PUBLIC LEILAC PRE-FEED SUMMARY REPORT

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Project LEILAC | Low Emission Intensity Lime and Cement project

Public LEILAC pre- FEED Summary Report

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The enhancements to the core technology are subject to pending patents. As much has been made public as is possible at this time.

Contents

List of figures

1 Executive Summary

The LEILAC project (Low Emissions Intensity Lime And Cement) will successfully pilot a breakthrough technology that aims to replace an existing part of the cement and lime making process, and enable the capture of unavoidable process carbon dioxide (CO_2) emissions without significant energy penalty (just compression) at comparable capital costs to conventional emitting equipment.

The LEILAC project is primarily based on the development and testing of a suitably sized pilot plant to validate the technology and facilitate scale up. Constructed next to the HeidelbergCement's plant at Lixhe, Belgium, the pilot will function in a realistic operating environment. The project will follow engineering stage gates to ensure that the concept is developed accurately and on time, minimising risks and ensuring that no grant funds are wasted. As such a significant amount of work will take place early within the project to understand and mitigate key known risks.

The LEILAC partners are dedicated to knowledge sharing as widely as possible, and this Pre-FEED summary represents the evolution, achievements and intentions of this initial phase of the project. As such, this report summarises the main research, development and engineering actions contributing to the first formal project stage-gate. It covers the period from the commencement of the project in January 2016 to the go/no go decision in October 2016.

Throughout the pre-FEED a number of research, modelling, design evaluation and enhancement studies have been successfully undertaken for the pilot plant, with the aim of reducing the major scale-up risks. A detailed Basis of Design (BoD) of the pilot plant was created, fulfilling all of the objectives of the project. The exact site of the LEILAC pilot unit within the host plant at Lixhe has also been agreed and tie-in points identified. Comprehensive safety and environmental risk assessments have been completed. In addition to a recommendation on the design option for development, costs for the pilot's construction have been evaluated to within a ±30% level of accuracy.

The resulting design option, discussed within this report, was accepted by the project's governing bodies, and the project will now enter the next stage of development. During the FEED phase a detailed design of the pilot and its equipment will be developed, along with its integration into the HeidelbergCement cement plant at Lixhe, Belgium. The process for construction of the plant will be determined, and a ±15% cost estimate generated for approval. This will underpin the Final Investment Decision in mid-2017.

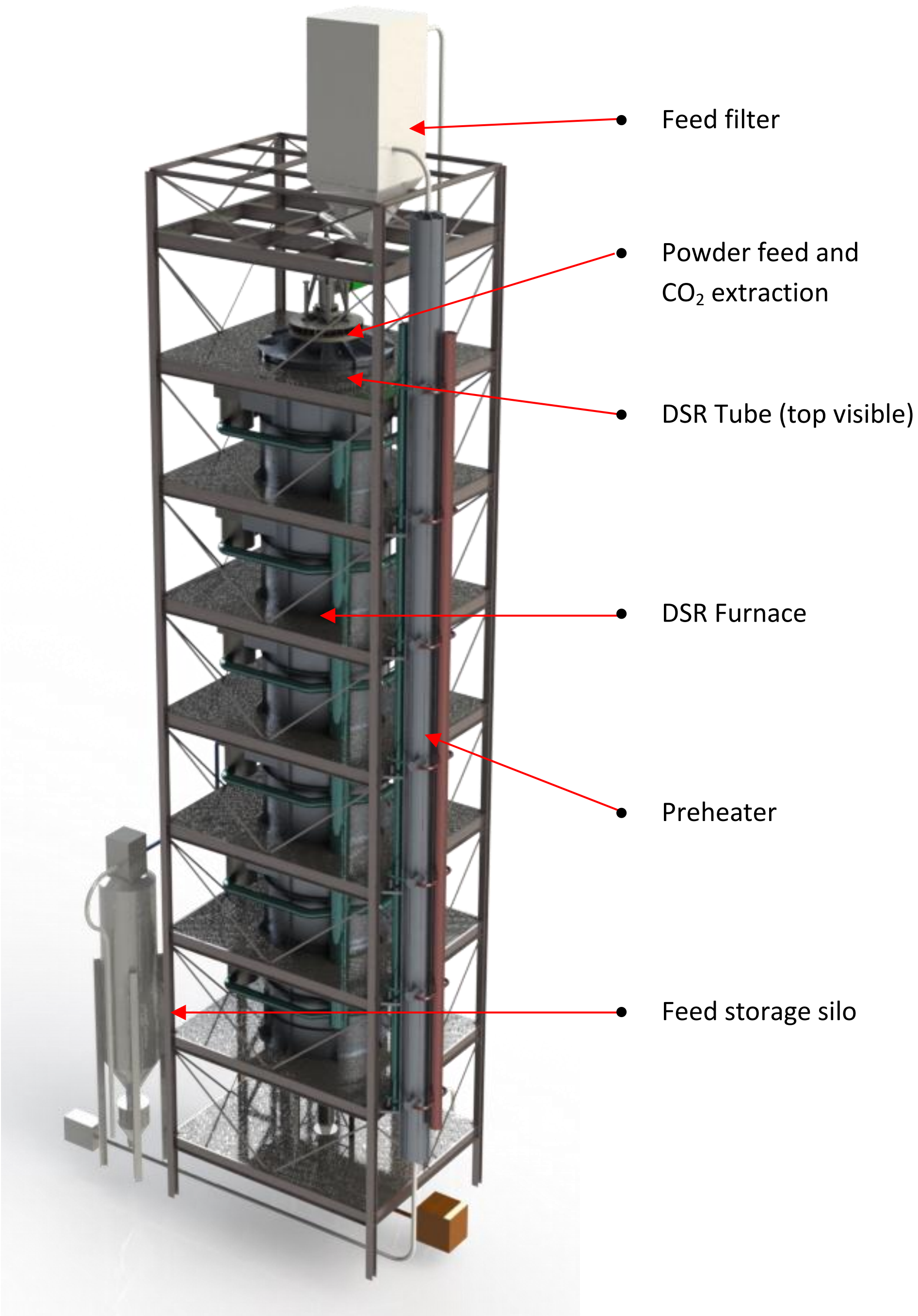

Figure 1 – 3D view of the LEILAC pilot

2 Introduction

The LEILAC project is divided into a number of milestones, the first of these (MS1) at month 10 is the Pre-FEED (Preliminary Front End Engineering Design) to FEED stage gate. The objective of Pre-FEED was to determine whether the project can proceed into the more detailed design phase based on a number of criteria: that the major risks for applying this technology to the cement and lime sectors at this scale are considered, that future integration risks start to be mitigated and designed for, that a resulting suitable design of the pilot is produced that is technically viable, that the pilot will fulfil the operational objectives of the overall project, and that it is within the cost constraints of the budget. The cost estimate for the Pre-FEED should aim to achieve a variance of +/-30%. The governing bodies were to be shown that the major risks have been considered, given a recommended design option for development, and cost estimates resulting in a go/no go decision.

This report is split into a number of sections, reflecting the main interdependent areas of activity taking place in support of the pre-FEED conclusions.

- The report starts with a brief recap of the Pre-FEED objective and a basic overview of the LEILAC project to provide context for the report.
- When applied to the cement and lime sectors the technology faces a number of key risks and design challenges. These risks have been carefully assessed by the project partners, and dedicated **research and development actions** were implemented to understand and address these risks. Section 4 discusses the main risks, and then the actions, findings and conclusions that have been made on the major areas of focus.
- Section 5 outlines the **Basis of Design and Engineering** which establishes the design criteria and assumptions for the main systems involved in the pilot plant. In addition to utilising the research and development activity mentioned above, the Design builds on the experience gained by Calix through the development of the CFC850 pilot plant and the CFC15000 production demonstration plant.
- Section 6 provides a summary of the **Preliminary Front End Engineering Costing**, built from the Basis of Design and Engineering activity and early procurement actions.
- Section 7 provides a brief overview of the **Pre-FEED results, and the next steps** for the project.

3 Objective and background

Pre-FEED Objective:

The LEILAC project is divided into a number of milestones, the first of these (MS1) at month 9 is the Pre-FEED (Front End Engineering Design) to FEED stage gate. For LEILAC, the objective of Pre-FEED is defined as:

The Preliminary Front End Engineering Design (Pre-FEED) study will provide a number of preliminary design evaluation and performance studies for the pilot plant, reducing the major scale-up risks. It will provide a recommended design option (BOD-basis of design) for development, cost and schedule estimates resulting in a go/no go decision. The cost estimate for the Pre-FEED should aim to achieve a variance of +/-30%.

Background:

The LEILAC project (Low Emissions Intensity Lime And Cement) will successfully pilot a breakthrough technology that aims to replace an existing part of the cement and lime making process, and enable the capture of unavoidable process carbon dioxide (CO_2) emissions without significant energy penalty (just compression) at comparable capital costs to conventional emitting equipment. The consortium is led by technology provider Calix, and comprises Heidelberg Cement, CEMEX, Tarmac, Lhoist, Amec Foster Wheeler, ECN, Imperial College, PSE, Quantis and the Carbon Trust. It is supported by CEMBUREAU, ECRA, and EuLA. This five-year project has been funded by the consortium members (€9M) and the European Commission through the Horizon 2020 research and innovation programme (€12M, grant no. 654465).

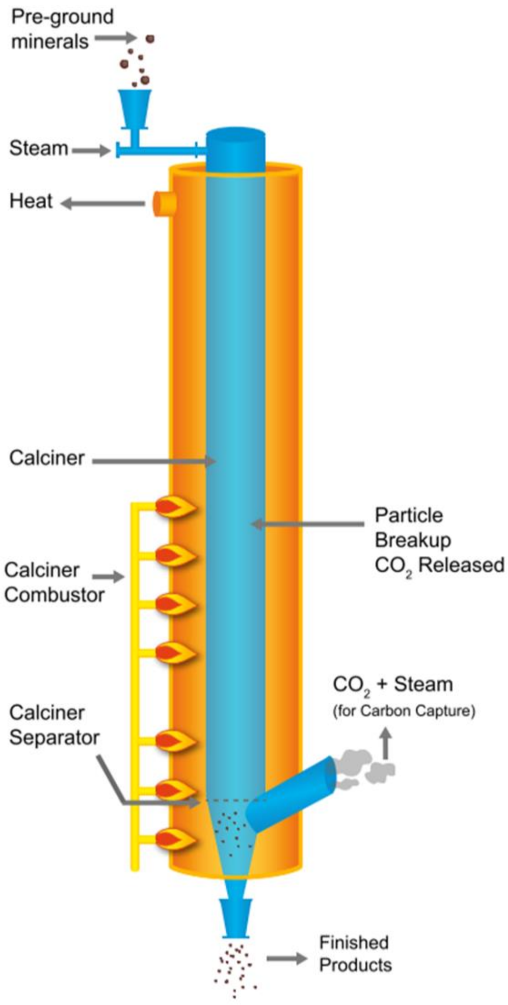

Figure 2 – A Direct Separation design

The LEILAC project is based on a technology developed by Calix called Direct Separation, which aims to enable the efficient capture of the unavoidable process emissions from lime and cement production. The process CO_2 which is chemically released from the limestone accounts for more than 60% of the total CO_2 emitted from lime and cement processing. It seeks to simply re-engineer the existing process flows of a traditional calciner, by indirectly heating the material being processed via a special steel vessel. This unique system enables pure CO_2 to be captured, in the case of limestone ($CaCO_3$), as it is released during calcination to lime (CaO), as the furnace exhaust gases are kept separate. This elegant solution requires no additional chemicals or processes.

LEILAC will develop, build, operate and test a 240 tonne per day pilot plant at HeidelbergCement's plant in Lixhe, Belgium, demonstrating that over 95% of the process CO_2 emissions can be captured (60 % of a plant's total CO_2 emissions). While demonstrated at commercial scale for processing magnesite, applying this technology to a cement or lime plant requires research, development and careful engineering – as these materials need to be calcined at much higher temperatures and scale.

Once built the pilot will be trialled under actual operating conditions, with a variety of extensive tests over two years to see if the technology performs as expected, paving the way for full scale demonstration. Once proven at a suitable scale (approximately within 5 years for the lime industry, and 10 years for larger cement plant) this will become the Best Available Technology for both industries. For a plant using this technology, the main additional 'cost' would only be for compressing the CO_2 for further useful purposes (CCU) or safely storing it underground (CCS).

The LEILAC project commenced on the 1st January 2016, and will run for five years. The project is built around a number of phases and milestones including Pre-FEED, FEED, detailed design and construction, commissioning and testing/operations.

4 Risk reduction, efficiency, and design development

Direct Separation is a new technology. It has been awarded an H2020 grant on its potential for decarbonising the cement and lime industry. The technology has been developed for over eight years by Calix, resulting in its commercial scale demonstration in the magnesite processing industry (specifically the CFC850 pilot plant and the CFC15000 production demonstration plant). However, as indicated above, applying this technology to a cement or lime plant requires research, development and careful engineering – as these materials need to be calcined at much higher temperatures and scale. Cement meal processing, particularly when integrated into a full scale plant, has different properties that add considerable complexity due to potential corrosive effects of certain compounds.

Ultimately the technology once proven at a suitable scale (approximately within 5 years for the lime industry, and likely more than 10 years for a larger cement plant) should directly compete on an efficiency basis with the state-of-the-art emitting technology - becoming the Best Available Technology for both industries independent of CO_2 prices, de-risking the decarbonisation investments needed for plant owners.

The LEILAC project has, therefore, a dedicated work-stream focusing on the major risks associated with applying this technology – ensuring that it can be successful at this scale (processing 10 tonnes per hour of cement), and de-risking the major future scale up issues.

4.1 Summary of the major risks

A focus for the project and in particular pre-FEED is to manage the major risks associated with the scale up of the Direct Separation Reactor (DSR). These risks have been identified as follows:

Temperature:

> CO_2 capture is achieved in the DSR by separating the limestone from the heating flue gas which contains large quantities of other gases. To achieve this, the streams are separated by a steel reactor tube. The temperatures required for calcination mean the reactor tube is under high stress. The DSR technology is proven for the production of magnesium oxide (MgO) from magnesium carbonate ($MgCO_3$) where the required calcination temperature is around 760°C. In the case of limestone calcination in the DSR the temperature must exceed 900°C for the reaction to occur. Steel selection for the DSR will be critically important in mitigating the risks associated with these high temperatures.

Corrosion and Fouling:

> The Calix DSR reactor in Bacchus Marsh, Australia has predominately run on magnesite with some short trial campaigns on other minerals. There has been no impact on the reactor tube due to scale or corrosion, but cement meal in particular is known to contain trace amounts elements which may introduce corrosion issues. The impact of these corrosive compounds

on the DSR must be well understood and compensated for in the design of the plant. The cement meal if formulated to react at high temperatures, near 1400°C in the rotary kiln to form clinker, and there is the potential of the materials to partially react on the hot steel surfaces, at about 1050°C, to form a scale that may not ony impair heat transfer and throughput, but also accumulate to add stress on the steel reactor tube. An allowance for scale build up will be made, and the scale formation will be mitigated and measured during the project.

Calcination level and throughput:

The target calcination level for the LEILAC plant is 95% molar conversion of the limestone to lime at 10 tonnes per hour of cement meal feed. This will only be achieved in the DSR through a thorough understanding of the reaction kinetics and heat transfer. Simulation modelling of the process will be used to provide reactor dimensions and operating conditions.

Future scale-up and integration:

The target throughput of the LEILAC plant of 10tph of cement meal feed is only 5% of the total capacity of the host plant at Lixhe, Belgium. It is important that the design of the LEILAC plant considers future scale up requirements. This includes the impact of throughput but also the issue of integration. For DSR to be a successful technology it must be cost competitive with other carbon capture technologies, but it ultimately aims to be cost competitive with traditional calcining technologies.

Capital cost of the plant:

There is a risk that the budget (while based on the cost data for building the Calix plant in Bacchus Marsh and recent quotes for the LEILAC Pilot) is insufficient following the pre-FEED phase. Process and engineering design must consider the nature of the LEILAC pilot as an R&D demonstrator in order to contain build costs.

Conclusions:

Following discussions between the considerable technical and academic expertise represented within the consortium of partners, a detailed set of tasks were assigned. The tasks relating to the pre-FEED activities are outlined in the following sections.

4.2 Design optimisation

4.2.1 Understanding the effect of powder feed on process performance

One of the key areas of consideration for the pilot plant is the impact on the process performance as a result of different powder feeding techniques.

The design for feeding material into the main reactor of the LEILAC project was initially based on the system used by Calix for the CFC15000 in Australia. This design uses a gas stream to pneumatically transport the raw powder to the reactor. For the CFC15000 the powder and carrier gas are fed together into the DSR. This is done to encourage the powder to disperse and travel down the reactor in such a way that promotes conductive, convective and radiative heat transfer from the wall.

To fully understand and improve the powder feed system's design and operation, large scale trials were undertaken on the operating plant in Australia, using finely ground Magnesite (Magnesium Carbonate). These trials had the objective of understanding the calcination levels, throughput, and energy requirement, when the powder feed method was modified.

Figure 3 – A novel test feed systems being connected to the Magnesite processing DSR

As a result of these design developments, a new powder feed system has been developed that improves process performance. This refined design will be utilised in the LEILAC pilot improving the anticipated efficiency for lime and cement processing.

4.2.2 Separation of gas and solids

An important component of Direct Separation technology is its ability to separate process CO_2 for capture, allowing it to be stored or used. There are many means of separating solids and gases, and these will generally have a major impact on the reactor design. Thus LEILAC needed to determine the most promising approach for the pre-FEED phase of the project.

Calix has successfully used reversing axial separator (RAS) technology on the CFC850 DSR pilot in Bacchus Marsh, Australia. This is a simple and compact design, which maintains centrosymmetric geometry, minimising stress on the reactor. In this case, the process CO_2 stream, released by the calcined material, is separated from the powder by reversing the direction of flow at the bottom of the reactor. The gas and a small percentage of solids travel up a central internal tube, exiting the top of reactor where it is filtered. The calcined solids exit from the bottom of the reactor.

A trial was conducted to measure the separation efficiency of the RAS in the CFC850. Separation efficiency was measured using a material with a similar particle size distribution to LEILAC's raw meal, a fixed gas flow, and a variable solids flow that scale to the regime to be used in LEILAC. The results indicated a design can be achieved that should enable the required separation efficiency of the CO_2 and powder. However, significant modelling and design work, by a number of the project's partners, will continue in order to ensure the required separation rates can be realised.

4.3 Process modelling of the pilot plant

The modelling of the kinetics and heat transfer is a key step required for the design of the Direct Separation Reactor. Prior to commencement of LEILAC, over the course of eight years, Calix developed code for DS reactors. This was first applied to the processing of magnesite and ratified through the results of the CFC850 pilot plant and the CFC15000 production demonstration plant. This code was upgraded with data from the extensive literature on the calcination of limestone. Refining the calcination kinetics, carbonation kinetics and heat transfer model, the code was then used to model the proposed LEILAC pilot reactor designs using conservative assumptions. The model accounts for the high calcination temperature, near 900^{o}C, resulting from the high CO_2 partial pressure in the calciner.

The model was used to help narrow down the design options through the initial stages of the project, resulting in an approved single primary design basis (BoD). The code was used to design the reactor dimensions, energy requirements and material residence times so that the pilot plant would meet the specifications for LEILAC, namely 95% calcination of raw cement meal at 10,000 kg/hr and limestone at 8,000 kg/hr.

The code was, in turn, enhanced based on information obtained from vendors regarding the steel and combustion systems, and parameters extracted from analysis of the actual raw meal that will be used by the pilot.

Following from this, PSE and Calix have collaborated on the transfer of the code to gPROMS, an advanced process modelling system that allows the user (a) to define the physics and chemistry relationships governing a process easily and (b) to solve the resulting system in many different ways. For example, it is possible to perform steady-state and dynamic simulation and optimisation, or parameter estimation to determine empirical parameters such as reaction kinetic parameters or heat transfer coefficients from experimental or operating data, or global system analysis to determine the effects of variations in input parameters on KPIs. A first version of the gPROMS model has been developed, which calculated the same result as the original code to within 1% for the BOD. The use of gPROMS allows the LEILAC plant as a whole to be modelled and optimised, including the ancillaries, which will assist the engineering development of LEILAC during FEED. It also enables the development of reactor and plant designs for future scaled-up plants.

4.4 Tube evaluation

4.4.1 Steel selection for LEILAC DSR

At the core of the DSR technology is a steel reactor that separates the flue (heating) gases from the carbonate allowing for CO_2 capture. By nature of the process it must operate under extreme conditions of temperature and stress. In the case of cement processing it must also deal with corrosion due to volatile compounds present in the raw meal. The choice of steel for this reactor is critically important. It must be able to cope with the extreme conditions but also be readily available, easy to shape and weld and most importantly cost competitive.

It has only been in the last 20-30 years that steel manufacturing companies have been able to provide stable alloys for repetitive use in operating temperatures up to and sometimes greater than 1000°C. Whilst over the last decade the provision of stable alloys has increased and have become more readily available, the majority are only suitable for a small range of process conditions, with strengths often focusing on a single corrosion issue.

The environment and temperature duty that the LEILAC DSR reactor will experience during its service are more demanding in comparison to Calix Australia's current process tube. A review of usable steels, including an assessment of their operating parameters and cost, was undertaken. Three of the project's partners undertook extensive testing and analysis of the cement meal that will be supplied by the Lixhe plant and will be used for the bulk of the pilot's operations. While the raw feed material at the Lixhe plant is not necessarily indicative of every cement plant's inputs, this activity identified some of the potentially challenging elements that LEILAC must address. The outcome from this testing allowed for a wide range of steels to be investigated, as the process's corrosive environments were identified and the required operating temperature of the steel were known from process modelling. This assessment involved literature reviews, expert options, and discussions with vendors. Alloys were assessed against the following parameters:

- Availability
- Material Cost
- Material Creep Strength
- Workability and Fabrication Cost
- Cross – Alloy Welding
- Resistance to Corrosion

From the alloys reviewed a clear choice emerged. The selected metal has the shortest lead time, is the most cost effective

Figure 4 – The LEILAC reactor

solution, allows for dis-similar metal welding and flanged connections to reduce cost through the use of alternative stainless steels in cooler sections, has superior high temperature creep data and strength, and requires no special manufacture procedures.

4.4.2 Testing of the steel under DSR conditions

There was a literature review of the suitability of the chosen steel material to be applied for the integrated tubes of the DSR reactor. Based on the literature review, it can be expected that the use of the steel is appropriate for the construction and the operation of the LEILAC pilot plant, provided that it is pre-treated appropriately, that the feedstock is monitored and controlled, that pre-heating is utilised (mirroring commercial plant conditions), that the condition of the reactor is monitored.

The chosen steel, in tube form, was physically tested using Lixhe kiln feed material at the ECN facility. During the testing, wall temperatures were maintained around 1000°C, mirroring the conditions that will be seen in the full scale reactor. The impact of potentially corrosive compounds present in the raw feed material was investigated. The chosen material, at this stage, is recommended for use in the LEILAC pilot. The long term suitability of the chosen alloy will be investigated during the life of the project through further laboratory studies and in-situ testing of the LEILAC DSR tube.

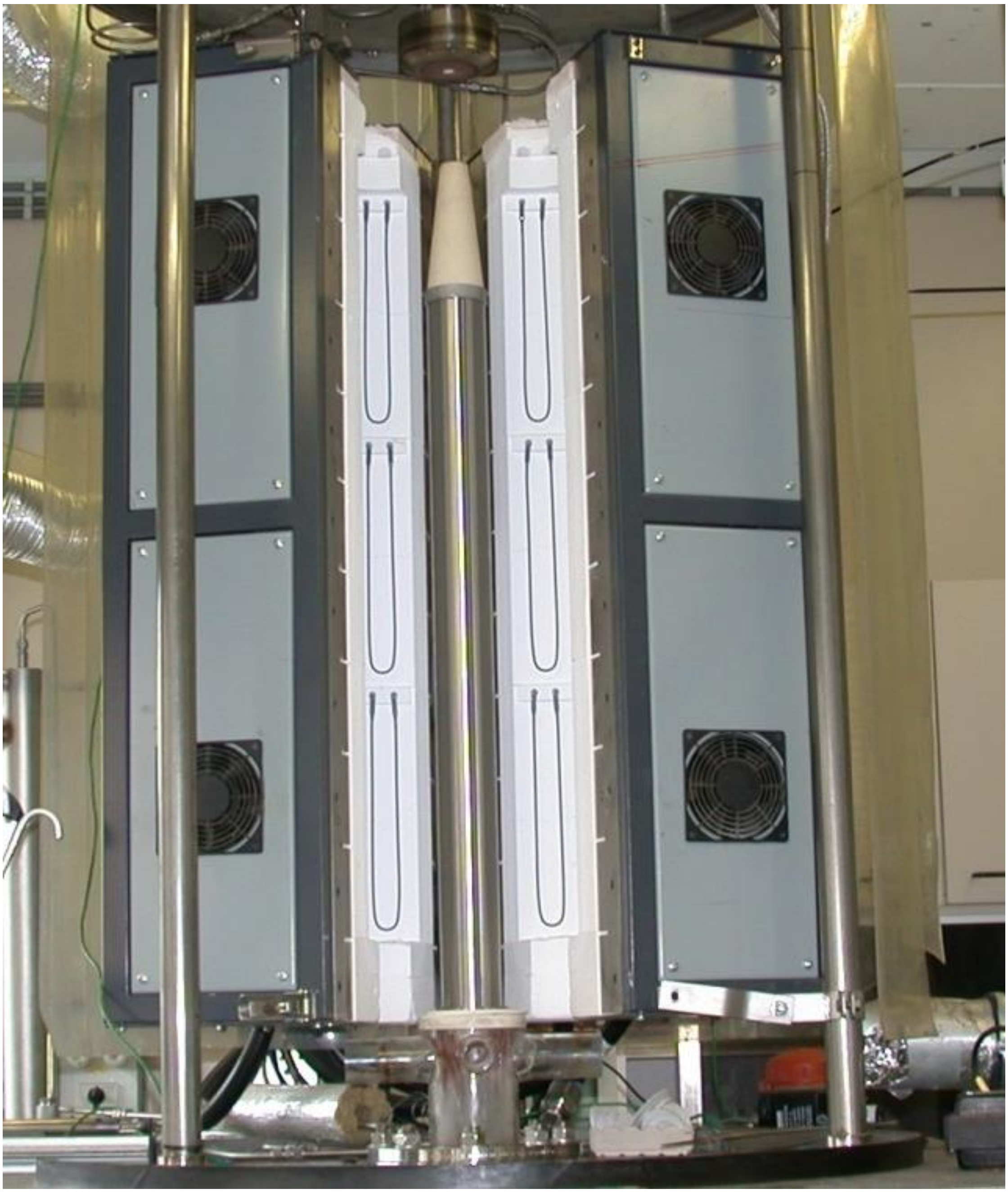

Figure 5 – Testing steel pipe in ECN's LCS facility

4.5 Retrofit/replacement feasibility examination

This task required the engineers designing the LEILAC plant to understand and consider the retrofit and replacement issues associated with scale up and the wide deployment of the DSR technology. As a result of this work, several design features have been incorporated into the Basis of Design of the pilot that begin to address these issues. These include:

- Pre-heating:

  - A modern cement plant uses excess process energy to heat the incoming raw feed. To more closely simulate these conditions a pre-heater is incorporated in the design of the LEILAC plant. The pre-heater is also useful in “burning off” volatile components in the feed that may attack the steel in the DSR calciner.
- Plant footprint:
  - The modification of the CO_2 exhaust system, compared to the Calix Bacchus Marsh plant, dramatically reduces the future footprint of the DSR allowing for reactors to be arranged more efficiently.
- Structure weight and sizing:
  - Changes to the refractory design lighten the overall weight of the structure.
- Maintenance:
  - The configuration of the LEILAC reactor simplifies access for future replacement of the DSR tube reducing downtime and cost.

4.6 Definition of the test program and design requirements

This task required the engineers designing the LEILAC plant to understand and consider how the operational testing program of the project impacts the pilot plant’s design at the pre-FEED, FEED and detailed engineering stages. The following testing requirements have been considered in the development of the basis of design for pre-FEED.

- Undertaking long duration campaigns to allow technical issues to arise.
- Environmental compliance.
- Running experimental campaigns for cement meal from the host plant at Lixhe and from other participating cement companies.
- Running campaigns optimised for lime and cement production for the participating companies.
- Monitoring all the operating parameters of the plant.
- Testing CO_2 quality.
- Analysis of the reactor tube’s performance including corrosion, fouling and creep.
- Demonstrating the quality of the lime and clinker produced through the DSR.

These testing requirements have been assessed in detail, and either considered, or shaped the Basis of Design.

5 Basis of Design and Engineering

The purpose of this phase of assessment was to determine whether the project can proceed into the more detailed design phase based on a number of criteria: that the pilot's design is technically viable, that it will fulfil the operational objectives of the overall project, and that is within the cost constraints of the budget. Again risk mitigation was a major consideration, building on the tasks and outputs discussed above.

As such, the overall system configuration has been largely defined, and schematics, diagrams, and layouts of the plant provide early project configuration - creating the general framework from which the pilot will be built. For LEILAC this has involved defining the location of the pilot, it's tie-in points to the Lixhe plant and associated boundary conditions, confirming utilities, conducting comprehensive safety and environmental risk reviews, making key design decisions (particularly regarding the choice of steel, furnace, combustion system, tube design, pipework, auxiliaries), and undertaking a constructability review.

The steps outlined above have been detailed, as far as possible, in the following sections. While the parameters will be changed and optimised, these actions will provide the foundation for the front-end engineering and design phase.

5.1 Basis of Design

The Basis of Design establishes the design criteria and assumptions for the main systems involved in the pilot plant. At the commencement of the project, over 40 process flow options were tabled. Through detailed assessment of these options, shaped by the initial results of the investigations and experimental work discussed above and building on the experience gained by Calix through the development of the CFC850 pilot plant and the CFC15000 production demonstration plant, a single primary design basis was proposed and approved. The Basis of Design (BOD) used mass and energy balances to determine and size the pilot plant, addresses the primary risks identified, with significant input from all of the project partners, and enabled preliminary engineering work and costing to commence.

5.2 Design philosophy:

The design philosophies and objectives intended for the design of the LEILAC Demonstration plant are as follows:

- Health and safety shall meet all required standards and policies from the commencement of the project through the entirety of the pilot plant's lifetime to its decommissioning.
- Environmental issues shall be proactively managed and shall meet all approval conditions and standards.
- The pilot plant shall be extending existing Direct Separation calcination technology, which will require advanced modelling and testing during the all phases of the project.

- The pilot plant shall be designed to be operable, reliable and maintainable.
- The pilot plant shall be designed to minimise process risks as far as is practicable.
- The pilot plant is designed to develop and apply a new technology – decisions made during its design should reflect this in order to maximise the technical outcomes and learnings from this project.

The pilot plant shall be designed, to the best of existing knowledge, such that its functional operation can reasonably be expected to last for the duration of the test programme without exceeding any of the allowable design criteria. Additionally, due to the developmental and demonstrational nature of the plant, equipment including the DSR and furnace shall be designed such that frequent start-ups and shutdowns can be withstood by the materials and equipment without significant adverse effects. For the avoidance of doubt, the plant shall be designed for up to 3000 hours of operation per year, over two years.

The DSR is designed to process up to 12,000 kg/hr of feedstock. The operating throughputs are 10,000 kg/hr of raw cement meal or 8,000 kg/hr of limestone.

5.3 Process description:

The DSR process developed by Calix is a calcination process whereby a powdered mineral is heated indirectly, enabling the separation of the gaseous CO_2 from the decarbonated particulate product with minimal further post processing. The plant is able to operate without great energy penalty or capital cost, directly replacing a cement calciner tower or lime kiln. The carbon dioxide which is separated from the product may in future be captured, however as this plant is a Pilot this is not within the scope of this project. Figure 6 – The LEILAC pilot process flowbelow shows the process flow of the LEILAC plant.

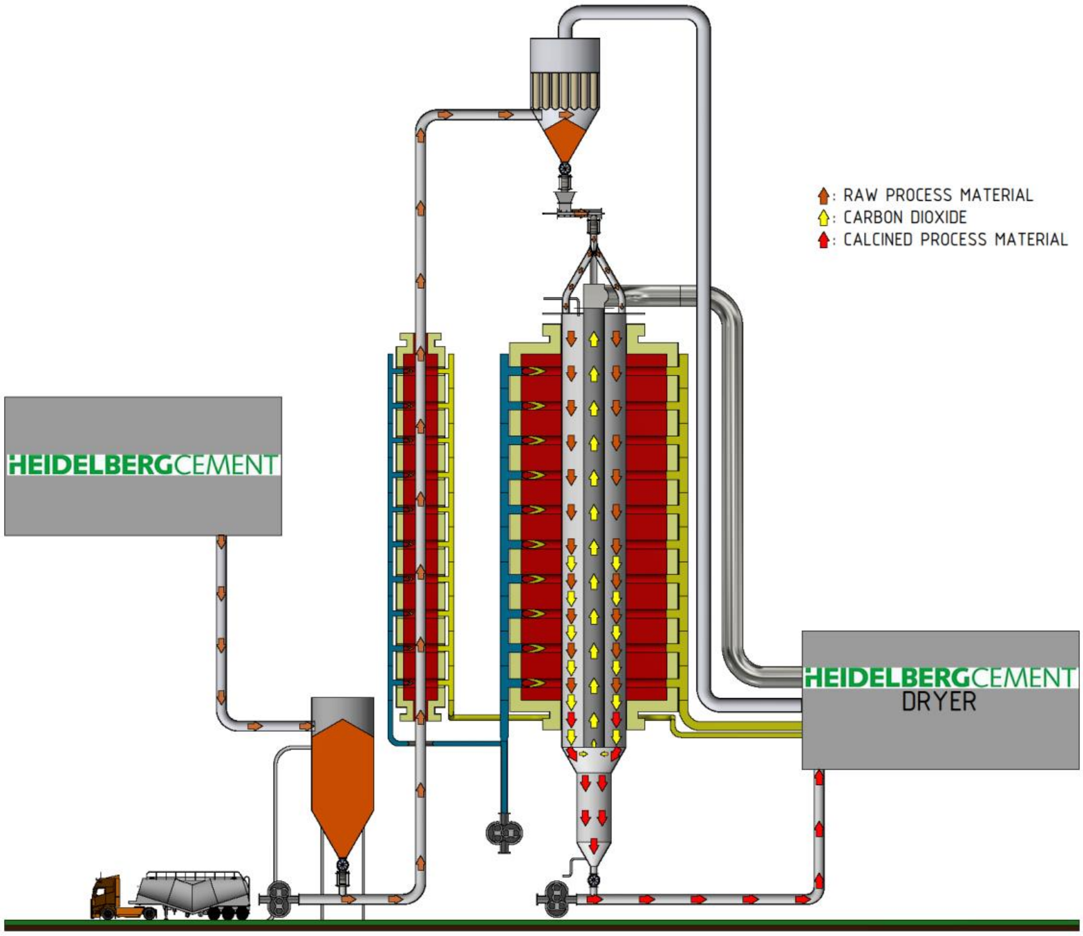

Figure 6 – The LEILAC pilot process flow

Description of the process:

- Material, from the main cement plant or from road tankers, is stored in the feed silo.
- The material is lifted to the top of the reactor, heated, filtered, and fed into the reactor.
- The Direct Separation Reactor uses external burners to indirectly heat the outer tube to over 1000°c.
- As the material falls through the reactor it is calcined - releasing CO_2.
- The calcined material drops down through the base of the reactor.
- The CO_2 travels up the inner tube. At a full scale plant, the uncontaminated CO_2 could then be used or stored.
- For the pilot, all gases and material are returned to the Lixhe plant.

5.4 LEILAC pilot location

Site Location

The site is the located within the CBR Lixhe cement plant, located on the eastern border of Belgium.

- Address - Rue des Trois Fermes
  4600 Lixhe-les-Visé
  Belgium
- Latitude - 50.762536°
- Longitude - 5.673225°

It will be located alongside the existing calciner tower of the cement plant.

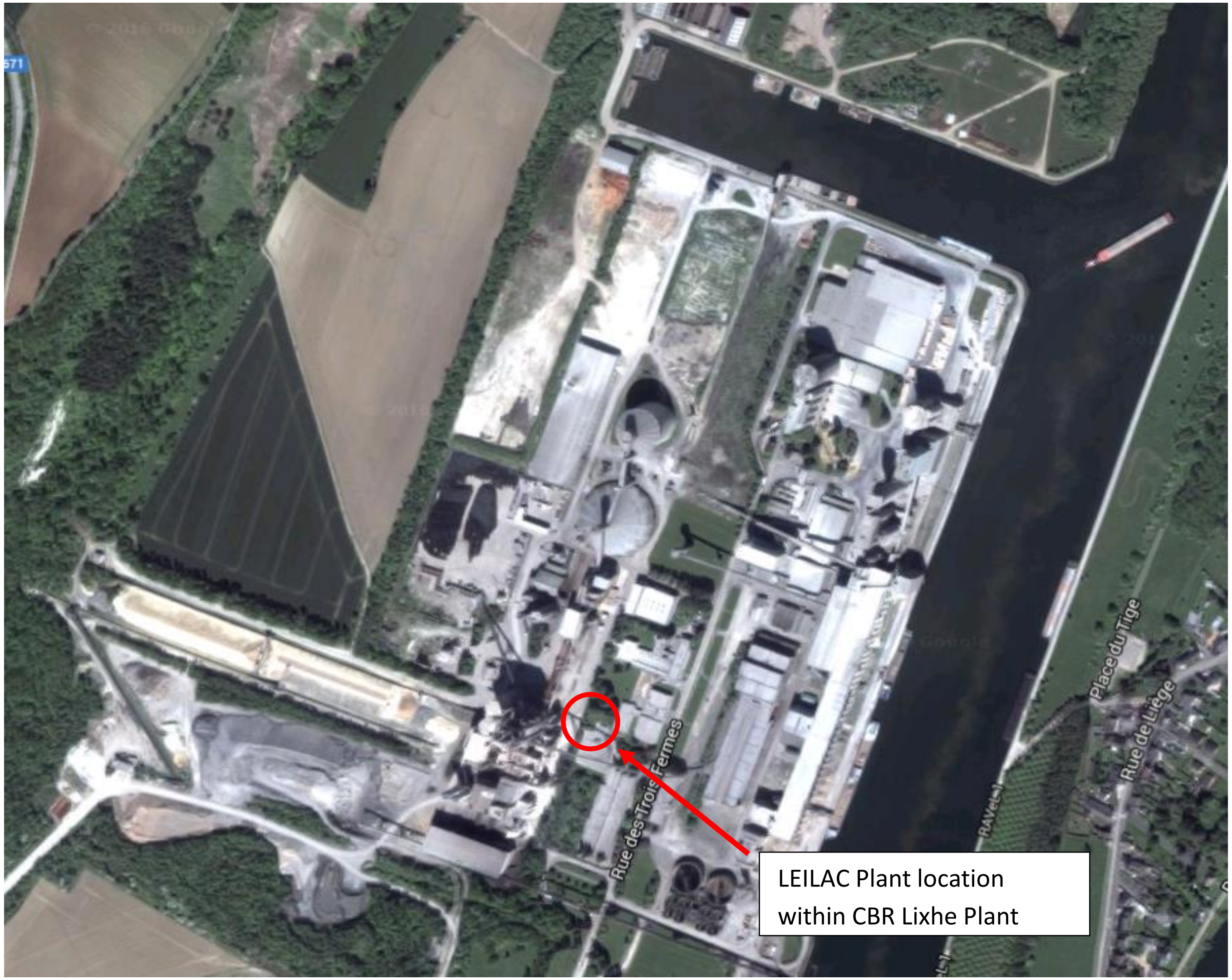

Figure 7 – Site Overview

Figure 8 – LEILAC plot view from ground level

Plot plan

A plot plan has been developed which accounts for locating the new equipment and tying it in to the existing plant, allowing for concurrent operation. This plot plan was reviewed on the 21st of July 2016 to assess its suitability, both from the perspective of the projects requirements and those of the existing plant into which it is to be installed. The site layout is shown below:

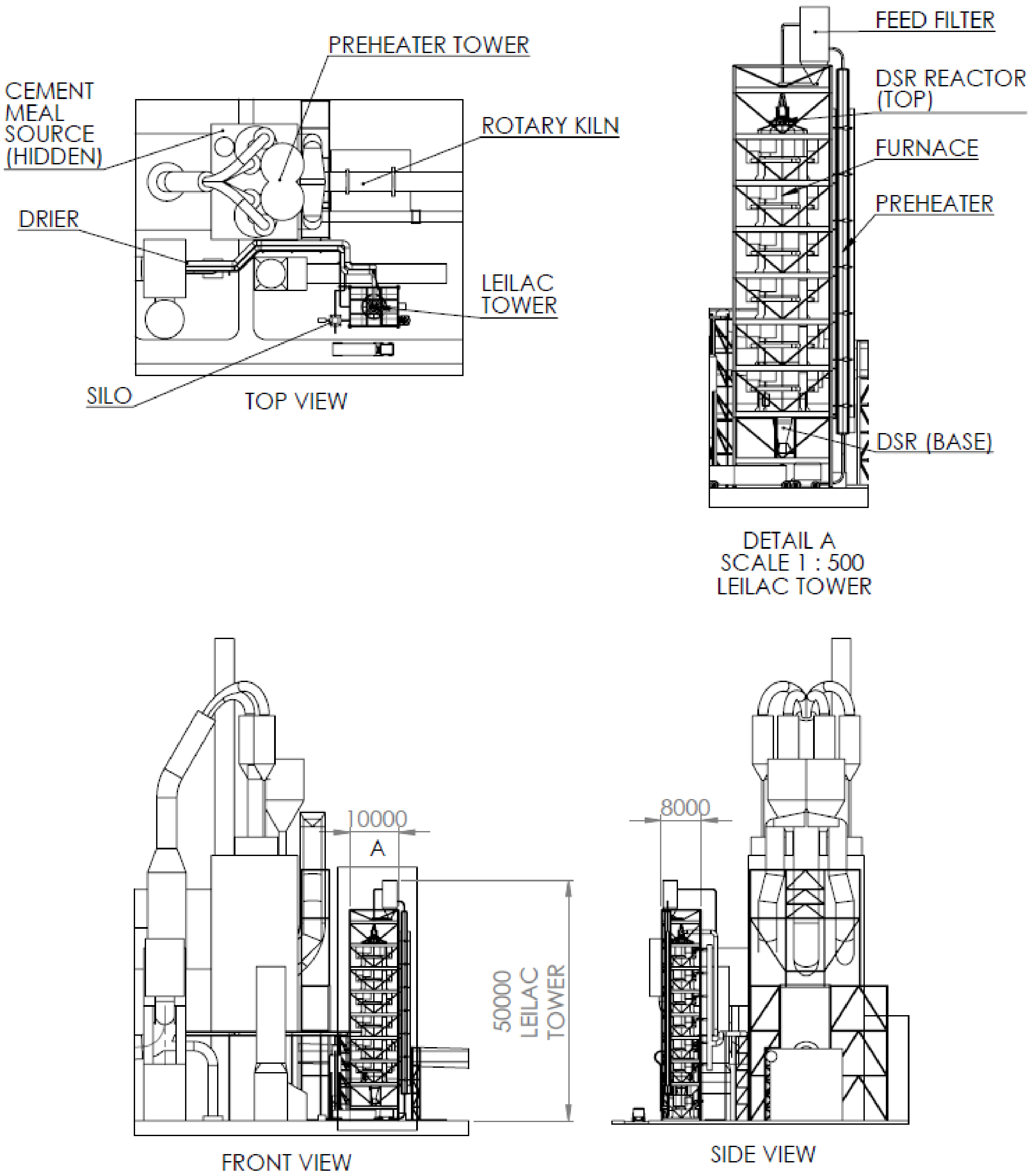

Figure 9 – Tower, shown within existing CBR Lixhe cement plant

5.5 Process interfaces with the Lixhe plant

The LEILAC plant will have a number of process connections with the Lixhe plant, and an important aspect of the pilot's design has been ensuring that the operations of the main plant are not impacted by the pilot.

As such, the identification of tie-in points and associated boundary conditions (maximum allowable flow and temperature), and the availability of supporting utilities has been an important aspect of the pre-FEED activity.

5.6 Safety

Engineering - Heath safety and environment:

As part of the pre-FEED study it is important to consider the impact of health, safety and environment on the basis of design. One of the key activities during the pre-FEED stage of the project was to run a HAZID and ENVID study. The reviews' scope covered the main elements of the LEILAC plant including the preheater and the Direct Separation Reactor calciner, and recognised potential health and safety hazards and environmental impacts during normal and abnormal operation. The outcomes of these studies were used to inform the project's design and operation.

Purpose of HAZID:

The purpose of a Hazard Identification Study (HAZID) review is to carry out a qualitative hazard identification and assessment of the project facilities. This was undertaken early within the project's life in order to identify key issues for resolution. This involved the systematic identification of any hazards, which may have the potential to cause harm, followed by a review of whether adequate safeguards exist, or whether additional safeguards are required to mitigate the potential consequences.

Purpose of ENVID:

An ENVID (ENVironmental aspects IDentification) Review is a systematic assessment of a plant, system or operation intended primarily to identify environmental aspects and potential impacts. The method is often used during projects as a basis for risk assessment and for populating the Environmental Aspects Register. The purpose of an ENVID Review is to:

- Identify the environmental aspects/potential impacts and opportunities generated by the project or activity under review in a structured fashion,
- Identify appropriate mitigation techniques to ensure the potential impacts are effectively managed,
- Provide input to the qualitative Aspects Register and develop a risk ranking of the impacts to ensure that the significant elements are suitably addressed in a timely manner,

- Provide input to an action tracking process to ensure that all the environmental aspects and potential impacts identified are addressed in a suitable manner.

The review identified the environmental aspects requiring consideration. It also considered potential impacts generated not only by the pilot, but also those caused by interactions with the surrounding environment. As such it was a holistic study which attempted to capture all the issues of the project. As with the HAZID, it was conducted early within the project, as it enabled key issues to be identified for resolution with as few constraints as possible.

Outputs:

The actions described were carried out in July 2016 at the Heidelberg Cement Works in Lixhe, Belgium. Actions generated during the review were transferred onto individual response sheets and issued to the relevant person identified at the study. Action close out is managed by the Amec Foster Wheeler Technical SHE discipline, in conjunction with the study leader who had final sign off of the action response sheet.

The actions identified were all achievable, and have been largely actioned in during the design of the pilot through the pre-FEED phase. Remaining actions aim to be closed by the end of FEED.

5.7 General aspects of the design

5.7.1 Pilot Plant

The ability to take samples is a requirement for the plant, both of the solids and the gas produced. As a minimum, the following lines will require the ability to take samples:

- Solids sampling of powder from storage silo,
- Gas sampling of preheater conveying off-gas,
- Solids sampling of preheated powder,
- Gas and solids sampling of CO_2 off-gas from reactor,
- Solids sampling of calcined product.

As the plant is a Pilot, there may be additions or changes after construction, commissioning or even a period of operation. Where these are anticipated, there should be an allowance made for the possible change, whether this be room to add pipework or equipment, blanked flanges to allow for tapping into process lines or additional capacity (where reasonable) in equipment.

Currently anticipated possible changes are the addition of CO_2 off gas processing, solids cooling after the reactor and the ability to store product for distribution by truck outside the Lixhe cement plant.

5.7.2 Direct Separation Reactor (DSR)

As previously discussed, it is necessary for the reactor tubes to withstand the temperatures required to indirectly calcine limestone and cement meal. Such steel needs to be able withstand an operating temperatures up to, and sometimes greater, than 1000°C.

While the raw feed material at the Lixhe plant is not necessarily indicative of every cement plant's inputs, testing of the meal, and the plant's operators, have identified some of the potential challenging elements that LEILAC must address. As such, steel was chosen that could cope with potential corrosion, and will be combined with measures to control corrosive conditions.

The reactor vessel is a large heat exchanger, through process powdered solids and gases moves from top to bottom on the inside while combustion flue gas travels externally from the bottom to the top of the reactor or may be extracted at certain locations along the furnace. The powder is heated through a combination of radiative, convective and conductive heat transfer. The feed powder is dropped into the reactor from a location in the top cap of the calciner.

Within the main reactor tube is a second inner tube referred to as the CO_2 return tube. This tube experiences much the same effects as the main reactor tube, though is generally maintained at a lower temperature than the DSR tube. Both tubes however are designed such that a build-up of material on the process facing surfaces will not exceed the design parameters of the steel.

The ability to install and remove the tubes was also an aspect of design and consideration.

5.7.3 Furnace and Combustion system

The furnace is designed to provide an annulus in which the flue gasses may flow around the reactor. The furnace must be designed to accommodate the thermal stress and growth experienced during all operating modes. The furnace will require some additions to fulfil its purpose as a pilot, specifically around research and development for future plants.

Alongside the main furnace will be the Preheater Furnace, another long thin furnace which operates similarly to the main DSR furnace.

The Structure is designed sufficient to support all of the equipment required. The structure will incorporate platforms and access ladders to allow access to the top platform, burners and instrumentation

The **DSR Furnace Combustion System** heats the interior of the furnace and the exterior surface of the DSR Tube. There will need to be an ability to adjust and set the temperature (and heat) profile along the vertical length of the DSR tube.

The **Preheater Furnace Combustion System** heats the interior of the furnace and the exterior surface of the Preheater Riser Pipe.

Both furnaces will be fired by a number of natural gas fuelled combustors spread over the length of the furnace. The intent is for the energy input to be distributed over the entire surface of the reactor. The spacing between combustors will be tuned to provide more or less energy on certain areas of the reactor, complemented by a sophisticated control system. This will enable the reactor to match the outputs of the simulation model for the DSR.

5.7.4 Filter and powder feed systems

Sizing and specifications have been made for the major ancillary equipment items, such as the filter, feed silo, blowers and fans.

5.7.5 Preheater

A conveying system shall convey fresh feed to the feed filter from the base of the tower. This shall be designed to operate on air as the primary motive fluid, however CO_2 should also be considered in the design, should it be decided to upgrade the system for its use after construction.

The preheat riser portion of the conveying system will pose the greatest challenge in its design. The control system will incorporate a method of calculating the flow within the riser along its length and varying the blower speed.

Other elements involved in the design of the riser are thermal expansion, wear, pressure, supporting the line and creep.

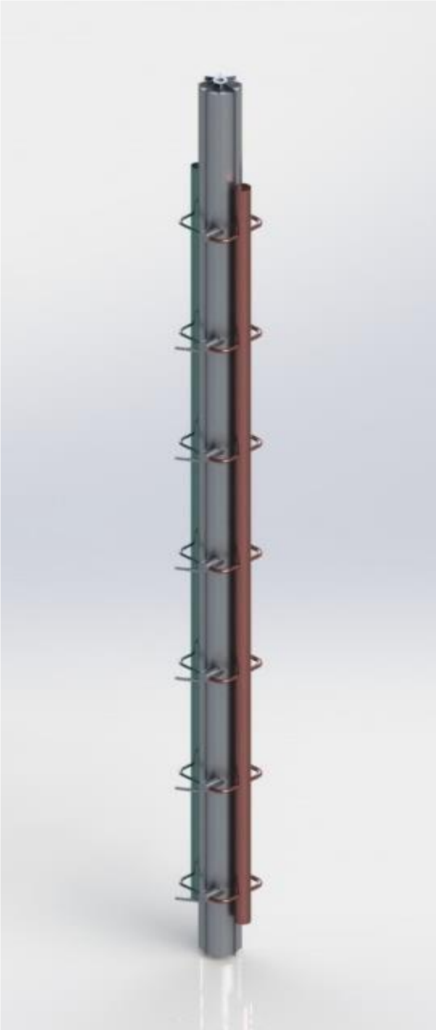

Figure 10 – Riser preheater with combustors shown

5.8 Constructability

As part of the pre-FEED, a site visit and constructability review was conducted to assess how the construction phase of the project would be undertaken. It was found that the work area is relatively small, necessitating a high level of coordination between the surrounding operating plant and the work site. Two areas will be defined during this phase, IBL (Inside Battery Limits) and OBL (Outside Battery Limits). Within the IBL area, the work and access would be controlled by the EPC contractor permit to work system. Within the OBL area, control is retained by Heidelberg Cement.

The furnace is inherently modular by nature, allowing preassembly of the tower, platforms, furnace and combustion system on or off site before being quickly erected. This will allow the construction process to be optimised for both cost and time on site.

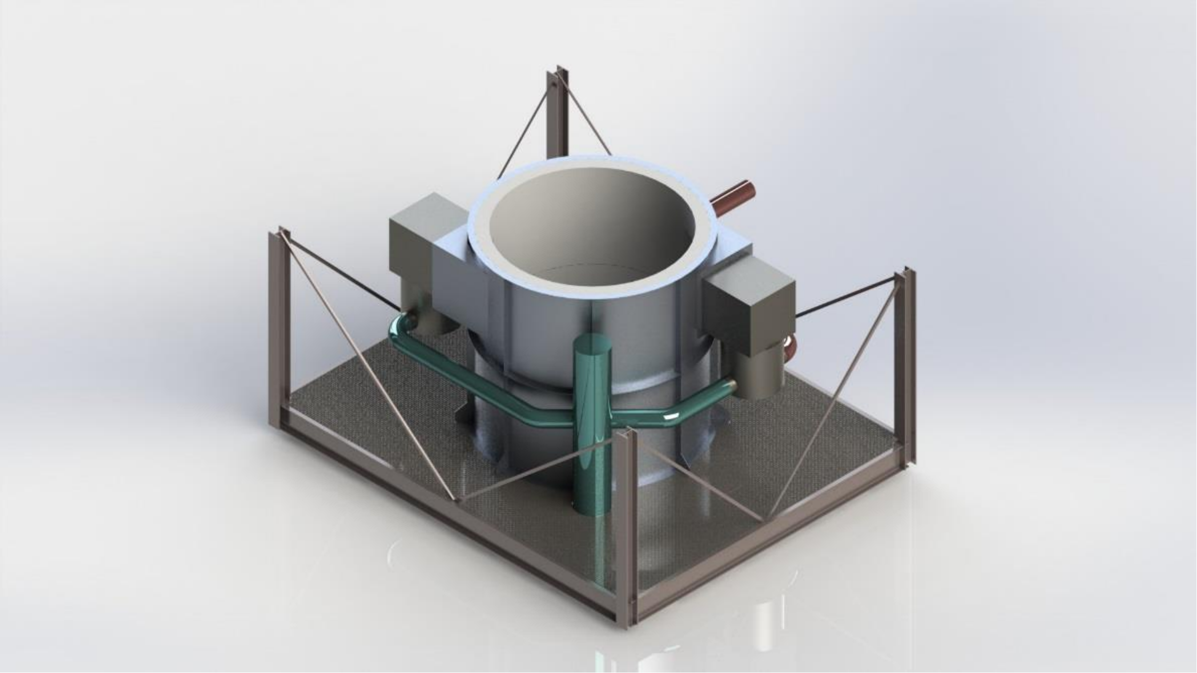

Figure 11 – A module of the pilot's tower

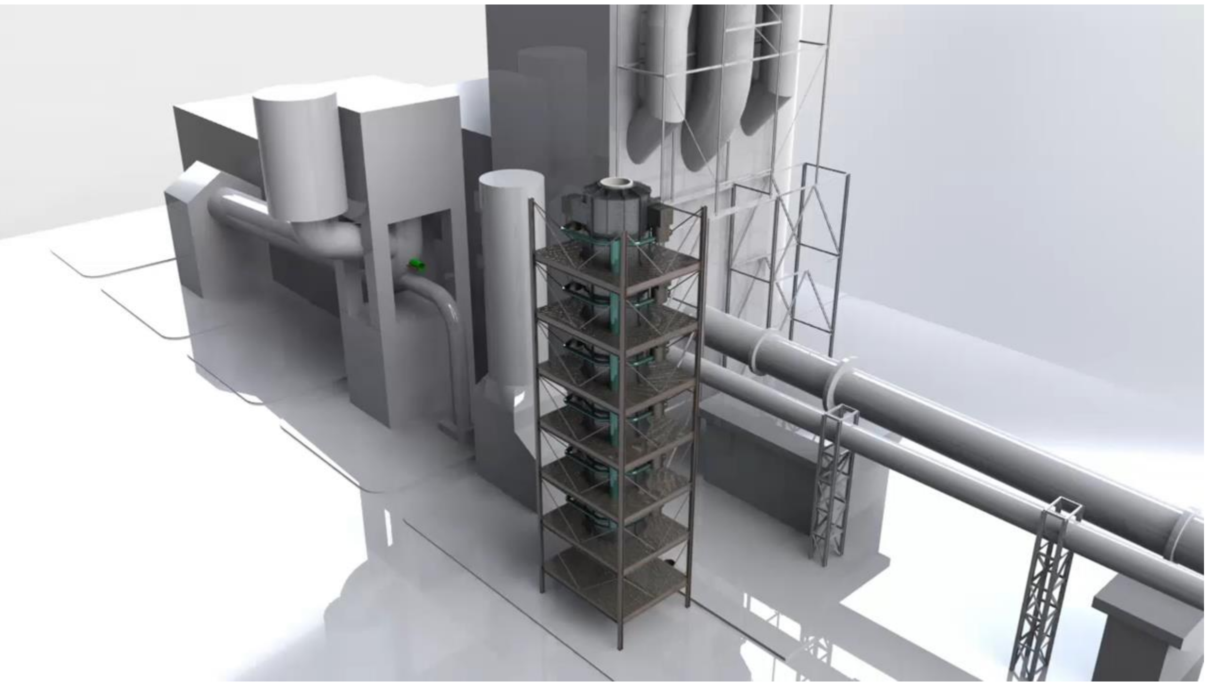

Figure 12 – How the pilot's modular tower may look against the current calciner tower

5.9 Summary of the key outputs of the preliminary Front End Engineering Design

- Selection of the LEILAC plant location within the host plant of Lixhe.
- Identification of tie-in points to the Lixhe plant and associated boundary conditions.
- Confirmation of utilities (gas and power) – location and capacity to service the demonstrator.
- Hazard and environmental reviews to identify risks – some design changes implemented.
- Modelling of the process to generate plant sizing for the:
  - Pre-heater tube and furnace,
  - Main DSR reactor tube,
  - CO_2 exhaust tube,
  - Furnace internal and external dimensions.
- Selection of a stainless steel, with measures to control corrosion. This followed the evaluation of alternative steels which were found to be price prohibitive for the LEILAC project.
- Specification of the furnace including the type of refractory resulting in reduced weight.
- Specification of the combustion system.
- Sizing and specification of major equipment items including hot filter, feed silo, blowers and fans.
- Sizing and material choice for the pipework.
- Construction review resulting in the preferred method of erection – modular assembly of the support structure and furnace with a single lift of the main reactor tubes.

6 Pre-FEED Cost estimate

6.1 Creating the estimate for the pilot's construction

The cost estimate for the LEILAC plant was built using a number of techniques including vendor quotes, factoring (% of total build cost), and estimating (from industry data bases). To obtain the required +/-30% accuracy a significant amount of the plant was divided into major packages for vendor quoting.

The aim of developing these packages was to group like items so the most appropriate vendors could be chosen to price the work and to improve the accuracy of the quotes. For example, furnace manufacturing has specific knowledge requirements that general engineering fabricators may not have, including the understanding and selection of the furnace insulation. A pre-qualification process was conducted whereby recommended vendors were visited and questioned on their ability to deliver against the package specifications.

Between three and four vendors were then asked to provide quotations for the packages. After analysis the preferred equipment offers and associated costs were selected. The balance of the plant cost estimate was built using the techniques described above.

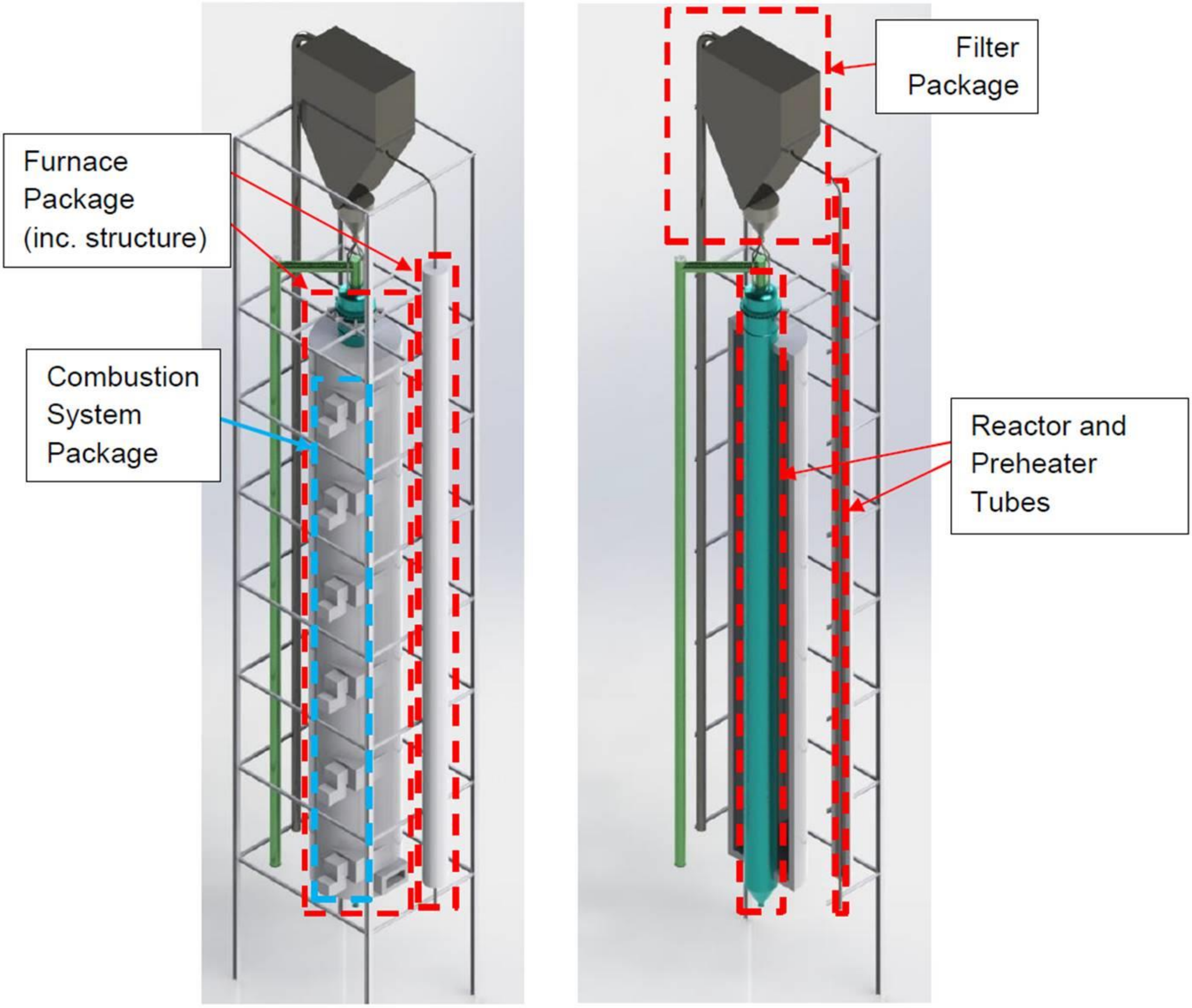

Figure 13 – The major equipment packages

Additionally, a “development cost” has been applied to some items to allow for the typical change in scope that occurs during the FEED stage of a project. At the same time a budget costing for the EPCm requirements of the project was developed which includes:

- FEED stage engineering and services,
- Detailed engineering services (E),
- Procurement services (Pm),
- Construction management (Cm).

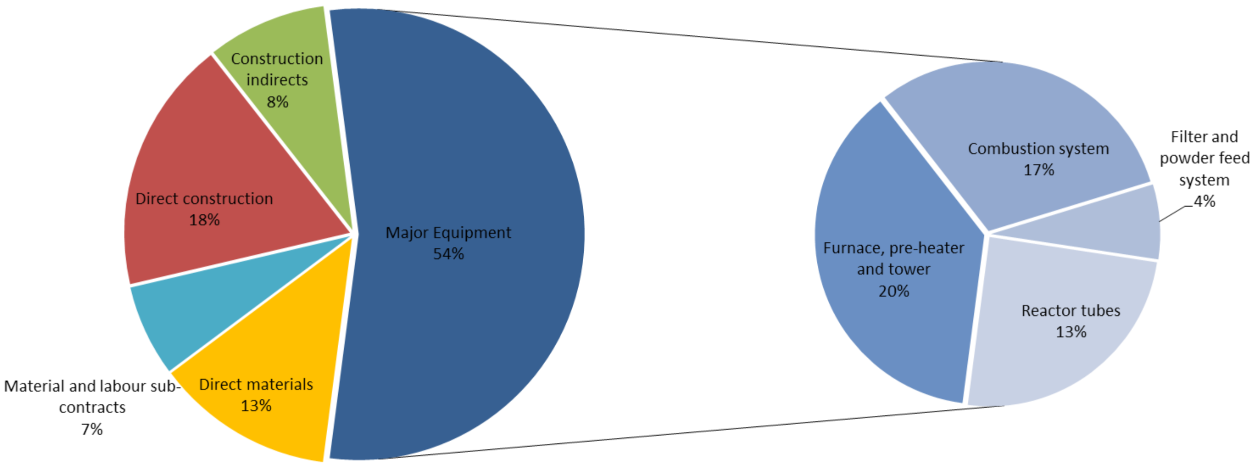

Figure 14 – Pilot's material and construction cost split

The pre-FEED cost estimate for the approved BOD for the LEILAC plant has a weighted cost estimate of +/-27%.

6.2 Value engineering (VE)

Following this, in order to identify cost savings a process of value engineering was commenced. Through this exercise all design and costing assumptions are challenged against the key objectives of the project. In particular LEILAC is an R&D pilot plant with a limited operating life. The plan is to decommission the plant at the end of the project and all design decisions and standards should be made with this in mind. The value engineering approach asks the following questions:

- **Process Technology Selection:**
  - Is the selected process technology essential to achieve the function it is designed for?
  - Are cheaper materials of construction available?
  - Method of construction?
  - Can the process function be achieved by cheaper equipment?
  - Is the equipment sizing basis correct?
  - Can the equipment be easily maintained?
- **Process Simplification and Integration:**
  - Can process conditions be changed to reduce the overall costs?
  - Can elements of the process scheme be simplified?
  - Does the integration of equipment increase the overall capital cost?
  - Is the level of piping/equipment appropriate for the required operating reliability?

  - Does the proposed specification support a low cost construction strategy?
- **Waste minimisation**
  - Have waste minimisation aspects been considered in the design?
  - Have waste routes been identified and appropriate solutions selected?
  - Are emissions routed back to the process?
- **Energy Optimisation and Pinch Technology**
  - What is the minimum energy required for the process?
  - How much can be saved?
  - Energy-Capital trade off?
- **Design to Capacity and Design Margin**
  - Is the design capacity appropriate for the plant function/purpose?
  - Are the design margins appropriate for the plant function and the individual equipment design uncertainty?
  - Are design codes appropriate for the equipment?
- **Class of Facility Quality**
  - Is the proposed specification of the facility appropriate?

The value engineering exercise has been useful particularly for an R&D plant such as LEILAC. Quite a number of the recommended areas for action are already built into the design. However, it has been possible through this task to identify a number of opportunities to remove cost for the plant and will be pursued through the FEED stage of the project.

6.3 Operating costs

Operating cost is driven by process efficiency and integration. This is not a focus for the LEILAC pilot plant in itself, as the budget is limited as is the operating life. However, the design for the LEILAC pilot will be assessed, along with scale up factors, in the techno-economic study for how Direct Separation would be applied to a full scale plant. The potential scale-up and integration of the DSR technology is critical and the design should not price DSR technology out of the market through high operating costs and as such should not introduce fundamental changes that drive the long term operating costs up.

7 Pre-FEED results and next steps

7.1 Conclusions

The purpose of the Preliminary Front End Engineering Design phase of assessment was to determine whether the project can proceed into the more detailed design phase based on a number of criteria: that the pilot's design is technically viable, that it will fulfil the operational objectives of the overall project, and that is within the cost constraints of the budget. Again risk mitigation was a major consideration of the engineering design, building on the tasks and outputs discussed above.

As outlined above, a basis of design for the LEILAC plant has been developed through a process of design, research, testing and consultation between the LEILAC consortium members. Extensive risk-mitigation actions and tasks were carried out: improving and developing of critical aspects of the core technology was used to greatly improve the approach taken by the project.

The pre-FEED has produced an end-to-end design basis, incorporating the initial R&D results, modelling, process flow mapping, mass balance calculations, equipment requirements, constructability, site integration, logistics options and HAZID review. Vendor discussions and qualification assessment were carried out, followed by initial quotations. These were then rationalised and used to build more accurate estimate costs for the pilot.

From the outcomes of the pre-FEED study the proposed pilot will fulfil the objectives required of the LEILAC project, providing a significant step in enabling these key European industries to capture their process emissions at low risk and low cost.

The technical and economic criteria for the proposed LEILAC project were met, and based on the results of the activity undertaken, the project's governing bodies agreed to support the progression of the project into the FEED phase expected to be completed in June 2017 (M18).

7.2 Next steps

Following the successful completion of the pre-FEED phase of the project, LEILAC will now enter the FEED phase. The Front End Engineering and Design (FEED) study will design and cost the optimal plant configuration to a completed point such that no material variations are required following Financial Investment Decision (FID). The FEED will provide estimates in the order of ±15% accuracy for capital costs and ±10% accuracy for operating costs. It is scheduled to run until July 2017. This will form the basis of the Financial Investment Decision (FID), allowing the project to proceed.

Following the FID decision, the project will undertake detailed design work, procurement and construction through the course of 2018. The intent is for the pilot to be operational in early 2019, followed by a period of extensive testing.

At the conclusion of the project a Cement and Lime industry CCS Roadmap will be developed. This Roadmap will be based on the outcomes of the LEILAC pilot's construction and test, full-scale techno-economic study, Life Cycle Analysis, and retrofit report. This roadmap will explore, in depth, the timing and opportunities for the widespread roll out of this technology. This will be important in informing decision makers and industry of the viability of the widespread deployment of Direct Separation as a means of accelerating the decarbonisation efforts of the industry, based on verified data. Using the European targets for emissions reduction, this should also provide tangible information regarding potential costs for the industry, which has had limited economic deep decarbonisation options until this point.

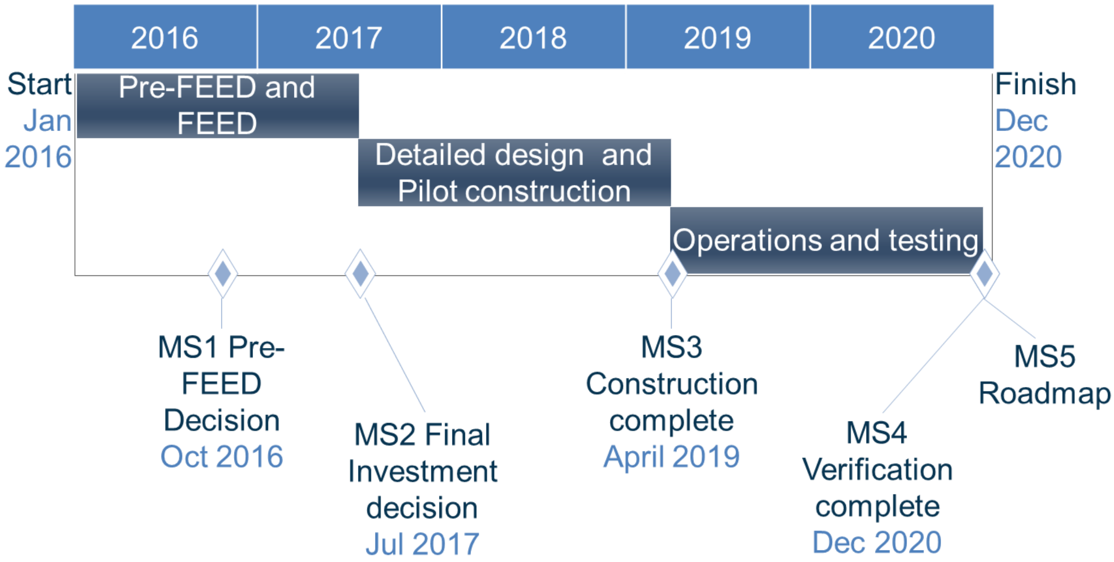

Figure 15 – The LEILAC project's high level timing

8 Abbreviations

BOD	-	Basis of Design
BS	-	British Standards
CFD	-	Computational Fluid Dynamics
CO_2	-	Carbon dioxide
EC	-	European Commission
ENVID	-	ENVironmental Impact IDentification
DSR	-	Direct Separation Reactor
FAD	-	Free Air Delivery
FEA	-	Finite Element Analysis
FEED	-	Front End Engineering Design
FSI	-	Fluid Solid Interaction
gPROMS	-	PSE's advanced process modelling product
H&MB	-	Heat and Mass Balance
HAZID	-	HAZard IDentification
HSE	-	Health, Safety and Environment
LEILAC	-	Low Emissions Intensity Lime and Cement Project
LHV	-	Lower Heating Value
LPM	-	Litres per Minute
RAS	-	Reverse Axial Separator
P&ID	-	Piping and Instrumentation Diagram
PFD	-	Process Flow Diagram
SI	-	International System of Units
TBD	-	To Be Determined