheating furnaces. These tools are not optimized to represent the combined effects of hydrogen combustion, resistive heating, and material temperature uniformity under industrial conditions.

Within the project, the aim is to:

- Develop and attempt to validate a CFD model for hybrid (H_2 + electric) reheating furnaces.
- Use pilot-scale data from Swerim's experimental walking beam furnace to support model development and validation.
- Explore advanced heat transfer and flow simulations tailored for hybrid furnace environments.
- Work towards a scalable model architecture that could be integrated into furnace design and optimization workflows.

The work is carried out in collaboration between KAN (CFD model design and validation), SWE (experimental data and pilot testing), and BFI (model integration and process validation).

The project is currently at TRL 3–4, with the goal to reach TRL 6 by the end of the project, aiming to provide an industrially validated digital tool for furnace design and optimization.

4.5.3 Market and Users

The model is intended to deliver benefits such as potential energy savings in the range of 10–20%, significant CO_2 reduction (up to 100% in electric zones), and improved temperature control. It is also expected to support and potentially accelerate the design and validation of sustainable furnace technologies. Actual results will depend on further development, validation, and industrial implementation.

- Potential users include:
- Steel and metal producers
- Furnace and heating equipment manufacturers
- Engineering and consulting services, such as Kanthal's internal R&D teams, who are seeking validated digital tools for hybrid furnace design and optimization
- Research and development organizations focused on industrial decarbonization

Key stakeholders for KER5 are expected to include steel producers, furnace OEMs, and project partners Kanthal, SWE, and BFI, with additional support from policy makers aligned with the EU Green Deal. Stakeholder engagement is planned through workshops, pilot demonstrations, webinars, and direct collaboration within the consortium to encourage feedback and facilitate industrial adoption.

The initial market focus is on Sweden, Germany, and Italy, leveraging the industrial presence and partner networks in these countries. The estimated market potential for digital tools and engineering services is in the range of €10–50M per year, although actual uptake will depend on market development and industry needs. The broader European market, with over 150 major steel plants, could represent a future deployment base as hydrogen-ready and electric retrofits expand.

4.5.4 Exploitation Strategy and Sustainability

The exploitation strategy is to work towards transforming the validated CFD model into a potential commercial digital solution and consulting service that could support the transition to low-carbon steelmaking.

Key exploitable results are expected to include a validated CFD model, pilot-scale validation data, and best-practice guidelines for hybrid furnace design and operation.

Adoption is anticipated to require the integration of CFD modelling into furnace design workflows and access to process data for calibration and validation.

Potential exploitation challenges include a conservative industrial mindset, limited digital expertise, and uncertainty around regulatory incentives. The project plans to address these through training, dissemination of pilot results, sharing of success stories, and policy engagement via European networks such as ESTEP, EUROFER, and Jernkontoret.

The main exploitation routes being considered are:

- Direct integration into Kanthal's R&D and customer projects,
- Licensing to OEMs and industrial users, and
- Consulting services to support hybrid furnace implementation.

Through joint efforts by Kanthal, Swerim, and BFI, the intention is for the validated CFD model to evolve from a research outcome into a practical engineering tool that could support industrial-scale decarbonization.

4.5.5 Transferability and Cross-Sector Potential

The CFD furnace model developed under KER5 is considered to have potential for transferability to other energy-intensive industries, such as non-ferrous metals, glass, ceramics, and cement, particularly if these sectors move towards electrified or hybrid high-temperature furnaces.

Adapting the model—such as by tuning parameters and validating performance for different furnace geometries and operating conditions—could enable cross-sector implementation, provided sufficient sector-specific data and validation are available.

If successfully adapted, transferability may offer benefits such as improved energy efficiency, reduced CO_2 emissions, enhanced process control, and lower operational costs, thereby supporting broader industrial decarbonization objectives.

Main barriers are expected to include limited validation data for specific sectors, established operational practices, and high initial investment costs. These challenges are planned to be addressed through training programs, demonstration projects, and collaboration with industry associations to promote digitalization and develop best-practice guidelines for hybrid and electric furnace design.

4.6 KER6 – Economic and ecological impact assessment for decision making

4.6.1 Overview

KER6 delivers an integrated decision-support framework that combines Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and techno-economic modelling to evaluate both the environmental and financial performance of new heating and energy recovery technologies in the downstream steel sector. It enables the comparison of different technology pathways — such as hydrogen retrofits, hybrid heating, and waste heat recovery — by assessing CO_2 reduction potential, energy savings, and overall economic viability.

4.6.2 Technical Innovation and Development

Conventional assessment tools for industrial decarbonization — such as generic LCA[4] and cost-model — offer useful insights but are often too generic and disconnected from the operational and environmental realities of downstream steelmaking. They typically lack integration between ecological and economic aspects, rely on default datasets, and fail to reflect the real process conditions or pilot-scale data necessary for credible industrial decision-making.

KER6 bridges this gap through an integrated framework that combines:

- LCA and LCC with techno-economic modelling for comprehensive assessment,
- Scenario analysis to compare hydrogen retrofits, hybrid heating, and waste-heat recovery pathways,
- Real industrial data to ensure credible, sector-specific results validated under realistic conditions.

This development combines the expertise of SSSA (LCA and support on LCC) and BFI (LCC, techno-economic modelling, cost analysis, validation, and data integration), with industrial partners providing validation data. Currently at TRL 5, the framework is being refined for full industrial and policy deployment by the end of the project and TRL 6-7.

4.6.3 Market and Users

KER6 targets decision-makers in the steel industry and related sectors seeking transparent, data-driven tools to guide decarbonization investments.

Primary users include:

- Steel producers planning or evaluating low-carbon transition pathways,
- Policy makers and funding agencies designing or assessing decarbonization programs, and
- Consultancies and research organizations offering techno-economic and sustainability advisory services.

The main stakeholders — steel producers, policymakers, and funding agencies — will be engaged throughout validation and dissemination activities via targeted workshops, policy dialogues, and case study demonstrations.

[4] https://simapro.com/

As a knowledge-based tool, KER6 can be implemented by universities, research institutes, or consultancies, addressing approximately 400 downstream steel plants across the EU, as well as industry platforms such as EUROFER and ESTEP.

Initial rollout in Germany, Italy, and Sweden — regions leading in industrial decarbonization — requires only data input and staff training, offering strong economic value through smarter, lower-risk investment planning.

4.6.4 Exploitation Strategy and Sustainability

The exploitation strategy for KER6 focuses on transforming the developed framework into a decision-support tool that enables industries and policymakers to make evidence-based, low-risk investment decisions in the context of industrial decarbonization.

Exploitation opportunities are foreseen across three main levels:

- Industrial use: Integration into corporate strategy, investment planning, and sustainability reporting by steel producers.
- Policy support: Inclusion in EU and national industrial decarbonization roadmaps and impact assessments.
- Advisory services: Adoption by consultancy firms and research organizations as part of their sustainability and strategy offerings.

Adoption requires minimal infrastructure, limited to data provision, staff training, and integration into existing decision-making workflows.

Potential barriers include data confidentiality, trust in model assumptions, and policy uncertainty. These will be mitigated through transparent methodologies, sensitivity analyses, and joint validation with industrial partners to ensure credibility and acceptance.

Exploitation routes focus on:

- Knowledge transfer and consultancy services, offering the framework for strategic and sustainability planning.
- Policy advisory and standardization, integrating outputs into regulatory and funding frameworks.
- Training and capacity building, ensuring end-users can apply the methodology effectively.

Through coordinated collaboration between SSSA, BFI, and industrial partners, the KER6 framework will evolve from a validated research output into a widely adopted decision-support tool for sustainable industrial transformation. By aligning economic competitiveness with environmental responsibility, it will guide investment decisions, support policy formulation, and foster evidence-based decarbonization across the European steel value chain and beyond.

4.6.5 Transferability and Cross-Sector Potential

The KER6 framework is highly transferable to other energy-intensive industries such as cement, glass, ceramics, and chemicals, which face similar challenges in evaluating decarbonization options and balancing ecological with economic performance.

Effective transfer requires access to reliable process and emission data and regulatory incentives for decarbonization. With minor adaptations — such as sector-specific parameters, emission factors, and data structures — the tool can be easily customized for other industrial sectors.

The adoption of KER6 in new sectors could enhance decision quality, reduce financial risk, and accelerate sustainable investments.

Potential barriers include data confidentiality, process-specific variations, and limited expertise in LCA/LCC methods. These can be overcome through training programs, collaboration with industry associations, and standardization initiatives, ensuring the framework's broad applicability across European industries pursuing carbon neutrality.

4.7 KER7 – Roadmap and implementation timeline for future technologies

4.7.1 Overview

KER7 delivers a comprehensive roadmap and implementation timeline for the decarbonization of downstream steelmaking processes, addressing a major gap in existing industrial strategies that primarily focus on upstream steel production. The roadmap will serve as a guiding framework for both industry and policymakers, outlining technological pathways, boundary conditions, and barriers for achieving CO_2 reductions in reheating and heat recovery systems.

4.7.2 Technical Innovation and Development

Existing decarbonization roadmaps for the steel industry — such as those developed by EUROFER[5,6] and the International Energy Agency (IEA)[7] — primarily address upstream steelmaking and provide only general guidance for downstream processes. They overlook the specific requirements of reheating and heat treatment furnaces and the barriers faced by small and medium-sized enterprises that often lack dedicated decarbonization expertise.

KER7 directly addresses this gap by focusing on technology integration, process adaptation, and implementation challenges unique to downstream operations. It provides:

- A comprehensive analysis of reheating and waste heat recovery technologies, including hybrid and hydrogen-based systems.
- Economic and energy mapping tools for identifying efficient transformation pathways.
- Guidelines for adapting existing industrial infrastructure to future fuel-flexible and electrified systems.

This roadmap represents a first-of-its-kind strategic framework that integrates technical feasibility, economic assessment, and policy alignment for downstream decarbonization. It enables companies to plan their transition toward low-carbon operations in a structured, cost-efficient, and evidence-based manner. KER7 combines the expertise of BFI (Technical and economic assessment, energy mapping), SSSA (LCA) and SWE (reheating technology and hybrid heating), with industrial partners providing boundary conditions and inputs from industry's view.

4.7.3 Market and Users

KER7 targets energy-intensive industries, particularly those relying on high-temperature thermal processes, that are planning or initiating their transition toward low-CO_2 or hydrogen-based operations.

Primary users include:

- Steel and metal producers operating reheating furnaces,
- Engineering consultants and plant designers developing decarbonization strategies,
- Technology providers and equipment manufacturers, such as suppliers of high-temperature burners and heat exchangers.

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[5] EUROFER: A Steel Roadmap for a Low Carbon Europe 2050, 2013
[6] EUROFER: Low Carbon Roadmap - Pathways to a CO_2-neutral European Steel Industry, Nov 2019
[7] International Energy Agency : Iron and Steel Technology Roadmap – Towards More Sustainable Steelmaking, Oct 2020

- Policymakers seeking structured guidance for energy transition

Key stakeholders also encompass policy and regulatory bodies, industrial clusters, and research organizations supporting the green transition. Engagement will be fostered through technical workshops, round tables, and targeted dissemination leveraging consortium networks across Europe.

Initial adoption is expected in Germany, Italy, Sweden, Spain, and France, where strong industrial bases, policy alignment with the EU Green Deal, and existing decarbonization initiatives provide fertile ground for implementation.

KER7 specifically supports small and medium-sized enterprises, which often lack dedicated personnel and expertise to plan process decarbonization. By offering a clear, data-driven roadmap, it helps these companies reduce planning costs, avoid delays, and improve competitiveness in emerging green markets.

4.7.4 Exploitation Strategy and Sustainability

The exploitation of KER7 focuses on transforming the developed roadmap into a strategic guideline that provides practical direction on technology integration, investment planning, and emission reduction strategies for downstream steelmaking.

For industrial users, it offers a comprehensive overview of available technologies, their performance, implementation requirements, and expected impacts on energy efficiency and emissions — thereby reducing planning costs and accelerating the deployment of sustainable heating technologies.

For policymakers, the roadmap provides concise background knowledge on downstream heating processes and their boundary conditions, helping to identify and remove regulatory barriers that could hinder the adoption of innovative, low-carbon solutions.

The main exploitation routes include:

- Strategic guidance for industrial decarbonization and technology transition planning.
- Policy advisory and standardization support, enabling regulatory adaptation and long-term sustainability.
- Knowledge dissemination and capacity building, particularly for small and medium-sized enterprises.
- Collaboration with European platforms such as Clean Steel Partnership (CSP), Hydrogen Europe, ESTEP, European Energy Research Alliance (EERA), Processes4Planet, and FOSTA to ensure broad dissemination and alignment with EU climate objectives.

KER7 presents no direct ethical or environmental risks. However, transitioning to new technologies may require workforce retraining to prevent job displacement. Ensuring transparency and inclusive stakeholder engagement will support equitable access to its benefits and promote sustainable industrial transformation.

4.7.5 Transferability and Cross-Sector Potential

KER7 is highly transferable to other energy-intensive industries such as non-ferrous metals, glass, ceramics, and pulp and paper, which rely on high-temperature processes and face similar challenges in planning their decarbonization pathways.

Its applicability relies on the existence of stable high-temperature processes with consistent exhaust gas and temperature profiles. In these industries, the roadmap can guide the transformation of heating processes, providing a clear overview of technological options and requirements, thereby reducing planning costs, accelerating sustainable technology deployment, and enhancing access to green markets.

While certain differences in process characteristics, industrial setups, and regulatory frameworks may limit direct transferability, the roadmap nonetheless offers a valuable reference framework to support cross-sector decarbonization planning in high-temperature process industries.

4.8 KER8 – Hybrid heating concepts

4.8.1 Overview

KER8 – Hybrid Heating Concepts develops and demonstrates a low-carbon, flexible heating system that combines hydrogen combustion with electrical resistive heating in industrial furnaces. The concept enables fuel flexibility, energy efficiency, and load shifting between hydrogen and electricity, supporting the steel industry's transition to CO_2-neutral production.

The technology will be validated in a 3 t/h pilot walking beam furnace, using laboratory tests and modeling to optimize electrical heating elements, heat transfer, and furnace atmospheres.

4.8.2 Technical Innovation and Development

Conventional furnace systems rely almost entirely on fossil fuel combustion, while emerging alternatives typically focus on either hydrogen combustion or electrical heating in isolation.

KER8 bridges this technological gap by developing and testing a hybrid heating concept that allows:

- Flexible operation between hydrogen combustion and electrical heating, enabling load shifting according to fuel prices or energy availability.
- Improved material quality, thanks to an oxygen-free atmosphere in the resistive heating zone, reducing oxidation and material loss.
- Higher overall energy efficiency and lower CO_2-emissions through optimized use of renewable electricity and hydrogen.
- Potential cost savings by dynamically balancing thermal input between electricity and gas.

The development is led by Swerim (SWE) with its pilot infrastructure and furnace expertise, supported by KAN (electrical heating technology), and FER and ADI (process knowledge and KPI evaluation).

Currently at TRL 4, KER8 advances two mature heating technologies (combustion and resistive heating, each at TRL 9) into a single hybrid configuration for large-scale reheating applications at TRL6 by end of 2027.

4.8.3 Market and Users

KER8 targets energy-intensive industries, especially steel and metal producers, seeking flexible, low-CO_2 heating solutions. By combining hydrogen combustion and electrical heating, it improves energy efficiency, material quality, and operational flexibility, while reducing emissions and operating costs.

Potential users include steel plants, OEMs of furnaces and burners, and electrical heating providers, along with policy bodies and engineering consultants and technology suppliers supporting decarbonization. The EU market covers about 80 hot-rolling plants — with 20–25 furnaces replaced annually — and more than 20 major industrial stakeholders, representing significant adoption potential within a 10-year modernization cycle, indicating strong retrofit potential.

Initial deployment is expected in Germany, Italy, Sweden, Spain, and France, regions with active hydrogen roadmaps and industrial decarbonization policies.

4.8.4 Exploitation Strategy and Sustainability

The exploitation strategy for KER8 focuses on validating and demonstrating a hybrid heating solution that combines resistive electrical heating and hydrogen combustion.

Key exploitable results include laboratory and pilot-scale validation data on oxidation behavior, heat transfer, and temperature distribution under hybrid conditions, alongside process-specific KPIs on productivity, energy efficiency, CO_2 emissions, and material quality.

Adoption requires moderate adjustments to existing infrastructure such as electrical element integration, furnace retrofitting, process control integration, and staff training, as well as compliance with hydrogen safety and environmental standards.

Industrial adoption will require furnace retrofitting, process control integration, and staff training, as well as compliance with hydrogen safety and environmental standards.

Barriers to exploitation include industrial reluctance to retrofit existing systems, high upfront costs, fuel-transition uncertainty and evolving hydrogen safety standards. These will be addressed through comprehensive pilot demonstrations, cost-benefit analyses, stakeholder engagement and proactive engagement with regulatory authorities to secure compliance and build confidence.

The main exploitation routes include:

- Pilot testing and industrial validation, offering testing services and hybrid heating expertise.
- Technology development and supply.
- Scenario analysis and process optimization for hybrid heating applications.
- Industrial demonstration and metallurgical assessment to ensure product quality and process feasibility.
- Knowledge transfer and collaboration: across partners via training, dissemination, and industry cooperation.

By aligning with European platforms such as CSP, Hydrogen Europe, and ESTEP, KER8 will advance from pilot validation (TRL 6) to industrial deployment, driving flexible and sustainable heating solutions across the steel and other energy-intensive industries.

4.8.5 Transferability and Cross-Sector Potential

The hybrid heating concept developed under KER8 can be transferred to other energy-intensive industries and equipment suppliers using large-scale furnaces with combustion or electrical heating systems.

Successful application requires high-temperature processes, access to hydrogen or oxygen-enriched fuels, and advanced control and monitoring infrastructure. Adaptation will involve enhanced control systems, compliance with safety and APEX standards, and engineering adjustments to maintain precise temperature control.

Transfer to new sectors offers clear benefits, including higher efficiency, cost savings, improved sustainability, and greater operational flexibility amid volatile energy markets.

Main barriers — such as infrastructure compatibility, operational differences, and investment costs — can be mitigated through technical training, alignment with industry standards, pilot demonstrations, and supplier-supported design optimization.

5 Conclusions

This deliverable presents the initial exploitation strategy and transferability analysis for the E-ECO Downstream project, outlining how the project's KERs can deliver tangible impact for industrial decarbonization in downstream steelmaking and beyond.

The analysis demonstrates that each KER contributes uniquely to improving energy efficiency, CO_2 reduction, and technological readiness for hydrogen-based and electrified industrial processes. Together, these results form a coherent pathway for enabling cost-effective, sustainable transformation of furnace systems, heat recovery, hybrid heating, and digital assessment tools across the value chain.

The report also highlights the importance of stakeholder engagement, including industrial partners, policy makers, OEMs, and research organizations, to ensure alignment between technological development and market needs. The integration of exploitation and transferability activities across KERs strengthens the overall innovation impact and supports Europe's transition toward climate-neutral industrial production.

Next steps will focus on refining exploitation routes, validating business models, and strengthening collaboration with European technology platforms such as ESTEP, A.SPIRE, and the CSP. The final version of the exploitation strategy will consolidate industrial feedback, pilot results, and market insights, ensuring that the project outcomes are positioned for long-term adoption, scalability, and policy relevance.

6 Appendix

6.1 KER1 questionnaire

TABLE 2: KER1 DEFINITION

1	**Unique KER Identifier/Name**: Experimental results from retrofitted burner operation at pilot scale when exploiting new fuels
2	**Owner of this KER:** All
3	**Roles and responsibilities of each partner in the project in relation to this KER:** BFI contributes by simulation work to optimize burner configurations and by investigating burners at pilot scale on its testing facility. FER and ADI provide data of existing heating equipment and define boundary conditions for new systems and test support. KUP support material development for AM by VDM. SSSA data analysis, evaluation of hydrogen embrittlement with its subcontractor and modelling of combustion results for mass and energy balance process models. ALL will support analyzing furnace components with available analysis technology.
4	**Brief Technical Description of the KER:** Elaborate a low cost retrofit of burners for reheating furnaces to achieve fuel flexibility regarding renewable C-free fuels, implemented by parametric modelling, CFD-simulations and active learning techniques. Through AM, using resistant powder materials, complex designs of nozzles and other burner parts are generated. Currently installed burners shall be retrofitted by “spare parts” to operate with selected C-free fuels and fuel mixtures. It validates retrofit feasibility by demonstrating stable combustion, acceptable NOx emissions, and efficiency at industrially relevant scales.
5	**Current TRL of this specific KER:** TRL4
6	**Provide specific evidence justifying the current TRL:** Burner for NG and H2 are available on the market (TRL9). Existing NG-burners have to be replaced by new systems, when fuel is switched to H2. Adaptions to furnace walls are necessary. This procedure is time and cost intensive and leads to production loss. AM of steel parts is also available (TRL9). Suitable powders to manufacture parts for high temperature up to 1,200 °C are missing. Concepts for improved burner design have been developed (TRL 4) but could not been put into praxis due to lack of production technology.
7	**Is this KER a standalone output or is it designed to be integrated into another system/product?** This KER is both standalone and will play an important role in other KERs as well. Retrofitting of burners to match new fuel requirements in furnaces is expected to be useful in any combustion related context. At the same time, the Know-how of this KER will be part of the KER5, KER7 and KER 8.

TABLE 3: KER1 GAP ANALYSIS

1	**What specific problem does this KER solve or what fundamental need does it address for users, industry, or society?** Usually, technical equipment today is optimized for a small operating range. Efficiency, emission and service life are getting worse when boundary conditions are altered. Thus, plants and furnaces will be revamped by incorporating new heating technologies (burner, heat exchanger…) or building new plants entirely. The development approach for modifying small parts (parametric modelling, simulation and experiments in combination with active learning) as well as the usage of AM and modern materials enables the industry to improve their processes at lower costs, in shorter time and with less interruptions of the production due to revamping.

2	**What comparable developments or products are available on the market which have a comparable use case this KER?** Hydrogen burners exist, but they require full replacement of systems, with high CAPEX. Other pilot projects focus on upstream processes but not downstream furnaces. Retrofits are not yet validated in operational environments. Components have been developed for high temperature conditions with ceramic components like silicon carbide and fibre reinforced ceramics. New burners have been developed to operate with fuel mixtures of NG and H_2 up to pure hydrogen.
3	**Which gaps do these products have on the market?** Existing solutions are expensive, lack flexibility to use transitional fuel mixtures, and often cannot be integrated into current furnaces without major infrastructure changes. They also lack robust pilot-scale validation. To use new developed burners existing technology must be replaced completely. Components of ceramic materials are difficult to combine with metallic constructions and are sensible to mechanical stress. Furthermore, AM may be not possible.
4	**What do this KER achieve in addition?** By using modern techniques like active learning and AM the developing process will be more focused. This lowers adoption barriers for industry. Accordingly, time and costs for development are decreasing. Support from experts of process industry in early stage enhances this effect.
5	**What is the unique selling point of this KER compared to existing technology/products?** Fast and focused development of new parts for revamping existing technology at industrial plants leads to less interruptions in production and significantly lower costs. Pilot-scale, real-world evidence of cost-effective retrofitting with proven operational data on efficiency, flexibility, and emissions.

TABLE 4 : KER1 MARKET ANALYSIS AND TARGET USERS

1	**What specific benefits will potential users gain from applying the developed technology compared to existing solutions or products?** The main benefit is the reduction of costs and/due to production stops when adapting burner technology to the use of new fuels and their mixtures with NG. This way a decarbonization can be achieved without the necessity to replace entire (sub-)systems within the respective plant. The acceptance on the steel industry side to revamp only parts to become H_2-ready for the future is considerably higher. The part design can use new fuels and sustain the existing heating configuration in the production plants
2	**Who are users in industry?** The addressees of this KER are industrial producers where NG-burners are the main technology for heating. The steel industry will be primarily targeted, but the need of decarbonization without replacing entire systems may be interesting for every industry branch in which burners play a central role in heating. Potential customers also include OEMs of burners and furnace systems, who can adopt retrofit designs into their service portfolios
3	**Who can manufacture this KER who are possible suppliers?** Manufacturing replaceable parts for burners requires two parties: a company providing a specific burner and (if not existent in the same company) a manufacturer from the 3D printing branch to build the required new parts. Due to the Know-how type of this KER the methodology can be easily transferred, such that the development of replacement parts can be carried out for all existing burners.
4	**How big is the market?** The EU downstream steel sector alone operates more than 400 reheating furnaces, each of which will require decarbonization solutions in the coming years. This represents a substantial market of potential customers who must decide between replacing systems entirely or retrofitting existing infrastructure.

5	**Expected cost for implementation/invest of new technology**? The major part of implementation costs is the development of new parts for revamping. The replacement of burner parts can be done step by step for each burner in use at the respective industrial plant, and therefore significantly reduces the costs on the plant side. The expertise to develop new parts for burners defines the largest cost position but occurs just once for each burner.
6	**savings per year achieved in industry with new technology?** Depending on the costs for providing, storage and purchase of hydrogen fuels the savings are mainly defined by reduced need for CO_2 certificates and the advantage of replacing parts in existing (sub-)systems instead of entire technologies.
7	**Who are the key stakeholders?** Key stakeholders include steel plant operators, burner and furnace OEMs, industrial associations, AM companies, research partners, regulators, and hydrogen providers. Their involvement is crucial to ensure technical feasibility, regulatory approval, and market adoption.
8	**Strategy for engaging the stakeholder?** Engagement will be achieved through pilot demonstrations, joint dissemination workshops, and active participation in industrial clusters. Early involvement of regulators ensures smoother approval processes, while direct cooperation with OEMs facilitates integration into commercial offerings.
9	**Are there any specific geographical regions within the EU that are of particular interest for initial market entry? Why?** Any country with (steel) production and the (political) motivation to enforce decarbonization strategies. Germany, Italy, and Sweden are strategic entry points due to their strong steel industries, pilot sites already engaged in E-ECO Downstream, and national hydrogen roadmaps. These countries represent early adopters with supportive policy frameworks.
10	**What is the estimated market size for this KER within the EU?** Considering over 400 reheating furnaces in EU where adapting to new fuels by replacing instead of rebuilding is wanted.
11	**What are the specific needs of these target users that this KER directly addresses?** The general insecurity in the steel industry on how to adapt to future technologies while keeping the costs of investment and interruptions in production low is directly addressed. By minimizing the adaption process due to part replacement, the production output is affected in a minimal way.

TABLE 5: KER1 INITIAL EXPLOITATION STRATEGY

1	**What is your expected result and/or development?** The result is the methodology to produce parts to retrofit burners to allow the usage of new fuels other than NG. Part replacement is expected to be less cost ntensive.
2	**What is your value proposition concerning exploitation?** Instead of rebuilding/replacing entire systems the same change can be provided by replacing burner parts while keeping costs and interruptions to production at a minimum.
3	**Description of exploitable results?** Exploitable results are the approach on how to develop new parts for burners and which materials are to be used when 3D printing these. Further, case studies on the effect of part replacement at pilot scale regarding the fuel mixture of hydrogen and NG.
4	**When do you expect your results?** By the end of the project in Q2 2028.
5	**Which deployment opportunities do your results and /or developments have for industrial use?** Deployment can take place in industrial plants, where the burners, for which parts are developed during this project, are currently employed. They can also be offered as retrofit packages by OEMs or service providers, expanding market opportunities.
6	**At what TRL are your results and/or developments?** While the technologies of powder metal alloys, AM and burner design are at TRL 9, the combination of the former

	for retrofitting burners is TRL 4 at the beginning of the project. After testing the facility of the BFI under near service conditions TRL 6 will be reached.
7	**What must industrial end-users do or change in their setup to adopt and use it?** If replacement of burner parts is desired, the end-users should provide the necessary infrastructure to make the usage of new fuels possible. End-users must replace burner inserts or retrofit specific components, adopt updated safety procedures, and ensure adequate C-free fuels supply. Full infrastructure replacement is not necessary.
8	**Which stakeholders and decision makers will be involved in exploiting your developments? When will they be involved?** Steel producers that employ NG burner technology for their heating processes, AM and burner designer are involved along the entire development chain. Their involvement will ensure that results are credible, safe, and market-ready.
9	**With which platforms do you expect to cooperate?** Cooperation with ESTEP, Hydrogen Europe, and national industrial decarbonization clusters will ensure sustainability and visibility of results.
10	**Which barriers do you see for exploitation?** Providing the necessary infrastructure to make hydrogen assessable for the local heating processes. Replacement parts for various burners need to be developed in accordance with the methodology provided during this project. Potential barriers include safety regulations for C-free fuels (e.g. hydrogen), volatility of C-free fuels supply, and conservative investment attitudes within the steel sector.
11	**Which strategy is foreseen to react on this/these barrier(s)?** Providing clear instructions on the development process for replacement parts and the documentation of the simulation and test results. Strategies include early engagement with regulators, transparent communication of safety data, and demonstration of cost-effectiveness to reduce hesitation among decision-makers.
12	**Preliminary definition of business and sustainable model?** The results of this KER can be imposed on business and sustainable models due to the adaption of existing technology for long-term use with the benefit of decarbonization and cost reduction. The sustainable model involves knowledge transfer through consultancy, licensing of retrofit concepts, and dissemination via industrial associations.
13	**Are there any ethical, societal, or environmental considerations related to the exploitation of this KER that need to be addressed?** The data privacy concerning burner and material technology is mandatory. The technical details of existing technologies of industrial partners must be kept disclosed. Worker safety for C-free fuels (e.g. hydrogen) handling and emission reduction are key considerations. The KER contributes positively by lowering CO_2 and pollutant emissions, supporting climate goals.
14	**What are the top concrete exploitation-related actions your organization plans to undertake during the project's remaining lifetime related to this KER?** It will actively use the potential of collaboration with partners' academic and business networks, technological platforms as well as with other Horizon EU clusters, and collaborate with stakeholders in public and private sectors across diverse domains, for sharing, adapting and/or extending the gained knowledge, and best practices towards their wide adoption in the EU steel sector.
15	**Which primary exploitation route(s) do you envision for this KER?** Providing the methodology, documentation and guidelines for retrofitting burners. The knowledge transfer consists of the theoretical and practical side of the development process. consultancy services, and licensing of retrofit designs.
16	**Which consortium partners do you foresee collaborating most closely with on the exploitation of this KER, and for what specific activities?** KUP providing the burner to be investigated, VDM on materials for AM.

17	**What internal resources will your organization commit to these initial exploitation activities for this KER?** Personnel for the optimization, simulation and testing of the replacement parts for the burner adaptation. Personnel for modelling and analysis, data collection and interpretation, coordination of roadmap input

TABLE 6: KER1 TRANSFERABILITY ANALYSIS

1	**Which other sectors or industries could potentially benefit from this KER?** Methods and materials can be used in many industrial processes at temperature, in corrosive conditions or even in a more challenging environment of legal limits concerning efficiency and emissions. For example, these could be heat exchanger, transporting systems or cleaning systems in raw materials industry and in processing companies. Glass, ceramics, cement, and petrochemical industries could benefit, as they operate high-temperature furnaces where fuel flexibility and decarbonization are critical.
2	**What conditions must be present in the target sectors to enable the use of this KER?** The required infrastructure to employ burners with variable fuel mixtures, especially the possibility to store and employ hydrogen. There must be access to C-free fuels supply, high-temperature furnace systems, and regulatory frameworks permitting their use.
3	**What modifications or adaptations would be needed to make the KER applicable in other sectors or use cases?** The replacement parts for burner adaption are dependent on the respective burner. Accordingly, for different burners new replacement parts must be developed in accordance with the method/approach provided by the KER. Burner geometry, material choice, and safety protocols would need adaptation to sector-specific process requirements
4	**What potential improvements could the KER bring when applied to other sectors?** Improvements are decarbonization and adaption to variable fuel mixtures (flexibility) without having to rebuild/replace entire burner systems or plants, and hence reducing the transformation costs significantly.
5	**What are the main barriers or limitations to applying this KER in other sectors?** Providing a hydrogen infrastructure and developing the replacement parts for the respective burner technology, which might not be covered during this project. The price of hydrogen to justify the transformation. High upfront investments despite lower long-term costs, sector-specific regulations.
6	**What support might be needed to overcome these barriers?** Clear framework conditions from policy makers to allow for a precises assessment for a transformation towards hydrogen combustion. Especially prices for hydrogen and CO_2 certificate prices play important roles in the economical security of potential investments. Support will include training for operators, development of harmonized standards, sector-specific adaptation of retrofit concepts, and engagement with regulators.

6.2 KER2 questionnaire

Table 7: KER2 Definition

1	**Unique KER Identifier/Name?** Concepts for heat recovery from off-gases and from other sensible heat sources considering future downstream processes
2	**Owner of this KER?** SSSA, BFI, KUP
3	**Roles and responsibilities of each partner in the project in relation to this KER?** BFI & KUP: Development of heat recovery concepts, SSSA: Leading process and scenario analyses for assessing and developing concepts for heat recovery under future fuel conditions, performing thermodynamic modeling and balancing, and assessing mid- to long-term impacts and feasibility of integration in downstream steel processes. KUP: Design and manufacturing of recuperators using AM. ADI & FER: Provide industrial data, support modelling, pilot testing, and assess integration feasibility.
4	**Brief Technical Description of the KER?** Development and adaptation of heat recovery systems (recuperators/regenerators) for future fuels like hydrogen and biofuels. Focus on preheating of fuel and oxidizers using off-gas and other sensible heat sources.
5	**Current TRL of this specific KER?** Not applicable
6	**Provide specific evidence justifying the current TRL?** Concepts are developed and tested at pilot scale (BFI test facility).
7	**Is this KER a standalone output or is it designed to be integrated into another system/product?** Designed to be integrated into reheating and heat treatment furnaces in downstream steel processes.

Table 8: KER2 Gap analysis

1	**What specific problem does this KER solve or what fundamental need does it address for users, industry, or society?** KER2 addresses the need for efficient heat recovery in steel downstream processes, especially under future fuel conditions (e.g. hydrogen, biofuels). It aims to reduce energy losses and improve energy efficiency, contributing to decarbonization and cost reduction in steel production.
2	**What comparable developments or products are available on the market which have a comparable use case this KER?** Conventional recuperators and regenerators for NG-based furnaces are widely used. However, they are not optimized for hydrogen combustion or future fuel mixtures and often lack flexibility and material resilience for high-temperature, reactive atmospheres.,
3	**Which gaps do these products have on the market?** Existing systems are not designed for: High H_2O content in exhaust gases, Reactive fuel mixtures, Integration with AM, Flexible adaptation to changing fuel compositions, High-temperature operation with advanced materials
4	**What do this KER achieve in addition**? Use of 3D-printed recuperators with optimized geometries for enhanced heat exchange, Application of high-performance Ni-based alloys for durability, Adaptation to future fuels (H_2, biofuels), Improved energy efficiency and reduced CO_2 emissions, Pilot-tested under realistic industrial conditions
5	**What is the unique selling point of this KER compared to existing technology/products?** (supports KER3) The combination of AM, advanced materials, and fuel-flexible design tailored for future downstream steel processes. Enables cost-effective retrofitting and high-efficiency heat recovery under hydrogen-rich conditions, which current systems cannot support.

TABLE 9: KER2 MARKET ANALYSIS AND TARGET USERS

1	**What specific benefits will potential users gain from applying the developed technology compared to existing solutions or products ?** Increased energy efficiency in reheating and heat treatment processes, Reduced CO_2 emissions, Cost savings through fuel reduction and optimized heat recovery, Compatibility with future fuels (H_2, biofuels), Retrofitting existing systems instead of full replacement
2	**Who are users in industry?** Steel producers (e.g., ADI, FER, SMEs with reheating furnaces, Foundries and forging companies, Non-ferrous metal industries, Furnace and burner manufacturers
3	**Who can manufacture this KER who are possible suppliers?** KUP (burner and recuperator manufacturer), VDM (metal powder supplier for AM), OEMs in industrial heating systems, AM service providers
4	**How big is the market?** ~400 downstream steel processing plants in the EU, Additional potential in non-ferrous and high-temperature industries, Estimated 100 customers per year in early adoption phase
5	**Expected cost for implementation/invest of new technology**? Each furnace must be investigated individually. Actual invest must be determined inside the project
6	**savings per year achieved in industry with new technology?** Energy savings of 10–30% through optimized heat recovery
7	**Who are the key stakeholders?** Steel producers, OEMs, Hydrogen suppliers, Policy makers, Research institutions and platforms (e.g., ESTEP, EUROFER and national e.g., VDEh, AIM)
8	**Strategy for engaging the stakeholder?** Advisory Board involvement, Dissemination via conferences, webinars, and trade fairs, Collaboration with platforms and clusters, Open access publications and demonstrator visits
9	**Are there any specific geographical regions within the EU that are of particular interest for initial market entry? Why?** Germany, Italy, Sweden: high concentration of steel producers and project partners, Strong industrial infrastructure and policy support for hydrogen and decarbonization
10	**What is the estimated market size for this KER within the EU?** Estimated annual revenue potential: >100 million €, Market size: 400+ plants in steel sector, plus additional in related industries
11	**What are the specific needs of these target users that this KER directly addresses?** Need for cost-effective decarbonization, Compatibility with future fuels, Reduction of energy costs and emissions, Avoidance of full system replacement, Regulatory compliance and sustainability goals

TABLE 10: KER2 INITIAL EXPLOITATION STRATEGY

1	**What is your expected result and/or development?** KER 2 Concepts and KER3: validated designs for heat recovery systems (recuperators/regenerators) adapted to future fuels like hydrogen and biofuels, including pilot-tested components.
2	**What is your value proposition concerning exploitation?** Cost-effective retrofitting of existing furnaces with fuel-flexible heat recovery systems, enabling decarbonization and energy efficiency improvements without full system replacement.
3	**Description of exploitable results?** Know-how on heat recovery concepts for future fuels, Pilot-tested recuperator designs, Material data for high-temperature applications,Validated scenario studies for different plant configurations and future energy system evolution, for industrial deployment
4	**When do you expect your results?** Final results expected by M42 (October 2028); initial exploitation strategy by M12 (December 2025)

5	**Which deployment opportunities do your results and /or developments have for industrial use?** Retrofitting of reheating and heat treatment furnaces, Integration into new furnace designs, Application in steel, non-ferrous, and high-temperature industries, Developed models enables targeting heat recovery integration in plants with evolving fuel mixes or planned retrofits, supporting both short-term and future-oriented investments.
6	**At what TRL are your results and/or developments?** Support for KER 3: TRL 4–6 (pilot-tested, validated in relevant environment)
7	**What must industrial end-users do or change in their setup to adopt and use it?** Integrate modified recuperators into existing furnace systems, Adapt fuel and oxidizer supply systems, Ensure compatibility with safety and regulatory standards
8	**Which stakeholders and decision makers will be involved in exploiting your developments? When will they be involved ?** Steel producers (ADI, FER), OEMs (KUP), Policy makers and platforms (ESTEP, EUROFER), Involved from M12 onward
9	**With which platforms do you expect to cooperate?** ESTEP, EUROFER, A.SPIRE, SusChem, national steel associations
10	**Which barriers do you see for exploitation?** Safety concerns with hydrogen, Lack of standardization for future fuels, Investment costs and risk aversion, Limited availability of green hydrogen
11	**Which strategy is foreseen to react on this/these barrier(s)?** Pilot demonstrations and KPIs, Dissemination and stakeholder engagement, Scenario analyses and roadmap development, Collaboration with regulatory bodies
12	**Preliminary definition of business and sustainable model?** Licensing of designs and know-how, Joint exploitation by consortium partners, Integration into OEM product portfolios
13	**Are there any ethical, societal, or environmental considerations related to the exploitation of this KER that need to be addressed?** Positive impact on climate and sustainability, Resource-efficient retrofitting, Avoidance of carbon leakage, Occupational safety in hydrogen handling
14	**What are the top concrete exploitation-related actions your organization plans to undertake during the project's remaining lifetime related to this KER?** Pilot testing and validation, Dissemination of results, Stakeholder workshops, Development of implementation roadmap, Advanced scenario analyses for stakeholders, Development of guidelines for best-practice heat recovery integration under variable future fuel scenarios
15	**Which primary exploitation route(s) do you envision for this KER?** Use in industrial processes; integration into OEM offerings; licensing of know-how
16	**Which consortium partners do you foresee collaborating most closely with on the exploitation of this KER, and for what specific activities?** BFI, SSSA, KUP, ADI, FER , VDM– for technical development, testing, and industrial integration
17	**What internal resources will your organization commit to these initial exploitation activities for this KER?** Dedicated personnel for modelling, testing, and dissemination, Access to pilot testing facilities, Internal budget for material development and stakeholder

TABLE 11: KER2 TRANSFERABILITY ANALYSIS

1	**Which other sectors or industries could potentially benefit from this KER?** Non-ferrous metal industries (e.g. aluminum, copper), Glass industry, Cement industry, Ceramics and brick manufacturing, Chemical processing with high-temperature furnaces
2	**What conditions must be present in the target sectors to enable the use of this KER?** Presence of high-temperature heating processes, Use of combustion-based

	heating systems, Availability of hydrogen or biofuels, Regulatory support for decarbonization and energy efficiency, Safety protocols for hydrogen handling
3	**What modifications or adaptations would be needed to make the KER applicable in other sectors or use cases?** supports KER 3: Material selection tailored to sector-specific atmospheres, Integration with sector-specific control systems, Compliance with sector-specific safety and emission standards
4	**What potential improvements could the KER bring when applied to other sectors?** Enhanced energy efficiency (10–30%), Reduced CO_2 and NO_x emissions Lower fuel costs, Increased operational flexibility with fuel mixtures, Improved sustainability and regulatory compliance
5	**What are the main barriers or limitations to applying this KER in other sectors?** Lack of awareness or technical expertise, supports KER 3: High upfront investment costs, Limited availability of hydrogen infrastructure, Sector-specific safety and certification requirements, Resistance to change from established practices
6	**What support might be needed to overcome these barriers?** Training programs for operators and engineers, Development of sector-specific standards for hydrogen use, Demonstration projects and pilot installations, Engagement with industry, associations and regulators, Technical documentation and open-access publications

6.3 KER3 questionnaire

TABLE 12: KER3 DEFINITION

1	**Unique KER Identifier/Name:** KER 3 / Modified and efficient recuperator for preheating fuel and oxidizers
2	**Owner of this KER?** BFI, KUP, VDM
3	**Roles and responsibilities of each partner within the project in relation to this KER:** T2.1, T2.2, T2.3 BFI contributes its expertise in the areas of thermal system testing, process integration, and energy efficiency assessment, making it an important technical partner in the implementation and validation of the innovative recuperator system developed as part of KER3. Pilot testing of recuperators, simulation and assessment of heat recovery systems. VDM contributes its expertise in metal powder production and material development for the production of AM recuperator. KUP contributes its expertise in AM, particularly metal powder bed fusion, for industrial burner and heat exchanger recuperator applications.
4	**Brief Technical Description of the KER:** KER3 is a modified highly efficient recuperator designed to preheat fuels and oxidizers using waste heat from exhaust gases. It is designed to support the transition to low-carbon and hydrogen-based fuels and is designed for changes in gas composition and operation at high temperatures (up to 1200 °C).
5	**Current TRL of this specific KER:** TRL4
6	**Provide specific evidence justifying the current TRL:** VDM, KUP, and BFI will operate on laboratory level to test the production process (3D-printing), the produced material properties and their performance in synthetic environmental use. --> TRL4 The use of printed burners will be demonstrated in WP1 --> TRL5-6 Concepts are developed and tested at pilot scale (BFI test facility). Recuperators manufactured and tested with new materials.
7	**Is this KER a standalone output or is it designed to be integrated into another system/product?** This KER is designed for integration into industrial heating systems. It is not a stand-alone device, but part or addition of a larger combustion or heat recovery system.

TABLE 13: KER3 GAP ANALYSIS

1	**What specific problem does this KER solve or what fundamental need does it address for users, industry, or society?** The modified recuperator enables safe and efficient continuously preheating of fuel and oxidizers above 1000 °C, resulting in lower energy consumption, reduced CO_2 emissions, and better integration of renewable and alternative fuels—supporting both industrial decarbonization and energy cost reduction.
2	**What comparable developments or products are available on the market which have a comparable use case this KER?** Many existing recuperator systems are designed primarily for fossil fuel combustion and are not well-suited to the unique challenges posed by hydrogen or hydrogen-fossil fuel blends. Trymax Industrial Recuperator Trymax offers counterflow heat recovery units specifically designed for reheating furnaces. These units operate in a temperature range for preheated fluids of 100 to 600 °C and are made of mild or stainless steel. They are designed to increase furnace efficiency and reduce fuel consumption in industrial environments. Tsb Energy Recuperators

	TSB Energy (TSB) offers custom-designed smoke-tube recuperators for a wide range of industrial heat recovery applications, including boilers, furnaces, and dryers. Units support flue gas cooling to as low as 50 °C using carbon steel or stainless-steel materials. Heatcor & Silit recuperators Saint-Gobain produces SiC based twisted plate recuperators direct and indirect heating applications with operating temperatures of 1380 °Ch. The manufacturing process utilizes “Amasic-3D”, a 3D printing process for ceramics.
3	**Which gaps do these products have on the market?** Most existing commercial recuperators and regenerators: Operate within moderate temperature ranges, Lack of fuel flexibility, Missing dual-preheating capability, Insufficient data for new combustion atmospheres, Reduced adaptability for retrofitting Trymax Industrial Recuperator: Limited Temperature Range, Low Fuel Flexibility, Basic Materials, No Dual Preheating Support (preheating both fuel and oxidizer streams) Tsb Energy Recuperators: Standard Fuel Orientation, Moderate Operating Temperatures, Single-stream Preheating Only Heatcor & Silit recuperators: Brittle ceramic structure, susceptible to cracking or fracture under thermal cycling and mechanical stress. Moderate thermal conductivity, limiting overall heat transfer efficiency and reducing potential fuel savings. Rough internal surfaces, causing higher flow resistance and pressure losses, which necessitate increased intake compression. Challenging maintenance and inspection, as ceramic components cannot be welded or patched, increasing downtime and replacement costs. Requires interfaces between metal and ceramic components. KER3 Existing systems are not designed for: High H_2O content in exhaust gases, Reactive fuel mixtures, Integration with AM, Flexible adaptation to changing fuel compositions, High-temperature operation with advanced materials
4	**What do this KER achieve in addition?** KER3 advantage compared to Trymax Industrial Recuperator**:** Designed for high-temperature operation (~1200 °C in flue), compatible with hydrogen and oxygen-enriched air, uses advanced materials (e.g., VDM alloy), and supports simultaneous preheating of fuel and oxidizer. KER3 advantage compared to Tsb Energy Recuperators: Offers dual-stream preheating (fuel and oxidizer), validated under hydrogen combustion conditions, and built from high-temperature-resistant alloys suitable for hydrogen atmospheres. KER3 advantage compared to Heatcor and Silit recuperators: Metallic structure provides mechanical robustness, higher thermal conductivity, and smoother internal surfaces resulting in lower pressure losses and more efficient heat exchange. If applicable: sealed system for reactive gases. Material homogeneity (all-metal design) eliminates interfaces between dissimilar materials, reducing risks of thermal mismatch and simplifying assembly. Improved durability and rigidity under thermal and mechanical loads. This reduces constraints during manufacturing, installation, inspection, and maintenance. Higher thermal conductivity enhances heat recovery performance and enables greater fuel savings. Complex TPMS gyroid recuperator structure for enhanced thermal conductivity. KER3: Use of 3D-printed recuperators with optimized geometries for enhanced heat exchange , Application of high-performance Ni-based alloys for durability Adaptation to future fuels (H_2, biofuels), Improved energy efficiency and reduced CO_2 emissions, Pilot-tested under realistic industrial conditions

5	**What is the unique selling point of this KER compared to existing technology/products?** Hydrogen-ready, High-Temperature Resistance, Material Innovation, Fuel and Oxidizer Flexibility, Improved Energy Efficiency, Lower CO_2 Emissions, Industrial Validation, Improved durability and rigidity under thermal and mechanical loads, compared to ceramics, Sealed construction for reactive gases The combination of AM, advanced materials, and fuel-flexible design tailored for future downstream steel processes. Enables cost-effective retrofitting and high-efficiency heat recovery under hydrogen-rich conditions, which current systems cannot support.

TABLE 14: KER3 MARKET ANALYSIS AND TARGET USERS

1	**What specific benefits will potential users gain from applying the developed technology compared to existing solutions or products?** Improved Production Performance, Ecological Benefits, Economic Benefits, Higher Efficiency
2	**Who are users in industry?** The primary users are energy-intensive industries that rely on high-temperature thermal processes and are transitioning to low-CO_2 or hydrogen-based fuels. Steel and metal production plants, Glass and ceramics industries, Chemical and petrochemical industries using process heaters, Energy and Aerospace industry (turbines), OEMs of industrial burners and furnace systems seeking hydrogen-compatible solutions, Plant engineering companies integrating energy recovery solutions in retrofits or new installations Within these sectors, customers are typically: Plant operators aiming to reduce energy costs and emissions, Technology providers and equipment manufacturer looking to upgrade their systems for hydrogen-readiness, Engineering consultants planning decarbonization strategies for clients
3	**Who can manufacture this KER who are possible suppliers?** Manufacturer of high-temperature heat exchangers, Manufacturer of Industrial furnace components, Equipment manufacturer using advanced material processing and 3D metal printing, Other material / powder supplier for high-temperature materials like Carpenter, Oerlikon, Höganäs, …
4	**How big is the market?**
5	**Expected cost for implementation/invest of new technology**? The expected investment depends on the scale of the installation, the material used (e.g., VDM alloy vs. standard Inconel), and the degree of integration required in the plant's existing infrastructure. 602 CA Selling Price: approx. 70,90€/kg, -625 Selling Price: approx. 69,10€/kg
6	**savings per year achieved in industry with new technology?** Enables significant energy savings the result of this project .
7	**Who are the key stakeholders?** Industrial End-Users: Steel and metal processing companies operating reheating furnaces (Acerinox, Haynes, VDM, ThyssenKrupp, Arcelor Mittal, DEW, FER, ADI, Mannesmann …) Technology Suppliers: Heat exchanger and burner manufacturers (Alfa Laval, Kelvion, Küppers, … Policy and Regulatory Bodies: National and EU agencies supporting energy efficiency and decarbonization. Research and Technical Partners: Consortium members. Investors / Industrial Clusters: Organizations supporting innovation in sustainable manufacturing.
8	**Strategy for engaging the stakeholder?** 1. Identify Key Stakeholders 2. Customize communication to the interests of stakeholders by focusing on aspects that are important to them. 3. Use Multi-Channel Communication like: Technical workshops, social media, print media, round tables .., 4. Leverage Consortium

	Networks to reach wider stakeholders across the EU, .., 5. Plan for Post-Project Continuit, By developing exploitation agreements and IPR arrangements, ..
9	**Are there any specific geographical regions within the EU that are of particular interest for initial market entry? Why?** This applies to industries that want to use waste heat and also use the new fuel like. Germany, Italy, Sweden, Spain, France, High density of target industries (steel, aluminum, glass, etc.), Policy alignment with EU Green Deal and national decarbonization roadmaps. Existing infrastructure where retrofitting is feasible. Local partners and stakeholders already engaged in the E-ECO project.
10	**What is the estimated market size for this KER within the EU?**
11	**What are the specific needs of these target users that this KER directly addresses?** Energy efficiency improvements: Users in the steel industry and other heavy industries are confronted with high energy consumption in reheating and combustion processes. They need solutions for effective waste heat recovery in order to reduce fuel consumption and operating costs. Fuel flexibility and conversion: With the switch to low-carbon fuels such as hydrogen or fuel mixtures, existing recuperators are often incompatible or inefficient. Users need modified heat recovery systems that can safely and efficiently process different fuel compositions. Material resistance at high temperatures: Current recuperators have problems with resistance at high temperatures and aggressive gas mixtures, which limits their performance and maintenance intervals. The new materials and designs of the recuperators are intended to withstand these harsh conditions for longer durability. Process integration and scalability: Industrial users need solutions that can be integrated into existing furnace systems without major disruptions and offer scalable retrofit options suitable for different furnace sizes and operating conditions. Compliance with emission regulations: Stricter environmental regulations require optimization of combustion efficiency and reduction of CO_2 emissions, which depends to a large extent on effective heat recovery. Operational safety and reliability: Safe operation at high preheating temperatures with various requires reliable heat exchanger designs to avoid operational risks.

TABLE 15: KER3 INITIAL EXPLOITATION STRATEGY

1	**What is your expected result and/or development?** The expected result is the development and validation of a modified and efficient recuperator capable of preheating fuels and oxidizers, including hydrogen and fuel mixtures, to improve heat recovery and process efficiency in industrial heating applications. This includes pilot-scale testing of new high-temperature resistant materials (such as VDM's material) in 3D-printed recuperators, demonstrating their suitability and performance under real operating conditions up to 1200°C. The outcome will provide a reliable, flexible heat recovery solution that supports the transition to low CO_2 fuels by enabling safer and more efficient preheating, ultimately reducing fuel consumption and emissions.
2	**What is your value proposition concerning exploitation?** Enables industrial users to transition to future fuels such as hydrogen without requiring major infrastructure changes, thanks to burner design and material selection. Provides equipment manufacturers with advanced simulation tools for designing combustion systems optimized for alternative gas atmospheres. Helps plant operators reduce fuel costs and CO_2 emissions by maximizing heat recovery efficiency. Provides technology providers and integrators with validated, scalable solutions that accelerate the deployment of sustainable heating technologies.

3	**Description of exploitable results?** The result includes a validated design concept, pilot-scale testing data, and modelling tools to support integration into existing or new burner systems.
4	**When do you expect your results?** end of 2027
5	**Which deployment opportunities do your results and /or developments have for industrial use?** retrofitting of existing combustion systems or integration into new installations, supporting energy efficiency goals, reducing emissions
6	**At what TRL are your results and/or developments?** TRL 4–6 (pilot-tested, validated in relevant environment)
7	**What must industrial end-users do or change in their setup to adopt and use it?** Adaptation of furnace infrastructure, Integration with existing process controls, Fuel supply compatibility, Regulatory and safety compliance, Staff training and operation protocols, Heat integration studies, Potential mechanical adjustments
8	**Which stakeholders and decision makers will be involved in exploiting your developments? When will they be involved?** Industrial partners (e.g., steel producers, burner manufacturers) – as potential adopters and integrators of the recuperator technology. Involved from Month 18 onward during testing, validation, and feedback phases. Material suppliers (e.g., VDM Metals) –Involved from early stages (Month 6) through pilot-scale development. Plant engineering companies – potential partners for scaling and integrating the technology into industrial systems. Involved from Month 24 onward, once technical feasibility is proven. Policy makers / standardization bodies – for alignment with safety and environmental regulations. Engaged in the later stages (Month 30–End) to support commercialization.
9	**With which platforms do you expect to cooperate?** CSP, Hydrogen Europe, ESTEP, EERA, SPIRE / Processes4Planet National German platforms (e.g., Forschungsvereinigung Stahlanwendung - FOSTA)
10	**Which barriers do you see for exploitation?** Operational barriers: Integration challenges, Need for material Market barriers: Reluctance of industrial users to invest in new heat recovery technologies without proven long-term cost savings and reliability. Cost disadvantages do not justify the technological and ecological advantages compared to established competing technologies. Uncertainty about fuel transition timelines, which can delay adoption of hydrogen-compatible systems. Regulatory barriers: Compliance with evolving safety standards for handling oxygen-enriched or pure hydrogen combustion atmospheres. Certification and approval processes for new materials and 3D-printed heat exchangers might be lengthy and complex.
11	**Which strategy is foreseen to react on this/these barrier(s)?** Operational barriers: Conduct thorough pilot testing and material validation under realistic industrial conditions to demonstrate durability and performance.Collaborate closely with industrial partners to customize solutions for their specific processes and fuel mixes. Market barriers: Showcase clear economic and ecological benefits through detailed cost-benefit analyses and real-world case studies. Engage early adopters and key industrial stakeholders through workshops and demonstrations to build trust and confidence. Highlight the future-proof design compatible with hydrogen and low-CO2 fuels to align with industry's energy transition goals. Regulatory barriers: Work proactively with certification bodies and regulatory agencies during development to ensure compliance and streamline approval processes. Leverage the expertise of partners with experience in safety standards and material certifications.

12	**Preliminary definition of business and sustainable model?** Business model: Offering advanced recuperator technologies and material evaluation services as integrated solutions or upgrades for existing systems. Providing consulting and pilot testing services to support industrial partners during transition phases. Licensing or partnering with manufacturers for large-scale production and deployment. Sustainability model: Reducing fossil fuel consumption and CO2 emissions through improved heat recovery efficiency. Supporting the integration of renewable energy sources and hydrogen fuels, aligning with EU climate targets. Promoting circular economy principles by extending equipment lifespan through durable materials and modular designs. Licensing of designs and know-how, Joint exploitation by consortium partners Integration into OEM product portfolios
13	**Are there any ethical, societal, or environmental considerations related to the exploitation of this KER that need to be addressed?** Environmental: The primary goal is to reduce CO2 emissions and energy consumption, which supports climate goals. However, sourcing advanced materials (like new high-temperature alloys or 3D-printed metals) should consider sustainable and responsible supply chains to minimize environmental impact. Societal: Transitioning to new technologies may require workforce retraining. It's important to manage this to avoid job displacement and support upskilling for employees adapting to new industrial processes. Ethical: No significant data privacy concerns are directly linked to this KER. However, transparency and stakeholder engagement during deployment will be crucial to ensure fair access and benefits across different industry players.
14	**What are the top concrete exploitation-related actions your organization plans to undertake during the project's remaining lifetime related to this KER?** BFI: Pilot Testing & Validation, Material Behavior Analysis: Ensure that the 3D-printed material meets the application requirements or define material-specific limits for use. Modelling & Simulation Enhancements, Knowledge Dissemination, Industrial Partner Support, Preparation for Commercialization: VDM: Testing & Validation of material characteristics and properties – optimization if necessary, Testing & Validation of powder characteristics and properties – optimization if necessary, Knowledge Dissemination to project partner and internal/external customer, Preparation for Commercialization by integrating new data to material datasheet and publication, Project partner & customer support KUP: Explorative AM intended to optimize printing parameters for industrial burner and recuperator applications. Comparative analysis of powder material behavior in the SLM process under varying process conditions. Investigation of mechanical material properties when printing under varying process conditions. Preparation for testing under real industrial process conditions to validate TRL for industrial application. Documentation and knowledge dissemination to internal/external business partners to facilitate technical support. Integration into ongoing product development pipelines and preparation for commercialization.
15	**Which primary exploitation route(s) do you envision for this KER?** BFI: Service Expansion: Offering advanced evaluation and testing services for material behavior and burner design tailored to new fuel mixtures and combustion conditions. Technology Licensing: Licensing the modified recuperator designs and related know-how to manufacturers and industrial partners for integration into existing and new heating systems. Collaborative Industrial Projects: Partnering with steelworks and other heavy industries to implement pilot installations and co-develop customized heat recovery solutions. Consulting & Modelling Services: Providing specialized combustion atmosphere modelling and process optimization consulting to support the transition to sustainable fuels.

	VDM: Collaborative Industrial Projects: Partnering with customers (e.g. component manufacturer, AM service provider) to implement and qualify the powder alloy to burner applications or similar high temperature applications. Technology Transfer: Providing new technology results to internal departments working in the downstream process KUP: Direct application and industrial integration of optimized AM parameters, validated materials and process insights into the development of next-generation burners and recuperators. Internal capability building and strategic positioning. Strengthening of in-house know-how in AM for high-performance metallic components. Strengthen joint industrial cooperations with powder metallurgy partners to implement and advanced powder alloys for use in high-temperature applications.
16	**Which consortium partners do you foresee collaborating most closely with on the exploitation of this KER, and for what specific activities?** BFI: thermal system testing, process integration, and energy efficiency assessment, KUP: For the manufacturing and 3D-printing of advanced recuperator components using novel materials. VDM: For the development and testing of high-temperature resistant materials for recuperators. FER: For process modelling and energy recovery analyses to optimize heat exchanger integration. ADI: For industrial testing, measurements, and evaluation of heat recovery performance in real operating conditions. SSSA: For thermodynamic and scenario analyses supporting strategic exploitation and market positioning.
17	**What internal resources will your organization commit to these initial exploitation activities for this KER?** BFI: Dedicated personnel, Specific equipment, Laboratory furnaces, material testing equipment, Internal budget: VDM: Dedicated personnel, Specific equipment: Powder production facility, Laboratory for chemical analysis, powder properties and metallography, Material testing equipment, Internal budget KUP: Dedicated personnel for designing, preprocessing, 3D Printing and postprocessing, Specific equipment: AM equipment, Density testing equipment, Testbench for hot and cold flow analysis, Software for preprocessing, designing and post-processing. Utilization of partners for specialized manufacturing, Internal Budget

TABLE 16: KER3 TRANSFERABILITY ANALYSIS

1	**Which other sectors or industries could potentially benefit from this KER?** Non-ferrous metals industry (Aluminum, copper), rely on high-temperature furnaces Glass manufacturing, Ceramics and refractory industry, Pulp and paper (drying sections), Energy and Aerospace industry, Work also with high temperature application and combustion processes (turbines)
2	**What conditions must be present in the target sectors to enable the use of this KER?** High-temperature process environments, Presence of flue gases with compatible temperature and chemical characteristics (e.g., non-corrosive, stable composition, sufficient thermal energy) to enable efficient and durable heat recovery. Availability of hydrogen or oxygen-enriched fuels, Availability of advanced control and monitoring systems, Processes with consistent or predictable exhaust gas flow and temperature profiles
3	**What modifications or adaptations would be needed to make the KER applicable in other sectors or use cases?** Material adjustments, Size and design customization, Integration interfaces, Operational flexibility, Safety and compliance adjustments
4	**What potential improvements could the KER bring when applied to other sectors?** Performance, Efficiency, Cost reduction, Sustainability, Flexibility

5	**What are the main barriers or limitations to applying this KER in other sectors?** Infrastructure compatibility, Material integration and/or qualification challenges Operating conditions mismatch, High initial investment cost, Uncertain return on investment
6	**What support might be needed to overcome these barriers?** Technical training programs, Development or alignment with industry standards, Best practice guidelines

6.4 KER4 questionnaire

Table 17: KER4 Definition

1	**Unique KER Identifier/Name:** KER4: Model of warm/hot charging solutions.
2	**Owner of this KER:** All (in WP is ADI, BFI, FER, SSSA)
3	**Roles and responsibilities of each partner within the project in relation to this KER:** BFI: Coordination of KER. Experimental investigations: Measuring heat flow through coated uncoated steel. Theoretical investigations: Modelling of bar and slab heating at cold (reference), warm and hot charging with energy and emission process models. Analyse saving potentials. SSSA: Simulative investigations of bar and slab heating. Analyse saving potentials. ADI & FER: Provide industrial information, specifications and data of the heating process and existing production facilities to support modelling and simulation.
4	**Brief Technical Description of the KER:** Development of heat transfer model and simulation of the product heating process at warm and hot charging to estimate CO2 and fuel savings specifically at ADI and FER production.
5	**Current TRL of this specific KER:** TRL 4
6	**Provide specific evidence justifying the current TRL:** Theoretical analysis and calculation of fuel savings when applying hot and warm charging by decreasing reheating energy or avoiding heat loss between production steps: steel making (transportation and storage) and hot rolling.
7	**Is this KER a standalone output or is it designed to be integrated into another system/product?** It can be a standalone output as well as a combination with fuel saving technologies developed in this project. Standalone output for each specific production at industrial partners. This KER can function as standalone know-how for production optimization or be integrated with other project KERs (KER2 for heat recovery, KER6 for economic assessment, KER7 for implementation roadmap, and KER8 for hybrid heating). The models and know-how will be tailored to specific production conditions at ADI and FER, but transferable to other steel producers.

Table 18: KER4 Gap analysis

1	**What specific problem does this KER solve or what fundamental need does it address for users, industry, or society?** KER4 addresses the need for efficient production in steel mills with downstream processes, especially for management of the slab/billets reheating programming. This can contribute to reducing the energy input together with the use of future fuels (e.g. hydrogen, biofuels). It aims to reduce energy losses and improve energy efficiency, contributing to decarbonization and cost reduction in steel production.
2	**What comparable developments or products are available on the market which have a comparable use case this KER?** Hot rolling is applied in new built plants where the connection of steel production with the rolling process and the production is planned for continuous casting and rolling. However, in existing plants combining the casting process with the reheating process is not foreseen. To achieve hot charging large and complex conversions of steel plants are necessary, both to connect the hot rolling and continuous casting plants and to modify the current slab inspection procedure, for example Another possibility is warm charging by reducing heat loss of casted bars or beams before reheating them. This needs space in the existing plant and production management.
3	**Which gaps do these products have on the market?** Most existing plants were traditionally designed with slab yards where the casted hot product cools down. The heat loss before reheating was taken into account due to the high flexibility of the

	production and lower investment costs. Missing spaces for efficient and insulated product storage and logistics are current gaps to achieve warm or hot charging. Additionally, the production planning needs to be significantly changed. These changes and high investment costs are the most relevant gaps.
4	**What do this KER achieve in addition?**significant decrease in energy demand for the reheating process (10 to 40%), decreased demand for future fuels or electrical power at hybrid heating (combustion and electric heating) in the future, decarbonisation and decrease of CO2 costs in the transition from current to future fuels, decrease of scaling and material loss as the reheating process is faster.
5	**What is the unique selling point of this KER compared to existing technology/products?** Unique selling points can be defined on the basis of project results. TRL too low to define unique selling points.

TABLE 19: KER4 MARKET ANALYSIS AND TARGET USERS

1	**What specific benefits will potential users gain from applying the developed technology compared to existing solutions or products?** Increased energy efficiency in reheating and heat treatment processes, Reduced CO_2 emissions, Cost savings through energetically optimized production process, Avoiding the heat loss and the use of energy directly in the process
2	**Who are users in industry?** Steel producers (e.g., ADI, FER, SMEs with reheating furnaces), Foundries and forging companies, Non-ferrous metal industries, Furnace and plant suppliers
3	**Who can manufacture this KER who are possible suppliers?** OEMs in industrial heating systems, furnaces, insulation and transport-systems, suppliers for process management and optimization
4	**How big is the market?** Ideally all discontinuous productions in EAF and BOF steel plants in the EU, about 400 downstream steel processing plants in the EU (data from Eurofer 2022), Additional potential in non-ferrous and high-temperature industries, Estimated 1-3 customers per year in the early adoption phase
5	**Expected cost for implementation/invest of new technology**? estimation as result of the project. Each plant is individual, and costs vary significantly
6	**savings per year achieved in industry with new technology:** Only estimation is possible: up to 40% fuel savings with hot charging, Estimation: up to 25% energy savings can be achieved through warm charging. CO_2 savings potential of ~13 Miot/year across EU downstream steel sector. Therin the savings only BOF production in the EU states of 71.8 Mt (data from Eurofer 2025) and a balanced production with coke oven gas and natural gas, CO2 saving potential can range from 0.6 MtCO2 to 2.4 MtCO2 per year. The EAF production in the EU states counts about 59,4 Mt (data from BFI-study in project TransHyDe2023) and 88% of them are EAF-steel-plants with rolling mills (calculated from project TransHyDe data) with an energy demand for rolling 94,049 TJ. This leads to an saving potential of 9,405 to 37,617 TJ or 0,53 Mt CO2 to 2,11 Mt CO2 at Heating with natural Gas.
7	**Who are the key stakeholders?** Steel producers, OEMs, Policy makers, Research institutions and platforms (e.g., ESTEP, EUROFER and national e.g., VDEh, AIM, Jernkontoret)
8	**Strategy for engaging the stakeholder?** Advisory Board involvement, Dissemination via conferences, webinars, and trade fairs, Collaboration with platforms and clusters, Open access publications and demonstrator visits
9	**Are there any specific geographical regions within the EU that are of particular interest for initial market entry? Why** Germany, Italy, Spain, Sweden: high concentration of steel producers and project partners. Strong industrial infrastructure and policy support for hydrogen and decarbonization

10	**What is the estimated market size for this KER within the EU?** Estimated annual revenue potential: Market size: 400+ plants in steel sector, plus additional in related industries
11	**What are the specific needs of these target users that this KER directly addresses?** Need for cost-effective decarbonization, Compatibility with future fuels, Reduction of energy costs and emissions, Regulatory compliance and sustainability goals

TABLE 20: KER4 INITIAL EXPLOITATION STRATEGY

1	**What is your expected result and/or development?** Process, production and logistic concepts and plans, Insulation concepts and designs for avoiding or minimizing heat loss of product before the reheating process, Calculated energy saving in the reheating process for decision. Making processes. KER 6 und 7 based on these concepts.
2	**What is your value proposition concerning exploitation?** Saving potentials for current and future reheating processes. Cost, energy and emission-decrease potentials. As basis information for investments.
3	**Description of exploitable results?** Know-how on avoiding and minimizing heat loss between casting and reheating process steps, production and plant data based on calculated saving potentials. Scenario analyses for industrial deployment.
4	**When do you expect your results?** Final results expected by **M42 (October 2028)**; initial exploitation strategy by **M12 (December 2025)**
5	**Which deployment opportunities do your results and /or developments have for industrial use?** Planning of heating and reheating processes with hot products, Decision making processes for direct charging or insulating the product. Integration into new heating concepts (hybrid heating), Application in steel, non-ferrous, and high-temperature industries
6	**At what TRL are your results and/or developments?** TRL 4-5 (theoretical calculations based on available technology)
7	**What must industrial end-users do or change in their setup to adopt and use it?** Install, set up hot charging, direct charging from casting or insulation of product after casting before reheating, ensure compatibility with the process and production, Ensure compatibility with safety and regulatory standards
8	**Which stakeholders and decision makers will be involved in exploiting your developments? When will they be involved?** Steel producers (ADI, FER) involved from M16 onward, Policy makers and platforms (ESTEP, EUROFER) – Involved from M24 onward
9	**With which platforms do you expect to cooperate?** ESTEP, EUROFER, A. SPIRE, SusChem, national steel associations
10	**Which barriers do you see for exploitation?** CAPEX – due to significant investigations, Production organisation related to time and space demands caused by insulation, storing time, space and scheduling of products with different qualities (based on the quality check before the hot rolling). Limited space, Material issues due to storage at high or medium temperatures.
11	**Which strategy is foreseen to react on this/these barrier(s)?** Simplified technology for insulation. Minimize space demand for insulation, Dissemination and stakeholder engagement, Scenario analyses and roadmap development
12	**Preliminary definition of business and sustainable model?** for this development not planned.
13	**Are there any ethical, societal, or environmental considerations related to the exploitation of this KER that need to be addressed?** Positive impact on climate

	and sustainability, Resource-efficient production, Efficient consumption of renewable and future fuels
14	**What are the top concrete exploitation-related actions your organization plans to undertake during the project's remaining lifetime related to this KER?** Dissemination of results, Stakeholder workshops
15	**Which primary exploitation route(s) do you envision for this KER?** Use in industrial processes, integration into OEM offerings, licensing of know-how
16	**Which consortium partners do you foresee collaborating most closely with on the exploitation of this KER, and for what specific activities?** BFI, SSSA, ADI, FER – for technical development, calculations, process analysis and industrial integration
17	**What internal resources will your organization commit to these initial exploitation activities for this KER?** Dedicated personnel for modelling and dissemination, Access to production, plant and data, Internal budget for further development by stakeholders

TABLE 21: KER4 TRANSFERABILITY ANALYSIS

1	**Which other sectors or industries could potentially benefit from this KER?** Non-ferrous metal industries (e.g. aluminium, copper)
2	**What conditions must be present in the target sectors to enable the use of this KER?** Presence of high-temperature heating processes, Product needs high temperature in between process steps, but due to production planning, the product has to be stored or a break in the production line/ production procedure exists.
3	**What modifications or adaptations would be needed to make the KER applicable in other sectors or use cases?** Integration in specific production procedures and boundary conditions.
4	**What potential improvements could the KER bring when applied to other sectors?** increase efficiency in heating processes. improvements comparable to those in steel production. (i.e., lower fuel costs, decreased CO2 certificates), possible advantages in product quality
5	**What are the main barriers or limitations to applying this KER in other sectors?** CAPEX and return of investment (financial), space in the existing plant
6	**What support might be needed to overcome these barriers?** Demonstration projects and pilot installations, Engagement with industry associations and regulators, technical documentation and open-access publications

6.5 KER5 questionnaire

TABLE 22: KER5 DEFINITION

1	**Unique KER Identifier/Name: KER5:** CFD furnace model for heat transfer due to electrical heating
2	**Owner of this KER** : Kanthal AB (KAN)
3	**Roles and responsibilities of each partner in the project in relation to this KER** Kanthal: Task leader, responsible for CFD model development and validation. SWE: Provides experimental data and pilot furnace for validation. BFI: Supports with modelling expertise and integration with overall WP4 objectives.
4	**Brief Technical Description of the KER**: A CFD model of a reheating furnace, focusing on heat transfer mechanisms in electrically heated (resistive) zones
5	**Current Technology TRL of this specific KER**:TRL 3–4 (Analytical and experimental proof-of-concept; model development not yet started)
6	**Provide specific evidence justifying the current TRL**: The project is in the initial phase for this KER. No CFD model has been developed yet, but the methodology and requirements are defined in the project plan (see WP4, Grant Agreement).
7	**Is this KER a standalone output or is it designed to be integrated into another system/product?** The CFD model is a standalone tool but is intended to be integrated into the design and optimization workflow for hybrid reheating furnaces.

TABLE 23: KER5 GAP ANALYSIS

1	**What specific problem does this KER solve or what fundamental need does it address for users, industry, or society?** Enables the design and optimization of hybrid (H_2 + electric) reheating furnaces, supporting decarbonization and energy efficiency in steel production. Addresses the need for validated digital tools to predict heat transfer and temperature uniformity in new furnace concepts.
2	**What comparable developments or products are available on the market which have a comparable use case this KER?** Commercial CFD software (e.g., ANSYS Fluent) is widely used, but there are few validated models specifically for hybrid or fully electric reheating furnaces in the steel industry.
3	**Which gaps do these products have on the market?** Lack of validated models for resistive/electric heating in industrial-scale furnaces; limited data on hybrid operation (H_2 + electric).
4	**What do this KER achieve in addition?** The KER5 model will be validated with pilot-scale data from SWE, specifically for hybrid heating and supporting industrial adoption.

5	**What is the unique selling point of this KER compared to existing technology/products?** First validated CFD model for hybrid (H_2 + electric) reheating furnaces, developed in close collaboration with leading industrial partners and based on real pilot data. Enables faster, lower-risk transition to decarbonized furnace operation.

TABLE 24: KER5 MARKET ANALYSIS AND TARGET USERS

1	**What specific benefits will potential users gain from applying the developed technology compared to existing solutions or products?** Improved energy efficiency, reduced CO_2 emissions, better temperature control, and faster time-to-market for new furnace designs. Supports compliance with EU Green Deal targets.
2	**Who are users in industry?** Steel producers, furnace OEMs, engineering consultants, and Kanthal's internal R&D.
3	**Who can manufacture this KER who are possible suppliers?** Kanthal (heating elements), SWE (pilot plant), furnace OEMs (integrators).
4	**How big is the market?** The EU steel sector includes ~150 major plants and hundreds of smaller facilities; initial target is 5–10 pilot users, scaling up as hybrid/electric retrofits accelerate.
5	**Expected cost for implementation/invest of new technology**? CFD model is a digital tool; main costs are engineering time and integration. Full-scale furnace retrofits/investments are in the range of €1–5M per furnace.
6	**savings per year achieved in industry with new technology?** Potential energy savings up to 10–20% per furnace; CO_2 reduction up to 100% in electric zones.
7	**Who are the key stakeholders?** Steel producers, furnace OEMs, Kanthal, SWE, BFI, policy makers (EU Green Deal).
8	**Strategy for engaging the stakeholder?** Workshops, pilot demonstrations, technical webinars, direct engagement via project consortium.
9	**Are there any specific geographical regions within the EU that are of particular interest for initial market entry? Why?** Sweden, Germany, Italy – due to project partners and strong steel industry presence.
10	**What is the estimated market size for this KER within the EU?** Potential market: €10–50M/year for digital tools and engineering services; much larger for hardware retrofits.
11	**What are the specific needs of these target users that this KER directly addresses?** Need for validated digital tools for hybrid furnace design; uncertainty about process performance and investment risk for new heating technologies.

TABLE 25: KER5 INITIAL EXPLOITATION STRATEGY

1	**What is your expected result and/or development?** A validated CFD model for hybrid reheating furnaces, ready for industrial use and further customization.
2	**What is your value proposition concerning exploitation?** Accelerates the transition to decarbonized steel production by de-risking hybrid furnace investments.
3	**Description of exploitable results?** CFD model, validation data, best-practice guidelines for hybrid furnace design.
4	**When do you expect your results?** First version: Q4 2026; validated and documented model: Q2 2027.
5	**Which deployment opportunities do your results and /or developments have for industrial use?** Direct use in furnace design/retrofit projects, consulting, and as a basis for further R&D.
6	**At what TRL are your results and/or developments?** Target TRL 6 (technology demonstrated in relevant environment) by project end.
7	**What must industrial end-users do or change in their setup to adopt and use it?** Integrate CFD modelling into design workflow; provide process data for calibration/validation.
8	**Which stakeholders and decision makers will be involved in exploiting your developments? When will they be involved?** Kanthal, SWE, BFI, OEMs; engagement starts Q2 2026 with pilot results and continues through project end.
9	**With which platforms do you expect to cooperate?** ESTEP, Jernkontoret, EUROFER, national steel associations.
10	**Which barriers do you see for exploitation?** Conservative industry culture, lack of digital skills, uncertainty about regulatory incentives.
11	**Which strategy is foreseen to react on this/these barrier(s)?** Demonstration projects, training, dissemination of success stories, policy engagement.
12	**Preliminary definition of business and sustainable model?** Service-based model: CFD consulting, licensing, and support for furnace OEMs and steel producers.
13	**Are there any ethical, societal, or environmental considerations related to the exploitation of this KER that need to be addressed?** No major concerns; positive environmental impact by reducing CO_2 emissions.
14	**What are the top concrete exploitation-related actions your organization plans to undertake during the project's remaining lifetime related to this KER?** Develop and validate the model, engage with pilot users, prepare commercialization plan.
15	**Which primary exploitation route(s) do you envision for this KER?** Direct use in Kanthal's R&D and customer projects; licensing to OEMs; consulting.
16	**Which consortium partners do you foresee collaborating most closely with on the exploitation of this KER, and for what specific activities?** SWE (pilot data, validation), BFI (modelling expertise), OEMs (integration into commercial projects).

17	**What internal resources will your organization commit to these initial exploitation activities for this KER?** CFD engineers, access to pilot furnace data, internal R&D budget, collaboration with SWE and BFI.

TABLE 26: KER5 TRANSFERABILITY ANALYSIS

1	**Which other sectors or industries could potentially benefit from this KER**? Non-ferrous metals, glass, ceramics, cement industries.
2	**What conditions must be present in the target sectors to enable the use of this KER?** Electrification or hybridization of high-temperature furnaces; willingness to adopt digital tools.
3	**What modifications or adaptations would be needed to make the KER applicable in other sectors or use cases?** Adaptation of model parameters and validation for different furnace geometries and process conditions.
4	**What potential improvements could the KER bring when applied to other sectors?** Improved energy efficiency, reduced emissions, better process control, lower operational costs.
5	**What are the main barriers or limitations to applying this KER in other sectors?** Lack of sector-specific validation data, conservative industry practices, investment costs.
6	**What support might be needed to overcome these barriers?** Training, demonstration projects, collaboration with sector associations, development of best-practice guidelines.

6.6 KER6 questionnaire

TABLE 27: KER6 DEFINITION

1	**Unique KER Identifier/Name:** KER6 – Economic and ecological impact assessment for decision making
2	**Owner of this KER:** SSSA, BFI
3	**Roles and responsibilities of each partner in the project in relation to this KER:** SSSA leads KER implementation related to the development of the integrated LCA, LCC, and techno-economic modelling tools; in particular, SSSA leads LCA and develops models aimed at making scenario analyses and obtaining useful data (e.g. related to CO_2 and fuel saving, heat recovery) for economic and environmental assessments. BFI contributes mainly in following LCC and NPV approaches for techno-economic analyses. Industrial partners supply operational data and participate in the validation of case studies, ensuring that results reflect actual industrial conditions. Other partners provide support.
4	**Brief Technical Description of the KER:** This KER consists of a decision-support framework that combines ecological indicators (e.g., CO_2 emissions, energy intensity, environmental impact) with economic metrics (e.g., CAPEX, OPEX, payback periods) for new heating technologies in the downstream steel sector. By integrating data from pilots and modelling, the KER helps users compare different technology pathways—such as hydrogen retrofits, hybrid heating, and waste heat recovery—and understand their trade-offs.
5	**Current TRL of this specific KER?** TRL 5
6	**Provide specific evidence justifying the current TRL?** The framework has been tested on project case studies using validated datasets, showing that it can produce credible results in different contexts. However, it is still at an early validation stage and has not yet been fully applied in industry-wide strategic planning related to downstream processes, justifying a TRL5 classification.
7	**Is this KER a standalone output or is it designed to be integrated into another system/product?** This KER is both standalone and complementary. As a knowledge product, it can be directly used by industry and policymakers, while also providing crucial inputs to KER7 (roadmap) and supporting the adoption of KER1, KER2, KER3 and KER8 technologies.

TABLE 28: KER6 GAP ANALYSIS

1	**What specific problem does this KER solve or what fundamental need does it address for users, industry, or society?** The steel sector lacks robust, transparent tools to evaluate the ecological and economic trade-offs of decarbonization pathways. Decisions are often made with incomplete data, which can result in stranded investments or missed opportunities. This KER addresses that gap by offering integrated assessments that clearly show both costs and benefits, enabling more informed and sustainable decisions.
2	**What comparable developments or products are available on the market which have a comparable use case this KER?** Generic LCA software and cost modelling tools exist, but they are not tailored to the specific conditions of downstream steelmaking. Their results are generally not integrated/aggregated for providing decision support on both economic and ecological point of view on decarbonization of downstream steelmaking processes.
3	**Which gaps do these products have on the market?** These tools are too generic, not adapted to reheating furnaces or downstream processes, and often rely on limited

	default data. They rarely integrate pilot-scale experimental data, and they do not combine environmental and financial metrics in a single coherent framework.
4	**What do this KER achieve in addition?** The E-ECO Downstream approach integrates both ecological and economic assessments, validated with real project data. This means that steelmakers receive results that are more realistic, sector-specific, and actionable, directly linked to technologies they might adopt.
5	**What is the unique selling point of this KER compared to existing technology/products?** The unique selling point is the simultaneous evaluation of costs and ecological impacts tailored to downstream processes, ensuring that decision-makers have a clear, evidence-based foundation for choosing the most effective and sustainable decarbonization strategies.

TABLE 29: KER6 MARKET ANALYSIS AND TARGET USERS

1	**What specific benefits will potential users gain from applying the developed technology compared to existing solutions or products?** The main benefit is improved decision-making: users can avoid stranded investments and prioritize technologies that maximize both economic viability and environmental performance. Compared to generic tools, this framework provides tailored insights specific to the steel sector.
2	**Who are users in industry?** The primary users are steel producers, particularly those responsible for planning investments in decarbonization. Policymakers and EU/national agencies can also use the framework to design funding programs, while consultancy firms may adopt it as part of their service portfolio.
3	**Who can manufacture this KER who are possible suppliers?** As a knowledge-based output, it will be delivered by universities, research organizations, consultancies, and industry associations. There is no manufacturing component, but the methodology can be embedded into consultancy services.
4	**How big is the market?** The EU has approximately 400 downstream steel plants as direct potential users. In addition, policymakers, consultancies, and funding bodies represent an expanded user base, making the total addressable market significant.
5	**Expected cost for implementation/invest of new technology**? Implementation costs are relatively low, as the framework primarily requires staff training and data provision. Most of the investment is in time and expertise, not in new equipment.
6	**savings per year achieved in industry with new technology?** The tool enables indirect savings by avoiding poor investment choices, improving energy efficiency decisions, and reducing risks. Companies can save millions by avoiding stranded assets.
7	**Who are the key stakeholders?** Key stakeholders are steel producers, policymakers, industry associations (e.g., EUROFER, ESTEP), and consultancy firms.
8	**Strategy for engaging the stakeholder?** The consortium will present results at stakeholder workshops, engage associations through ESTEP, and provide demonstration case studies for validation and feedback.
9	**Are there any specific geographical regions within the EU that are of particular interest for initial market entry? Why?** Germany, Italy, and Sweden are priority regions, as they combine high steel production with active decarbonization strategies. These countries will benefit most from early adoption.
10	**What is the estimated market size for this KER within the EU?** With ~400 potential plant users plus policymakers and advisors, the EU market is significant. The consultancy and policy advisory market for industrial decarbonization is worth >100 M€ annually, suggesting strong uptake potential.
11	**What are the specific needs of these target users that this KER directly addresses?** The KER addresses uncertainty about technology maturity, fluctuating

	C-free fuels (e.g. hydrogen) prices, and unclear cost-benefit balances. By providing clear evidence, it reduces risk and improves confidence in decarbonization pathways.

TABLE 30: KER6 INITIAL EXPLOITATION STRATEGY

1	**What is your expected result and/or development?** A validated set of assessment tools and reports that combine ecological and economic performance indicators for decarbonization technologies related to steelmaking downstream processes.
2	**What is your value proposition concerning exploitation?** The value lies in providing clarity for investment decisions, enabling industry and policymakers to pursue sustainable strategies with lower risk.
3	**Description of exploitable results?** Exploitable results include methodological frameworks, validated case studies, and decision-support guidelines.
4	**When do you expect your results?** End of project (Q2 2028)
5	**Which deployment opportunities do your results and /or developments have for industrial use?** They can be deployed in corporate strategy planning, sustainability reporting, and EU/national policy frameworks.
6	**At what TRL are your results and/or developments**? Currently TRL 5
7	**What must industrial end-users do or change in their setup to adopt and use it?** They must provide plant data, integrate results into strategic planning, and train staff in using the methodology.
8	**Which stakeholders and decision makers will be involved in exploiting your developments? When will they be involved?** Steel producers, policymakers, and funding agencies will be engaged during the dissemination activities.
9	**With which platforms do you expect to cooperate?** Partnership with ESTEP, EUROFER, Hydrogen Europe, and EU energy efficiency platforms.
10	**Which barriers do you see for exploitation?** Potential barriers include data confidentiality, trust in model assumptions, and changing policy contexts.
11	**Which strategy is foreseen to react on this/these barrier(s**)?The strategy includes ensuring transparency, using sensitivity analyses, and validating models in collaboration with industrial partners.
12	**Preliminary definition of business and sustainable model?** The KER can be sustained as a consultancy service, integrated into policy roadmaps, and offered as part of cluster activities.
13	**Are there any ethical, societal, or environmental considerations related to the exploitation of this KER that need to be addressed?** Data privacy is crucial, as industrial partners will share sensitive operational data. Safeguards will be put in place.
14	**What are the top concrete exploitation-related actions your organization plans to undertake during the project's remaining lifetime related to this KER?** SSSA will finalize the models, validate results with industrial data, and disseminate results through policy workshops and academic conferences.
15	**Which primary exploitation route(s) do you envision for this KER?** Knowledge transfer, consultancy, and policy advisory services.
16	**Which consortium partners do you foresee collaborating most closely with on the exploitation of this KER, and for what specific activities?** SSSA and BFI will collaborate on methodology, supported by industrial partners supplying data and feedback.
17	**What internal resources will your organization commit to these initial exploitation activities for this KER?** SSSA will allocate staff specialized in LCA and process modelling; dedicated LCA software, databases and coordination resources. BFI will provide staff specialized in techno-economic analyses, in total 2 PM.

TABLE 31: KER6 TRANSFERABILITY ANALYSIS

1	**Which other sectors or industries could potentially benefit from this KER?** The cement, glass, ceramics, and chemical industries could benefit from similar decision-support tools for decarbonization.
2	**What conditions must be present in the target sectors to enable the use of this KER?** These sectors need access to reliable process and emission data, as well as regulatory frameworks pushing for decarbonization.
3	**What modifications or adaptations would be needed to make the KER applicable in other sectors or use cases?** Sector-specific data inputs, functional units, and emission factors would need to be integrated into the framework.
4	**What potential improvements could the KER bring when applied to other sectors?** It would improve decision-making, reduce financial risk, and accelerate decarbonization adoption in multiple industries.
5	**What are the main barriers or limitations to applying this KER in other sectors?** Barriers include reluctance to share confidential data, sectoral differences in processes, and limited expertise in applying advanced LCA/LCC methods.
6	**What support might be needed to overcome these barriers?** Support could include training programs, sector-specific adaptations, and collaborations with industry associations to encourage data sharing.

6.7 KER7 questionnaire

TABLE 32:KER7 DEFINITION

1	**Unique KER Identifier/Name**: KER 7 / Roadmap and implementation timeline for future technologies
2	**Owner of this KER:** All partners
3	**Roles and responsibilities of each partner within the project in relation to this KER:** BFI contributes its expertise in: Leader in the KER development, Technical and economic assessment of reheating/recovery technologies, Energy mapping, Calculations of CO_2-emissions and H_2 demand, Dissemination/exploitation of the roadmap. SSSA contributes its expertise in: LCA, Dissemination/exploitation of the roadmap. SWE contributes its expertise in: Technical and economic assessment of reheating/recovery technologies especially hybrid heating, Dissemination/exploitation of the roadmap. FER contributes its expertise in: Scenario analysis and studies on application of hybrid heating, Energy mapping of steel works, Reheating technologies, Boundary conditions and barriers from steelworks view. ADI contributes its expertise in: Reheating technologies, Boundary conditions and barriers from steelworks view (e.g. the use and the risks related to biofuels and their blends with technical gas produced in the steel plant) KUP contributes its expertise in: Burner design and production, Boundary conditions and barriers from manufacturer view. KAN contributes its expertise in: Electrical heating technologies, Boundary conditions and barriers from manufacturer view. VDM contributes its expertise in: Materials engineering especially new alloys for the 3D burner printing.
4	**Brief Technical Description of the KER:** KER7 is a guideline including a roadmap and an implementation timeline for decarbonization pathways of downstream processes. It will support decision makers about possibilities of decarbonization of downstream processes, based on detailed technology evaluation and process KPIs (focus for industrial decision makers) as well as barriers and required boundary conditions (focus for policymakers).
5	**Current TRL of this specific KER:** not applicable due to the kind (roadmap) of the KER.
6	**Provide specific evidence justifying the current TRL:** not applicable due to the kind (roadmap) of the KER.
7	**Is this KER a standalone output or is it designed to be integrated into another system/product?** Not applicable due to the kind (roadmap) of the KER.

TABLE 33: KER7 GAP ANALYSIS

1	**What specific problem does this KER solve or what fundamental need does it address for users, industry, or society?** There is a lack in roadmaps/guidelines for steel making downstream processes, since the focus of research and industry was on the upstream steel making processes in the recent years, particularly on the primary steel production which is much more CO2 intense than the downstream processes. However, the specific CO_2-emissions in reheating furnaces currently amount up to a maximum of 83.4 kg_{CO2}/t_{steel}, when using NG as a fuel, which amounts to an entire CO_2 saving potential in the European steel industry of approx. 13.33 $Miot_{CO2}$/year. In contrast to steel production, which takes place in large steel works, the downstream processing can also take place in small to medium-sized companies. These

	companies often do not have specialized staff working on process decarbonization. Therefore, it is crucial to support them by the roadmap and by showing them other and more cost-efficient opportunities for the decarbonization of their processes beside pure electrification or H_2-usage.
2	**What comparable developments or products are available on the market which have a comparable use case this KER?** Several roadmaps for decarbonization pathways of the steel industry are accessible. However, most of them are focused on the upstream steel making processes (mainly on the primary steel making), and do not include detailed decarbonization measures for downstream processes, e. g. *The Net-Zero Steel Pathway Methodology Project, Final Report and Recommendations, July 2021.* *EUROFER: A Steel Roadmap for a Low Carbon Europe 2050, 2013.* *INTERNATIONAL ENERGY AGENCY: Iron and Steel Technology Roadmap, Oct 2020.* The *RFCS-Dissemination Project DissHeat (Grant agreement No 101057930)* is about technologies of downstream processes but focusses on current technologies and future research needs.
3	**Which gaps do these products have on the market?** Most roadmaps focus heavily on upstream processes and provide only general provisions for electrification and H_2 use in downstream processes, without addressing: the specific requirements of downstream processes itself, the availability of technologies for downstream processes, or the conversion/adjustment of plants. Furthermore, evaluation of specific boundary conditions and barriers for the decarbonization of the downstream processes, especially in small to medium-sized companies, is missing.
4	**What do this KER achieve in addition?** Focus on downstream processes. Includes the adaptation of existing systems to new requirements. Better planning of the transformation of downstream processes in companies thanks to a roadmap as a guiding document.
5	**What is the unique selling point of this KER compared to existing technology/products?** Not applicable due to the kind (roadmap) of the KER.

TABLE 34: KER7 MARKET ANALYSIS AND TARGET USERS

1	**What specific benefits will potential users gain from applying the developed technology compared to existing solutions or products?** Support for the transformation of heating processes using a roadmap as a guiding document. Quick overview of technologies and their possibilities and requirements, enabling savings in personnel and costs during the planning of the transformation and enabling faster implementation of decarbonization measures.
2	**Who are users in industry?** The primary users are energy-intensive industries that rely on high-temperature thermal processes and are transitioning to low-CO_2 or hydrogen-based fuels. Steel and metal production plants. Plant engineering companies integrating energy recovery solutions in retrofits or new installations. Within these sectors, customers are typically: Plant operators aiming to reduce energy costs and emissions. Engineering consultants planning decarbonization strategies for clients. Technology providers and equipment manufacturer e.g. of high-temperature heat exchangers and industrial furnace components.
3	**Who can manufacture this KER who are possible suppliers?** Not applicable due to the kind (roadmap) of the KER.
4	**How big is the market?** Not applicable due to the kind (roadmap) of the KER.
5	**Expected cost for implementation/invest of new technology**? Not applicable due to the kind (roadmap) of the KER.

6	**savings per year achieved in industry with new technology?** Not applicable due to the kind (roadmap) of the KER.
7	**Who are the key stakeholders?** Industrial End-Users: Steel and metal processingcompanies operating reheating furnaces (e.g. Acerinox, Haynes, VDM, ThyssenKrupp, Arcelor Mittal, DEW, FER, ADI, Mannesmann). Technology Suppliers: Heat exchanger and burner manufacturers (e.g. Alfa Laval, Kelvion, Küppers). Policy and Regulatory Bodies: National and EU agencies supporting energy efficiency and decarbonization. Research and Technical Partners: Consortium members. Investors / Industrial Clusters: Organizations supporting innovation in sustainable manufacturing.
8	**Strategy for engaging the stakeholder?** 1.Identify Key Stakeholders. 2.Customize communication to the interests of stakeholders by focusing on aspects that are important to them. 3. Use Multi-Channel Communication like: technical workshops, social media, print media, round tables. 4. Leverage Consortium Networks to reach wider stakeholders across the EU.
9	**Are there any specific geographical regions within the EU that are of particular interest for initial market entry? Why?** This applies to industries that want to decarbonize downstream processes especially in: Germany, Italy, Sweden, Spain, France. High density of the steel industry as the main target industry. Policy alignment with EU Green Deal and national decarbonization roadmaps. Existing infrastructure where retrofitting is feasible. Local partners and stakeholders already engaged in the E-ECO project.
10	**What is the estimated market size for this KER within the EU?** Not applicable due to the kind (roadmap) of the KER.
11	**What are the specific needs of these target users that this KER directly addresses?** Particularly in medium-sized industries/companies, there is often a lack of personnel to carry out in-depth planning of decarbonization of their processes, as well as a lack of expertise regarding new technologies and their requirements, possibilities, and limitations. This can delay the transformation and lead to economic disadvantages in the medium term due to high CO_2 taxes, inefficient technologies, and no access to green lead markets. Thus, they need support in this point.

TABLE 35: KER7 INITIAL EXPLOITATION STRATEGY

1	**What is your expected result and/or development?** The expected result is a roadmap for the implementation of the new technologies to reach the decarbonization of downstream processes. The roadmap will include emission reduction stages, required financial investment, derivation of required resources and required measures (on site and in a regulatory manner). It should work as a guideline for industrial decision makers to support them in planning the decarbonization of downstream processes, based on detailed technology evaluation and process KPIs. Furthermore, the roadmap gives policymakers background knowledge of heating processes and their required boundary conditions in a short and clearly arranged manner, so that specific regulatory barriers for implementing new technologies can be broke down or avoided.
2	**What is your value proposition concerning exploitation?** Industry: Support for the transformation of downstream processes using a roadmap as a guiding document. Quick overview of technologies and their possibilities and requirements, enabling savings in personnel and costs during the planning of the transformation and enabling faster implementation of decarbonization measures. Acceleration of the deployment of sustainable heating technologies. Improved access to green lead markets. Policy makers: Give policymakers background knowledge of heating processes and their required boundary conditions in a short and clearly arranged manner, so that specific regulatory barriers for implementing new technologies can be broke down or avoided.

3	**Description of exploitable results?** Roadmap for the decarbonization of heating processes including a timeline, emission reduction stages, required financial investment, derivation of required resources and required measures.
4	**When do you expect your results?** 06/2028
5	**Which deployment opportunities do your results and /or developments have for industrial use?** Accelerating the decarbonization of downstream processes and supporting energy efficiency goals.
6	**At what TRL are your results and/or developments?** Not applicable due to the kind (roadmap) of the KER.
7	**What must industrial end-users do or change in their setup to adopt and use it?** Not applicable due to the kind (roadmap) of the KER.
8	**Which stakeholders and decision makers will be involved in exploiting your developments? When will they be involved?** Industrial partners (e.g., steel producers, plant engineering companies, burner manufacturers) – as potential target group (involved from Month 38 to End). Policy makers – for alignment to environmental regulations (involved from Month 38 to End).
9	**With which platforms do you expect to cooperate?** CSP, Hydrogen Europe – to stay. ESTEP, EERA, SPIRE / Processes4Planet. National German platforms (e.g. Forschungsvereinigung Stahlanwendung – FOSTA).
10	**Which barriers do you see for exploitation?** Not applicable due to the kind (roadmap) of the KER.
11	**Which strategy is foreseen to react on this/these barrier(s)?** Not applicable due to the kind (roadmap) of the KER.
12	**Preliminary definition of business and sustainable model?** Not applicable due to the kind (roadmap) of the KER.
13	**Are there any ethical, societal, or environmental considerations related to the exploitation of this KER that need to be addressed?** Environmental: Not applicable due to the kind (roadmap) of the KER. Societal: Transitioning to new technologies may require workforce retraining. It's important to manage this to avoid job displacement and support upskilling for employees adapting to new industrial processes. Ethical: No significant data privacy concerns are directly linked to this KER. However, transparency and stakeholder engagement during deployment will be crucial to ensure fair access and benefits across different industry players.
14	**What are the top concrete exploitation-related actions your organization plans to undertake during the project's remaining lifetime related to this KER?** It will actively use the potential of collaboration with partners' academic and business networks, technological platforms as well as with other Horizon EU clusters, and collaborate with stakeholders in public and private sectors across diverse domains, for sharing, adapting and/or extending the gained knowledge, and best practices towards their wide adoption in the EU steel sector.
15	**Which primary exploitation route(s) do you envision for this KER?** Collaboration with technological platforms. Scientific and open access publications, conference presentations.
16	**Which consortium partners do you foresee collaborating most closely with on the exploitation of this KER, and for what specific activities?** BFI: Collaboration with technological platforms. Scientific and open access publications, conference presentations. Webinars and workshops. SSSA: Collaboration with technological platforms. Scientific and open access publications, conference presentations. Webinars and workshops. SWE: Collaboration with technological platforms. Scientific and open access publications, conference presentations. Webinars and workshops.

17	**What internal resources will your organization commit to these initial exploitation activities for this KER?** Dedicated personnel, Conference contributions and spread of knowledge

TABLE 36: KER7 TRANSFERABILITY ANALYSIS

1	**Which other sectors or industries could potentially benefit from this KER?** Non-ferrous metals industry (Aluminum, copper), rely on high-temperature furnaces. Glass manufacturing. Ceramics and refractory industry. Pulp and paper (drying sections).
2	**What conditions must be present in the target sectors to enable the use of this KER?** High-temperature process environments. Processes with consistent or predictable exhaust gas flow and temperature profiles.
3	**What modifications or adaptations would be needed to make the KER applicable in other sectors or use cases?** Not applicable due to the kind (roadmap) of the KER.
4	**What potential improvements could the KER bring when applied to other sectors?** Support for the transformation of heating processes. Quick overview of technologies and their possibilities and requirements, enabling savings in personnel and costs during the planning of transformation measures. Acceleration of the deployment of sustainable heating technologies. Improved access to green lead markets
5	**What are the main barriers or limitations to applying this KER in other sectors?** Processes could be too different from steel reheating technologies, so that the proposed technologies are not applicable. Industrial boundary conditions (regulations, markets, company structures, …) too different from iron and steel industry so that the roadmap cannot be transferred to other industries.
6	**What support might be needed to overcome these barriers?** Not applicable due to the kind (roadmap) of the KER.

6.8 KER8 questionnaire

TABLE 37: KER8 DEFINITION

1	**Unique KER Identifier/Name:** Hybrid heating concepts
2	**Owner of this KER:** SWE, KAN, FER, ADI
3	**Roles and responsibilities of each partner within the project in relation to this KER:** SWE contributes with equipment and expertise in the field of furnace and energy technology. Swerim's research infrastructure and pilot facilities, in this case media infrastructure and large-scale pilot facilities, allows for experimental tests in a retrofitted set-up of the pilot walking beam furnace for the specific case of testing and demonstrating a hybrid heating concept using a combination of combustion of hydrogen combined with electrical resistive heating as part of KER8. KAN as a producer of electrical heating solutions on a worldwide level contributes with expertise, equipment and lab and simulations results to provide a state-of-the-art solution for the pilot tests. FER and ADI contribute with process knowledge and background information for test planning, including relevant KPIs for high quality test result evaluation
4	**Brief Technical Description of the KER:** A hybrid heating concept will be tested and evaluated in a continuous reheating 3 ton/h walking beam furnace. The concept combines two types of heating, combustion and electrical heating. Since the fuel used for combustion, this makes up for a very flexible and low CO2 heating approach. Supporting the tests are laboratory tests and modeling of the concept of electrical heating element configurations and furnace atmospheres and heat transfer. Evaluation of results transferability to the industrial process is a last and important step to assess how the hybrid technology can be applied on billet and slab reheating furnaces.
5	**Current TRL of this specific KER:** TRL 4
6	**Provide specific evidence justifying the current TRL:** The hybrid heating reheating walking beam furnace (WBF) will advance two already developed concepts, which are on their own at TRL 9. Combustive heating is commercially used and implemented since long time, for various fuels. Resistive heating is widely implemented in continuous heat treatment and in batch furnaces. The implementation of both technical solutions in continuous reheating WBF is still on a developmental stage. There are ongoing innovation actions to advance the concept of hydrogen heating in large scale continuous WBF before going towards implementation, TRL 5-7. The hybrid concept where these two technologies are combined aiming at large scale reheating furnace solutions are still at an experimental stage, TRL 4.
7	**Is this KER a standalone output or is it designed to be integrated into another system/product?** This KER will be analyzed by industrial partners about how the solution could applied on-site. KPI´s from the pilot tests will provide information of the competitiveness and expected outcomes on a wider scale i.e. fuel consumption, efficiency, quality, power shift options, flexibility and functionality. This KER is designed for integration into industrial heating systems. It is not a stand-alone device, but part or addition of a larger combustion system.

TABLE 38: KER8 GAP ANALYSIS

1	**What specific problem does this KER solve or what fundamental need does it address for users, industry, or society?** Conventional combustion of carbon based fuels is standard today. Many initiatives are investigating other fuels or energy carriers, such as hydrogen combustion or electrical solutions to find low carbon alternatives. This KER investigates how a flexible solution, combining combustion of hydrogen and

	electrical heating could be combined to allow load shift optionality between these two alternatives. So, this path offers load shift, fuel flexibility, energy efficiency and cost reductions possibilities, at pilot scale TRL.
2	**What comparable developments or products are available on the market which have a comparable use case this KER?** Individually, each solution is being used on an industrial scale, i.e. combustive heating and resistive heating. H2 combustion is being researched on ongoing projects for large scale continuous furnaces, and resistive heating is mostly used in heat treatment furnaces. The combination of these two techniques in a large scale continuous WBF furnace is on an experimental stage, laboratory investigations and modeling. No known project so far is looking into a combination of H2+electricity on a pilot scale for this type of furnace.
3	**Which gaps do these products have on the market?** Use case: pilot scale tests. The pilot tests showcase hybrid functionality and how well each of the two solutions can provide heating combined. However, we do not provide full flexibility during the tests as we don't have the possibility to switch type of heating up and down to still reach the target temperature, the set-up only allows a showcase of the combined use of heating source. During operation of the furnace zone 1 and 2 only use combustion and zone 3 only resistive heating. No double functionality in each zone, so we cannot switch over to full combustive heating or full resistive heating, so this type of flexibility is not possible. However, based on the results industrial installations can be designed to allow for full flexibility depending on site-specific conditions and project results.
4	**What do this KER achieve in addition?** Flexibility between two types of heating, Improved material quality as we can use an oxygen free atmosphere in the resistive heating zone, leading to a minimization of material loss due to oxidation, Higher energy efficiency using resistive heating, Possibility to cut costs using load shift when energy prices are high, Low to no CO2 heating using H2 combustion combined with green electricity if available
5	**What is the unique selling point of this KER compared to existing technology/products?** Low to no CO2 heating, Flexibility between combustion of hydrogen and electrical heating providing load shift options connected to energy price peaks, Electrical heating offers very high efficiency and combustive heating offers high volumetric heat input. Improved material quality.

TABLE 39: KER8 MARKET ANALYSIS AND TARGET USERS

1	**What specific benefits will potential users gain from applying the developed technology compared to existing solutions or products?** Improved material quality, Ecological Benefits, Economic Benefits, Higher Efficiency
2	**Who are users in industry?** Steel and metal production plants, OEMs of industrial burners and furnace systems seeking hydrogen-compatible solutions, Electrical heating solution providers Within these sectors, customers are typically: Plant operators aiming to reduce energy costs and emissions, Technology providers and equipment manufacturer looking to upgrade their systems for hydrogen-readiness, Engineering consultants planning decarbonization strategies for clients.
3	**Who can manufacture this KER who are possible suppliers?** Manufacturer of Industrial furnace and electrical heating components and solutions
4	**How big is the market?** Given the important benefits for the energy transition, the expected number of customers could depend on the installed base of hot-rolling steel plants (flat and long products) that are ready to undertake retrofit and fuel switching.

	A conservative estimate, using the current count of major sites in Europe, would be approximately at least 80 hot rolling plants (50 for flat products and 30 for long products) with more than 35 customers. Spreading potential investments across company facilities over a typical 10-year, revamp cycle yields an underlying replacement flow of one reheating furnace every three years (assuming an average of about three reheating furnaces per hot-rolling plant). Therefore, a hypothetical annual flow could be 20–25 furnaces per year only in the EU.
5	**Expected cost for implementation/invest of new technology**? The expected investment depends on the scale of the installation, the material used, the type of furnace and the performance requested in the installation zone.
6	**savings per year achieved in industry with new technology?** Savings are significantly important in terms of CO_2 reduction because of the introduction of electrical heating in the final zones of the furnace (soaking zone), in addition to the possible use of hydrogen. However, it's possible to carry out an estimate considering the only use of electrical green energy with actual burners and supposing that 17.5 % of the total reheating energy is spent in the soaking zones (hypothesis derived from the distribution of burners power in the ADI furnace). In addition, if we consider a specific consumption equal to 1.8 GJ/t and that burners are fed with NG, a saving equal to about 18642 tCO2/ Mt_{steel} is obtained. (emission factor equal to 59.182 tCO-$_2$/TJ)
7	**Who are the key stakeholders?** Industrial End-Users: Steel and metal processing companies operating reheating furnaces (Acerinox, Haynes, VDM, ThyssenKrupp, Arcelor Mittal, DEW, FER, ADI, Mannesmann …) (Providing the company name improves the quality of deliverables.). Technology Suppliers: Heat exchanger and burner manufacturers (Alfa Laval, Kelvion, Küppers, … (Providing the company name improves the quality of deliverables.) Policy and Regulatory Bodies: National and EU agencies supporting energy efficiency and decarbonization. Research and Technical Partners: Consortium members. (Providing the company name improves the quality of deliverables.) Investors / Industrial Clusters: Organizations supporting innovation in sustainable manufacturing. (Providing the company name improves the quality of deliverables.)
8	**Strategy for engaging the stakeholder?** 1. Identify Key Stakeholders, 2. Customize communication to the interests of stakeholders by focusing on aspects that are important to them. 3. Use Multi-Channel Communication like: Technical workshops, social media, print media, round tables ...4. Leverage Consortium Networks to reach wider stakeholders across the EU, 5. Plan for Post-Project Continuity. By developing exploitation agreements and IPR arrangements, ..
9	**Are there any specific geographical regions within the EU that are of particular interest for initial market entry? Why?** This applies to industries and regions with a clear framework to reduce CO2 and simultaneously are looking for a cost competitive solution. It also applies to markets where energy savings are critical and where there are potential large price fluctuations of energy prices like: Germany, Italy, Sweden, Spain, France Policy alignment with EU Green Deal and national decarbonization roadmaps. Existing infrastructure where retrofitting is feasible. Local partners and stakeholders already engaged in the E-ECO project.
10	**What is the estimated market size for this KER within the EU?** Considering the stakeholders like ADI (flat product producers), it's possible to refer to more than 20 potential users in Europe.
11	**What are the specific needs of these target users that this KER directly addresses?** Energy efficiency improvements: Users in the steel industry and other heavy industries are confronted with high energy consumption in reheating and

	combustion processes. They need solutions for high thermal energy efficiency, reduced fuel consumption and operating costs. Increased flexibility coupled to load shift optionalit. Improved OPEX due to load shift optionality. Improved material quality and yield due to decreased oxidation, Low CO2 solutions due to economical benefits and EU-regulations

TABLE 40: KER8 INITIAL EXPLOITATION STRATEGY

1	**What is your expected result and/or development?** Results from laboratory investigations providing results on atmosphere (N2+H2) effect on oxidation. Results from furnace modeling showcasing resistive element exposure sensitivity and heat transfer and temperature distribution, elemental power and material temperatures. The combination of these inputs together with process background information from steel manufacturers for a solid design of how the pilot tests can be designed to be representative. The outcomes from the pilot tests will provide important KPIs on productivity, economy, thermal efficiency, heat transfer and material quality. These outputs will be technical assessed by KAN, ADI and FER to provide the fundamental answer of the transferability and functionality of the solution on an industrial scale
2	**What is your value proposition concerning exploitation?** Helps plant operators to reduce costs and eliminate CO2 emissions, Helps plant operators to manage energy price peaks. Provides technology providers and integrators with validated, scalable solutions that accelerate the deployment of sustainable heating technologies.
3	**Description of exploitable results?** A set of pilot scale and technically assessed KPIs that verify a hybrid heating solution.
4	**When do you expect your results?** WP is finalized by Q4 2027
5	**Which deployment opportunities do your results and /or developments have for industrial use?** Provides insights and know how about: Functionality, Operation capacities, Economical targets, Load shift capacity, CO2 emissions, Material quality These feedbacks are essential for many industrial users to consider deployment of new technical solution implementations
6	**At what TRL are your results and/or developments?** TRL 6
7	**What must industrial end-users do or change in their setup to adopt and use it?** Adaptation of furnace infrastructure, Integration with existing process controls, Fuel supply compatibility, Resistive element installations and design, Adjustments to automation and control systems, Regulatory and safety compliance, Staff training and operation protocols.
8	**Which stakeholders and decision makers will be involved in exploiting your developments? When will they be involved?** Industrial partners (e.g., steel producers, electrical solutions supplier) Policy makers / standardization bodies – for alignment with safety and environmental regulations. Engaged in the later stages (Month 30–End) to support commercialization. Plant engineering companies – potential partners for scaling and integrating the technology into industrial systems. Involved from Month 24 onward, once technical feasibility is proven.
9	**With which platforms do you expect to cooperate?** CSP, Hydrogen Europe – to stay, ESTEP, EERA, SPIRE / Processes4Planet, Jernkontoret (Swedish steelmakers association)
10	**Which barriers do you see for exploitation?** Operational barriers:Proof of concept of new technologies, Reluctance to retrofit existing systems if results arent excellent or overly convincing. Market barriers: Reluctance of industrial users to invest in new heat recovery technologies without proven long-term cost savings and reliability.

	Cost disadvantages do not justify the technological and ecological advantages compared to established competing technologies, Uncertainty about fuel transition timelines, which can delay adoption of hydrogen-compatible systems. Regulatory barriers: Compliance with evolving safety standards for handling oxygen-enriched or pure hydrogen combustion atmospheres.
11	**Which strategy is foreseen to react on this/these barrier(s)?** Operational barriers: Conduct thorough pilot testing and material validation under realistic industrial conditions to demonstrate durability and performance. Collaborate closely with industrial partners to customize solutions for their specific processes. On their own, combustion and electrical heating are proven concepts which can be a major convincing factor Market barriers: Showcase clear economic and ecological benefits through detailed cost-benefit analyses and real-world case studies. Engage early adopters and key industrial stakeholders through workshops and demonstrations to build trust and confidence. Highlight the future-proof design compatible with hydrogen and low-CO2 fuels to align with industry's energy transition goals. Regulator barriers: Work proactively with certification bodies and regulatory agencies during development to ensure compliance and streamline approval processes. Leverage the expertise of partners with experience in safety standards and material certifications.
12	**Preliminary definition of business and sustainable model?** Not applicable
13	**Are there any ethical, societal, or environmental considerations related to the exploitation of this KER that need to be addressed?** Environmental: The primary goal is to reduce CO2 emissions and energy consumption, which supports climate goals. Societal: Transitioning to new technologies may require workforce retraining. It's important to manage this to avoid job displacement and support upskilling for employees adapting to new industrial processes. Ethical: No significant data privacy concerns are directly linked to this KER. However, transparency and stakeholder engagement during deployment will be crucial to ensure fair access and benefits across different industry players.
14	**What are the top concrete exploitation-related actions your organization plans to undertake during the project's remaining lifetime related to this KER?** SWE: Pilot Testing & Validation. Knowledge Dissemination. Industrial Partner Support. Technical assessment and analysis Support to FER in creating scenario analysis on hybrid heating KAN: CFD modelling, Design and manufacturing of heating éléments, Supply of slabs (Alleima) ADI: Definition of the KPIs related to the performance of the hybrid heating (metallurgical and reheating constraints), Consortium Support for the pilot testing and validation, Knowledge Dissemination
15	**Which primary exploitation route(s) do you envision for this KER?** SWE: Pilot testing facility available to industry specific testing, As a research organization, SWE offer know how and expertise in custom made solutions relating to hybrid heating, as well as modeling industry specific conditions, Collaborative research projects KAN: CFD modelling, Design and manufacturing of heating éléments, Supply of slabs (Alleima) ADI: As industrial demonstrator, ADI provides its own knowledge to support the design of solutions that meet the plant's requirements in terms of thermal homogeneity and oxidation behavior based on its experience and laboratory characterizations.
16	**Which consortium partners do you foresee collaborating most closely with on the exploitation of this KER, and for what specific activities?** KAN: Electrical heating solutions offers and industry specific solutions provider

	SWE: Pilot facilities and modeling- feeding industrial partners with relevant technical data for decision making FER: Scenario analysis on the application of hybrid heating and energy conversion in steel production relying on relevant process background information ADI: ADI will collaborate with SWE for the validation of the pilot testing, with KAN to find industrial solutions for hybrid heating in existing reheating furnaces and with other partners to validate the individualized concepts based on their material characterizations.
17	**What internal resources will your organization commit to these initial exploitation activities for this KER?** SWE: Personnel and expertise, Pilot equipment retrofitted for hybrid heating tests, Conference contributions and spread of knowledge KAN: Personnel and expertise, Electrical heating solutions custom made for each specific purpose, Modeling expertise related to heating element capacities, power and thermal efficiency in industrial furnaces, Conference contributions and spread of knowledge ADI: Personnel and expertise, Laboratory equipment for metallurgical and chemical analyses, Steel samples for SWE pilot testing, Operations and product quality expertise in rolling processes.

TABLE 41: KER8 TRANSFERABILITY ANALYSIS

1	**Which other sectors or industries could potentially benefit from this KER?** Energy intensive industries and related equipment suppliers using large scale furnaces normally operated with combustive or electrical heating technologies
2	**What conditions must be present in the target sectors to enable the use of this KER?** High-temperature process environments, Availability of hydrogen or oxygen-enriched fuels, Availability of advanced control and monitoring systems.
3	**What modifications or adaptations would be needed to make the KER applicable in other sectors or use cases?** Advanced control systems Safety standards and APEX classification, HAZOP risk analysis, Basic and detailed engineering of the use case, Detailed control of temperature throughout the process
4	**What potential improvements could the KER bring when applied to other sectors?** Performance, Efficiency, Cost reduction, Sustainability, Flexibility, more independent of energy price fluctuations
5	**What are the main barriers or limitations to applying this KER in other sectors?** Operating conditions mismatch, Infrastructure compatibility, CAPEX investment too high
6	**What support might be needed to overcome these barriers?** Technical training programs, Development or alignment with industry standards, Best practice, guidelines, Good support from suppliers offering technical solutions, Proof of concept and scenario analysis for the relevant sector, Pilot scale tests availability for the relevant sector, Modeling support

7 List of Figures

8 List of Tables

9 List of acronyms and abbreviations

Acronym	Full Name
KER	Key Exploitable Result
WP	Work Package
OEM	Original Equipment Manufacturer
TRL	Technology Readiness Level
CFD	Computational Fluid Dynamics
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
NG	Natural gas
C-free	Carbon free
AM	Additive manufacturing
CSP	Clean Steel Partnership
ESTEP	European Steel Technology Platform
EERA	European Energy Research Alliance