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Project acronym: SCARLET

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Table of Contents

1 Part 1 – Overview and Description of the Project and its Results

1.1 Executive summary of the project

Original research objectives:

Calcium carbonate looping (CCL) is a promising 2nd generation technology for low-cost post combustion CO_2 capture from fossil fuel-fired processes. The development of the CCL process is targeting small efficiency penalties of 5 to 7 percentage points (including CO_2 compression) and thus CO_2 avoidance costs lower than 20 €/tCO_2, i.e. far below than those of 1st generation capture processes. Previous pilot tests performed at 1 MW_{th} scale have confirmed the feasibility of the technology, while giving a solid ground to assess the required steps of further research, aiming mainly at conversion improvement and reliability.

The major goal of the SCARLET project is to obtain reliable information and tools for the scale-up and pre-engineering of a 20 MW_{th} CCL plant by continuous self-sustaining operation of an upgraded 1 MW_{th} pilot plant at TU Darmstadt (TUD). The project aims at providing technical, economic and environmental assessments of this promising technology, as well as the fundamental expertise needed for the scale-up and integration of pre-commercialisation CCL facilities. The following key objectives have been defined for the SCARLET project:

1. Identification of the key process parameters and control strategies for the upgraded 1 MW_{th} CCL pilot plant fuelled by hard coal and by lignite (to be achieved by M18).

2. Development of scale-up tools and guidelines for CCL reactor design and process layout, validated by experimental data of the 1 MW_{th} pilot plant (to be achieved by M24).

3. Design, cost estimation, and health, safety and technical risk assessment of a 20 MW_{th} CCL pilot plant using the Emile Huchet power plant owned and operated by Uniper as the reference host site (to be achieved by M36).

4. Techno-economic assessment of CCL application in hard coal- and lignite-fired power plants as well as cement and steel industry at commercial full-scale (to be achieved by M36).

5. Environmental assessment of CCL application in hard coal- and lignite-fired power plants as well as cement and steel industry at commercial full-scale (to be achieved by M36).

Expected deliverables:

The major deliverables of the SCARLET project are summarized as follows:

1. Upgrade of the 1 MW_{th} CCL pilot plant in Darmstadt.
2. Two long-term test campaigns (4 weeks each) with hard coal in the 1 MW_{th} CCL pilot plant.
3. Two long-term test campaigns (4 weeks each) with lignite in the 1 MW_{th} CCL pilot plant.
4. Development and validation of steady-state and unsteady (transient) process models as well as 3D models for scale-up of the CCL process.
5. Concepts for improved design of the CCL reactor setup.
6. Basic design (process layout, reactor concept, sizing and instrumentation) of a 20 MW_{th} CCL pilot plant.
7. Estimation of investment and operational costs for a 20 MW_{th} CCL pilot plant.
8. Health, safety and technical risk assessment for a 20 MW_{th} CCL pilot plant.
9. Thermodynamic, economic and environmental evaluation for full-scale implementation of CCL to a hard coal power plant.
10. Thermodynamic, economic and environmental evaluation for full-scale implementation of CCL to a lignite power plant.
11. Thermodynamic, economic and environmental evaluation for full-scale implementation of CCL to a cement production plant.
12. Thermodynamic, economic and environmental evaluation for full-scale implementation of CCL to a steel production plant.

Project’s actual outcome:

The outcome of the first project period with respect to the major deliverables (see above) is summarized as follows:

1. The 1 MW_{th} CCL pilot plant has been upgraded with new equipment (a) to enhance operability (using an automated pneumatic limestone supply system and a cone valve to control solids circulation); (b) to enable real operating conditions (by coupling a coal-fired combustion chamber with the carbonator and by applying flue gas recirculation in the calciner); (c) to widen the fuel spectrum (through the installation of a supply system for pre-dried lignite); and (d) to increase its thermal capacity (using new heat exchanger tube bundles and additional heat exchangers).

2./3. Four comprehensive test campaigns each with a total duration of 4 weeks have been performed using hard coal as well as lignite as fuel for the combustion chamber and calciner. The pilot plant has been operated for more than 3,000 hours in stable continuous (24 h/d) operation with more than 1,300 hours of stable CO_2 capture (280 hours with hard coal and 184 hours with lignite in the calciner). Several weeks of stable operation with maximum CO_2 capture rates above 90 % has been achieved with both fuels.

4. A method for the calculation of the particle size distribution has been incorporated into an existing steady-state process model for calculating heat and mass balances of CCL plants including an empirical 1D fluidized bed reactor model. A new transient process model has been developed to predict the dynamic behavior of CCL plants. Reaction models for carbonation/calcination and coal combustion have been implemented into various Computational Fluid Dynamics (CFD) codes. All models have been comprehensively validated using experimental data from a previous 1 MW_{th} test campaign.

5. Ideas regarding improved design have been collected. The coupling concept between carbonator and calciner, fluidization staging in the calciner, fat bottom design and sorbent staging in the carbonator had been discussed and were simulated.

6. Basis of Design document of the 20 MW_{th} CCL pilot plant has been established and the process configuration and control loops have been defined. The concept was depicted in process flow diagrams (PFD) and a process description was developed for the 20 MW_{th} CCL pilot.. The nominal operating conditions (heat & mass balance) for the Design case of the 20 MW_{th} CCL pilot plant have been calculated with the

validated simulation tools. Reactor design, equipment sizing and instrumentation planning have been started.

7. No action.

8. Potential health and safety risks during erection, operation, and future dismantling of the 20 MW_{th} CCL pilot were identified by conducting a Process Hazard analysis with Hazard Study 1 methodology (HAZID). The host hard coal power plant for full-scale implementation of CCL has been defined.

9. The Emile Huchet power station located in Saint-Avold, France has been defined as host hard coal power plant for full-scale implementation of CCL. The thermodynamic evaluation of the CCL process integrated into the host power station was finished and heat and mass balances for economic and environmental assessment are available.

10. The BoA 1 power station located in Niederaußem, Germany has been defined as host lignite power plant for full-scale implementation of CCL. The thermodynamic evaluation of the CCL process integrated into the host power station was finished and heat and mass balances for economic and environmental assessment are available.

11. The Rüdersdorf cement plant located in Berlin, Germany has been defined as cement plant for full-scale implementation of CCL. The thermodynamic evaluation of the CCL process integrated into the host cement process was finished and heat and mass balances for economic and environmental assessment are available.

12. The steel production process for full-scale implementation of CCL has been defined. The thermodynamic evaluation of the CCL process integrated into the host steel process was finished and heat and mass balances for economic and environmental assessment are available.

Description of dissemination plans:

Dissemination of the public information will be performed by at least five publications in peer-reviewed scientific journals and by participation in at least five international conferences on CO_2 capture technologies. Scientific and socio-economic topics ranging from general public information to more specialized scientific topics will be published or made available in three annual open reports and a six-monthly newsletter. A project web-site will be established by the third month of the project. It will be regularly maintained to include all relevant project information and reports. Generally, only unrestricted reports (classified as PU) will be made accessible to the public. Effective and efficient approval procedures agreed in the consortium agreement will help minimize time delays for publications and dissemination.

Education will include master courses and specific training programmes. The partners, Universities and research institutes involved in the project will initiate PhD programmes in which students will carry out specific research pertaining to the subject research area: CO_2 capture and fluidized bed technologies. At least three PhD theses will be completed on core issues in CO_2 capture within the three years of this project.

Two public workshops will be organized by the end of the second and third years. The first workshop was held in April 2016 at the 1 MW_{th} pilot site, i.e. at TUD, specially oriented towards members of the electricity utility companies, cement companies and steel companies, and the workshop participants will be able to visit the pilot plant. The second workshop will preferably be organized as an annex to a big international conference, such as the IEAGHG Network Meeting and Technical Workshop on Solid Looping Cycles, the IEA Greenhouse Gas Control Technologies Conference, or the Trondheim CCS Conference. Three public reports giving an account of the project results will be delivered. A newsletter is published every six months.

Use intentions for the expected outputs:

At any appropriate stage of implementation, the consortium will endeavour to make best use of the exploitable results of the project, in particular those with a commercial potential, through its own resources, CORDIS or other external services. This may include proof of concept outside the laboratory; the identification of market potential and opportunities; the evaluation of competing technologies; the assessment of the cost for scale-up from laboratory scale to industrial application; the development of a business plan; and protection of intellectual property rights.

1.2 Overview of all results

The major results, described in detail in Part 2, are summarized as follows:

1. Upgraded Pilot Plant (defined as Milestone 1 in Description of Work (DoW))
2. Long-term testing of CCL process with hard coal in upgraded 1 MW_{th} pilot plant (defined as Milestone 2 in DoW)
3. Long-term testing of CCL process with lignite in upgraded 1 MW_{th} pilot plant (defined as Milestone 3 in DoW)

4. Steady-state and unsteady (transient) CCL process model, 3D discrete element model (defined as Milestone 4 in DoW)
5. Process configurations and nominal operation conditions for 20 MW_{th} pilot plant (defined as Milestone 5 in DoW)
6. Engineering for 20 MW_{th} pilot plant (defined as Milestone 6 in DoW)
7. Definition of host plant for full-scale application to hard coal-fired power plants (defined as Milestone 7 in DoW)
8. Economic and environmental assessment for full-scale application to hard coal-fired power plants (defined as Milestone 8 in DoW)
9. Definition of host plant for full-scale application to lignite-fired power plants (defined as Milestone 9 in DoW)
10. Economic and environmental assessment for full-scale application to lignite-fired power plants (defined as Milestone 10 in DoW)
11. Definition of host plant for full-scale application to cement production plants (defined as Milestone 11 in DoW)
12. Economic and environmental assessment for full-scale application to cement production plants (defined as Milestone 12 in DoW)
13. Definition of host plant for full-scale application to steel production plants (defined as Milestone 14 in DoW)
14. Economic and environmental assessment for full-scale application to steel production plants (defined as Milestone 15 in DoW)

1.3 Assessment of the European interests

The final purpose of this project is of course the practical commercial application of its results, with the primary objective of fighting climate change and protecting the environment. Through its commercial implementation, the project will also support the European economy, driving exports, helping to improve the quality of life and creating jobs. For the realization of this purpose, the participation of two major power companies and of cement and steel companies in the consortium is of fundamental importance, particularly because they have activities in more than one European country. The benefits they see in the CCL process are multiple; two of the most important for their operations are the lower cost of CO_2 avoidance and the lower cost of electricity with respect to other capture processes.

The project will strengthen the position of Europe as the key driver of the CCL technology. In particular, the demonstration of the CCL process at a 1 MW_{th} scale will be a milestone in the development of this technology. The subsequent development towards full-scale demonstration of the CCL technology will confirm Europe as the major player for the demonstration of power plants with CO_2 capture. The application of this technology for power production will preserve and create jobs in the European market concerning technology development and energy supply, and by the steel industry.

In principle, realistic estimates by a technology provider forecast the introduction of CCL to the power generation market at some time no later than 2025. If the proposed project achieves its goals, a follow-up project to build a 20 MW_{th} pilot plant can start around 2018, allowing for the realization of a commercial power plant with CCL around 2025, probably in the order of 250 MW_{el}. Such a roadmap conforms with commercial expectations of technology providers and with the goals of the European Union. Of enormous importance for the commercial exploitation of CCL is the possibility of retrofitting the technology to existing power stations. It is also reasonable to consider the potential market represented by the cement industry, a user of large quantities of limestone and a source of significant CO_2 emissions, and the steel industry.

2 Part 2 – Description of each Result

2.1 Description of the results for WP1 – Long Term Pilot Testing

2.1.1 Result 1: Upgraded Pilot Plant

Milestone:

MS1 "Adaption of 1 MW_{th} pilot plant completed – upgraded pilot plant ready for long-term testing"

Description:

The 1 MW_{th} CCL pilot plant located in Darmstadt has been upgraded with new equipment (a) to enhance its operability (using an automated pneumatic limestone supply system and a cone valve to control solids circulation), (b) to enable real operating conditions (by coupling a coal-fired combustion chamber with the carbonator and flue gas recirculation in the calciner), (c) to widen the fuel spectrum (by a supply system for pre-dried lignite), and (d) to increase its thermal capacity (by new heat exchanger tube bundles and additional heat exchangers).

Summary of results:

- Results achieved so far:

  Flue gas recirculation has been integrated into the calciner of the 1 MW_{th} CCL pilot plant to enable real conditions of an oxy-fuel calciner. A piping connection between the flue gas and the primary air duct of the calciner as well as a flue gas recirculation fan, a flow measurement device and electrical dampers have been installed. A multistage axial fan compresses the recirculated flue gas stream consisting mostly of CO_2 and H_2O for fluidization of the calciner. The recirculated flue gas flow is measured by a ventury nozzle that is coupled with a gas analyzer measuring the CO_2 and O_2 concentrations. Switching the inlet streams of the fan from air to flue gas and vice versa is controlled by two electrical dampers.

  New reactor parts have been constructed to realize a new coupling concept between the reactors. A cone valve attached to the loop seal of the calciner is used to control the solids mass flow from calciner to carbonator. A solid flow measuring device based on microwave technology is integrated into the cone valve piping. In addition, pressure and temperature measurement ports are included.

New heat exchanger tube bundles in the first flue gas pass of the heat exchanger as well as an extra heat exchanger downstream of the flue gas duct of the calciner have been installed to increase the cooling capacity of the calciner flue gas. This enables an increased thermal input to the calciner while meeting the temperature limit of the fabric filter.

The pilot plant has been upgraded with an automated supply system for limestone to improve the operability of the pilot plant. The limestone dosing system is automatically filled with a vacuum conveying system. The limestone is transported by air in sub-atmospheric pressure provided by a rotary vane vacuum pump to a separator and the particles are collected in a storage tank above the existing dosing system.

The existing fuel supply of the pilot plant has been upgraded to use lignite as fuel. The lignite is stored in a silo that is flushed and blanketed with nitrogen from a tank. A pneumatic conveying system transports the lignite to the reservoirs of the combustion chamber and the calciner. The lignite extraction from the silo into the pneumatic transport piping has been realized by transportation shoe at the bottom of the silo. A two-way switch in the feed system provides the possibility to decide which reservoir is going to be filled. Nitrogen is used for pneumatic transport to always guarantee a non-explosive atmosphere in the supply system.

The capability to introduce sulphur dioxide (SO_2) and steam (H_2O) has been integrated into the pilot plant to investigate the influence of these gases on the performance of the sorbent. Ports for H_2O as well as SO_2 injection have been installed in the heated primary gas line of the carbonator. Superheated steam is provided by the existing steam generator and an electrical superheater. SO_2 is provided from gas bottles and regulated by a control system consisting of valves and a mass flow controller.

Enhanced measurement equipment and concepts have been realized in the pilot plant in form of a moisture analyzer for the flue gas entering the carbonator and an increased number of pressure and temperature measurements along the reactor height of carbonator and calciner.

Additional screw conveyor solid sampling systems have been installed in addition to the existing lock-sluice system to extract solid samples from the flow of carbonator to calciner and vice versa.

Adaptions have been made to the pulverized fuel-fired combustion chamber to guarantee stable long-term operation and to provide realistic flue gas composition similar to an industrial power plant. The combustion chamber has been equipped with a water quenching system and dry flue gas desulphurization to mimic the flue gas composition from a power plant after wet flue gas desulphurization (wet FGD) as close as possible. An extra heat exchanger downstream of the combustion chamber has been integrated into the flue gas duct to be able to reach the targeted thermal power for the flue gas.

The coupling concept of combustion chamber and carbonator has been revised. The combustion chamber has been equipped with its own induced draft (ID) fan, which allows operating the combustion chamber independently from the fluidized bed reactor. A new coupling damper with an electrical actuator has been installed to control the gas flow for fluidization of the carbonator. The incoming fluidization gas flow is defined with a restrictor measuring. Additional gas analysis and moisture measurement are integrated into the primary gas line for determining the incoming volume flow as precisely as possible.

Further collaboration, dissemination and use of the results:

The upgraded 1 MW_{th} CCL pilot plant is being used for performing four long-term test campaigns (4 weeks each) within the SCARLET project (Milestones MS2 and MS3 of WP1).

The upgraded pilot plant will also be used to perform further CCL test campaigns within the LISA2 project (funded by German authorities).

The upgraded pilot plant will be used for two test campaigns regarding chemical looping combustion of gaseous fuels in a slightly modified configuration within the FP7 project SUCCESS.

TUD has submitted an RFCS project proposal with the intention to use the upgraded pilot plant for further test campaigns regarding chemical looping combustion of solid fuels.

TUD intends to apply for further projects that include testing of emerging fluidized bed-based CO_2 capture technologies using the upgraded pilot plant, e.g. within Horizon 2020.

TUD intends to use the lignite supply system for fluidized bed gasification tests.

2.1.2 Result 2: Hard Coal Testing

Milestone:

MS2 ”Successful completion of long-term testing with hard coal in the upgraded pilot plant facility”

Description:

With the upgraded pilot plant, two comprehensive test campaigns (4 weeks, 24 h/d each) using hard coal as fuel are performed to investigate the long-term behavior of the process focusing on sorbent stability and reactivity as well as on acquisition of reliable data for model validation and scale-up. The influence of various process conditions is determined by parameter variations. After completion of long-term trials using the upgraded pilot facility at TU Darmstadt, representative sorbent samples – preferably collected during steady-state operation – shall be selected for detailed analysis featuring, for example, particle size distribution (PSD), chemical composition (by XRF), thermo-gravimetric analysis (TGA) and (optionally) specific surface area (SSA) and pore volume as well as scanning electron microscopy (SEM). Such analysis is required to validate steady-state operation and to facilitate the process simulation required for further scale-up. Furthermore, a solids flow measuring system is tested to create a reliable method for measuring solids mass flow at high temperatures.

Summary of results:

- Results achieved so far:
  Two comprehensive test campaigns each with a total duration of 4 weeks have been performed using hard coal as fuel for the combustion chamber and calciner. The pilot plant has been operated for more than 750 hours in stable continuous (24 h/d) operation, with more than 640 hours of stable CO_2 capture with crushed coal and pulverized coal in the calciner being achieved. More than one week of stable operation with maximum CO_2 capture rates above 90 % has been achieved with pulverized hard coal. Several operating points at steady-state conditions have been identified to provide consistent data sets for model validation.
  With respect to solid sample analysis, sorbent samples coming from the loop seals of the pilot unit were analyzed for chemical composition, grain size distribution and Loss on Ignition. The results were used to identify stable and/or

‘steady-state’ operation The samples of the hard coal long-term test campaigns are currently prepared for detailed analysis.

- Expected results:

  During the test campaign, solid samples are extracted and provided for further analyses by LRD. It is expected that the successful completion of the tasks assigned to LRD will finally allow establishing a link between results obtained at laboratory scale in the past and pilot scale behavior as recently observed. Such information is key to validating and/ or improving currently established test protocols in the future for effective sorbent characterization.

  More importantly, the long-term trial campaign will provide key information on the properties of the sorbent and open the possibility to assess the feasibility of using alternative sorbents if relevant from a socio-economic point of view.

Further collaboration, dissemination and use of the results:

The results of the test campaigns are used to demonstrate long-term operation of the CCL process at real conditions and to determine optimal process conditions.

The results are used in WP2 to validate a steady-state process model (in particular sub-models for sorbent reactivity, conversion in carbonator/calciner, attrition/fragmentation), a dynamic process model, and 3D CFD models.

The results are used in WP3 to define the plant setup (in terms of a process flow diagram), the basic reactor design, and the range of operating conditions of a 20 MW_{th} CCL pilot plant.

The results are used in WP4, WP5 and WP6 to define the plant setup (in terms of a process flow diagram) and the range of operating conditions of full-scale CCL units for CO_2 capture from power, cement, and steel plants.

The results are further used to optimize the 1 MW_{th} CCL pilot plant setup within the LISA2 project (funded by German authorities).

The results will be presented at scientific conferences and published in peer-reviewed journals.

The results will be used as a basis for doctoral theses.

The results will be used in lectures at Technische Universität Darmstadt.

LRD is committed to serving the power industry and other industries like steel or cement production by providing the best available sorbent material for a low-carbon footprint from fossil combustion. For this purpose, LRD is actively involved in the development of next generation carbon capture and utilization as well as storage (CCU & CCS) technologies like the CCL Technology.

2.1.3 Result 3: Lignite Testing

Milestone:

MS3 ”Successful completion of long-term testing with lignite in the upgraded pilot plant facility”

Description:

With the upgraded pilot plant, two comprehensive test campaigns (4 weeks, 24 h/d each) using lignite as fuel are performed to investigate the long-term behavior of the process focusing on sorbent stability and reactivity as well as on acquisition of reliable data for model validation and scale-up. The influence of various process conditions is determined by parameter variations. After completion of long-term trials using the upgraded pilot facility at TU Darmstadt, representative sorbent samples – preferably collected during steady-state operation – shall be selected for detailed analysis featuring, for example, particle size distribution (PSD), chemical composition (by XRF), thermo-gravimetric analysis (TGA) and (optionally) specific surface area (SSA) and pore volume as well as scanning electron microscopy (SEM). Such analysis is required to validate steady-state operation and to facilitate the process simulation required for further scale-up. Furthermore, a solids flow measuring system is tested to create a reliable method for measuring solids mass flow at high temperatures.

Summary of results:

- Results achieved so far:
  Two comprehensive test campaigns each with a total duration of 4 weeks have been performed using lignite as fuel for the combustion chamber and calciner. The pilot plant has been operated for more than 600 hours in stable continuous (24 h/d) operation, with more than 570 hours of stable CO_2 capture with coarse as well as pulverized lignite in the calciner being achieved. Stable operation with maximum CO_2 capture rates above 90 % has been achieved with pulverized lignite. Several operating points up to 60 hours without changing any parameters at steady-state conditions have been identified to provide consistent data sets for model validation.
  With respect to solid sample analysis, sorbent samples coming from the loop seals of the pilot unit were analyzed for chemical composition, grain size

distribution and Loss on Ignition. The results were used to identify stable and/or ‘steady-state’ operation The samples of the lignite long-term test campaigns are currently prepared for detailed analysis.

The samples of the long-term test campaigns are currently prepared for detailed analysis.

- Expected results:

  During the test campaigns, solid samples are extracted and provided for further analyses by LRD. It is expected that the successful completion of the tasks assigned to LRD will finally allow establishing a link between results obtained at laboratory scale in the past and pilot scale behavior as recently observed. Such information is key to validating and/ or improving currently established test protocols in the future for effective sorbent characterization.

  More importantly, the long-term trial campaign will provide key information on the properties of the sorbent and open the possibility to assess the feasibility of alternative sorbents if relevant from a socio-economic point of view.

Further collaboration, dissemination and use of the results:

The results of the test campaigns are used to demonstrate long-term operation of the CCL process at real conditions and to determine optimal process conditions.

The results are used in WP2 to validate a steady-state process model (in particular sub-models for sorbent reactivity, conversion in carbonator/calciner, attrition/fragmentation), a dynamic process model, and 3D CFD models.

The results are used in WP3 to define the plant setup (in terms of a process flow diagram), the basic reactor design, and the range of operating conditions of a 20 MW_{th} CCL pilot plant.

The results are used in WP4, WP5 and WP6 to define the plant setup (in terms of a process flow diagram) and the range of operating conditions of full-scale CCL units for CO_2 capture from power, cement, and steel plants.

The results are further used to optimize the 1 MW_{th} CCL pilot plant setup within the LISA2 project (funded by German authorities).

The results will be presented at scientific conferences and published in peer-reviewed journals.

The results will be used as a basis for doctoral theses.

The results will be used in lectures at Technische Universität Darmstadt.

LRD is committed to serving the power industry and other industries like steel or cement production by providing the best available sorbent material for a low-carbon footprint from fossil combustion. For this purpose, LRD is actively involved in the development of next generation carbon capture and utilization as well as storage (CCU & CCS) technologies like the CCL Technology.

2.2 Description of the results for WP2 – Development and Validation of Scale-up Tools

2.2.1 Results 4: Scale-up Tool Development

<u>Milestone:</u>

MS4 ”Scale-up tools validated and selected for 20 MW_{th} plant scale-up”

To provide a better overview, result 4 is divided into following sub-results:

4a: Steady-state CCL process model

4b: Unsteady (Transient) CCL process model

4c: 3D discrete element model

<u>Description:</u>

Result 4a:

An existing steady-state process model for calculating heat and mass balances of CCL plants including empirical 1D fluidized bed reactor models is further developed. A method for the calculation of the particle size distribution is incorporated into the process model, considering attrition, fragmentation, segregation, solids entrainment, and particle separation efficiency of the cyclones. The model is thoroughly validated and optimized by comparison with experimental data from 1 MW_{th} test campaigns.

With respect to GE Carbon Capture GmbH’s (GECC) contribution on result 4a, an own ASPEN PLUS™ based CCL process model, constructed within previous R&D projects, is applied and thoroughly validated and optimized by comparison with experimental data from 1 MWth test campaigns and other tests (TGA and TUD batch reactor tests).

<u>Result 4b:</u>

A new unsteady (transient) process model is developed to predict the dynamic behaviour of CCL plants. The model is thoroughly validated and optimized by comparison with data from 1 MW_{th} test campaigns in steady-state as well as during start-up, shutdown, and load change.

<u>Result 4c:</u>

With respect to milestone MS4 CERTH/CPERI set as main objective the effective and efficient simulation of Calcium Carbonate Looping process (CCL) by means of Computational Fluid Dynamics (CFD). More specifically, within the first 18 months, three-dimensional (3D) CFD tools have been developed for the simulation of the two reactors in the Dual Fluidized Bed system (DFB), i.e. the carbonator and the calciner. The CFD models are developed on the basis of the pure two-fluid model (TFM) Eulerian approach, for each reactor separately, using the commercial, user-friendly ANSYS FLUENT™ platform to take advantage of its parallel processing capability that accelerates such time-consuming calculations. When necessary, custom-built models in C++ programming language are integrated into the platform using USER-DEFINED-FUNCTIONS (UDFs).

It is well known that a reliable and cost-efficient CFD model is a prerequisite for the design optimization and scale-up of such fluidized bed reactors. This is due to their intrinsic ability to predict the complicated flow patterns with a lower cost compared to experimental campaigns. For validation reasons, the numerical results of the developed CFD models are compared with proper experimental data provided by TUD. These data correspond to the two pilot-scale FB reactors that are part of the 1 MW_{th} DFB installation located at the premises of TUD. It is noted that the input variables, boundary and operating conditions necessary for the setup of the run cases are delivered to CERTH/CPERI by TUD.

With respect to TUD's contribution on result 4c, a Computational Fluid Dynamics (CFD) code considering particle/particle interaction by means of the discrete element method (DEM) is further developed to study dedicated components, e.g. loop seals and cone valves of a CCL reactor system. Reaction models for carbonation/calcination and coal combustion are implemented into the CFD codes. The model is comprehensively validated by means of in-furnace and other measurements from the 1 MW_{th} test campaigns.

With respect to GECC's contribution on result 4c, a CFD based discrete particle model -considering particle/particle interaction by means of stochastic collision detection -using the BARRACUDA™ software is further developed and applied to study dedicated components, e.g. the CCL reactor systems. Reaction models for carbonation/calcination and coal combustion are implemented into the CFD codes.

The model is comprehensively validated by means of measurements from the 1 MW_{th} test campaigns and other tests (TGA and TUD batch reactor tests).

Summary of results:

- Results achieved so far:

  Result 4a:

  With respect to TUD's part of MS4 an existing steady-state process model (developed by TUD in ASPEN PLUS^{TM}) for calculating heat and mass balances is advanced to account for the physical effects inside coupled circulating fluidized bed reactors regarding the sorbent-gas and sorbent-sorbent interactions. The existing process model included a 1D fluidized bed reaction model and an empirical correlation for the sorbent reactivity to predict the absorption of CO_2 in the carbonator. The process model has been extended by a sophisticated calciner model, considering the hydrodynamics and a kinetic-controlled calcination reaction. An attrition model has been implemented to predict particle size distribution during steady-state operation. Characteristic component curves from the manufactures of compressors, draught fans and fabric filters have been added in the process model. Detailed relationships to account for the particle separation efficiency in the cyclones have been implemented. Detailed analysis on particle segregation in the fluidized bed will be performed applying empirical models. The process model will be validated by simulation of various steady-state operating points of the 1 MW_{th} test campaigns.

  With respect to GECC's contribution on result 4a, GECC has successfully applied own ASPEN PLUS™ based CCL process model, constructed within previous R&D projects. GECC's in-house steady-state model predictions for sorbent activity correspond well to batch fluidized bed measurements confirming sorbent activity of material extracted from the pilot plant during the operating period P2 of the test campaign #1 (long-term test campaign with hard coal). The model was also applied to provide a basis for the sorbent activity, expected for the 20MW design point (considering increase make-up and a resulting increase in active fraction).

  Result 4b:

  An unsteady (transient) process model has been developed using the software ASPEN PLUS DYNAMICS^{TM} together with ASPEN CUSTOM MODELER^{TM}. The model for the carbonator is capable of predicting the temperature profile during start-up and shutdown of the carbonate looping plant, as well as during steady-state operating conditions. Other components of the plant such as loop-seals, the calciner reactor and screw conveyer are modeled as simple blocks using experimental data. The model has been compared to experimental data in terms of carbonator reactor temperature and the CO_2 concentration at the outlet, showing good agreement.

<u>Result 4c:</u>

Regarding the carbonator unit, a powerful and validated tool has been developed by CERTH/CPERI, integrating into ANSYS FLUENT custom-built User Defined Functions (UDFs) the drag model and the carbonation reaction. The carbonation reaction rate is simulated based on an expression and limestone constants found in the open literature. Additionally, an advanced EMMS (Energy Minimization Multi-Scale)-type drag force model has been developed and implemented. The importance of developing a proper drag force model in order to predict as accurately as possible the complex multiphase flow inside the fluidized bed reactor should be underlined. The EMMS model developed by CERTH/CPERI incorporates a new cluster size correlation. The added value of this model compared to previous ones is that it considers the limitation that the riser diameter poses to the clusters size. Thus, this improved version of the EMMS model offers a higher level of accuracy. Moreover, this model provides more accurate results compared to conventional models, e.g. the Gidaspow model. As far as the associated computational cost is concerned, the EMMS runs in a low grid density, requiring a relatively affordable computational cost.

TUD has developed 3D CFD models based on the Discrete-Element-Method (DEM) with the objective to support the design of the CCL reactor system. Two software packages, namely the in-house code DEMEST and the commercial software ANSYS FLUENT™ have been compared using a cold flow experiment for validation purpose. The accuracy between both CFD/DEM codes is similar. The ANSYS FLUENT™ has been selected due to its advantages when applied on complex geometries (especially high effort for grid generation). The ANSYS FLUENT™ supports the concept of parcels that may represent several thousand of real particles. The DEM model together with the parcels concept has been successfully applied to the simulation of the carbonator reactor. The DEM model combined with the EMMS drag scheme shows good agreement with one distinct experimental pressure profile, while the conventional drag models provide less accurate simulation results.

With respect to GECC's contribution on result 4c GECC developed a CFD based discrete particle model -considering particle/particle interaction by means of stochastic collision detection -using the BARRACUDA™ software. Geometrical data for the TUD 1 MW_{th} pilot CFB reactor systems have been implemented into the model and CFD calculations with the established model have been executed. The GECC discrete particle 3D CFD modelling using BARRACUDA™ software was initially validated using experimental data of the operating period P2 of the test campaign #1 (long-term test campaign with hard coal). The Carbonator reactor calculations with the 3D discrete element model were accomplished based on test results of operational period P2 and some initial additional assumptions. The related Deliverable D2.4 Report „Results of 3D stochastic discrete particle model", comprising the results of GECC reactor modelling, was issued in June 2016.

Since the Deliverable D2.4 the particle size distribution (PSD) of sorbent was corrected and the PSD of bed material for P2 was been estimated from other operating points. Furthermore, assumptions for sorbent activity have been confirmed though batch reactor tests executed at TUD in a small-scale bubbling bed batch reactor using sorbent extracted during P2. Based on validated sorbent activity and adjusted kinetic parameters a match of batch reactor performance with simulated results were achieved. Applying the same kinetic model parameters in combination with an adjusted EMMS drag model, generated for the pilot Carbonator, a close match of measured Carbonator performance (pressure, temperature, conversion, velocities) for P2 was obtained. In addition, the same model (matching both batch and pilot test results) was applied to adjust carbonator design and confirm performance at the 20 MW scale.

The model for the carbonator has been implemented to investigate design optimization through testing of alternative reactor designs - fat bottom design. (FBD), sorbent staging design (SbS) and sorbent in the splash zone design (SZD). The numerical results indicate that a better CO_2 capture efficiency is achieved in all retrofit cases compared to the initial carbonator geometry of the DFB facility. More specifically, a higher capture efficiency is achieved in the SbS case (89.94 %) than in the SD case (87.03 %), mainly because a better mixing is achieved in the lower part of the reactor. The efficiency in the SZD case is lower than the SbS concept (88.7 %) a fact that confirms the advantages of staging the sorbent injection since either injecting all of the material to the bottom or to the splash zone leads to lower capture efficiency. The best CO_2 capture is achieved in the FBD concept, i.e. 90.36 % and 91.91 %, for a solids inventory equal to 282 and 340 kg, respectively, values that are close enough to the CO_2 equilibrium capture efficiency (93.33 %). The combination of low cost and high accuracy of the CFD model makes it a powerful tool towards design optimization. Therefore, this numerical tool incorporating custom-built UDF codes can be commercially exploited as it can assist manufacturing companies in the design phase of carbonator reactors. Among, the improvements investigated through the aforementioned numerical tools the sorbent staging idea could be implemented with not many technical complications in larger scale units to boost the efficiency of the carbonator.

<u>Result 4d:</u>

The case of a CFB calciner is much more complicated than that of the carbonator, since there are three, instead of two, discrete phases – gas, sorbent, fuel – and several homogeneous and heterogeneous reactions, which should be accounted for. Reaction rates retrieved from the recent literature have been incorporated into the model to take into account both the calcination reaction and the char combustion occurring inside the reactor. The carbonation reaction is also simulated, in order to test to which extent the reverse reaction takes place when the temperature inside the reactor is below calcining conditions. This is of high interest as unintentional carbonation in the calciner increases the sorbent carbonation / calcination cycles. So the state-of-the-art CFD model applied for the calciner reactor can be as well a powerful tool for scaling-up purposes, similar to the one developed for the carbonator unit. The model could be used to investigate carbonation conditions in the calciner which is of high technological interest since a lot of unintended carbonations – calcination cycles will have a negative effect on sorbent activity. However, the associated high computational cost makes this model at the moment not as efficient as that of the carbonator model, and further optimization techniques are required. The parallel processing capability, though, enabled in the Ansys Fluent program can enhance the model computational efficiency.

- Expected results:

  Result 4a:

  TUD's existing steady-state process model has been thoroughly validated and optimized through comparison with experimental data from 1 MW_{th} test campaigns.

  If possible GECC will further validate the in-house model by analysis of an additional experimental operation point. Like for TUD's model the focus will be given on a detailed analysis of the sorbent properties in terms of activity and CO_2-carrying capacity, and combined with further batch fluidized bed sorbent activity testing.

  Result 4b:

  The model developed by TUD will be further validated under different operating points using experimental data of the 1 MW_{th} test campaigns.

  Result 4c:

  TUD's CFD model will be further validated by simulation of various steady-state operating points of the 1 MW_{th} test campaigns. The results will be compared with measured data, i.e. pressure profiles, temperatures, flue gas composition, and in-furnace measurements.

  GECC's Carbonator modelling activities are complete. GECC will further apply the oxy-fired Calciner model to describe results of P2 and project/confirm 20 MW_{th} pilot plant design and performance.

Further collaboration, dissemination and use of the results:

Result 4a:

The steady-state process model will be used in WP3 to calculate heat and mass balances of various operating points of a 20 MW_{th} pilot plant.

The steady-state process model will be used in WP4, WP5, and WP6 to calculate heat and mass balances as well as optimize the operating conditions of full-scale CCL units for CO_2 capture from power, cement, and steel plants.

The results will be presented at scientific conferences and published in peer-reviewed journals.

The results will be used as a basis for doctoral theses.

The results will be used in lectures at Technische Universität Darmstadt.

Result 4b:

The unsteady (transient) process model will be used in WP3 to calculate heat and mass balances during start-up, shutdown, and load change of a 20 MW_{th} pilot plant.
The results will be presented at scientific conferences and published in peer-reviewed journals.
The results will be used as a basis for doctoral theses.
The results will be used in lectures at Technische Universität Darmstadt.

Result 4c:

With respect to CERTH's contribution to this milestone, the newly proposed EMMS model meets both accuracy and computational effectiveness criteria, being thus, a powerful tool for reactor scale-up and design optimization. It is worth mentioning that this model can also be implemented in other approaches, such as Dense Discrete Phase Method (DDPM) and Discrete Element Method (DEM). Such coupling could be of great scientific interest due to its innovative character, while an even higher accuracy and/or efficiency can be achieved especially for the DDPM-EMMS coupling case. As a first step, CERTH / CPERI provided TUD with the developed EMMS model to further use it and test its capabilities under the DEM framework. As a further step, CERTH/CPERI provided GE with an EMMS map constructed for a new operating point (P2 point of the 1 MW_{th} test campaigns) to be tested under the DDPM framework.

TUD's 3D DEM model will be used in WP3 to support the reactor design of a 20 MW_{th} pilot plant. The model will be further used to optimize the 1 MW_{th} CCL pilot plant setup within the LISA2 project (funded by German authorities).
The results will be presented at scientific conferences and published in peer-reviewed journals.
The results will be used as a basis for doctoral theses.
The results will be used in lectures at Technische Universität Darmstadt.
For GECC the results of the Barracuda modelling will further improve the predictive capabilities of the tool. Beyond the requirements imposed by this research project this will allow expediting the development of GE's carbonate looping technology with regards to bigger scale and time to market.

2.3 Description of the results for WP3 – Scale-up and Engineering of a 20 MW_{th} CCL Pilot Plant

2.3.1 Result 5: Process configurations and nominal operation conditions for 20 MW_{th} plant

Milestone:

MS5 “Process configurations and nominal operation conditions for 20 MW_{th} plant defined”

Description:

The CCL process has so far been demonstrated for very short periods and is still considered not mature enough for large-scale demonstration or even commercial implementation. Hence, more experience is needed to be able to go on to the next technology development step represented by a 20 MW_{th} pilot plant.
Initial investigation of the CCL technology has been done in previous research & development projects at 1 MW_{th} pilot plant scale. The evaluation and validation at this scale will be continued and extended in the WP1 and 2 of the SCARLET project.

Next milestone with respect to commercialization of the process would be the construction and operation of a 20 MW_{th} demonstration plant. An important intermediate step on the path to construction of such an extended pilot plant is the proper setup of process configuration and nominal operation conditions as it is planned in the current project and described in this section.
Thus one of the main objectives of WP3 – Scale-up and Engineering of a 20 MW_{th} CCL Pilot Plant – is the definition of the Calcium Carbonate Looping (CCL) process configuration and operation conditions for the 20 MW_{th} pilot plant, attached to the host facility 600 MW_{el} Emile Huchet coal-fired power plant in Saint Avold/ France operated by UNIPER.
Prior to definition of the best suited process configuration for the 20 MW_{th} pilot plant and nominal operation conditions, tests at adapted 1 MW_{th} TU Darmstadt pilot plant according to milestones MS2 and MS3 of this project shall be conducted. Based on the results achieved from these tests, scale-up tools for the 20 MW_{th} plant scale-up shall be selected and validated (Milestone MS4).
Main objective of WP3 with its milestones MS5 and MS6 is to plan a flexible but also cost-efficient pilot plant for carrying out extensive test programmes including parameter and sensitivity studies. Energy optimization is not the focus of the design considerations of the pilot plant, as the optimum energy efficiency of such a CCL

plant in commercial applications can be evaluated from the test results considering additional provisions and investment for optimized heat recovery.

Summary of results:

- Results achieved so far:

  A Basis of Design (BoD) for the 20 MW_{th} pilot plant has been established. The BoD is consolidating all elementary initial information and boundary conditions required for the design of the 20 MW_{th} field pilot plant based on the current project execution phase and related level of detail. The information collected in the BoD includes for example flue gas feed, coal and limestone composition and physical conditions, as well as definition of the products and utilities required to operate the plant, site conditions and standards to be used. The BoD serves for definition and freezing of the technical and economic basis on which the design of the pilot plant in this project shall be executed.

  The process configuration and control loops for the pilot plant have been defined. The selected concept was depicted in process flow diagrams (PFDs) and a related process description and equipment list was developed. The PFD was complemented with some findings from the health and safety risk assessment (Task 3.12). Further the process configuration included considerations resulting from an Emile Huchet host power plant site visit in Saint-Avold, which served to inspect and discuss the planned plot area for the pilot plant and the integration/tie-in locations to the host plant.

  The definition of the nominal operation conditions for the 20 MW_{th} CCL pilot plant involves definition of a test program (i.e. variation of load, reactor temperatures, circulating sorbent mass flow, sorbent make-up flow, flue gas recirculation, etc) for various operation points of the 20 MW_{th} pilot plant using the experience from 1 MW_{th} plant operation and performing process simulations to calculate related heat and mass balances for each selected operation point.

  Targets of a test program of the 20 MW_{th} pilot plant and related operation points have been collected and discussed during the reporting period. TUD started performing process simulations to calculate heat and mass balances for each selected operation point after test results from Test campaign #1 (Point P2) were evaluated in WP1 and process models developed were validated in WP2 against test data. The nominal operating conditions (heat & mass balance) for the Design case of the 20 MW_{th} CCL pilot plant have been calculated with the validated simulation tools. This allowed to start engineering activities related to milestone MS6 like reactor design, equipment sizing and instrumentation planning.

A detailed plan of measurements needed for evaluation of the carbonate looping process and for extending the validation of related tools to a larger range of scale has been initiated. Experiences and lessons learned with regards to measurement requirements and measurement systems design were gained and collected during the operation of the 1 MW_{th} Pilot plant in WP1 and from the model validation efforts in WP2. The information available so far with regards to measurements was implemented into the PFDs. Due to the novelty of the CCL technology, special solutions with respect to (hot) solid flow measurement and control need to be established. This activity is ongoing.

To understand the main HSE aspects of this technology a HAZID study was completed identifying the potential risk associated with the technology and the materials handled. The results of the HAZID study were incorporated into a risk mitigation plan.

- Expected results:

With respect to MS5 the process configuration is essentially finalized; however, GECC will continue to incorporate updates in case required modifications arise from the ongoing design and engineering of the 20 MW_{th} Pilot plant. The definition of a test programme for various operation points of the 20 MW_{th} pilot plant and the performance of process simulations to calculate heat and mass balances for each selected operation point will get completed

It is expected that the consolidated process configuration properly reflects the scale-up to field pilot size compared to currently realized pilot plants of a few MW_{th}. Further the definition of various operating points to be tested at the 20 MW_{th} pilot plant in connection with operating conditions of the host power plant will allow to provide sufficient flexibility in the pilot plant design to accommodate this test program.

The results derived from this milestone will allow operators of coal-fired power plants to understand the challenges and opportunities for the integration of a CCL pilot plant into an existing or new power plant. Of particular interest will be the aspects related to the management of fresh and spent sorbent which, due to the large quantities involved, will be new to power plant operators.

With respect to measurements it is expected to achieve a detailed concept on the measurement and controls requirements for a CCL plant of the proposed scale and for further validation of the technology and related modelling tools for further scale-up to commercial size

<u>Further collaboration, dissemination and use of the results:</u>

For the further collaboration and use in the SCARLET project, results gathered in MS5 of WP3 will be directly used in the tasks that are summarized in MS6. Thus, collaboration with all project partners involved in the preparation of WP3 is necessary.

The results of this milestone will be disseminated through the regular dissemination activities foreseen for the SCARLET project (website, newsletters, workshops, reports and publications). Dissemination of the particular results from this milestone will be integral part of the overall project and its results.

With respect to the proposed online mass flow measurement system based on the concept developed in this milestone, technical realization into a commercial product might be started by the involved company SWR if a technically feasible and techno-economically reasonable solution can be found.
GE will review the results of MS5 and, if applicable, feedback certain solutions into its own carbonate looping technology.

2.3.2 Result 6: Scale-up and Engineering of a 20 MW_{th} CCL Pilot Plant

<u>Milestone:</u>

MS6 "Engineering for 20 MW_{th} plant completed"

<u>Description:</u>

Second main objective to achieve in WP 3 – Scale-up and Engineering of a 20 MW_{th} CCL Pilot Plant – is the engineering of the 20 MW_{th} pilot plant after the process configuration and nominal operating conditions have been defined in MS5. Engineering includes the design of the CCL reactor system components with all required auxiliaries including all equipment required in the steam-water cycle for heat recovery. Further it involves design of coal, sorbent, O_2 supply and CO_2 purification systems. CCL Reactor design includes the CFD modelling (developed in WP2) and preparation of CAD drawings as well as investment cost estimation. For other equipment investment cost estimation is also to be performed.

MS6 also includes the preparation of Piping and Instrumentation Diagrams (P&ID) and development of a plant layout arrangement by means of a 3-D CAD software model. A concept of the supply (coal and sorbent), utilities (cooling water, technical gases and electric power), as well as of the waste management (ash and deactivated limestone) shall be prepared. This concept shall include estimation of the related investment costs for major utility supply requirements as well as estimation of the operational and maintenance costs.

Normal operation, start-up and planned/emergency shutdown procedures using the experience from 1 MW_{th} CCL pilot plant operation shall also be defined. Dynamic behavior of the 20 MW_{th} pilot plant during start-up, shutdown and other major transient scenarios shall be investigated by simulations with the unsteady (transient) process model developed in WP2.

<u>Summary of results:</u>

- Results achieved so far:

  Design and engineering of the reactors and auxiliary systems have been started and integration aspects to the host plant's existing auxiliary systems with were discussed with plant owner UNP. GECC started to perform 3D simulation of the two reactors of the scaled-up pilot plant with the CFD model developed and validated in WP2. The Carbonator reactor of the 20 MW_{th} pilot plant as currently foreseen was modelled and the modelling results confirmed the targeted performance.

  CERTH/CPERI developed an Eulerian CFD model for the 20 MW_{th} plant carbonator unit based on the validated model in WP2 and started the performance simulation. GECC set up the cooperation with the third party Alstom Power Inc. (API) in Windsor/USA to support this task.

  SBE started the design and engineering of the water/steam cycle and discussed steam/water cycle integration aspects to the host plant's existing steam/water cycle system with plant owner UNP.

  GECC started the design and engineering of the coal, sorbent, O_2 supply and CO_2 purification systems and discussed coal and sorbent integration aspects to the host plant's existing coal and limestone (for WFGD) systems with plant owner UNP. Messinghausen limestone from LRD was selected for the design of the 20 MW_{th} pilot. GECC set up the cooperation with the third party GE Boiler Deutschland GmbH (GEBD) in Stuttgart/Germany to support this task

  Preparation of Process and Instrumentation Diagrams (P&IDs) for the 20 MW_{th} Pilot plant has been started. Further the plant layout planning has been initiated with a visit of the host site.and agreement on cooperation procedures and software tools to be used for exchange of the 3D CAD modelling.

An evaluation of the process to obtain the required permits for erection and operation of the 20 MW_{th} pilot plant from authorities in France has been completed.

- Expected results:

Design and engineering of all major CCL reactor system components including auxiliaries TUD, CERTH/CPERI will be completed and 3D simulations of the two reactors of the scaled-up pilot plant will be performed with the CFD models developed and validated in Task 2.3. CERTH/CPERI received a proper geometry 3D design, numerical grid and boundary / operating conditions from TUD and developed an Eulerian CFD model for the 20 MW carbonator unit based on the validated model in WP2. Final results that would validate the 20 MW carbonator design is able to deliver the required capture efficiency are not yet available.

Design and engineering of the coal, sorbent, O_2 supply and CO_2 purification systems as well as of the steam/water cycle will be completed.

Normal operation, start-up and planned/ emergency shut-down procedures will be defined using the experience from 1 MW_{th} CCL pilot plant operation and unsteady process simulation models.

The planning for the supply of consumables (e.g. coal, sorbent) and utilities (technical gases, steam, auxiliary electrical power, cooling water, etc.) and disposal of residuals (e.g. ash, deactivated limestone) will be completed.

Required process instrumentation including analytical equipment and control loops will be defined, major piping/ducts will be sized. Basic process and instrumentation diagrams (P&IDs) for the 20 MW_{th} CCL pilot plant as well as the plant layout planning in a 3D CAD software model will be completed.

A technical risk analysis based on the Failure Mode Effect Analysis method (FMEA) will be executed and provide an understanding of the potential technical risks associated with the technology.

The evaluation of the process to obtain the required permission for the erection and operation of the 20 MW_{th} pilot from the authorities will be completed and will provide an understanding of the requirements for the 20 MW_{th} pilot plant with regards permission.

The overall investment cost, operation cost and maintenance cost for the 20 MW_{th} pilot plant will be estimated.

It is expected that with completion of MS6 sufficient information on the engineering strategies is available allowing designers and operators to understand the way in which a CCL pilot plant will be integrated into coal-fired power plants, and to enter the next phase of technology development for the CCL process by starting the planning and erection of a 20 MW_{th} field pilot in a follow-up project. It is expected that a 20 MW_{th} CCS pilot plant is designed as defined in the milestones.

The design of and interconnection between carbonator and calciner are particularly important because these are novel technologies applied in the power generation industry or other relevant industry sections like cement or iron & steel production. The optimised integration of the CCL process into the water/steam cycle is interesting as it has the potential to reduce the parasitic loss required for CO_2 capture from flue gases. A very important outcome of this milestone will be the determination of the costs (CAPEX and OPEX) associated with this technology.

Further collaboration, dissemination and use of the results:

The results of this milestone will be disseminated through the regular dissemination activities foreseen for the SCARLET project (website, newsletters, workshops, reports and publications). Dissemination of the particular results from this milestone will be integral part of the overall project and its results.

CCL is a second generation technology for post-combustion CO_2 capture with the potential of offering significantly reduced energy penalty without the production of large quantities of by-products that require waste disposal with special regulations regarding their handling. Spent sorbent generated in the CCL process is a valuable by-product that can be utilized e.g. in the cement production. The CCL technology is suitable for retrofit and for new power plants or industrial processes. The main application target for the CCL technology is CO_2 capture and storage or utilization (CCS/CCU) applied to fossil-fuelled power plants and to intensive CO_2 emitting industrial processes such as cement and iron & steel industries.

CCL itself is excellent for revamp and implementation in power and industrial processes as it will produce power and compensate the loss of net power output due to the energy penalty.

SCARLET will bring CCL technology to the next level of maturity, preparing the ground for pre-commercial demonstration of this promising technology. The results of WP3 will give confidence for investments into a larger-scale 20 MW_{th} unit. This will finally facilitate the design of a future large-scale demonstration project, aiming at short term commercialization of the process.

The cost estimate resulting from WP3 will provide a sound basis to start a discussion between the various stakeholders (universities and research institutes, industrial partners and funding organizations) on how to finance and realize this essential next technology development step.

The health and safety risk assessment as well as technical risk analysis done in WP3 will identify potential risks, allow to develop related mitigation plans and thus increase confidence level for realization of the 20 MW pilot plant.

The further implementation of the results shall lead to the construction of the planned 20 MW_{th} pilot in collaboration with a power plant owner or other industrial partner in a follow-up project. The proposed 20 MW_{th} scale pilot plant will be an important step towards commercialization of the technology.

In particular interesting is also the application of the CCL technology in industrial processes like steel or cement production. Industrial installations are generally smaller in size compared to power plant applications. Therefore smaller size designs retrieved during the development of the large scale power plant CCL technology may be already transferable into industrial solutions. The application of CCL technology in these sectors requires much smaller scale-up steps compared to power plants. Further, due to the fact that key principles of the CCL process are also used in industrial applications like cement or iron & steel, the introduction of this technology to these industrial sectors is simplified. Existing infrastructure and other process equipment may be used, thus minimizing the expenditures for the total installation. This means commercialization can be realized in a reasonable time frame based on the knowledge gained on the operation of the 20 MW_{th} pilot plant. However, CCL technology may also be interesting for incorporation into waste incineration plants or biomass power stations which would normally require a scale-up of the planned pilot plant by a factor of 3 to 5 only. A demonstration of the applicability of the CCL process at 20 MW_{th} scale could thus end up in a commercialization in such applications within the next decade.

However, Steinmüller Babcock Engineering (SBE) believes that while this demonstration plant – if financed and built in the future – will prove the availability of an efficient CCS technology, this technology will remain in pilot scale as long as political and public acceptance of carbon storage does not change substantially. Thus SBE is not expecting that the developed technology will be implemented in a commercial scale plant in the near future.

2.4 Description of the results for WP4 – Integration of CCL into a Full-scale Hard Coal Power Plant

2.4.1 Result 7: Hard coal Fired Host Plant for Full-scale Application

Milestone:

MS7 “Host plants for full scale applications to hard coal fired power plants defined”

Description:

Main objective of this milestone is to select an existing or planned hard coal power plant that shall be equipped with a CCL unit. In the course of the task, boundary conditions shall be defined in a Basis of Design (BoD) and reconciled with work packages WP5 and WP6 to guarantee comparability of the results for the different plants. Based on the selected hard coal power plant and the conditions defined in the BoD, the process model developed in WP2 will be scaled up to calculate heat and mass balances and net electrical efficiency of the power plant.

Summary of results:

- Results achieved so far:

  MS7 has been completed with the selection of Uniper’s Emile Huchet Unit 6 as the host coal-fired power plant. Full description of this plant has been documented in Deliverable 4.1. The basis of design and the boundary conditions defined in this milestone have provided the information needed to complete the environmental and techno-economic evaluation by the end of the project.

Further collaboration, dissemination and use of the results:

For the further collaboration and use in the SCARLET project, results gathered in MS7 of WP4 will be directly used in the tasks that are summarized in MS8.

The results of this milestone will be disseminated through the regular dissemination activities foreseen for the SCARLET project (website, newsletters, workshops, reports and publications). Dissemination of the particular results from this milestone will be integral part of the overall project and its results.

For reconciliation of the boundary conditions of the hard coal plant of this work package with the data defined in the WP5 and WP6 collaboration with the work package owners RWE (WP5) and CEMEX, Arcelor Mittal (AM) and Ulster (WP6) is required.

2.4.2 Result 8: Assessment for Full-scale Application to Hard Coal Power Plant

Milestone:

MS8 “Assessment for full scale applications to hard coal power plants completed”

Description:

This milestone comprises an economical as well as an environmental assessment of the CCL integrated in a hard coal power station. For the economical assessment investment and operational costs for the CCL unit shall be evaluated and based on this data cost of electricity (CoE) and cost of CO_2 avoiding shall be calculated using ECLIPSE software. Furthermore, these results achieved for the CCL technology shall be compared to other CCS solutions.

With respect to environmental assessment of CCL for a hard coal power plant a report on the environmental impacts of the proposed technology shall be prepared. This report will address the exposure of potential hazards to human, wildlife, and bio-systems.

Summary of results:

- Results achieved so far:

  The activities required to execute MS8 have started and will be completed by the end of the project as scheduled. These include a thermodynamic evaluation followed by an economic and environmental assessment of the CCL process.

- Expected results:

  It is expected that this milestone will provide enough information to have a good understanding of the main environmental aspects of this technology, of which the management of large quantities of fresh and spent sorbent will be particularly important. A thermodynamic evaluation will provide the opportunity to determine the challenges and opportunities for the integration of large energy streams between the CCL process and the power plant, with the potential to reduce the parasitic energy required for CO_2 capture from flue gases. Finally, an economic evaluation will determine the expected cost of the CCL process for comparison with other competing CO_2 capture technologies.

Further collaboration, dissemination and use of the results:

The results of this milestone will be disseminated through the regular dissemination activities foreseen for the SCARLET project (website, newsletters, workshops, reports and publications). Dissemination of the particular results from this milestone will be integral part of the overall project and its results.

The results from the economical assessment can be used as a first reference point for the future commercialization of the technology. The ecological assessment will also help to identify potentially environmental critical issues that need to be solved or mitigated prior commercialization. These results will enable plant engineering companies in collaboration with plant operators to focus on technology optimization with respect to economic and environmental point of view.

2.5 Description of the results for WP5 – Integration of CCL into a Full-scale Lignite Power Plant

2.5.1 Result 9: Lignite Fired Host Plant for Full-scale Application

Milestone:

MS9 “Host plants for full scale applications to lignite fired power plants defined”

Description:

Selection of an existing or planned lignite power plant to be equipped with a CCL unit; basis of design; definition of boundary conditions reconciled with WPs 4 and 6 to guarantee the comparability of the results for the different plants considering the European Benchmarking Task Force definitions.

Summary of results:

- Results achieved so far:

  MS9, the definition of a host plant, was reached in time. It was decided to select the lignite fired power plant unit BoA1 (1000MW, net efficiency>43%). Detailed description of the power plant and the reasons for its selection is presented in chapter WP5 in mid-term report.

- Expected results:

  Considering the decisions of the policy makers for a long term reduction of CO_2 emissions in the field of electricity production, CCS can play a vital role to fulfill these obligations. IPCC’s Fifth Assessment Synthesis Report found that most climate models could not meet emissions reduction targets without CCS.

Crucially, without CCS, the cost of mitigation would more than double. Over the long term, coal will be the cornerstone of a sustainability-focused energy supply both on a global and on a national scale. For this reason RWE is pressing ahead with the development of technologies that will provide us with a foundation for sustainable coal-based power generation. Therefore RWE investigates, develops and tests different carbon capture technologies.

The calcium carbonate looping (CCL) process has the potential of higher efficiencies and lower CO_2 avoidance costs compared with other carbon capture technologies.

The work packages 1 (long term pilot testing), 2 (development and validation of scale up tools) and 3 (scale up and engineering for a 20 MW_{th} CCL pilot plant) of the SCARLET project will deliver reliable information and tools for the scale up of the CCL process. The results gained in this work packages are the basis for WP5, the evaluation of the process regarding full scale implementation to a full scale lignite fired power plant.

Task 5.1 (Plant definition) started according to schedule in month 12 and has been completed with milestone MS9 in month 24 (March 2016) with the selection of the host plant, the basis of design and the definition of the boundary conditions.

The work on techno-economical analysis (Task 5.2 Thermodynamic evaluation, Task 5.3 Economic evaluation) as well as an environmental assessment (Task 5.4) started on schedule, to identify efficiency, CO_2 avoidance costs and environmental impacts of the proposed technology.

RWE expects that the results of WP1, 2 and 3 will represent a reliable basis for the evaluations to be conducted in WP5. It is expected, that the results of WP5 will give RWE solid information to compare calcium carbonate looping with other carbon capture technologies. Based on this comparison it will be decided, if and to what extend a scale up of the carbonate looping technology should be realized. Erection and operation of a pilot plant with a scale of 20 MW_{th} would be an important step towards commercialization of the technology and give valuable and necessary insights particularly with regard to full scale operation. Further collaboration between plant manufacturers, renowned universities and plant operators will be essentially required for successful up scaling.

Further collaboration, dissemination and use of the results:

The results of this milestone will be disseminated as defined per grant agreement with EU. Dissemination of the particular results from this milestone will always be integral part of the overall project and its results.

2.5.2 Result 10: Assessment for Full-scale Application to Lignite Fired Power Plant

Milestone:

MS10 “Assessment for full scale applications to lignite power plants completed”

Description:

This milestone comprises an economical as well as an environmental assessment of the CCL integrated into a lignite-fired power station. For the economical assessment investment and operational costs for the CCL unit shall be evaluated and based on this data cost of electricity (CoE) and cost of CO_2 avoiding shall be calculated using ECLIPSE software. Furthermore, these results achieved for the CCL technology shall be compared to other CCS solutions.

With respect to environmental assessment of CCL for a lignite power plant a report on the environmental impacts of the proposed technology shall be prepared. This report will address the exposure of potential hazards to human, wildlife, and bio-systems.

Summary of results:

- Results achieved so far:

  The activities required to execute MS10 have started and will be completed by the end of the project as scheduled. These include a thermodynamic evaluation followed by an economic and environmental assessment of the CCL process.

- Expected results:

  Starting in month 25 of the project the techno-economic analysis as well as an environmental assessment will be conducted, to identify efficiency, CO_2 avoidance costs and environmental impacts of the proposed technology.

  RWE expects that the results of WP1, 2 and 3 will represent a reliable basis for the evaluations to be conducted in WP5. It is expected, that the results of WP5 will give RWE solid information to compare calcium carbonate looping with other carbon capture technologies. Based on this comparison it will be decided, if and to what extend a scale-up of the carbonate looping technology should be realized. Erection and operation of a pilot plant with a scale of 20 MW_{th} would be an important step towards commercialization of the technology and give valuable and necessary insights particularly with regard to full scale operation. Further collaboration between plant manufacturers, renowned universities and plant operators will be essentially required for successful scale-up.

Further collaboration, dissemination and use of the results:

The results of this milestone will be disseminated through the regular dissemination activities foreseen for the SCARLET project (website, newsletters, workshops, reports and publications). Dissemination of the particular results from this milestone will be integral part of the overall project and its results.

The results from the economical assessment can be used as a first reference point for the future commercialization of the technology. The ecological assessment will also help to identify potentially environmental critical issues that need to be solved or mitigated prior commercialization. These results will enable plant engineering companies in collaboration with plant operators to focus on technology optimization with respect to economic and environmental point of view.

2.6 Description of the results for WP6 – Integration of CCL into Full-scale Industrial Plants

2.6.1 Result 11: Host Cement Plant for Full-scale Application

Milestone:

MS11 “Host Cement Plant Defined”

Description:

Following the experience acquired in the EU FP7 DECARBIT project, the Technology Roadmap for carbon capture and storage in Industrial applications, published by the International Energy Agency and the United Nations Industrial Development Organization, the first main objective to be achieved in WP6 is the selection of an existing or planned Cement Plant in order to establish the basis of design and integration of a CCL unit for the selected plant and define its Boundary Conditions. Considering the European Benchmarking Task Force definitions, the Boundary Conditions of the selected host Cement plant will not only be reconciled with those of the Hard Coal and Lignite plants in order to guarantee the comparability of their results, but they will be used to scale-up the process model developed in WP2 and calculate the Heat and Mass balances, as well as the

Thermal Efficiency of the selected Cement Plant with the integrated CCL Technology. CEMEX will also perform a series of standard laboratory tests in order to ascertain whether the purges from the CCL process can be used in the selected host plant as raw material or filler in the production of clinker and/or cement.

Summary of results:

- Results achieved so far:

  ULSTER reported the Boundary Conditions and integration of a CCL unit for an assumed cement plant to be built at a new site, i.e. as a green field site, including all installations to the fence and CEMEX is using this report as a guideline to establish the Boundary Conditions and the design of an integrated CCL unit for the Ruedersdorf plant in Germany that has been selected as the host plant for the cement industry.

  CEMEX has also performed standard laboratory tests with the purges obtained in the first Pilot Plant campaign ran with Hard Coal as a fuel. The Chemical and Mineralogical reports show, in principle, that the purges could be incorporated without any problem into the raw meal of a cement plant in order to produce clinker. In order to ascertain this, a series of laboratory tests will be conducted with Raw Meal and Clinker from the selected CEMEX Ruedersdorf host plant site.

- Expected results:

  If the results of the laboratory tests that will be conducted with the purges obtained from the first Pilot Plant campaign show that their incorporation into the Raw Meal and/or Clinker of the selected host plant is totally compatible, the expected increase in Clinker production for the selected host plant can be significant and greater than the 20% predicted in the general report made in a similar C3-CAPTURE FP6 project. This would also result in a significant reduction in the footprint of the process related CO_2 emissions and would constitute a strong case for the incorporation of a CCL unit into an existing or a new cement plant.

- Further collaboration, dissemination and use of the results:

  The results of this milestone will be disseminated as defined in the grant agreement with the EU. At the same time, and since CEMEX is an active member of the European Cement Research Association (ECRA), the dissemination of the particular results from this milestone MS11 will be an integral part of the report of its activities in CO_2 Capture and if positive, will definitely start to draw the attention of ECRA towards the use of CCL as a viable CO_2 Capture technology within the alternative options that ECRA has been evaluating in order to establish a general recommendation for its members.

2.6.2 Result 12: Assessment for Full-scale Application to Cement Plant

Milestone:

MS14 “Assessment for full scale applications to cement plant completed”

Description:

Third main objective to be achieved in WP6 – Assessment for Full Scale Applications to Cement Plant – is the Assessment of a potential existing cement production plant to be equipped with a full scale CCL unit as has been defined in MS11. Assessment includes the Thermodynamic and Economic evaluation, as well as the Environmental Assessment of CCL for a cement plant. The Thermodynamic evaluation will be performed by scaling up the process model developed in MS4 in order to calculate heat and mass balances and thermal efficiency of the plant defined in MS11. The Economic evaluation will then follow by handling the estimation of investment and operational costs for the CCL unit in order to calculate the cost of electricity (CoE) and the cost of CO_2 avoided and the CCL technology will be evaluated by comparing it to other CCS solutions. The Environmental assessment will report on the environmental impacts of the proposed plant technology and address the exposure of potential hazards to human, wildlife, and bio-systems.

Summary of results:

- Results achieved so far:

  The activities required to execute MS14 have started and will be completed by the end of the project as scheduled. These include a thermodynamic evaluation followed by an economic and environmental assessment of the CCL process.

- Expected results:

  Cement production has two major CO_2 emission points: fuel combustion to provide process heat (30 %) and process-related emissions (60 %; due to the decomposition of $CaCO_3$). Although some reductions in emissions have been so far achieved with the use of clinker substitution with waste materials from other process industries, fuel switching and changes in output, the CCL technology should help achieve much higher levels of reduced CO_2 footprint by suitably retrofitting or installing CCL technology in new cement plants.

Thus, the completion of MS14 should by itself provide significant and needed research results into developing CCL as a fundamental process within cement manufacture. The results are expected to positively address and resolve key barriers and challenges, such as the high decay in sorbent's capture capacity, or its proper use as a raw material or filler and provide a proper scale-up of the technology with high operating temperature and effective heat exchange designs. Regarding the Economic and Market Factors, the System is expected to be significantly cheaper than current methods due to abundant sorbent (limestone), harmless exhaust gas, low energy penalty and operational costs, considering the fact that it can generate steam from heat released in the carbonation reaction. Nevertheless, a very important outcome of this milestone will be the determination of the costs (CAPEX and OPEX) associated with this technology. The economic assessment will be made in terms of cost of cement/or steel against specific investment, raw material cost, electricity cost, fuel price, percentage change in operations and maintenance costs and capacity factor.

The environmental assessment of the CCL technology integration within the proposed cement plant will be implemented by the group. A report on the environmental impacts of the cement plant with CO_2 capture addressing the exposure of potential hazards to human, wildlife, and bio-systems will be prepared.

Further collaboration, dissemination and use of the results:

The results achieved in this milestone will be disseminated through the regular dissemination activities foreseen for the SCARLET project (website, newsletters, workshops, reports and publications). Dissemination of the particular results from this milestone will be integral part of the overall project and its results.

Since CEMEX is an active member of the European Cement Research Association (ECRA), the dissemination of the particular results from this milestone MS14 will be an integral part of the report of its activities in CO_2 Capture.

Since the results of MS14 will prepare the ground for the application of CCL technology to the cement sector, CEMEX is committed to collaborate fully with the equipment providers within the consortia to see if the designs retrieved during the development of the large scale power plant CCL technology may be already transferable into solutions for a cement plant. Given the smaller size of the cement installations, it is quite possible that existing infrastructure and other process equipment may be used to implement the CCL technology, thus minimizing the expenditures for the total installation and achieving commercialization in a shorter time frame.

CEMEX is also aware of the fact that the main application target for the CCL technology is not only CO_2 capture, but its storage or utilization (CCS/CCU) and in evaluating the results of MS14 it will also take into account the Value Creation, Commercial Dynamics, Market Demand and Costs associated with CCS/CCU.

2.6.3 Result 13: Host Steel Plant for Full-scale Application

Milestone:

MS12 “Host steel plant defined”

Description:

Following the experience acquired in the EU FP7 DECARBit project, the published results of the ULCOS project (Steel making) and the Technology Roadmap for carbon capture and storage in industrial applications, published by the International Energy Agency and the United Nations Industrial Development Organization, the research group will select existing steel production plants to be equipped with a CCL unit. ULSTER and CERTH will provide the basis of design and the boundary conditions for the selected steel production plant. The definition of boundary conditions will be reconciled with cement plant as well as with WP4 and WP5 to guarantee the comparability of the results for the different plants. In this package the CCL models validated in WP2 will be used to define the processes of full scale steel production plant. The effect of operating conditions on the process efficiency, economics and environment will be evaluated.

Main objectives of WP6 are:

1) Evaluation of the process regarding full-scale implementation to steel production plants;

2) Techno-economic analysis, identification of steel production cost and cost of CO_2 avoided evaluating CCL technology compared to other CCS solutions;

3) Assess the environmental impact of CCL system by conducting a life cycle analysis (LCA).

Summary of results:

- Results achieved so far:

  There are four major processes for steel production:

  - Blast Furnace / Basic Oxygen Furnace route
  - Direct melting of scrap (electric arc furnace)
  - Smelting Reduction
  - Direct Reduction

  Steel Production in EU-27 (2006 data) was primarily by the blast furnace / basic oxygen route (approximately 59.8 %) and the electric arc furnace (EAF) route (approximately 40.2 %). CO_2 emission from Electric Arc Furnace is mainly due to power generation. For this report, the hot metal production by blast furnace of 83.8 million tons is considered as a representative size and scale of integrated steel plant in Europe.

  The system boundary is defined as: Sinter Plant (87 million tons raw material), Coke Oven Plant (30 million tons coke), Blast Furnace (84 million tons hot metal) and Power Plant. According to references the sources of CO_2 emissions are from flue gases sinter plant (15 %), coke oven plant (16 %), blast furnace (20 %) and power plant (40 %). This consists of ~90 % of the total CO_2 emissions from the steel making process.

  <u>Result 13a:</u>

  CERTH/CPERI conducted a preliminary analysis regarding the capture and exploitation of CO_2 in a steel power plant. More specifically, it was concluded that a considerable amount of valuable fuel (methanol) can be produced from the captured CO_2 and the recovered H_2 that is available in high volumetric concentration (>60%) in Coke Oven Gasses (COG). Exept for this gas stream, significant amounts of H_2 exist in other streams (but with a lower concentration) in a steel manufacturing plant that can be also utilized under a Carbon Capture and Utilization process. Preliminary, results show that Hydrogen recovery is feasible from the COG stream with and without COG reforming prior to H2 recovery by a pressure swing adsorption unit. Further analysis of the whole steel production plant including the integration with the power plant and the CaL unit for CO2 capture is required to properly evaluate this idea.

- Expected results:

  The results derived from this milestone will allow operators of steel production plants to understand the challenges and opportunities for the integration of a CCL plant into an existing or new steel production plant. The basis of design and the boundary conditions defined in this milestone together with the heat and mass balance and thermal efficiency of the steel plants integrating CCL technology will provide the information needed to complete the environmental and techno-economic evaluation by the end of the project.

Further collaboration, dissemination and use of the results:

For the further collaboration and use in the SCARLET project, results gathered in MS12 of WP6 will be directly used in the tasks that are summarized in MS15.

The results achieved in MS12 will be disseminated through the regular dissemination activities foreseen for the SCARLET project (website, newsletters, workshops, reports and publications). Dissemination of the particular results from this milestone will be integral part of the overall project and its results.

For reconciliation of the boundary conditions of the steel production plant selected in this work package with the data defined in the WP4 and WP6 collaboration with the work package owners UNIPER (WP4) and RWE (WP5) as well as with participants of this work package (WP6) CEMEX and Ulster is required.

2.6.4 Result 14: Assessment for Full-scale Application to Steel Plant

Milestone:

MS15 “Assessment for full scale applications to steel plant completed”

Description:

Fourth main objective to be achieved in WP6 – Assessment for Full Scale Applications to Steel Plant – is the Assessment of a potential existing steel production plant to be equipped with a full scale CCL unit as has been defined in MS12. Assessment includes the Thermodynamic and Economic evaluation, as well as the Environmental Assessment of CCL for a steel plant. The Thermodynamic evaluation will be performed by scaling up the process model developed in MS4 in order to calculate heat and mass balances and thermal efficiency of the plant defined in MS12. The Economic evaluation will then follow by handling the estimation of investment and operational costs for the CCL unit in order to calculate the cost of electricity (CoE) and the cost of CO_2 avoided and the CCL technology will be evaluated by comparing it to other CCS solutions. The Environmental assessment will report on the environmental impacts of the proposed plant technology and address the exposure of potential hazards to human, wildlife, and bio-systems.

Summary of results:

- Results achieved so far:

  The activities required to execute MS15 have started and will be completed by the end of the project as scheduled. These include a thermodynamic evaluation followed by an economic and environmental assessment of the CCL process.

- Expected results:

  Completion of MS15 should by itself provide significant and needed research results into developing CCL as a fundamental process within steel production. The results are expected to positively address and resolve key barriers and challenges, such as the high decay in sorbent's capture capacity, or its proper use as a raw material in steel production and provide a proper scale-up of the technology with high operating temperature and effective heat exchange designs. Regarding the Economic and Market Factors, the System is expected to be significantly cheaper than current methods due to abundant sorbent (limestone), harmless exhaust gas, low energy penalty and operational costs, considering the fact that it can generate steam from heat released in the carbonation reaction. Nevertheless, a very important outcome of this milestone will be the determination of the costs (CAPEX and OPEX) associated with this technology. The economic assessment will be made in terms of cost of steel against specific investment, raw material cost, electricity cost, fuel price, percentage change in operations and maintenance costs and capacity factor.

  The environmental assessment of the CCL technology integration within the proposed steel plant will be implemented by the group. A report on the environmental impacts of the steel plant with CO_2 capture addressing the exposure of potential hazards to human, wildlife, and bio-systems will be prepared.

Further collaboration, dissemination and use of the results:

The results achieved in this milestone will be disseminated through the regular dissemination activities foreseen for the SCARLET project (website, newsletters, workshops, reports and publications). Dissemination of the particular results from this milestone will be integral part of the overall project and its results.

Since the results of MS15 will prepare the ground for the application of CCL technology to the steel sector, AM collaborates fully with the equipment providers within the consortia to see if the designs retrieved during the development of the large scale power plant CCL technology may be transferable into solutions for a steel plant. Given the smaller size of the steel installations, it is quite possible that existing infrastructure and other process equipment may be used to implement the CCL technology, thus minimizing the expenditures for the total installation and achieving commercialization in a shorter time frame.

Evaluating the results of MS15 it will also take into account the Value Creation, Commercial Dynamics, Market Demand and Costs associated with CCS/CCU.