

Combustion of Rechargeable Metal Fuels in Fluidized Bed Boilers

Project acronym: CORAL

Grant Agreement Number: 101155814

Deliverable D5.2:

Comprehensive overview

Version No.: 1
Dissemination level: PU - Public

Due date of deliverable: 2025-02-28
Submission date to coordinator: 2025-04-01
Actual submission date: 2025-04-01

Start date of project: 2024-09-01
End date of project: 2028-02-29

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This project has received funding from the European Union, Research Fund for Coal and Steel, under grant agreement number 101155814.

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PROJECT SUMMARY

The cyclic reduction/oxidation of metal oxide/metal is a promising approach for energy storage and flexible CO₂-free provision of heat and power. The project explores a novel concept of metal oxidation utilising retrofitted coal-fired fluidized bed power plants. Required modifications of the steam generator, solid feeding, and extraction systems are identified. A hydrogen-based process is used for the direct reduction of metal oxides. The reduction/oxidation process in fluidized beds is tested at various scales up to 1 MW thermal power. Various numerical models (steady-state, dynamic, and CFD models) are developed, validated by experiments, and applied to design modifications. The concept is assessed regarding electrical efficiency, economics, environmental and social impact.

1. Project Challenges and Objectives

1.1 Objectives and ambition

The project addresses a concept for energy storage based on redox reactions of metals. In periods of power surplus (or at a location rich in solar or wind energy), a metal oxide (e.g., hematite) is reduced to pure metal by the addition of green hydrogen (and heat) that stems from electrolysis (or gasification of residues). In periods of lack of power (when power production from renewable sources is not sufficient), the metal (e.g., iron) is oxidized in a fluidized bed furnace, and the released heat is used for power and heat generation in a power plant process. The metal, therefore, serves as an energy carrier and energy storage (see **Figure 1**). Compared to batteries, e.g., lithium batteries, the round-trip efficiency (power-to-power) of the redox reactions of metals in the fluidized bed system is relatively low (<35%), especially if old fluidized bed boilers are retrofitted with this technology, but roughly comparable to other power-to-X storage systems [1] or thermal energy storage [2]. The possible use of combined heat and power can lead to a significant increase in efficiency. Other **positive features** of the process include the following:

- Existing power plants can most likely be used for metal oxidation (i.e., existing infrastructure can be further used after coal phase-out).
- No CO₂ is formed during oxidation/reduction of metals/metal oxides (i.e., no greenhouse gas emissions are released).
- The metal has a high volumetric energy density (i.e., it can be stored for long periods and transported over long distances at a low cost). For example, one litre of reduced iron releases 11.3 kWh of thermal energy, while hydrogen delivers 0.003 kWh. Pressurized hydrogen contains about 0.5 kWh/litre at 200 bar, 1.1 kWh/litre at 500 bar, and 1.4 kWh/litre at 700 bar [3].
- For the reduction of metal oxides, synergies with the steel industry can be exploited. The 100% hydrogen-based process for direct reduction of iron ore fines produces highly metalized Direct Reduced Iron (DRI) or Hot Briquetted Iron (HBI) that can be fed directly to an electric arc furnace [4].
- The metal can be effectively used as a seasonal energy storage, to store the excess of PV production generated in the summer. Batteries, for example, while more efficient, are not suitable as seasonal storage or as large-scale storage systems for many reasons: the high self-discharge rate, the very high capital cost, and the need for special materials that are in limited supply. Hydrogen is currently being considered as a possible seasonal storage medium, but its use as seasonal storage is only economically viable if it is stored in “free” large containers (e.g., salt caverns). For storage in pressure vessels/pipes, the specific cost of storage would be high, reaching up to 13.5 Euro/kWh of H₂ LHV-based (thermal) [5].

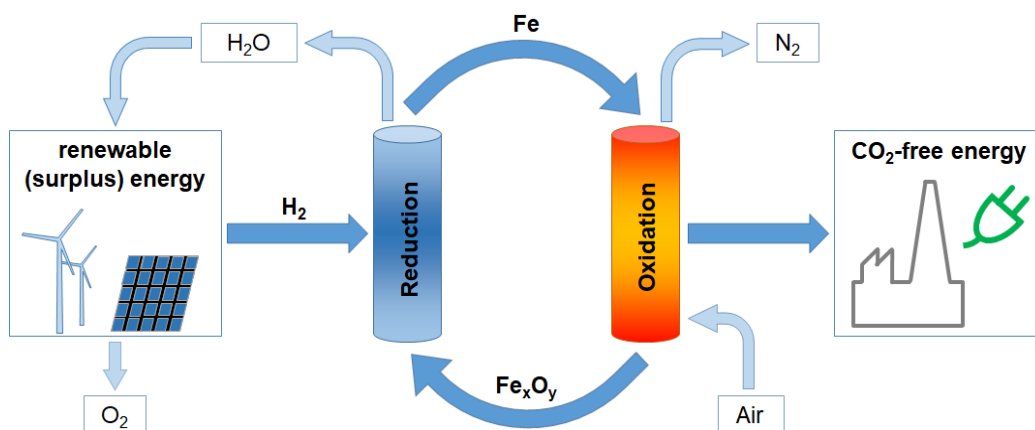


Figure 1: Scheme of the energy storage concept using metals

Fluidized beds are particularly suited for metal oxidation due to the well-controlled temperature and long residence time of the particles (in contrast to pulverized entrained-flow systems). It can be expected that existing fluidized bed power plants can be retrofitted for this purpose with only a few modifications. If the electrical output is maintained, the power train (steam turbine and generator), as well as most of the water-steam cycle, can be re-used. The most critical components that may require modifications are the steam generator (furnace walls, convective pass, external heat exchanger), the systems for feeding and extraction of metal particles, and the unit for separation of metal dust from the off-gas. When changing the fuel from coal to metal, the following **differences in fuel properties** need to be considered:

- The high density of the metal influences the hydrodynamics of the fluidized bed, which affects the distribution of particles in the furnace and therefore the heat transfer to the heating surfaces of the steam generator.
- The high thermal conductivity of metals increases the heat transfer to the heating surfaces of the steam generator.
- The change in reactivity affects the location/intensity of heat release in the furnace and therefore the heat transfer to the heating surfaces of the steam generator.
- The lower heating value of the metal (~ 7.4 MJ/kg) increases the fuel mass flow rate, which needs to be handled by the fuel feeding system.
- The mass of the metal increases by oxidation leading to large quantities of produced metal oxides that need to be extracted from the fluidized bed and the heat from the extracted material should therefore be recovered to reach a high boiler efficiency.
- The high electrical conductivity of the metal affects the propensity of the dust particles to be separated in an electrostatic precipitator.
- The metal does not include significant amounts of impurities, and thermal NO_x formation is not expected at the fluidized bed temperature ($\sim 900^\circ\text{C}$) so no measures for control of emissions (SO_x , NO_x , HCl , Hg , etc.) are required. Moreover, material wastage of heat exchanger tubes due to fouling and corrosion is low, which allows for high live steam parameters.
- The particle properties of metal differ from those of the bed material typically used in fluidized bed boilers. Particle properties, such as sharpness and hardness, play a key role in erosion-induced material wastage of boiler components.

The **overall aim** of this project is to develop and evaluate a concept to retrofit existing coal-fired fluidized bed power plants for the oxidation of metals. Critical components of the fluidized bed power plant are assessed regarding efficient power generation while utilising existing infrastructure, and technical concepts for required modifications is developed. Furthermore, the possibility of operating the existing fluidized bed plant as a reduction unit is also investigated. In this case, the riser equipped with the evaporator membrane tube must be changed to avoid the heat sink during the endothermic reduction

process. As redox material, iron is selected because of its relatively low price and high availability. The following **objectives** are defined for this project:

- 1) Identify modifications of the existing steam generator (including furnace walls, convective pass, and external heat exchangers) to obtain the highest possible boiler efficiency
- 2) Select appropriate technical solutions for feeding and extraction of metal particles to/from the fluidized bed boiler as well as for separation of metal dust from the off-gas
- 3) Specify and characterize a commercially available iron powder that is most suitable for combustion in a fluidized bed furnace
- 4) Determine the operating window of a fluidized bed boiler utilising fluidized bed tests at lab and pilot scale
- 5) Demonstrate the technical feasibility of metal combustion under industrial conditions at a pilot scale
- 6) Improve and optimize the energy efficiency and economic/environmental sustainability of the metal reduction process
- 7) Develop reliable numerical tools for scale-up of the fluidized bed through extensive validation
- 8) Determine the net electrical efficiency of the retrofitted power plant at various loads
- 9) Evaluate the flexibility of the fluidized bed power plant to provide power and heat by employing dynamic simulations
- 10) Evaluate the economic feasibility of the proposed concept by determining the market potential, investment, and operational costs as well as the cost of electricity
- 11) Determine the impact on the environment (e.g., climate, emissions) and society, such as maintaining or creating jobs

Relevance for the RFCS program

The project addresses the RFCS program objective of “supporting the just transition of the coal sector and regions”. In particular, the project objective of retrofitting existing coal-fired fluidized bed power plants by using metals as fuels contributes to the priority related to the European Green Deal “Projects should directly relate to the re-purposing of closed or end-of-life coal-related assets, such as ... coal power plants...”. By using metals as a renewable fuel, the project is also directed at “exploring or demonstrating new or improved technologies and business models that rely on renewable energy..., or contribute to the circular economy”. The project also seeks “the use of synergies through sector coupling” by utilising metals that are also used for steel production. The hydrogen-based direct reduction process is an alternative method to conventional steelmaking in blast furnaces. Many steelmakers have demonstrated its functionality and performance in demonstration plants, e.g., the Metso Circored™ process. Furthermore, the project includes an “economic assessment” of the proposed retrofit concepts and “socio-economic research” related to the region of these power plants.

Level of innovative value

The expected innovations of this project are briefly summarised below:

- The concept of using metals for energy storage is an innovative approach.
- The idea of re-purposing existing coal-fired fluidized bed power plants for metal oxidation is an innovative solution for the second life of these plants.
- The project develops innovative technical solutions for modifying the existing equipment for the new purpose of metal oxidation, such as the steam generator, feeding system, extraction of bed material, and dust removal.
- The project develops innovative modelling tools for the design and assessment of plant modifications, including sophisticated 1.5-D steady-state and dynamic process models as well as a DDPM-DEM model coupled with an advanced structure-dependent drag model scheme.

- The performance of the technology in terms of environmental, social, and economic impacts are considered to avoid unwanted side effects already at an early stage of technology development.

The pilot tests (e.g., metal storage and combustion process) and modelling tools are conducted under industrially relevant conditions and are intended to provide confidence in the technical feasibility of the proposed retrofit concepts and their modelling approaches (starting from **TRL 3** and reaching **TRL 6** at the end of the project).

Metals for storage of energy and flexible provision of power and heat

State of the art: Metal fuels are promising re-chargeable clean energy carriers in the future low-carbon economy [6]. They are expected to replace the essential roles of fossil fuels in transportation, power, and heat generation. Metal fuels can be combusted with air or reacted with water at various scales [7, 8], releasing their chemical energy as thermal energy. The combustion products of metal fuels are solids that can be recovered, and subsequently reduced by utilising carbon-free electrolysis processes powered by renewable energy. A major technological barrier to the increased use of metal fuels is the current lack of a clean and efficient prime mover to convert the chemical energy in metal fuels into electrical energy [9]. The first proof of concept based on a metal powder pulverized combustor (pulverized firing) has been shown by the project partner **POMETON** in collaboration with others (e.g., Eindhoven University of Technology) to supply heat to a brewery [10]. The oxidation of metals in fluidized beds has been proven to work within chemical looping combustion (see next paragraph). Nevertheless, no experimental proof has been shown for the oxidation of metal fuels in a fluidized bed as a stand-alone process.

Added value of this proposal: In the present project, the use of metals for the storage of energy and flexible provision of power and heat in fluidized bed power plants is investigated both theoretically and experimentally.

Chemical looping

State of the art: Chemical looping is a novel concept for the conversion of fuels, which has many similarities with the redox cycle for energy storage. A metal oxide (Me_xO_y) circulates between the two interconnected reactors providing oxygen for fuel conversion in the fuel reactor. The concept can be either applied to power/heat generation with inherent CO_2 capture, i.e., chemical looping combustion (CLC), or to syngas generation by partial oxidation, i.e., chemical looping gasification (CLG). Compared to competing CO_2 capture technologies, CLC requires significantly less pure oxygen, resulting in lower specific energy demand and lower cost for CO_2 capture [11]. CLC has been the topic of numerous research projects for the combustion of gaseous fuels (INNOCUOUS, SUCCESS), solid fuels (ECLAIR, ACCLAIM), and reforming of natural gas (CACHET) [12, 13]. **TUDA** (coordinator of the current project) and the project partner **CSIC** participated in these projects. **TUDA** has successfully operated a 1 MW_{th} CLC pilot plant with coal and biomass [14, 15] as well as natural gas [16], which is the largest CLC plant in operation. A 3 MW_{th} CLC plant for biomass and/or petcoke is currently being erected in the H2020 project CHEERS. A concept for the production of biofuels using CLG is being developed, tested in continuous units (also by CSIC) [17], and demonstrated at a 1 MW_{th} scale by **TUDA** [18] within the H2020 project CLARA.

Added value of this proposal: The proposed concept of oxidation of metal fuels in a fluidized bed furnace is similar to the air reactor of a CLC system. However, there are a few significant differences. First, the oxidizer is decoupled from the reducer, so that the metal enters the plant at low temperature, while the metal oxide is available at high temperature. Hence, heat integration is crucial to optimize boiler efficiency. This project develops appropriate systems for pre-heating the entering metal and heat recovery of the extracted metal oxide. Second, the metal enters the oxidizer preferably in completely reduced form, while only partial reduction is performed in CLC. This change is associated with a much higher heat release and change in reaction rate. This project evaluates the effect of these changes on the conversion efficiency in the fluidized bed and heat transfer to the heating surfaces of the boiler.

Oxidation of metal fuels

State of the art: There are currently quite a few ongoing projects dealing with pulverized combustion of metal fuels. Several European groups including McGill (Canada) collaborated on the project PERWAVES to carry out zero-gravity experiments on iron dust flame combustion using sounding rockets and a space lab. Fundamental research on metal powder combustion as CO₂-free fuels and the development of experimental and numerical tools is carried out by Eindhoven University of Technology (TUE) within the Metal-to-Power project. The ERC Advanced Grant MetalFuel of Prof. de Goey at TUE focuses on the key scientific knowledge gap, controlled combustion of dense aerosols of metal particles, and the impact of collective interactions between the particles and provides a multiscale framework for analysing and predicting full dynamics & structure of flames in dense aerosols. Here, the burn time and combustion of metal particles are assessed on a detailed level [19]. The Lighthouse Metal Power project, where the project partner **POMETON** is involved with TUE, developed a 100-kW metal-fuelled burner for a steam generator. In 2020, this setup was used to show the potential of metals as energy carriers and produced steam for a brewery [10]. The Lighthouse Metal Energy Carriers project (**POMETON** and TUE) develops a proof-of-concept regeneration system that can operate combined with the proof-of-concept combustion rig from the Lighthouse Metal Power project. The project Metal Power Living Lab at TUE scales the 100-kW metal burner towards a 1 MW demonstrator, which is an important step to promote metal fuels technology in the energy sector. To the best knowledge of the applicants, no experimental investigation related to fluidized bed combustion of metal fuels has been published so far. Fundamental research related to the reduction/oxidation of metal oxides/metals under entrained flow and fluidized bed conditions is foreseen in the ongoing project CleanCircles [20].

Added value of this proposal: This project investigates the oxidation of metal fuels in fluidized beds and demonstrate the technology in a semi-industrial 1 MW plant for the first time.

Reduction of metal oxides to pure metal fuels

State of the art: The reduction step of metal oxides to metal is very similar to the production of iron [21], which is a well-known process in the metal industry. Iron ore is mined in an oxidized state and is reduced with coke, generating large amounts of direct CO₂ emissions (using a blast furnace). Alternatively, iron ore can be reduced with pure hydrogen produced by electrolysis processes using renewable energies. However, due to the high cost compared to the traditional route, this technology is not yet used commercially. Many steelmakers have hydrogen-based technologies for reducing metal oxides. Metso Outotec, for example, has demonstrated the functionality and performance in a large-scale pilot plant in Trinidad (CircoredTM process) [4], using an established fluidized bed process. The reduction step plays a very important role in making metal fuels true cyclic fuels [22]. The combustion process affects the properties and states of the particles, which then have to be reduced [21]. For fluidized bed combustion, the reduction technology should provide metal particles of similar size to retain the combustion properties. To the best of the applicant's knowledge, no experimental research on the reduction of metal oxides previously combusted on a 1 MW thermal scale has been made available to date. Currently, this is one of the key technological hurdles, which needs to be overcome to close the cycle.

Added value of this proposal: This project evaluates the effect of the reduction process on the properties of the metal fuels for combustion in a fluidized bed. Cyclic reduction/oxidation processes are expected to change the particle properties, such as size, specific surface area, and porosity. These properties affect the reduction/oxidation rate and therefore the efficiency. Dedicated lab-scale, as well as semi-industrial 1 MW experiments with re-used particles combined with comprehensive analyses of the particles, are foreseen to investigate this effect. The reduction process of the metal oxide produced during combustion is tested at **TUDA** on a 1 MW scale. The reduction of metal oxide (not mineral ore) particles aims at obtaining iron particles of similar size – this has never been examined before – to retain the fluidization and combustion properties.

Re-use of coal-fired fluidized bed power plants

State of the art: There are several options for the further use of existing coal-fired fluidized bed boilers after the phase-out of coal for power and heat generation. One straightforward option is to replace coal with alternative energy sources, such as biomass or waste-derived fuels. Circulating Fluidized Bed (CFB) technology is perfectly suited to allow a wide range of fuels to be burnt in the same boiler. Here, fuels with a high ash content, which are very challenging for pulverized fuel firing, can be burned without any problems due to the moderate combustion temperatures (ash melting and thus slagging, and fouling of heat transfer surfaces are avoided). Even fuels with a low content of volatile components (e.g. petroleum coke) can be processed due to the long residence times of the fuel in the combustion chamber. The cost-effective option of direct desulphurization also allows the economical combustion of fuels with high sulphur content. Fuels previously used or tested in fluidized bed boilers include biomass, peat, municipal, industrial and animal waste, refuse-derived fuels, oil shale, sewage sludge, tyres and plastics [23-25].

The co-combustion of biomass and waste-derived fuels with coal in fluidized beds has been investigated in several previous projects (e.g., FLEX FLORES (**TUDA** and **SFW**), KME 711, KME 720) and is being applied in commercial boilers, e.g., Zabrze combined heat and power plant. In this CFB unit (power generation capacity: 75 MW_e, heat generation capacity: 145 MW_{th}), a fuel mix of locally sourced municipal solid waste, biomass, and coal is combusted providing energy security and waste recycling as well as heat and power to the town of Zabrze. Mono-combustion of biomass or waste-derived fuels is also commercially available technology and applied for instance in the world's largest biomass-only fluidized bed furnace with a power output of about 300 MW_e in Teesside, United Kingdom (designed by the project partner **SFW**) and the 23 MW_e Green Energy Centre CFB in Daegu, South Korea. The possibility of retrofitting existing coal-fired fluidized bed boilers for the combustion of waste-derived fuels and CO₂ capture is currently being investigated in the project REBECCA (project coordinator: **TUDA**). However, the use of biomass for power and heat generation poses some challenges and disadvantages [26]. These include high costs for harvesting, transport, storage, and pre-treatment processes; carbon emissions related to cultivation, transport, and other activities; possible competition for cultivation land (e.g. for food production); possible soil degradation and reduction of biodiversity due to the use of fertilizers and the cultivation of monocultures (monocultures). Using waste-derived fuels is also a challenge [27], as part of the fuel is made from fossil fuels. A method of CO₂ capture must therefore be used, which in practice leads to a loss of efficiency and additional investment costs. Furthermore, the availability of biomass and waste is limited, so alternative solutions for the re-use of existing fluidized bed boilers are needed. **Added value of this proposal:** This project develops a concept for retrofitting an existing coal-fired fluidized bed power plant for the combustion of metal fuels. Such a concept is not available so far.

Load flexibility of fluidized bed power plants

State of the art: In CFB combustion, ramp rates of up to 7% MCR/min (MCR: maximum continuous rating) are claimed to be possible by some suppliers during transients from medium to high load [28]. However, modern large-scale CFB boilers, such as the Polish CFBC unit at Łagisza have load-following capabilities of up to 4% MCR/min, which is similar to pulverized coal power plants [29]. Also, a minimum load operation of 25%-35% MCR has been reported for modern CFB boilers [30]. The minimum load limit that defines the lower boundary for negative load changes is of importance for the flexible operation of circulating fluidized bed boilers. Lower minimal load potentially reduces the number of shutdown/start-up procedures and thus positively affects the lifetime of thermally stressed components, which in turn saves costs. As the share of renewables increases, even faster load change rates and lower minimum load values are required.

Added value of this proposal: In this project, the load flexibility (ramp rate and minimum load limit) of CFB boilers with metal fuels are investigated experimentally (at different scales up to 1 MW thermal power) and numerically (using dynamic process and CFD simulations).

Simulation of fluidized bed systems

State of the art: Numerical simulations provide a quick evaluation of local and global flow field variables (e.g., temperature, velocity, and concentration) at the industrial scale and thereby support the plant design.

Reaction kinetics: Kinetics of the oxidation/reduction of metal powders is a complex process dependent on temperature, oxygen/hydrogen concentration, particle size, porous structure, and the diffusion properties of the solid layer. Thermo-gravimetric analysis (TGA) investigations under well-controlled conditions allow for determining reaction rates needed for kinetic modelling. Recent investigations on metal oxidation are mainly focused on oxygen carrier oxidation considering mainly FeO and Fe₃O₄ oxidation to Fe₂O₃ [31]. The oxidation process that follows the formation and disappearance of several different oxides (FeO, Fe₃O₄, Fe₂O₃) from Fe has been little explored (e.g., National Energy Technology Laboratory in the U.S.), but is studied in detail in this project, considering the effect of different oxidation/reduction cycles.

Steady-state process modelling: Knowledge of steady-state data of process components is sufficient in many practical engineering applications. Therefore, steady-state process simulation models are used to perform thermodynamic property analyses, mass and energy balances, and process efficiencies for a range of operating points. The literature contains numerous studies on steady-state process modelling of fluidized bed combustion [32], gasification [33], or CO₂ capture [34]. The project partner **CSIC** has developed a 1.5-dimensional model used in previous projects (ACCLAIM, SUCCESS) [35]. However, no steady-state model for the reduction/combustion process of metal oxides/metal fuels in fluidized beds can be found in the literature.

Dynamic process modelling: In the literature, dynamic process simulation is presented more rarely; in particular, very few authors have complemented their dynamic process simulation models with measurement-based validation [36, 37]. The dynamic process simulation, in contrast to steady-state process simulation, enables detailed data of the system behaviour during transients (e.g., load change, breakdowns, start-up, and shutdown procedure) with its related control structures (see the comprehensive review on dynamic simulation of thermal power plants published by **TUDA**, Alobaid et al. [38]). Considering the limited existing works, this project contributes to bridging the knowledge gap in the dynamic simulation of circulating fluidized bed boilers when metal is used as fuel. A sophisticated 1.5-D dynamic process model is developed, considering the up-flow and the down-flow of the solids in the riser. Compared with 1-D dynamic process models, the 1.5-D dynamic process model can provide more realistic temperature and pressure profiles along the riser. A detailed literature review shows that there are no studies on the dynamic modelling of the reduction/combustion process of metal oxides/metal fuels in the fluidized bed. The project partner **LUT** has developed several dynamic simulation models for CFBs fired with coal or biomass and guides the switch to metal fuels.

3-D CFD modelling: Process simulation models simplify the computational domain to one-dimensional, considering the micro-scale structures of the flow via empirical correlations. CFD models that are based on the Two-Fluid or Euler-Lagrange approach are sophisticated, solving numerically the micro-scale of the flow (e.g., gas-solids and particle-particle interactions). Despite the great efforts and progress achieved in recent years to improve the accuracy of the Two-Fluid models [39], basic flow properties are not taken into account, such as mixing and segregation processes, and the consideration of particles with complex shapes, sizes, and compositions. The Dense Discrete Particle Model-Discrete Element Method (DDPM-DEM) simulates the complicated multiphase flow within the CFB and properly resolves granular hydrodynamics as well as special reaction kinetics considering heterogeneous and homogeneous reactions. Currently, the DDPM-DEM model is computationally expensive as a means of tracking a few million particles within a reasonable time. The limitations can be overcome thanks to the so-called coarse-grained parcel method and parallel computing. These measures reduce the processing power required, which allows even large-scale gas-solid systems to be simulated in a comparable time frame to the two-fluid method [40]. Although the DDPM-DEM model is frequently applied to lab-scale and medium-scale CFB test rigs, no studies have been found in the literature for the

reduction/combustion process of metal oxides/metal fuels in the fluidized bed (according to a recent comprehensive review on CFD simulation of fluidized bed for chemical and energy process engineering published by **TUDA**, Alobaid et al. [41]). Moreover, an advanced drag scheme “EMMS” is applied, considering the effect of varying flow characteristics on flow heterogeneity. The project partner **Chalmers** has created many CFD models for CFB and validated them with a 12 MW fluidized bed power plant at Chalmers University of Technology. However, there is no CFD study in the literature for the reduction/combustion process of metal oxides/metal fuels in circulating fluidized beds.

Added value of this proposal: A highly sophisticated DDPM-DEM model with an advanced Energy Minimization Multi-Scale (EMMS) drag scheme is developed and embedded in the ANSYS-FLUENT platform. This work is expected to contribute significantly to a) technical evaluation and proposition of possible further improvements, b) providing insight into the overall conversion efficiency, c) the optimization of the technology, and directly in the identification of any additional technical limitations that need to be investigated. Furthermore, a 1.5 steady-state process simulation model and a sophisticated 1.5-D dynamic process simulation model is developed and validated towards the experimental data. Considering the limited existing works, this project contributes to bridging the knowledge gap in steady-state and dynamic modelling of circulating fluidized bed boilers when metal is used as fuel.

Design and operational optimization of the integrated energy system

State of the art: The design and sizing of power plants and energy systems are typically performed using rules of thumb and criteria developed over the years. Similarly, the operation of conventional power plants (e.g., coal-fired power plants) is performed by looking at simple rules or heuristic algorithms to minimize the marginal operating cost. However, such well-established design and operational criteria are not suitable for power plants integrated with storage systems and/or operating in highly volatile electricity markets, like those in most EU countries [42]. The conditions of these fluctuating markets require sophisticated solutions for determining the optimal design of highly integrated power plants, especially if the plant features energy storage. In particular, the optimization problem should consider the operational flexibility of the integrated system and its optimal operation during a typical operating year. In this regard, the project partner **POLIMI** recently developed a methodology for the combined design and operational optimization of integrated energy systems (power plants integrated with storages, microgrids, multi-energy systems, etc.), operating on different types of electricity markets. The optimization problem is formulated as a single large-scale Mixed Integer Linear Program (MILP) and solved with state-of-the-art optimization algorithms [43, 44]. The tool can optimize the key design decisions of the plant (e.g., size of the reduction plant, size of the PV plant, size of the electrolyser, size of the powder storage, etc.) while considering the actual operational constraints (start-up time, ramping limits, etc.) and the revenues gained from the electricity markets in a typical operating year. As for the optimal operation of the integrated system, both **POLIMI** [45, 46] and **FORTUM** developed rigorous optimization tools based on MILP models allowing an accurate representation of the operational constraints, unit commitment, and dynamics of the power plant components and storage (off-design and part-load performance maps, ramp-up rates, start-up time and cost, etc), as well as the rules and revenues of the electricity markets.

Added value of this proposal: This project applies the rigorous MILP-based design optimization tool developed by **POLIMI** to the overall integrated system comprising the reduction plant, metal storage/transport and retrofitted circulating fluidized bed boiler. This optimization has never been done before and it allows finding the minimum cost of electricity achievable with such an integrated system considering the overall conversion chain. The operational constraints (part-load maps, max ramp-up rates, etc.) are taken from the results of dynamic process modelling (above obtained). The design optimization is repeated for two different scenarios:

1. The overall integrated system is installed in central or northern European countries, e.g., Germany (i.e., the reduction and oxidation plants are in the same area).

2. The PV plant, the electrolyser and the reduction plant are in southern European countries, e.g., Italy, while the CFB power plant is in central or northern European countries, e.g., Poland. In collaboration with **FORTUM** and **POMETON**, the MILP design optimization model is extended by **POLIMI** to include the iron powder transport costs and the electricity markets in the investigated country.

Then, for the optimized design of the integrated system, the partners **FORTUM** and **POLIMI** apply their operational optimization algorithms to simulate the optimized system operation over one year on a day-by-day basis. The concluded outcomes of this evaluation are going to be compared with results obtained by real coal-fired units (including one currently operated by **FORTUM**).

Environmental, techno-, and socio-economic assessment

State of the art: According to Eurostat [47], EU CO₂ emissions from the combustion of fossil fuels for energy use in 2022 account for about 75% of all EU man-made greenhouse gas emissions, or nearly 2.4 Gt (global energy-related CO₂ emissions are 36.8 Gt). In this context, metal powders as energy carriers have a great potential to improve the sustainability performance of energy consumption by easing the substitution of fossil fuels for renewable energy sources. However, to achieve an effective reduction of the environmental, social, and economic burdens, the technology must ensure that these impacts are considered in the early stages of the technology's development. Previous literature has attempted to assess the sustainability of energy storage systems [48] and, in general, of energy systems [49]. To the best of the applicant's knowledge, there is no comprehensive sustainability framework following a life cycle perspective and including the necessary environmental, social, and economic impact categories that could be suitable to address the sustainability of using fluidized bed boilers for metal oxidation. When technology is commercialized, it follows a learning curve that drives efficiency gains through experience. This learning curve can be captured through the application of a prospective Life Cycle Assessment (LCA), which consists of modelling technology in an early stage of development at a future more developed phase [50-52]. Moreover, a key impact is the resource use efficiency, as the technology is intensive in the use of metals. In this sense, the method developed in the KIC EIT Raw Materials project SUPRIM accounts for the impact on the “depletion” of abiotic resources. In contrast to traditional methods, the method developed in SUPRIM does not account for the extraction of materials from nature but the dissipation of these materials along their life cycle. The main advantage of this new approach is that it captures the degree of utilization of the materials. This approach is very useful for the proposed technology, as it intends to enhance the circularity in the use of metals. The sustainability framework for assessment should consider the relevant stakeholders and follow a clearly defined and transparent process. Furthermore, the framework should include a comprehensive set of impact categories, addressing the main environmental, social, and economic issues related to the technology. Previous literature and expertise from the project partners is considered as a starting point [53, 54].

Added value of this proposal: The targeted advances related to the environmental impact of metal fuels for the proposed concept focuses on the evaluation of different sustainability aspects of the technology. The new technology is expected to have various positive contributions to sustainability. In particular, the application of metal fuels is expected to foster the development of renewable energies, which allows for addressing key global challenges such as global warming. For this reason, sustainability issues are properly considered during the development of this project. Moreover, key aspects such as social acceptance is addressed so that, when implemented, this new technology can make a real difference. Therefore, the performance of the technology in terms of environmental, social, and economic impacts are included to avoid unwanted side effects already at an early stage of technology development. To our knowledge, the environmental impact of the use of metal powders as a (cyclic) energy carrier has never been systematically shown in the literature.

1.2 Methodology

The proposed retrofit concept is developed and assessed by a combination of experimental and numerical work:

- The **experiments** are performed at various scales from small- over medium- to pilot-scale fluidized bed reactors, which reduces the risk of costly large-scale experiments. While small- and medium tests in electrically heated reactors are used to perform many parameter variations under well-controlled conditions, the pilot tests demonstrate the technology under semi-industrial conditions in autothermal mode. The experiments are accompanied by an extensive analysis of solid material samples to assess the properties of the produced metal oxide/metal fuel, such as the degree of reduction/oxidation.
- Various **models** with different purposes and degrees of detail are developed and extensively validated by the results of the experiments. A steady-state 1.5-D model is used to determine the solid distribution and metal conversion in the fluidized bed, allowing for many parameter variations due to the low computational time. A dynamic 1.5-D model is used to assess the transient behaviour of the fluidized bed and the effect on the water-steam cycle for power generation during load changes. A 3-D CFD model is applied to determine and evaluate the 3-D field of various parameters in the fluidized bed for a limited number of operational points (due to the high computational time). The fluidized bed models are complemented by appropriate tools for techno- and socio-economic assessment as well as life-cycle analysis. The details of the methodology used in this project are described below:

Large-scale pilot combustion tests

The oxidation of metal fuel is investigated under industrially relevant conditions in the 1 MW_{th} CFB pilot plant at TUDA, see **Figure 2**.

The CFB reactor (inner diameter: 590 mm, height: 8.6 m) is fully refractory-lined according to industrial standards. During the start-up and shut-down of the pilot plant, the CFB riser is heated by propane-fired burners at a temperature gradient of around 50 K/h. During nominal operation, the iron powder (~0.1-0.3 mm particles), which serves as both fuel and bed material, is fed to the return leg via a dedicated feeding system. Electrically preheated air is introduced to the CFB via the nozzle grid and partly via secondary air inlet nozzles at different heights. Heat is removed from the CFB riser by axially transferrable cooling tubes. Thereby, the temperature in the reactor can be controlled by varying the immersion depth of the cooling lances. Bed ash is extracted from the reactor bottom by a cooled screw conveyor and can be stored in big bags. Particles are separated from the exhaust gas (off-gas) by a cyclone and returned to the reactor by the loop seal. The exhaust gas is cooled in a heat exchanger and then passes through a fabric filter. The exhaust gas composition is analysed at various locations. For the cooling lances and heat exchangers, the inlet and outlet temperatures of the cooling water are measured to determine the heat flux to these cooling surfaces.

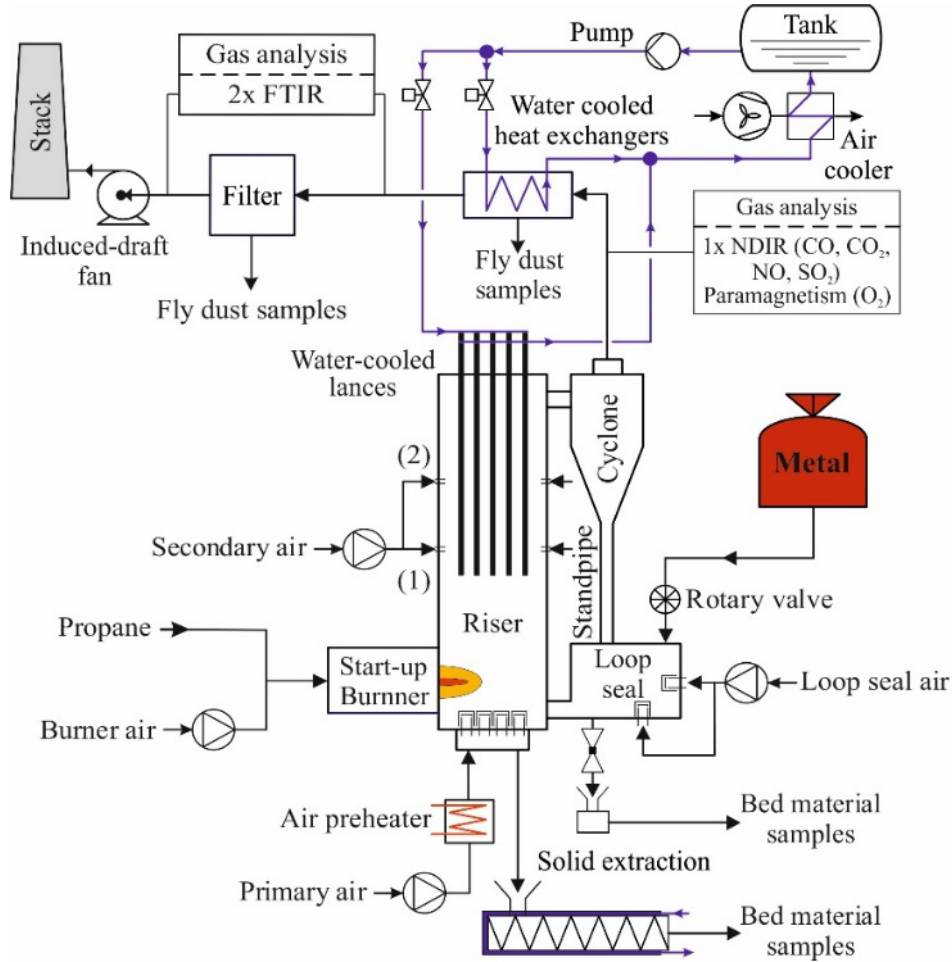


Figure 2: Experimental setup of the 1 MW_{th} CFB pilot plant

Capacitance probes (developed at **TUDA**) are used to measure radial profiles of particle concentration and velocity inside the CFB riser (see **Figure 3**). The capacitance of the suspension flow is detected with two vertically aligned probes mounted at the front end of a water-cooled housing. Two similar but time-shifted signal curves are recorded. The velocity of particles or particle clusters is calculated with this time offset and the known vertical distance of the two probes. The time offset is determined with the help of the cross-correlation technique. For data acquisition and pre-processing, a commercially available capacitance measurement system is used enabling a high measurement frequency of 7812 s^{-1} and a very stable signal.

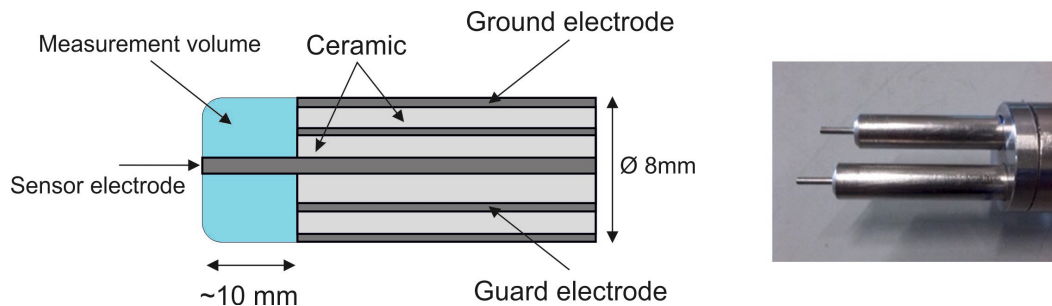


Figure 3: Schematic representation of the capacitance probe

A hot gas extraction probe (developed at **TUDA**) is used to measure radial profiles of gas concentrations inside the CFB riser. The probe is made from fire-proof material 1.4841 to ensure stability at temperatures of up to $1000 \text{ }^{\circ}\text{C}$. The concentration of O_2 is detected by paramagnetic analysis.

SFW uses several types of fouling probe systems for furnace panel walls and convective passes, which all are designed to be installed while a commercial or a pilot plant is in operation. The investigated fouling rate is based on the weight change of test pieces. Each probe includes its thermocouple to verify the material temperature. Furnace probes are installed in the hot loop of a pilot plant. During exposure, the probe can be cooled by air to simulate the target metal temperature with the help of a control unit.

Nevertheless, the retrofitting of an existing coal-fired fluidized bed plant to the oxidation of metal requires the consideration of several engineering and technical aspects, e.g.:

- Modifications to the existing steam generator are necessary, e.g. to furnace walls, convective pass, and external heat exchangers, to achieve the highest possible boiler efficiency at nominal load and part load. This is because of metal has a high density compared to coal, which influences the hydrodynamics of the fluidized bed and thus the heat transfer to the heating surfaces of the steam generator. In addition, the high thermal conductivity of metals leads to increased heat transfer to the heating surfaces of the steam generator. The erosion rate on furnace walls and heat exchangers is also increasing, which must be particularly emphasized from a technical point of view.
- Selection of a suitable technical solution for the supply and extraction of metal particles to/from the fluidized bed boiler and for the separation of metal dust from the flue gas. This is due to the fact that the lower calorific value of the metal (~ 7.4 MJ/kg) leads to an increase in the mass flow of fuel that must be handled by the fuel supply system and the extraction of the oxidized metal.
- Characterization of a commercially available iron powder best suited for combustion in a fluidized bed boiler with a possibly high number of combustion/reduction cycles.
- Storing large quantities of high-energy-density metal powders for use in fluidized bed boilers is also a technical challenge, as the metal should be stored in safe containers (inert with nitrogen).

Medium-scale fluidized bed combustion test rig

Medium-scale oxidation with heat extraction is investigated by **CSIC** in a fluidized bed test rig (inner diameter of 95 mm, 1.1 m height with 0.4 m bed height), see **Figure 4-(left)**. Electrically preheated air is used for combustion/fluidization and iron powder is fed by one screw feeder. Solid extraction is realized by overflow to keep the bed height, and a continuous gas analyser is used to measure the outlet oxygen concentration. Bed temperature is controlled by modifying the length of the heat exchanger introduced inside the bed. Entrained solids are recovered by a cyclone followed by a filter.

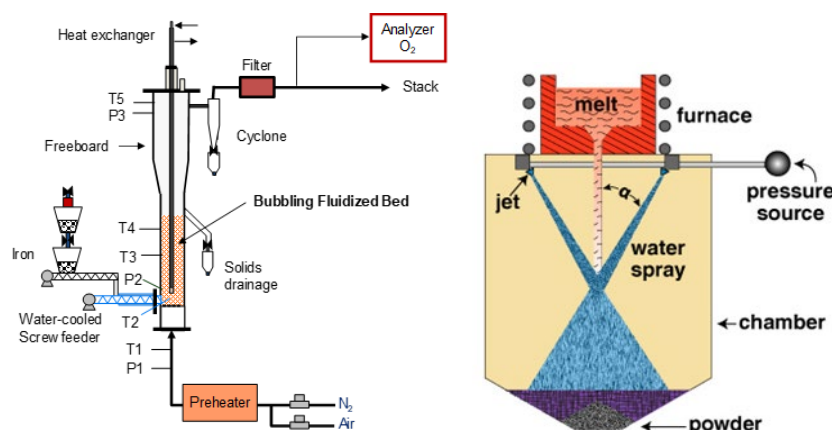


Figure 4: Experimental setup of the medium-scale fluidized bed (left) and Schematic of the water atomization process (right)

Small-scale fluidized bed combustion test rig

The small-scale fluidized bed test rig for metal oxidation, erected at **TUDA**, is equipped with a complete control system for the air supply, the feeding system, and the electrical heating system. The test rig consists of a tube (inner diameter of 54.5 mm and 550 mm in height) as well as a porous plate for gas

distribution at the bottom. Temperature and pressure are measured at heights of 90, 350, and 550 mm. The reactor is heated from the outside by two electric heating elements. The fuel is continuously fed from a hopper into the reactor at 90 mm height by a screw conveyor. Air is preheated to 300 °C and fed into the reactor through the porous plate. A small amount of the flue gas drawn off at the top of the reactor is used for continuous measurement of the volume fraction of the main components in a gas analysis unit. The remainder of the flue gas is blown outside with a jet pump to maintain the negative pressure in the reactor.

Large-scale pilot reduction tests

The hydrogen-based direct reduction of recycled metal oxides is to be investigated at **TUDA** under industrially relevant conditions. The hydrogen-based direct reduction pilot plant consists of a preheat reactor (CFB600) and a reduction reactor (CFB400), see **Figure 5**. The CFB600 reactor (preheater) has an inner diameter of 0.59 m and a height of 11.35 m, while the reduction reactor has an inner diameter of 0.4 m and a height of 8.66 m. Both the reactors and the coupling element are lined with refractory concrete, which is state-of-the-art for large-scale fluidized bed plants. The metal oxides are fed to the CFB600 reactor, where they are heated to the required temperature by a propane burner. The supplied air to the CFB600 reactor for the propane combustion can be heated up to 400 °C by electric heaters. At the exit of the CFB600 reactor, the flue gas and the solids mixture are directed into a cyclone, from which the flue gas exits from the top. The hot flue gas is cooled by water-cooled heat exchangers before it is discharged into the atmosphere. The hot metal oxides separated from the cyclone are then fed into the CFB400 reactor. Preheated hydrogen at a temperature of up to 600 °C is supplied as fluidization and reduction medium at the bottom of the CFB400 reactor. The hydrogen can be delivered to the pilot plant in pressurized containers. In addition, there are contracts with suppliers for technical gases, for C₃H₈, N₂, CO₂ and O₂ tanks, which are located inside the pilot plant. The label of the hydrogen (green, blue, etc.) does not influence the process since the experimental investigation can be performed regardless of the availability of labelled hydrogen. At the exit of the CFB400, the water vapour, hydrogen and metal are passed into the cyclone. In the cyclone, the reduced metal is separated from the gas mixture. The metal powders are removed from the pilot plant utilizing water-cooled conveying screws and are collected at ambient temperature in sealed containers, which are flushed with nitrogen. Afterwards, the high-energy density metal powders are transferred to closed metal containers and metal barrels for storage and later for combustion. The water vapour and remaining hydrogen are then directed into a condensation system, the water is separated, and the hydrogen is returned to the CFB400 reactor. The 1 MW_{th} pilot plant is equipped with temperature, pressure and gas composition measurement ports in all inlet and outlet streams, for process control and analysis. Also, pressure and temperature measurement points are installed along the height of the reactors to provide better insight into the condition of the reactors during operation. The mass flow rate of all streams that enter the reactors and the coupling element is either measured with orifice plates, and rotameters or controlled by a mass flow controller. Furthermore, all streams leaving the reactors are recorded (mass flow, temperature, and pressure), with side streams for offline analysis of gas composition.

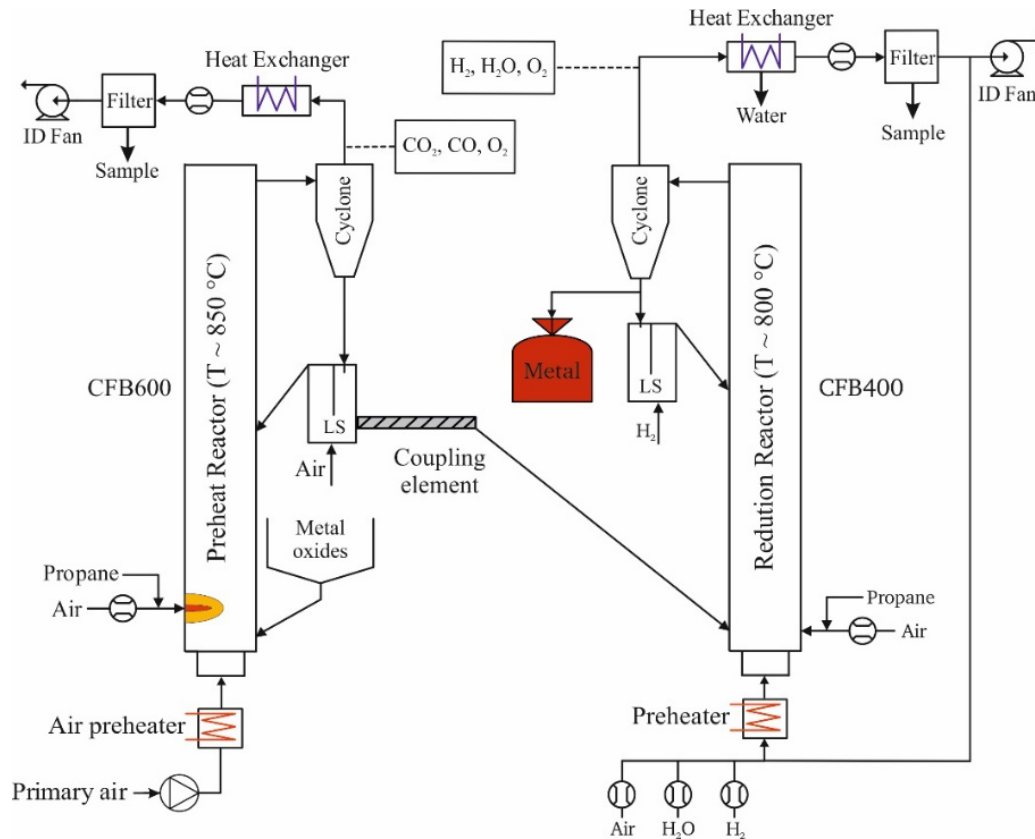


Figure 5: Experimental setup of the 1 MW_{th} hydrogen-based direct reduction of metal oxides

Production of metal powder for fluidized bed combustion tests

The metal powders used for the first cycle in this project are produced by an atomization process (at **POMETON**), which is the most commercially used method to produce large tonnages of metal powders with fine particle size distributions. The main material input of the production chain is metal scrap. The powder production process includes the following steps: the metal scrap is melted in an Electric Arc Furnace. The molten metal is atomized by water jets in an atomization chamber (see **Figure 4-(right)**). During the atomization process, the size of the iron particles is controlled by the pressure, the number of atomizers, and the temperature of the melted metal. The parameters (temperature, gas composition, etc.) for the subsequent drying process are selected to create the correct morphology and porosity of the particles. For the fluidized bed combustion tests, iron powders with a fairly irregular shape, a high specific surface area, a certain granulometry, and porosity is carefully selected to meet the requirements of high performance for oxidation reactions, which are favourable kinetics, good fluidization properties (low tendency to agglomerate), resistance to attrition, limited cost, and environmentally friendly behaviour.

Analysis of metal and metal oxide

The technical properties (reactivity, flowability, etc.) of the powder (metal and metal oxide) significantly depend on its physicochemical properties, such as particle size, specific surface area, particle shape, and condition of the particle surface (e.g., oxidation level, purity, and morphology). The properties of the metal fuel and the samples from cyclic fluidized bed tests are determined as follows:

- Particle size distribution by dynamic light scattering (DLS): The DLS is an established and accurate measurement technique for characterizing particle sizes in suspensions and emulsions, allowing the analysis of particles in a size range from 0.3 nm to 10000 nm. It is built on the Brownian motion of particles, which states that smaller particles move faster, while larger particles move slower in a liquid. Information about the diffusion speed and thus about the size distribution is contained in the light scattered by the particles.

- Specific surface area: One of the traditional methods for measuring the specific surface area of a material is the Blaine permeability. The Blaine air permeability apparatus is used to measure the specific surface area of fine materials in square centimetres per gram of test sample. This apparatus is used to draw a volume of air through a bed of specified porosity.
- The velocity of the airflow is determined by the pore volume in the bed, which depends on the size of the particles.
- Morphology and shape by Scanning Electron Microscopy (SEM): The SEM scans a material with a focused electron beam to create images. If electrons collide with atoms in a sample, they produce signals that identify the surface morphology and properties of the material.
- Measurement of oxidation/reduction level and purity by Inert Gas Fusion Infrared (IGFI), Thermal Conductivity Detection (TCD) and X-ray diffraction analysis, respectively.
- Rheology and flow properties of powders by a Powder Rheometer (a device that measures the flow resistance of the powder while the powder is in motion).

Reduction tests with combusted metal fuel

The reduction process has a very important role in the properties of the metal fuel. The combustion process affects the properties and states of the powder particles, which then must be reduced. After obtaining information about the properties of the combusted metal powder (particle size, degradation, attrition, oxidation, shape, etc.) from the fluidized bed tests, the captured metal oxides are stored in a special container for the following reduction process. Various reduction tests are performed at different scales (laboratory reduction system up to 1 MW of thermal power). The ability of the powders combusted in the first cycle to be reduced is investigated. The reduction of the metal oxides (not the mineral ores) aims to obtain metal fuels of the proper size to retain the combustion properties. While the number of cycles to be performed at the 1 MW scale are 5, a higher number of cycles can be considered with laboratory scale experiments.

Erosion test rig

The erosion test rig is a bench-scale gas-blast testing unit, which has been successfully used for alloys, coatings, and refractory materials. The test rig allows the use of different erodants (sand, ash, metal powders), particle velocities (4-60 m/s), impact angles (20-90°), temperatures (up to 600 °C) and material samples (representing boiler tube materials). Test conditions can therefore be closely adjusted according to the operation conditions typically prevailing in fluidized bed boilers. The eroded material samples are further analysed utilising visual inspection, weight, and material thickness measurements, Confocal Microscope (COM) and Scanning Electron Microscope (SEM).

Steady-state 1.5-D fluidized bed model

The 1.5-D steady-state model that considers a core-annulus flow structure, developed in previous projects for Chemical Looping Combustion by CSIC, can be adapted to the combustion of metal fuels in circulating fluidized boilers, considering both the riser and the auxiliary bed. Correlations obtained in industrial boilers are used to predict the solid and gas flows inside the riser. This type of model, once validated, predicts the solid oxidation conversion together with the oxygen concentration and the heat generation profiles in the boiler as a function of the operating variables. Accurate predictions can be obtained with low computing effort allowing the simulation and optimization of the metal combustion.

Dynamic 1.5-D fluidized bed model

The Advanced PROcess Simulation software APROS developed by Fortum, and the Technical Research Centre of Finland (VTT) is used for dynamic process simulations of small, medium, and large-scale pilots as well as the commercial CFB boiler. The program contains specialized component libraries for the process, automation, and electrical systems for the dynamic modelling of thermal power plants, energy, and industrial processes. The modelling is performed by selecting the required process components (e.g., circulating fluidized bed, pump, and fan) and connecting them via flows of material, energy, or heat properties to build a model of an existing process and/or a new system for research. All

necessary design data (e.g., the characteristic curve of the pump or fan as well as the geometry of the circulating fluidized bed) can be inserted in the process components that are linked by electrical and automation signals for controlling purposes. The CFB riser is represented by a 1.5-D dynamic process core-annulus model that differentiates between the dense wall region and the more dilute centre region.

Dynamic optimization model

A MILP model (Mixed Integer Linear Programming to dynamic optimization of profitability from the operation of large-scale installation) is used to find the optimal schedule for a generation fleet, which contains a fluidized bed boiler combusting metal fuel, by determination of production output in each time to obtain the highest possible sales margin. A key deliverable of the proposed solution is dedicated to large-scale installations – CFB boilers – installed in CHP plants, where the flexibility of runs and fuel usage play a very important role. The results of dynamic process modelling are inputs for the evaluation of the Unit Commitment problem using the MILP approach.

CFD model

The Dense Discrete Particle Model-Discrete Element Method (DDPM-DEM) is used for CFD simulations of the CFB riser. The DDPM-DEM model, implemented in ANSYS-FLUENT, tracks individual particles and their properties such as their chemical composition, density, diameter, shape, etc. which might change due to chemical reactions during the transient simulation. To reduce computational costs, the coarse-grained parcel model is used, which allows the DDPM-DEM model to simulate particle systems at a semi-industrial scale in a reasonable time frame comparable to the two-fluid model. In-house codes of the project partners (for the metal fuel reactions) are used and upgraded to be applicable for CFB conditions. Furthermore, an advanced drag scheme EMMS is applied to consider the effect of varying flow characteristics on flow heterogeneity in the riser.

Process modelling and economic assessment

The use of metal particles (instead of coal or biomass) as fuel eventually affects the heat transfer rate in the fluidized bed boiler leading, in turn, to a variation in flow rate, temperature and pressure of the generated steam. **POLIMI** develops a tool for modelling the steam cycle of the full-scale fluidized bed boiler based on the extensive experience gained in the field of power plant simulation and optimization. The goal is achieved by creating a mathematical model of the steam cycle (based on the constitutive equations of each unit, i.e., steam turbine, feedwater pumps, feedwater preheaters, condenser, and the key auxiliaries). Depending on the peculiarities of the power plant taken as reference, the model is implemented either in commercially available software specific for power plants (Thermoflex) or in a general-purpose language (Python). The model is validated using literature data and, possibly, the operational data of the reference plant under different operating conditions (loads and cooling water temperatures). **SFW** supports this task based on its extensive experience in large-scale (40-600 MW) power plants based on fluidized bed boilers. With these models, **SFW** and **POLIMI** calculate the heat and mass balances for the water-steam cycle and determine the net electrical efficiency of the power plant for various load scenarios and cooling water temperatures. Moreover, **SFW**, **POLIMI** and **POMETON** assesses the capital and operating costs of each component of the overall energy system (power plant, reduction process, powder transport chain, etc.) using both industrial and literature cost-related data. The result is a preliminary (+/- 40%) economic analysis.

Design and operational optimization of the integrated energy system

POLIMI adapts and use the recently developed methodology for the combined design and operational optimization of integrated energy systems (power plants integrated with storage, microgrids, multi-energy systems, etc.), operating on different types of electricity markets. The optimization problem is formulated as a single large-scale Mixed Integer Linear Program (MILP) and solved with state-of-the-art optimization algorithms [43, 44]. The tool can optimize the key design decisions of the plant (e.g., size of the reduction plant, sizes of the PV and wind plants, size of the electrolyser, size of the powder storage, etc.) while considering all the operational constraints, (start-up time, ramping limits, etc.), capital (with economies of scales) and operating costs, and the revenues gained from the electricity

markets in a typical operating year. The methodology is extended by including the performance (at full-load, off-design, and part-load), and costs of the plants (steam cycle, CFB, powder transport and storage, etc.) and processes (reduction plant) determined in the project. Once the optimal system design and sizing have been determined, the optimal operation of the integrated system is determined by **POLIMI** and **FORTUM** using the advanced optimization methodologies developed by the two partners [45, 46]. Such rigorous optimization tools are based on MILP models and include an accurate representation of the operational constraints, unit commitment, and dynamics of the power plant components and storages (off-design and part-load performance maps, ramp-up rates, start-up time and cost, etc.), as well as the rules and revenues of the electricity markets. The approaches can be applied also to combined heat and power plants and this is an important feature since several of today's steam cycle power plants are serving district heating networks or providing steam to industries. Also, the volatility of the ancillary markets can be included in the models using a stochastic programming approach, as reported in the recent work of **POLIMI** [45, 46].

Environmental, techno-, and socio-economic assessment

The environmental sustainability assessment of the system focuses on the environmental performance from a life cycle perspective, i.e., considering the upstream impacts of resources used (e.g., energy, water, reactants) and the infrastructure as well as downstream impacts (e.g., the treatment of waste in another facility). This holistic approach towards environmental issues is expected to effectively prevent substantial environmental impacts during and after the implementation of the technology. The application of the Life Cycle Assessment (LCA) methodology is carried out based on a Multi-Regional and Multi-Sectorial Dynamic Input-Output framework. This framework is the state of the art in LCA analysis, and it enables quantitative assessment of the changes induced by the project in future years to a set of environmental and socio-economic parameters from an economy-wide perspective. Specifically, GHGs, local pollutants emissions and particulates are considered proxies for environmental impacts, while gross domestic product, products imports and exports, and employment are assumed as the main socio-economic impact indicators. The defined model enables, quantifying the economy-wide impact of the project with a sectoral disaggregation (e.g., power sector, construction, services, etc.), including direct, indirect, and induced effects on upstream supply chains. The model is defined based on the MARIO python package (<https://mario-suite.readthedocs.io/>): it relies on a detailed inventory of the system, consisting of raw technical project data collected in previous work packages, and on freely available national economic and social accountings provided by Eurostat. Experimental data is included whenever possible and otherwise reliable secondary sources or estimations are used. The analysis addresses the whole life cycle, including the manufacturing, operation, and end-of-life of the technology.

An economic analysis of the integrated system (PV, wind, electrolyser, reduction process and retrofitted fluidized bed furnace dedicated to metal fuel oxidation (including steam cycle)) to evaluate the CAPEX and OPEX are performed. The social impact study is based on the methodology from the Handbook for Product Social Impact Assessment (PSIA), which describes a conservation-based methodology for assessing the positive and negative social impacts of products and services on four stakeholder groups: Workers, local communities, small businesses, and users. The social impact study considers two scenarios: reduction and oxidation facilities at the same site or reduction and oxidation facilities at different sites.

2. Added Value and Impact

2.1 Project's pathways towards impact

The main outcomes of the project are listed below:

- The pilot tests are performed under industrially relevant conditions (**TRL 6**). These results are very important since they give confidence in the technical feasibility of the proposed retrofit concepts, spurring other industry-funded R&D projects and attracting private investors. Indeed, after the successful demonstration of the project, the technology provider (**SFW**) and the fluidized bed operators (represented by **VGBE** and **Fortum**) are willing to build a demonstration power plant based on the concept developed in this project, which is the last step before commercialization (retrofitting their power plants with metal as fuel).
- The validated models and simulation tools are suitable for guiding engineers in future retrofit studies (concerning the boiler design, control strategies definition, etc.).
- The advanced design and operational optimization tools: the involved companies (steel production companies, power plant operators, utility companies, etc.) have the opportunity to see the economic and efficiency improvements achievable by applying the tools developed by **POLIMI** for the design and operational optimization of integrated energy systems. Moreover, the industries learn about the added value (in terms of cost and energy savings) achievable with system integration and optimization.
- The results of the environmental as well as techno- and socio-economic assessment. These analyses help utilities to consider technical/non-technical barriers and to evaluate the economic feasibility of the proposed retrofit concepts.
- This technology is transferred from the laboratory to the market by:
 - Reach out to the scientific community: The research results on metal combustion and the validated numerical models (reliable tools for fluidized bed scale-up) can be used by other universities, organizations, and fluidized bed operators.
 - Knowledge transfer from academia to industry about advanced simulation, design, and operational optimization tools: This is an important outcome of the study, which has also pushed the industrial partners to participate in this proposal. An important part of the knowledge transfer is also the fact that many PhD students (for **TUDA**, **POLIMI**, **LUT**, and **Chalmers**) work on the project (acquiring advanced knowledge about the experiments and tools conducted in the project) and, in the end, will leave university to be hired by industry.

The target groups that benefit from the results of the project are the fluidized bed power plant operators (e.g., RWE and Fortum), original equipment manufacturers of steam cycles, steel production companies (e.g., Saar Stahl and Danieli), engineering companies, in particular companies specialized in combustion such as Valmet Oyj and Sumitomo SHI FW as well as companies specialized in iron ore reduction (based on hydrogen) such as ThyssenKrupp AG and Metso Outotec.

Wider impact

1) Spurring other industrial R&D activities and attracting private funds: The TRL achieved (**TRL 6**) and the validated models and tools developed in the project are very important since they give confidence in the technical feasibility of the proposed retrofit concepts, spurring other industry-funded R&D projects and attracting private investors. As written before, after the successful demonstration of the project, the technology provider (**SFW**) and the fluidized bed operators (represented by **VGBE** and **Fortum**) are willing to build a demonstration power plant based on the concept developed in this project, which is the last step before commercialization (retrofitting their power plants with metal as fuel).

2) Considerable reduction of the cost of “CO₂-free” dispatchable heat and power generation: The project provides technical concepts for retrofitting existing coal-fired CFB boilers concerning the utilization of metal as fuel. These concepts enable operators of these CFB boilers to use their existing assets beyond

the phase-out of coal, which is a political goal in many European countries. The use of iron as fuel is an economic solution due to its low price, availability, and potential reusability. Using this CO₂-free fuel supports the goal of many utilities to reduce their carbon footprint. Furthermore, the flexible operation of these boilers can be used by power utilities to stabilize the electrical grid. The participation of **VGBE** (a technical association of energy plants and operators), **Fortum** as operator of coal-fired CFB power plants, **SFW** as a market-leading engineering company in CFB technology, **TUDA** as an expert in the redox cycle for chemical looping combustion (easy entry into the reduction of iron ores with hydrogen), and **POMETON** as a potential supplier of metal iron particles covers the main part of the value chain related to the implementation of the proposed retrofit concepts, which is a solid basis for a smooth transfer of project results to commercial application. The preliminary cost estimate for different cases of a 10 MW_{th} baseload facility (in the Netherlands) for the different types of energy carriers (metal powders, hydrogen, ammonia) is shown in **Figure 6**. The result of the study shows that the heat produced from iron powder in the Netherlands is less expensive than the cost of hydrogen stored in a tank. However, hydrogen supplied from salt caverns is slightly less costly than iron powders. In this regard, it is important to notice that salt caverns suitable for H₂ storage are not always available and only a few EU countries have them (there are suitable salt caverns in Germany, while there are no such caverns in Italy, for example). If the metal powder is ‘charged’ with renewable energy in Spain or Qatar and this energy is ‘discharged’ in the Netherlands, the yearly costs for metal powder drop below the price of hydrogen storage in caverns.

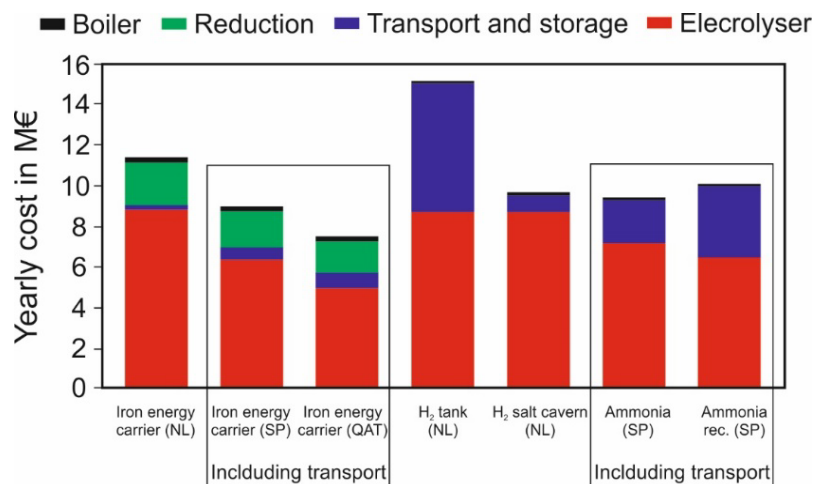


Figure 6: Yearly cost in M€ for different energy carriers (with and without transport from Spain and Qatar)

Also, it is shown that the production of iron powder, for heat production, can be cheaper than using ammonia since the expected transportation costs for iron fuel are lower than for ammonia. Even without the additional costs for reconversion to hydrogen in the Netherlands, iron fuel is still less expensive than transporting ammonia (by rail). Most of the yearly costs for all energy carriers can be directly related to the production costs of hydrogen (electrolysis) and this depends highly on the local electricity prices. The cost for the boiler is low since existing infrastructure can be used, which highlights that a rather high impact can be achieved at low costs when using existing fluidized bed boilers for metal oxidation. Overall, metal energy carriers can be seen as competitive renewable energy carriers for storage and conversion. Based on the above cost estimates, a price for heat between 75 and 135 €/MWh_{th} can be expected from the present concept. Although this is highly dependent on the local electricity prices of renewables, these costs appear to be competitive for industrial heating or district heating in most European countries [55, 56], especially if compared to the cost of other renewable and dispatchable heat sources (e.g., producing and then burning green H₂ in a boiler or using PV panels with battery and high-temperature heat pumps).

3) Incentive the iron and steel industry: As a circular process, an up-and-running iron fuel energy system does not require the input of “new” iron powder apart from “top-ups” to compensate for losses incurred

during the cycle. That said, building up the stocks required to allow for the continuous operation of a circular system (plus margin) is considerable. Given current assumptions as to the pace at which the circular process of combustion and reduction would operate, the continuous operation of a 1 GW installation would require 100,000 tons of iron powder. The total world production of iron powder in 2017 was 1.4 million tons spread across manufacturers and suppliers. The current production of iron powder is thus only sufficient to supply roughly 33% of the stock needed for one power plant with a capacity of 1 GW_{th} to operate continuously. Once the iron fuel concept has been demonstrated successfully in the market and starts gaining traction, the current iron powder production market thus is not capable of immediately satisfying the projected demand. The availability of iron powder thus quickly become the rate-limiting step for the uptake of the technology. Current iron powder production only accounts for ca. 0.09% of the total world production of iron (ore). In 2018, the metal content of the total iron ore produced worldwide was some 1.5 billion metric tons. Exponential growth in iron powder production would be required to enable iron fuels to substitute fossil fuels before 2050. This would in turn require a large share of total global iron ore production. Furthermore, considering that the iron production process is part of the iron fuel production cycle, the growing demand can also be an incentive for the iron industry to invest in more sustainable production processes, reducing the overall carbon footprint.

4) Perspective of wider and general use in the European Union: The results of this project are not only applicable to one specific fluidized bed unit but can be transferred to other existing fluidized bed boilers owned by other utilities. The results may also be used to design new metal-fired fluidized bed boilers. This is significant because most existing fluidized bed power plants are expected to reach the end of their service life if European policy targets are met as planned. The results also improve the understanding of the behaviour of metal as fuels in other applications, such as pulverized fuel boilers or in the transport sector (e.g., ships). The modelling tools developed in this project may also be transferred to other fluidized bed applications and pulverized fuel boilers.

5) Climate change or environment-related challenges and other important benefits for society: Using metal as CO₂-free fuel eliminates the direct CO₂ emissions of existing fluidized bed power plants. Indirect emissions are low if the metal is reduced using renewable energy (hydrogen, heat) and if the transport is realized by renewable fuels. The provision of highly flexible power to the electrical grid also supports the feed-in of fluctuating power from renewable sources, such as solar and wind. The use of metal as fuel also avoids other pollutant emissions (such as Hg, NO_x, SO₂, and HCl) since the fuel does not contain these elements. The formation of thermal NO_x is expected to be negligible due to the homogeneously low temperatures (<1000 °C) in the fluidized bed. The further use of the existing fluidized bed power plant beyond the phase-out of coal supports the related coal regions in transition by preserving jobs and creating new value chains.

The proposed technology of using metal as fuel reduces CO₂ emissions and provide benefits to existing fluidized bed operators. In addition, the hydrogen-based process used in the proposed technology for the direct reduction of metal oxides produces highly direct-reduced iron or hot briquetted iron that can be fed into an electric arc furnace, creating synergies with the steel industry. In recent decades, the development of circulating fluidized bed boilers has grown into ever larger thermal power plants [57]. The simple size scaling (cross-sectional area and height) is not easy, as there is a limit to the cross-sectional area of the combustion chamber to avoid inhomogeneous temperature distribution in the bed. Also, the height of the combustion chamber cannot be increased arbitrarily (maximum 50 m), as otherwise less material would recirculate, and the heat released during combustion could not be easily transferred to the water/steam side [29]. Furthermore, cyclones become inefficient when they are scaled up due to the lower flow velocities. Instead of increasing the size, it is possible to arrange the combustor and cyclone modules next to each other. Based on this, CFB boilers (using coal) with an electrical output of 350 MW_{el} have been developed and widely commercialized, especially in China. One of the largest circulating fluidized beds in the world with an electrical output of 460 MW is in Europe in the Łagisza power plant in Będzin, Poland. The Samcheok Green Power Project in South Korea has an electrical

output of 550 MW with an ultra-supercritical once-through boiler (steam temperature and pressure of 603 °C and 257 bar, respectively). Today's largest fluidized bed power plants can achieve gross electrical outputs of more than 550 MW_{el}. For example, Shenhua Group successfully developed and demonstrated the first 600 MW_{el} CFB boiler in Sichuan Province, China. The latest plans are ongoing for 2 x 660 MW_{el} at Shaanxi Binchnag by Tianjin Power Construction Co. Ltd. In China.

The global CFB market size was estimated at USD 985 million in 2024 and is forecast to reach a size of USD 1162 million by 2032. Europe is the main market and accounts for around 30% of the global market [58]. Key players in the global CFB market include GE-Alstom, **Sumitomo SHI FW** (the project partner), Babcock & Wilcox, etc. The three largest suppliers have a share of around 35% of the global market. The proposed technology has a very good chance of being implemented in the medium to long term, particularly in countries such as Poland and Germany. In 2020, the German government passed a law that provides for the phase-out of coal-fired power generation by 2038 at the latest and, if possible, by 2035. While the phase-out is underway, the German government is pushing ahead with the expansion of renewable energies. The share of renewable energies (e.g. wind and solar energy) in the public electricity supply in Germany has, therefore, reached a record level of over 50% in 2023. Globally, wind and solar energy cover 12% of electricity demand, and their share is expected to increase further in the future, while their costs continue to fall. However, if electricity grids are to accommodate a greater share of variable-feed renewables, they need the flexibility of supporting infrastructure such as energy storage systems [38], and the proposed technology to retrofit coal-fired fluidized bed plants with metal as fuel is of great importance.

2.2 Dissemination, exploitation and communication

Various actions are foreseen to achieve the best possible visibility of the project among a wide audience by disseminating the scientific results, and their social and technological impact, as well as by exploiting the actual use of the results by the power plant operators and engineering companies. The plan to maximize the impact of the project includes three actions: dissemination, exploitation, and communication. Dissemination aims to make the knowledge obtained available to the scientific community. It is mainly associated with the project results (e.g., scientific publications, launching and updating the project website) and takes place throughout the life of the project. The exploitation is related to the actual use of the results (intellectual property rights, standards, policy recommendations, etc.) by the fluidized bed operators, combustion, and reduction engineering companies. The result exploitation takes place during the entire duration of the project. The communication activities are directed at the public and aim to promote the project and inform people about the benefits of science. In addition, they should be made aware of the concept developed in this project and the contribution of EU funding to addressing societal challenges. This includes, for example, an active presence on social media and social networks (e.g., Facebook, Twitter), events, press releases, dedicated forums, and advertising. The communication takes place throughout the life of the project. Standardization is not addressed in this project since the metal combustion technology in fluidized beds is in a rather early stage of development.

TUDA creates a project logo to make the vision and concept of the project recognizable. **TUDA** also creates a fully interactive project website during the first three months of the project. The website is updated regularly during the project and even beyond for at least one year after the project is completed. A public workshop is organized to present the results of the project including a visit to the pilot test site. The target audience of the workshop includes researchers, industry representatives, technology developers, potential investors, regulators, and policymakers. **All partners** present project results at international conferences and publish them in peer-reviewed journals with open access. At least five conference publications and five journal publications are produced. The results of the large-scale demonstration (at 1 MW thermal output) are disseminated to the scientific community and benefit utilities in broader terms. In most cases, this includes activities such as submitting manuscripts for publication in scientific journals (and possibly providing open access), presenting research results at

scientific conferences, posting research data on a publicly available website, making data available to scientists upon request, and participating in media interviews that meet dissemination expectations and requests. In addition, a public workshop is held to show how the project's findings are relevant to our daily lives.

Effective exploitation of project outcomes facilitates the commercialization of the novel process concept and allow the implementation of marketable solutions. Exploitable paths and strategies differ among project partners given the various nature and organizational status. Exploitable results include for instance increasing technical, economical, and societal know-how, methods and components covered by intellectual property rights (IPR) and dedicated computational tools and models to be applied for the current purpose and/or similar applications in the future. To align all exploitation activities among the project consortium, an exploitation plan is established, in which all results developed within the framework of the project are examined to consider them as highly protected (patents, trademarks) or less protected items (e.g. know-how, designs, internal reports, drawings, etc.). Based on the draft exploitation that is released in the early stage of the project, a revised version is released at the end of the project. The exploitation plan identifies who can and should use the results and under what conditions they can be used. The scope of the plan to maximize the impact of the project differs in its functions and target audiences. During the project, the dissemination, exploitation, and communication activities aim to expand the impact of the project by providing information about the project, its results (scientific publications, experimental data, modelling approaches), and its potential involvement of operators, engineering companies, and the public.

3. Project Implementation

3.1 Work plan

The project is structured into 5 work packages (WP) as illustrated in **Figure 7**. In WP1, a concept for retrofitting an existing fluidized bed boiler for the combustion of metals is developed. The reduction/oxidation of metal oxides/metals in fluidized beds is tested at various scales in WP2. In WP3, models of the fluidized are validated with experimental data from WP2. WP4 uses these models for detailed simulations of a commercial boiler to evaluate the developed concept regarding efficiency, economics, environment, and society. WP5 includes project management, dissemination, and exploitation of results.

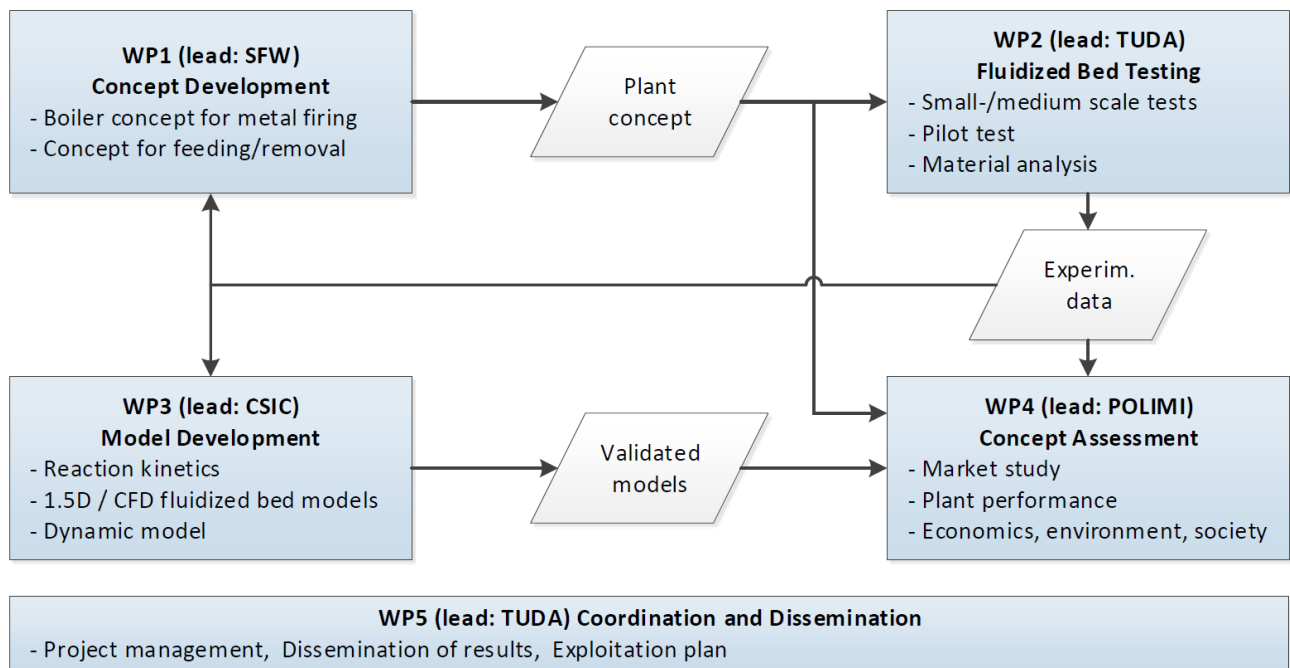


Figure 7: Overview of the work program

3.1 Work Package Objectives

WP1: Retrofit Concept Development

- Identify modifications of the existing steam generator of a fluidized bed boiler (including furnace walls, convective pass, and external heat exchangers) to obtain the highest possible boiler efficiency
- Select appropriate technical solutions for feeding and extraction of metal particles to/from the fluidized bed boiler
- Select appropriate technical solutions for the separation of metal dust from the off-gas
- Identify and characterize iron powders for combustion in fluidized

WP2: Fluidized Bed Tests

- Demonstrate the technical feasibility of metal fuel combustion and reduction in a fluidized bed by tests at lab and pilot scale
- Determine the operating window of the fluidized bed reactor for metal combustion
- Evaluate the characteristics of the oxidized metal
- Determine the cyclic performance of the metal fuel
- Provide data for model validation

WP3: Model Development

- Determine the reaction kinetics of the selected metal fuels
- Develop reliable tools for scale-up of the fluidized bed through extensive validation
- Develop a reliable tool for determining the dynamic performance of the fluidized bed
- Develop a reliable tool for understanding the hydrodynamic behaviour of gas-solid interaction in fluidized beds for metal fuel and metal oxide

WP4: Techno-Economic Assessment

- Determine the market potential of the technology
- Determine the net electrical efficiency of the power plant at various loads
- Evaluate the flexibility of the power plant to feed electricity and heat to the grid by means of dynamic simulations
- Evaluate the economic feasibility of the proposed concept by determining investment and operational costs as well as the cost of electricity
- Determine the impact on the environment (e.g., resource requirements, emissions) and on the society, such as maintaining or creating jobs

WP5: Coordination and Dissemination

- Constitute an interface to the European Commission (EC), providing technical and administrative progress reports to the EC according to the specified requirements
- Control, manage and monitor the administrative, financial, and legal tasks of the project
- Achieve the best possible project recognition over a broad audience by disseminating the scientific results, the targets, and their social and technological impact
- Exploit the project results and maximize the innovation

3.3 Milestones

No	Milestone Name	Due Date (month)	Means of Verification
1	Data of reference plant available	3	Documents with all necessary data of the reference plant
2	Concept for fluidized bed boiler retrofit available	12	Documents with all necessary modifications for retrofitting existing fluidized bed furnaces using metal as fuel
3	Tests in small and medium-scale fluidized bed completed	22	Documents with all the results obtained during the small and medium-scale tests
4	Large-scale pilot test campaign (combustion) completed	33	Documents with all the results obtained during the large-scale tests
5	Large-scale pilot test campaign (reduction) completed	33	Documents with all the results obtained during the large-scale tests
6	Reaction kinetics ready for implementation into models	9	Documents including kinetic parameters (activation energies, frequency factors)
7	Validated models available for concept assessment	27	Documents with results from steady-state, dynamic process and CFD simulation models
8	Heat and mass balances of retrofitted power plant available	36	Documents including market study, heat, and mass balances of the retrofitted power plant
9	Assessment of impact on economics, environment, and society completed	42	Documents containing economic, environmental, and social assessments and market uptake strategies

3.4 Consortium

The work is carried out by experienced partners with complementary expertise and synergies in combustion (**SFW, FORTUM, VGB, TUDA, Chalmers, CSIC**) and reduction processes (**POMETON, TUDA**), steady-state modelling (**CSIC, POLIMI**), dynamic simulation (**LUT, TUDA**), and CFD simulation (**Chalmers, TUDA**), and techno-economic-social assessment of new technologies (**POLIMI, SFW, FORTUM, VGB, POMETON**), so that the planned tasks are expected to be completed within the project duration.

1) **Technical University of Darmstadt (TUDA)**

The Institute of Energy Systems and Technology (www.est.tu-darmstadt.de; head: Prof. Dr-Ing. Bernd Epple) at TUDA has extensive experience in the field of power plant technology, particularly in solid fuel combustion processes and related CO₂ capture technologies, with key expertise in modelling and simulation of multiphase flows and power plant processes, as well as experimental investigations in pilot-scale test facilities. TUDA has erected and operated a 1 MW_{th} pilot plant for investigations of CO₂ capture (e.g., chemical looping combustion, carbonate looping) and gasification processes (e.g., chemical looping gasification) in a dual fluidized bed system. One fluidized bed reactor can also be used for pilot testing of High-Temperature Winkler (HTW) gasification. The other reactor can be applied to fluidized bed combustion of solid fuels, such as lignite, straw, and SRF. This 1 MW_{th} fluidized bed reactor system is used for pilot testing of metal combustion in this project. The team consists of more than 20 researchers and technicians who can operate the pilot plant in 3-shift mode. TUDA has developed a capacitance probe for measuring the flow field in fluidized beds. TUDA has also erected a lab-scale electrically heated fluidized bed reactor that allows performance parameter studies regarding the conversion of solid fuels under well-controlled conditions. Previously, this test rig has been applied to investigate the gasification of coal/waste and the carbonation of lime. The rig is used in this project for the small-scale fluidized bed test of metal oxidation. TUDA has more than 10 years of professional experience in the field of CFD and dynamic process simulation, which is used for developing CFD and dynamic 1.5-D models for fluidized bed reactors in this project.

TUDA has been the coordinator of various national and international collaborative research projects, such as RFCS projects (CARINA, LIG2LIQ, REBECCA), an FP7 project (SCARLET), a H2020 project (CLARA), and various German projects (LISA, MONIKA, KORINNA, FABIENE, VERENA).

2) **Pometon S.p.a. (POMETON)**

a) For almost 80 years, Pometon (<https://www.pometon.com/en/>) has been the Powder metallurgy industry standard for innovation and quality for both ferrous and non-ferrous metallic powders. Pometon melts, atomises and anneals metallic powders and alloys to develop unique be-spoke powders. Powder production capacity is 80000 thousand tonnes per year, including 60000 thousand tonnes of iron powders. In total Pometon has 600 types of coded metal powders. Pometon uses electric arc furnaces with scrap as raw material. This is one of the most sustainable ways (as far as possible) of producing iron on an industrial scale that is currently available.

b) Equipped with the latest technology, the Pometon R&D Department is the heart of Pometon product development and is undertaken by our team of experienced Research Engineers who work in close collaboration with R&D departments of our customers, research partners from universities and research centres over the world. We encourage our customers and partners to collaborate with us at our research facilities and we provide customers technical assistance with the application of metal powders, creating a unique solution for everyone. The R&D department creates each powder as a specific technical solution with specialised characteristics depending on the application.

c) For more than two years Pometon has been actively cooperating with industrial companies, universities and research centres on the use of iron as an energy carrier. Now, Pometon is continuing

to explore this application and is expanding the possible use of atomized iron powders as a potential recyclable energy carrier.

3) Sumitomo SHI FW (SFW)

SFW (www.shi-fw.com) is part of an international company Sumitomo Heavy Industries, Ltd. The main products of SFW are steam generators and gasifiers based on fluidized bed technology, cryogenic energy storage, waste heat boilers, multipollutant scrubbers, auxiliary equipment and services to the utilities and industry. The company is the world leader in fluidized bed boiler technology (CFB/BFB), which has superior multifuel capabilities (e.g., coal, lignite, biomass and various residues) and low emissions. SFW has supplied nearly 540 CFB boilers up to 550 MW_e and has developed a design for 800 MW_e (EU CFB800 project). SFW is a forerunner of FB technologies, delivering the very first CFB (Suonenjoki, 2 MW_e, 1979), the world's first supercritical CFB (Łagisza, 460MW_e, 2009), the most advanced ultra-supercritical CFBs (Samcheok, 4x550 MW_e, 2016), and the world's largest biomass plant (Polaniec, 205 MW_e, 2012). Our vision is to provide sustainable energy solutions through decarbonization, decentralization and digitalization of the energy industry. We continuously broaden our portfolio of products and services by advancing our in-house technologies and developing further alliances with new partners.

4) Consejo Superior de Investigaciones Científicas (CSIC)

Instituto de Carboquímica (ICB) (www.icb.csic.es) is a part of Consejo Superior de Investigaciones Científicas (CSIC), which is the largest public institution dedicated to research in Spain and the third largest in Europe. The Combustion and Gasification research group at ICB is composed of about 20 researchers including staff, PhD students and technicians. The group has a long expertise in gas-solid reaction kinetics and modelling applied to fluidized bed combustion and gasification processes as well as on Chemical Looping processes. Since 2000 the group has worked in the development, testing and characterization of metal oxide-based oxygen carriers suitable for gaseous, liquid, and solid fuels for Chemical Looping Combustion (CLC), Chemical-looping reforming (CLR) and Chemical-looping Gasification (CLG) of solid fuels. ICB-CSIC currently has a 100 mm ID bubbling fluidized combustion reactor and five interconnected circulating fluidized reactor units for CL redox process processes for gaseous/solid/liquid fuels (G/S/L) using metal oxides synthetic or ores as ilmenite and iron ore. All the continuous units are equipped for continuous gas analysis systems and ICB has facilities for porous and structural characterization of solids. ICB-CSIC has > 200 publications in redox processes using Chemical Looping. They have participated in several EU and RFCS projects related to metal oxide reduction and oxidation reactions CLC: ÉCLAIR (RFCS), ACCLAIM (RFCS), GRACE (FP6), CLC GAS POWER (FP6), CACHET (FP6), UNIQUE (FP7), INNOCUOUS (FP7), SUCCESS (FP7), CLARA (H2020) and other Spanish research projects and research contracts with the energy and oil sectors. The research group has long experience in kinetic modelling of oxidation and reduction reactions of metal oxides in Chemical Looping processes. Moreover, modelling of interconnected circulating fluidized reactors has been developed for processes of Chemical Looping Combustion of gaseous and solid fuels. ICB has worked in the redox processes to transfer the concept from the laboratory to the prototype scale to demonstrate the technology.

5) Chalmers University of Technology (Chalmers)

Chalmers University of Technology (<https://www.chalmers.se/en/>) hosts the division for Energy Technology, where different applications based on fluidization bed technology have been investigated and developed. The division has been a main actor in the introduction of fluidized bed combustion of biomass (with units sized 16 MW and 12 MW) and later gasification (with an indirect steam-blown gasifier sized 4 MW). The division has also developed and been a world-leading profile in chemical looping applications – which are of high relevance for the project here applied. The division has held a total of 7 chemical looping reactors (sizing up to 100 kW) in which more than

100 oxygen carrier materials have been tested. The division has participated in several EU/RFCs projects dealing with the cyclic oxidation and reduction of metal oxides, e.g. ACCLAIM (RFCs), GRACE (FP6), ÉCLAIR (RFCs), CACHET (FP6), INNOCUOUS (FP7), CLARA (H2020). In terms of the study of fluidized bed fluid-dynamics, the division has a long experience of experimental research in the units mentioned above and has also applied fluid-dynamic scaling laws to investigate the gas-solids mixing in cold flow models (one of which resembles an existing 300 MW CFB boiler). Finally, the division has hosted the development of novel diagnostic techniques for fluidized bed units, such as magnetic particle tracking, and the use of THz radar for online measurement of solids concentrations and solids velocity distributions.

6) Lappeenranta-Lahti University of Technology (LUT)

LUT (<https://www.lut.fi/en>) is a Finnish public research university that integrates technology, business, and social sciences. The university specializes in research areas including renewable energy technologies, clean water, climate change mitigation, and sustainable engineering solutions. Contributing to this project, the Laboratory of Thermal Engineering has particular skills in energy conversion systems that utilize multiphase flows. This expertise is applied to the computational modelling of fluidized bed processes, encompassing combustion, gasification, and calcium looping. For this purpose, both in-house developed models and externally available commercial and open-source software are employed.

7) Politecnico di Milano (POLIMI)

Politecnico di Milano (<https://www.polimi.it/>) is a public technical university organized into 12 departments and a network of 6 Schools of Engineering, Architecture, and Industrial Design. The number of students enrolled on all campuses is approximately 44,000, which makes the Politecnico di Milano the largest Engineering School in Italy. On the last QS ranking 2022, Politecnico di Milano ranked 13th in the world, 7th in Europe and 1st in Italy among the Engineering and Technology universities. The support for the MOF4AIR project is provided by the Group of Energy Conversion Systems (GECOS) of the Department of Energy. The GECOS group currently includes 4 full professors, 6 associate professors, 8 assistant professors and more than 30 post-doc and PhD fellows. Over the last few years, significant efforts have been devoted to the research on power plants' decarbonization via carbon capture technologies (oxy-combustion, chemical looping, post-combustion, pre-combustion) and hybridization with renewable sources. In this field, the GECOS group has participated and is currently contributing to several EU FP7 (CAESAR, CACHET-II, DEMOYS, DEMOCLOCK, ASCENT, MATESA), H2020 (CEMCAP, STEPWISE, CLEANKER, FLEDGED, etc.) and horizon Europe projects (OUTFOX, ENCASE, etc), optimizing the integration of novel thermodynamic cycles and advanced separation technologies in plants for the production of power and/or cement, steel and hydrogen. In addition to the above-mentioned research projects, the GECOS group has a long history of collaboration with the leading energy companies (Eni, SNAM, Enel, Edison, SIRAM, BP, etc.) and equipment manufacturers (GE Baker Hughes, Ansaldo, etc.).

In the framework of Italian research projects funded by the Ministry of Economic Development, the research team headed by Prof. Martelli developed software for the combined design and operational optimization (unit commitment) of integrated power plants (e.g., hybrid concentrated solar power plants – PV with battery and thermal energy storages, polygeneration plants coproducing electricity and blue hydrogen, microgrids with batteries, combined heat and power plants with thermal storage, etc.). The code can account for the different electricity markets (day ahead and ancillary service markets) and return the optimal plant design configuration considering the expected hour-by-hour operation. The code is being used in the framework of four research projects funded by leading energy companies.

8) Fortum Power and Heat Polska Sp. z o.o. (FORTUM)

Fortum (www.fortum.com) is a leading clean-energy company developing and offering solutions for our customers in electricity, heating, and cooling, as well as solutions to improve resource efficiency. We also provide services for the power generation industry and solutions for consumers so that they can be smarter in their energy choices. Fortum has over 150 power plants in total: hydro, CHP (combined heat and power), condensing, nuclear, solar and wind. We are the 3rd largest power generator in the Nordic countries and one of the leading heat producers globally. Fortum Power and Heat Polska is a Polish subsidiary focused on heat production and distribution in five Polish cities.

9) VGBE ENERGY EV

VGBE (<https://www.vgbe.energy/vgbe/>) is the technical association of energy plant operators. The members of VGBE operate power, heat, and cooling plants as well as energy storage and sector coupling all around the world. VGBE is committed to the goal of developing the economy and society in a climate-neutral and sustainable way. The contribution is to demonstrate and actively shape the technical options required for an environmentally friendly, safe, and economical energy supply. As an independent technical competence centre and network, VGBE supports international members in their respective business activities and the implementation of innovations and strategic tasks. VGBE is the voice of plant operators, and actively and fact-based contribute to the political and social debate on technical issues. Cooperation with all partners along the energy value chain, especially with manufacturers and service providers, is an essential criterion. VGBE is also the international and central contact for all technical issues relating to the operation of energy plants. VGBE is committed to a secure, cost-effective, and environmentally friendly energy supply. The focus is on controllable generation and volatile generation from renewable energies as well as on energy storage and sector coupling. Since in the future energy system plant engineering is simpler in many areas than before, but the overall system is more complex, activities related to system integration plays a greater role in the VGBE portfolio of the future. On the way to a climate-friendly energy system, a balanced energy mix remains important – especially against the background that controllable generation is the most important flexibility option in the energy system.

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