Deliverable 3.4

Leilac-2 Demonstration Plant
Front End Engineering Design (FEED) Study Summary
Public Version

OCTOBER 2023

Project partners:

- CALIX – Europe SARL
- HeidelbergCement AG (rebranded as Heidelberg Materials)
- Lhoist Recherche et Developpement SA
- Calix Limited
- PORT ROTTERDAM – Havenbedrijf Rotterdam NV
- CIMPOR – Industria De Cimentos SA
- IKN GMBH – Ingenieurburo-Kuhlerbau-Neustadt
- ENGIE Laborelec – Belgisch Laboratorium Van De Elektriciteitsindustrie Laborelec CVBA
- RBINS - GSB Royal Belgian Institute of Natural Sciences
- BGR – Bundesanstalt Fuer Geowissenschaften Und Rohstoffe
- POLIMI – Politecnico Di Milano
- CERTH – Ethniko Kentro Erevnas Kai Technologikis Anaptyxis
- CEMEX Innovation Holding AG

Leilac2

Partners

Note: This report has been reviewed and approved by the Leilac-2 consortium members.
15 October 2023

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1 EXECUTIVE SUMMARY

The Leilac-2 project aims to develop a retrofittable, integrated module for the capture of process CO_2 emissions released unavoidably in the production of cement and lime. The Leilac-2 demonstration plant is an important de-risking step for application of the Leilac technology. A successful demonstration through the Leilac-2 project can pave the way for the Leilac module to be optimised, replicated, and applied at any scale.

The Leilac-2 module will provide a strong basis to scale from, with each module capable of separating in the order of 100 000 tonnes of CO_2 per year at more than 95% purity and operating with alternative fuels. Its retrofittable, modular design can provide flexible layout and integration options that minimise disruption to the host plant. The Leilac-2 project also aims to develop future-proof fuel options by demonstrating the use of alternative fuels and furthering the electrification of the Leilac technology.

Supporting a vision for low-cost and scalable capture solutions

The Leilac-2 Demonstration Plant Front End Engineering Design (FEED) study provides a significant update to the original Leilac-2 module design. Value Engineering work was undertaken to:

- enable operations running on alternative fuels, following EU directive to reduce use of fossil fuels
- reduce costs in response to inflationary pressures resulting from the COVID-19 pandemic and war in Ukraine and
- ensure that Leilac-2 directly supports the full-scale vision for the technology

The continued Value Engineering work has resulted in a lighter and simplified design, with a revised Leilac-2 CAPEX of €27m (subject to market conditions and more stable supply chains). Importantly, the improved module design, developed during FEED, better supports the vision for a low-cost, scalable, and accessible capture solution that can be implemented through a blueprint model, for a global roll out delivered by local companies using local resources.

An elegant multi-tube furnace design

The Leilac-2 furnace design, through Value Engineering, was successfully optimised, resulting in significant reductions in weight, cost, and complexity. Ongoing technology development within Calix and Leilac has simplified the design of a multi-tube furnace for the Leilac-2 project, reducing both the furnace size and the footprint of the total tower.

Additional efficiencies result from further simplifications in the alternative fuel combustion system. Subsequently, alternative fuels handling and distribution system capacity has increased, and the complexity and risk profile has decreased. These changes have made the design more consistent with cement industry standards.

Commissioning and testing to start by March 2025

The Leilac-2 Value Engineering phase was not originally planned in the project and has therefore resulted in an approximate six-month additional phase. The COVID-19 pandemic and the war in Ukraine have also disrupted supply chains and restricted access to external services and materials required for the FEED study. Heidelberg Materials is also undertaking site development and upgrades. Wildlife, including bats and falcons, currently living within and near the decommissioned towers which will be demolished as part of the site upgrades work in October, also required further consideration. Site preparation works will start following the demolition of the towers, the permits for the site work have been approved by local authorities.

Despite these considerable challenges, the project team expect to minimise these delays through the Engineering Procurement and Construction (EPC) phase of the project and expects to start commissioning and initial testing within the grant completion date of March 2025.

Leilac-2 is a first-of-a-kind demonstration plant and thus involves considerable risk, yet the improved design, along with the de-risking and technology development activities undertaken during the FEED phase, mitigates many risks identified in the original design. As part of this derisking program, the Leilac-1 pilot was upgraded with a cyclone preheater stack and new conveying systems. Campaigns since this upgrade work have had positive results. A new staged operations plan is now a part of the final design, including parallel natural gas and alternative fuel combustion systems, and integration options allowing operations using fresh air, vent air, or tertiary air. In this way, the risk of disruption to the host plant is further minimised. Finally, the improved design provides an elegant and simplified modular solution that has the potential to capture unavoidable process emissions from cement plants at any scale, providing a low-cost carbon capture technology.

2 PURPOSE

This report details work done by the Leilac-2 consortium related to the European Union's Grant Agreement 884170 for the Innovation and Networks Executive Agency. This report represents Deliverable D3.4 FEED Study Summary (public) of the Agreement.

The report details the work done for Work Package 3/ Task 3.2 FEED Study from key contributors Calix, IKN, and Heidelberg Materials, up to the end of Value Engineering (VE) in September 2022.

This FEED Study builds upon the work done within the Pre-FEED phase and serves to further develop the Demonstration Plant design and to enable the project to proceed with the endorsement of the entire consortium, on a fully risked and costed basis.

3 PROJECT BACKGROUND

THE LEILAC TECHNOLOGY

The cement industry, responsible for around 6–8% of global CO_2 emissions[1], is one of the most essential and hard-to-abate sectors of the economy. GCCA member companies, covering 80% of global cement production outside of China, have set a net zero by 2050 target[2].

The Leilac (Low Emissions Intensity Cement and Lime) technology, shown in Figure 1, was developed for, and in collaboration with, the cement and lime industries. It aims to enable the efficient and affordable abatement of unavoidable process emissions from cement and lime production.

During calcination of limestone ($CaCO_3$) to lime (CaO), the heated raw material releases CO_2 as a direct and unavoidable result of the chemical reaction. These process emissions account for 50-100% of the total CO_2 emitted from cement and lime production, depending on the type of fuel used, with a typical fraction for cement manufacture being 60%.

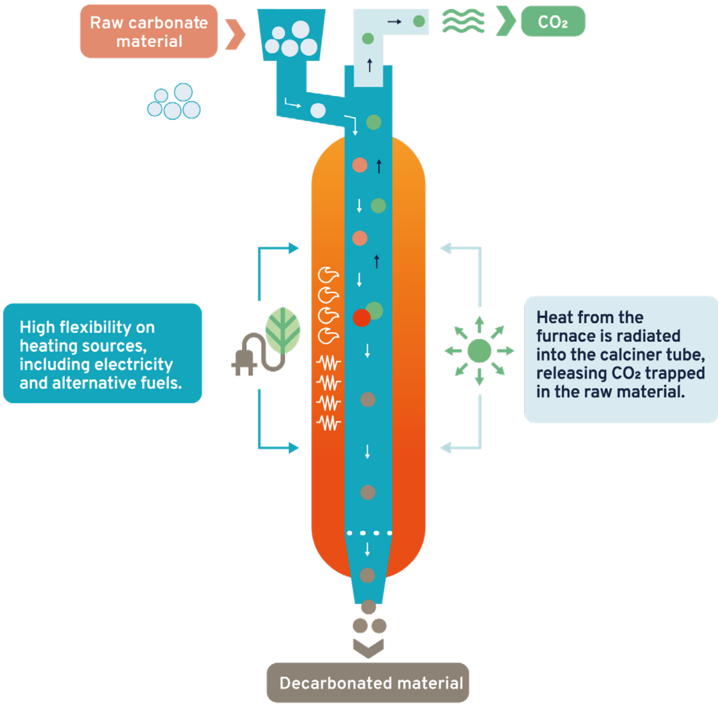

Figure 1: The Leilac technology indirectly heats the calcination reaction, ensuring the released process CO2 is not contaminated by flue gas. This carbon capture process requires minimal additional energy, and no additional chemicals or processes.

By indirectly heating the calcination reaction, the Leilac technology simply re-engineers the existing process flows of a traditional calciner to keep the furnace exhaust gases separate from the reaction products, as shown in Figure 2. This unique system enables unavoidable process emissions to be efficiently captured as more than 95% high purity CO_2 (as confirmed at the Leilac-1 pilot plant), with no need for additional chemicals or processes.

[1] Based on an estimated 2.43 Gt CO_2 scope 1 emissions from global cement production (Chen et al. *Env. Res. Lett. 17(4), 044007*) with total average anthropogenic CO_2 emissions of 11.5 ± 0.9 Gt C (42.2 Gt CO_2) per year. (Friedlingstein et al. *Earth System Science Data*). Figures include land use change and concrete carbonation and excludes scope 2 emissions from cement. Trends in global CO2 emissions; 2016 Report, The Hague: PBL Netherlands Environmental Assessment Agency gives cement's contribution to global CO_2 at 8%.
[2] https://gccassociation.org/wp-content/uploads/2023/01/GCCA-Roadmap-One-Year-On-Action-and-Progress.pdf

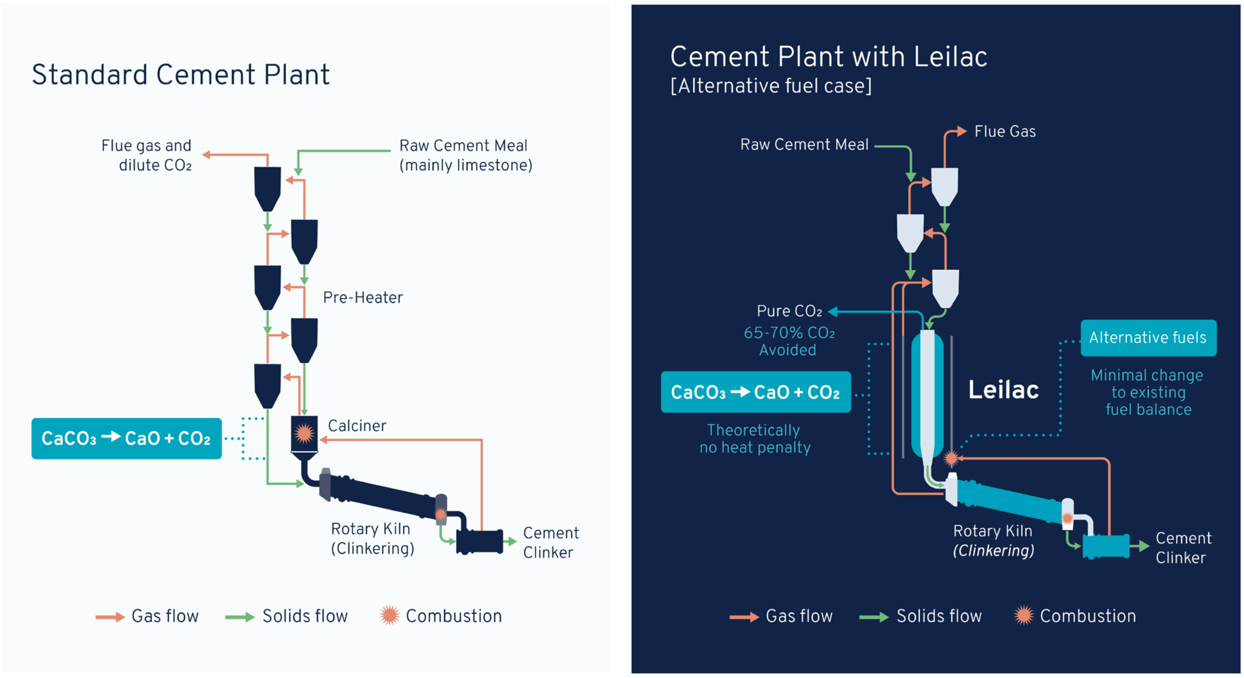

Figure 2: Leilac's efficient process modification approach

To achieve net-zero emissions, decarbonisation solutions must either enable the use of carbon neutral fuel sources or abate emissions resulting from energy consumption, typically accounting for 40% of total CO_2 emitted. The Leilac technology is being developed to run on a variety of energy sources, including electricity and alternative fuels, biomass, and hydrogen, to provide viable, flexible, and economical pathways to carbon neutral cement and lime. It can also be used in conjunction with other capture approaches to capture residual flue gas emissions, including conventional post-combustion approaches such as amines, but also calcium looping a proportion of its own product.

THE LEILAC-2 PROJECT

Leilac-2 aims to demonstrate a retrofittable and modular technology that can capture a cement or lime plant's unavoidable process emissions for minimal energy penalty, therefore providing a viable and cost-effective decarbonisation solution.

The concept of the Leilac technology has been proven at pilot scale through the Horizon2020 (H2020) Leilac-1 project. Located at CBR's cement plant in Lixhe, Belgium, Leilac-1 has a capture capacity of 25 000 tonnes of CO_2 per year, about 5% of a typical cement plant's CO_2 emissions.

Building on this success, Leilac-2 will develop, build, and validate a module with a capture capacity of 100 000 tonnes of CO_2 per year with estimated purity of >95%, about 20% of a typical cement plant's process CO_2 emissions.

The Leilac-2 project aims to develop a module that:

- Is replicable and retrofittable
- Can be efficiently integrated into an operational plant
- Is compatible with multiple fuel sources (particularly electricity with rapid ramping, to enable renewables load-balancing); and
- Demonstrates an accessible, economical, and scalable decarbonisation solution that can be retrofitted to all cement plants

The Leilac technology, developed through the Leilac-2 project, can provide urgently required solutions to enable Europe's cement and lime industries to decarbonise, helping them to dramatically reduce their emissions while maintaining their international competitiveness.

Leilac-2 will develop, build, operate, and evaluate a 960 tonne per day of raw meal (20% of the host plant's raw feed) demonstration plant at Heidelberg Materials' plant in Hannover, Germany. This is a 4x scale up from the Leilac-1 pilot plant that will demonstrate, at a commercially relevant scale, that over 95% of the process CO_2 emissions in this slipstream can be captured, while totally integrating with the host plant.

Once built, the demonstration plant will be evaluated and validated under actual operating conditions, with a staged integration and fuels commissioning programme and a variety of tests to confirm the technology's performance and integration is as expected, paving the way for full-scale demonstration.

Once proven at a suitable scale, Leilac-2 may represent the Best Available Technology (BAT) for decarbonisation of both the cement and lime industries. For a plant using this technology, the main additional 'cost' would be compression of captured CO_2 for further useful purposes (CCU) or safe, permanent storage (CCS).

The Leilac-2 consortium is led by technology provider Calix Limited and its subsidiary, Leilac Limited, and further comprises Heidelberg Materials, CEMEX, Lhoist, Cimpor, IKN, CERTH, Royal Belgian Institute of Natural Sciences, BGR, POLIMI, Engie Laborelec and the Port of Rotterdam. The project is also supported by the GCCA, CEMBUREAU, ECRA, EuLA, VDZ and the University of Clausthal as the External Advisory Board.

The five-year project is funded by the European Commission through the Horizon 2020 research and innovation programme (€16M, grant no. 884170), and a further €18M contributed by consortium members, including cash contributions towards the development of the demonstration plant and in-kind contribution for staff.

The Leilac-2 project commenced on the 1st of April 2020 and will run for five years, through 2025. The project is built around several phases and milestones including Pre-FEED, FEED, and a combined Engineering, Procurement and Construction phase (EPC), and subsequent commissioning and testing. The project also includes developing CCUS business cases (WP4) and dissemination and communications (WP5).

As a first-of-its-kind demonstration plant, the development of Leilac-2 involves considerable risk. In addition to risks inherent with technology development, the COVID-19 pandemic, war in Ukraine, and ongoing supply chain disruption and inflationary pressures, all have a major impact, increasing Leilac-2's CapEx beyond expectation, yet in-line with the original budget, using pre-COVID pricing and scope.

LEILAC'S FULL-SCALE VISION

The Leilac-2 project aims to develop a low-cost and retrofittable modular capture unit for process CO_2 emissions released unavoidably in the production of cement and lime. Once developed, this modular design can be replicated and applied at any scale. The development and demonstration of a replicable module within the Leilac-2 project therefore represents the critical de-risking step for the full-scale commercialisation of the Leilac technology.

As detailed later in this report, every effort has been made to ensure the design of the Leilac-2 module directly supports the long-term technology vision. The Leilac-2 module will provide a strong basis to scale from, with each module capable of separating in the order of 100 000 tonnes of CO_2 per year at >95% purity. Its retrofittable, modular design can provide flexible layout and integration options that minimise disruption to the host plant and enable full scalability to capture up to 100% of the process emissions from any plant.

Currently, the cost of emitting CO_2 within the EU is around €90 under the EU ETS (Emissions Trading Systems), while the US Inflation Reduction Act increased the incentive to capture CO_2 from industry to US$85 per tonne. For our illustrative plant operating under the EU ETS, the study finds that full-scale implementation of the Leilac technology could capture CO_2 emissions worth €53 million per year for a total annual cost of €28 to €49 million, depending on the costs of CO_2 transport and storage.[3]

Optionality on fuel sources, including electrification, will also be realised through the Leilac-2 project. Leilac's compatibility with multiple fuel sources, in addition to strong synergies with post-combustion capture technologies for fuel emissions, can provide flexible and future-proof pathways towards carbon neutral and even carbon negative cement and lime.

Scale-up of the Leilac technology through the Leilac-2 project will enable the demonstration of a commercially relevant module and near-term commercial roll out of the technology. Eventual delivery through a blueprint model for roll out by local engineering firms is being designed to urgently deliver scalable and accessible decarbonisation solutions for the global cement industry.

Figure 3: An impression of a Leilac plant at typical full-scale. Capable of capturing ~600 000 tonnes of CO2 per year, with a footprint of 54 x 27m and height of 90m.

PROJECT OBJECTIVES

The project objectives, as outlined within the H2020 Grant agreement, are to **construct a Demonstration Plant to**

- **Capture 20% of a full-scale cement plant's** (and 100% of a large lime kiln's) process emissions – capturing around 100 000 tonnes of CO2 per year of pure CO_2 for minimal energy penalty (just compression), a x4 scale up from the Leilac-1 pilot plant:

[3] *Decarbonising Cement: Leilac at Full Commercial Scale,* a new study produced by the Leilac-2 consortium for the European Union, provides a detailed analysis of the Leilac technology's potential to deliver flexible and low-cost decarbonisation solutions for a cement plant with a capacity of 1.2 million tonnes of clinker per year, with costs based on central European prices. Note that certain costs, particularly electricity, will vary dramatically by region.

- Prove the **effective retrofit and full integration** of the Demonstration Plant into the host plant's operations
- Prove the **efficiency and stability** of the complete cement-kiln process and resulting clinker quality when operating on the Leilac calcining technology
- Prove an easily **replicable modular design** for scale-up – enabling the accelerated full-scale commercial deployment
- **Demonstrate the use of alternative fuels** (such as biomass) and electricity for the process, enabling a calciner/lime kiln to be zero-emissions
- **Demonstrate the ability to use electricity, with rapid switching from fuel to electricity** with fast ramp up/down times. This capability is intended to be retrofitted to the Leilac-1 pilot plant. Compatibility with electricity and conventional fuel sources with rapid switching could allow a cement plant to undertake load balancing of renewables on the grid – enabling the electrification of the cement industry and a resulting low cost, local, and effective solution for grid stability with high
  renewable use. Under the grant, in addition to the study, this involves installing elements on the Leilac-1 pilot plant.

The project objectives are broken down into 5 Work Packages. The Structure of the project has been developed to focus working groups as technical, cross partner teams to address these objectives and the challenges within each.

MILESTONES & TIMELINE

The project is structured around distinct engineering and development phases and milestones with two key stage gates at Milestone 1 and 2 consisting of formal Go/ No-go decisions by the General Assembly. This structure ensures the project proceeds with the endorsement and support of the entire consortium, and that it does so on a risked basis, regarding the estimated budget and chance of success.

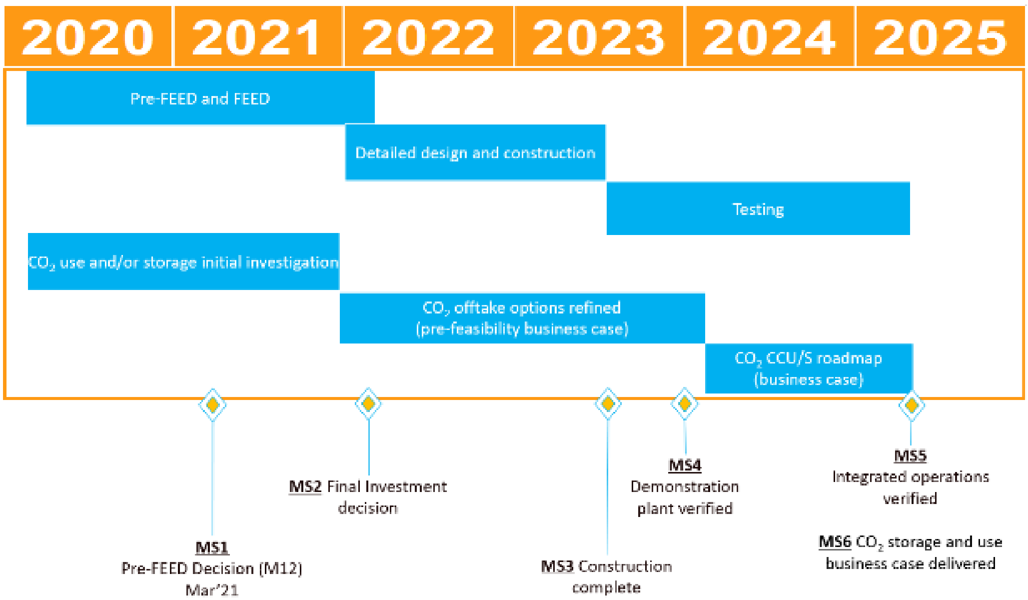

Figure 4: Leilac-2 Timeline, including project milestones determined in the Grant Agreement after the agreed MS2 revision

Delays have been experienced, resulting in part from additional time required for value engineering to identify ways to simplify the design, increase capacity for alternative fuels and reduce costs. Additionally, permitting lead times are longer than were anticipated within the original schedule in the grant agreement, and the need to undertake upgrade works on the Hannover Plant undertaken by Heidelberg Materials as part of a wider site works programme to enable the delivery of the Demonstration Plant, have resulted in further delays.

The project team will minimise these delays through the EPC phase of the project and anticipate starting commissioning and initial testing within the grant completion date of March 2025.

4 FEED REPORT SUMMARY

The front-end engineering design (FEED) for Leilac-2 was performed in the period up to April 2022 with a significant and successful value engineering (VE) phase undertaken between April and September 2022. The final value engineered basis of design was approved by the Executive Board in September 2022.

This section lays out a summary of the design at the end of FEED, and what major changes were made during VE. Later sections of the report focus on the design at the end of VE.

SUMMARY OF LEILAC-2 AT END OF FEED

At the end of FEED, there was a technically viable design for the Leilac-2 Demonstration Plant that would capture around 100 000 tonnes of CO_2 per year of high purity CO_2. Furthermore, a well-developed, staged retrofit design and commissioning/ start up approach was developed to have minimal impact on the host plant. This would gradually enable integration of the Demonstration Plant into the host plant's operations.

This staged integration approach would allow Leilac-2 to run from low to high throughput, with varying levels of integration, and varying fuels. The integrated Leilac plant was designed to run within permitting levels, at full throughput, for both alternative fuels and natural gas operations.

4.1.1 *Project Assurance Review – end FEED*

The FEED Assurance Review, an independent review, was held in February 2022 with the following goals:

- Assess whether the Development team was ready for the Construction and Commissioning Phase had completed a robust and appropriate Basis of Design (BoD) and FEED and was set up to achieve a successful Financial Investment Decision (FID) and Project Execution.

- Assess whether the Basis of Design and development plans were in line with the contractual obligations of the project, as outlined in the consortium and grant agreements.

- Determine whether the plan and cost estimates were sound and adequately resourced to advance to the next decision point.

VALUE ENGINEERING OVERVIEW

At the request of the Executive Board, the project design team was directed to undertake a Value Engineering (VE) exercise after the FID. This value engineering phase was not originally planned in the project. It was, however, able to deliver a significant reduction in capital cost for the Demonstration Plant delivery (€10m reduction, 27% lower), and a revised design that was more in line with the full-scale vision of the technology. The executive board approved the revised, value engineered basis of design in September 2022. This formally completed early phase engineering design.

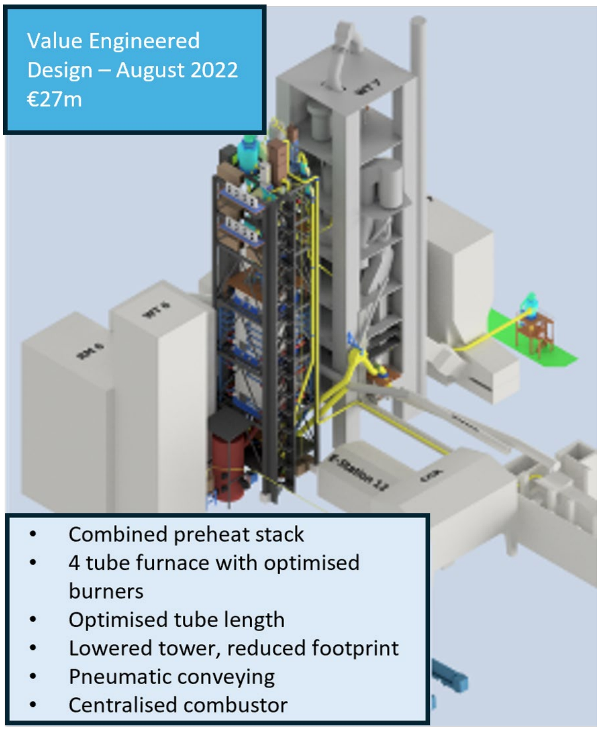

Figure 5: Value Engineered Basis of Design

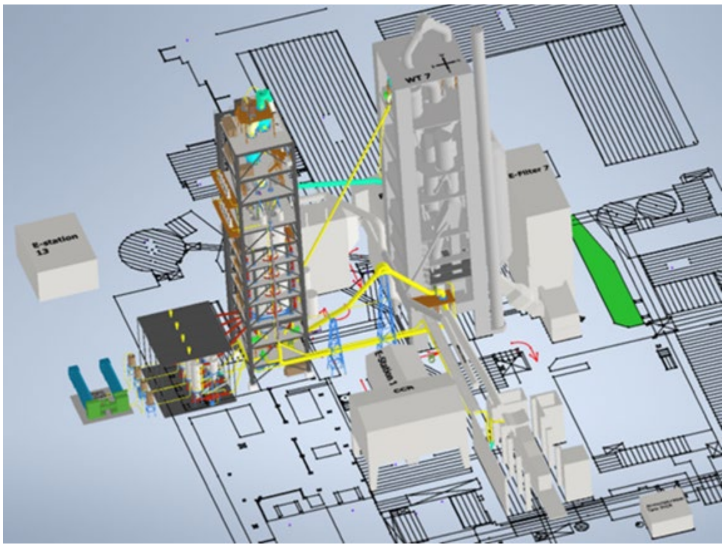

Figure 6: LEILAC-2 Demonstration Plant Tower: Value Engineered design moving into Detailed Design

UPDATED SCHEDULE

The project team will focus efforts on minimising the delays to date through the EPC phase of the project and start commissioning and initial testing within the grant completion date (March 2025). Operations will also continue beyond March 2025. In this way, the full activities under the grant will be completed, with planned continued operations.

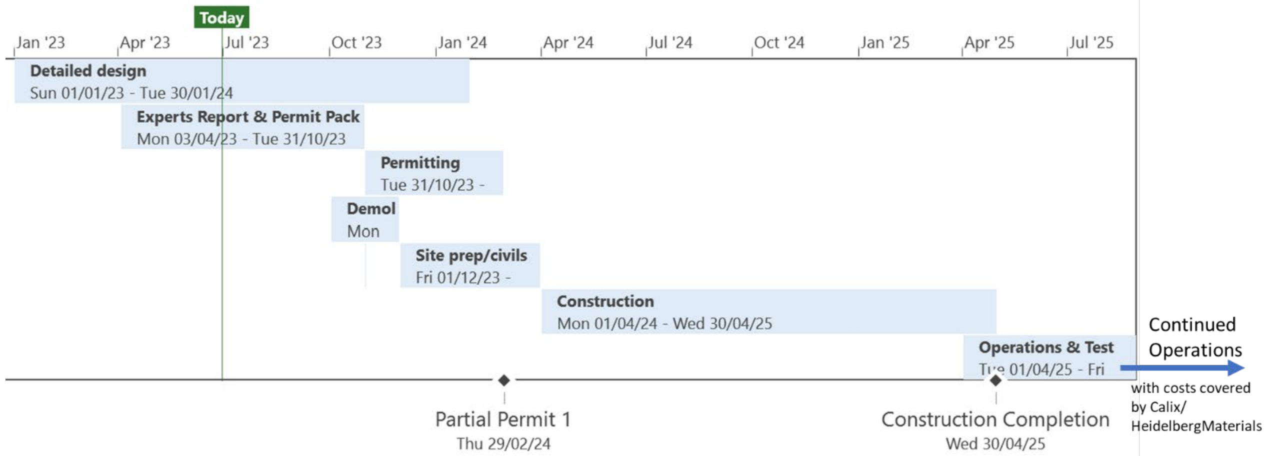

Figure 7: Updated EPC Schedule

5 THE LEILAC-2 SITE – HANNOVER

The Heidelberg Materials Plant in Hannover, formerly known as "Teutonia Zement," is in the southern central part of Lower Saxony and utilizes, alongside the neighbouring Lafarge Holcim's Höver Plant, which is across the highway.

Figure 8: Cement plants in Germany and their geological limestone origin[4]

The plant is in Misburg Süd, a sub-district of Misburg-Anderten, a district in the east of Hannover. It is located between two rail lines (9), the public one in the south and the so called Güterumgehungsbahn, an industrial rail transport track in the north.

[4] Environmental Data of the German Cement Industry 2011 Edition, VDZ, 2012. Accessed 26th July 2023: https://www.vdz-online.de/fileadmin/wissensportal/publikationen/umweltschutz/Umweltdaten/VDZ_Environmental_Data_2011.pdf

Directly across the northern rails, the so called Stichkanal (stitch channel) establishes a connection to the Mittellandkanal, Germany's longest artificial waterway, providing direct access to the west-east European water way transport grid for the Hannover cement plant. The plant itself is connected to its harbour by a bulk material transport bridge, conveying marl & coal as well as a tunnel below the rail tracks and some streets.

Thus, water way connections offer many advantageous transport options.

East of the plant, the Autobahn A7 provides direct connection to roadway transport, while in the south the Südschnellweg (city speed way) provides the best connection to the city centre of Hannover.

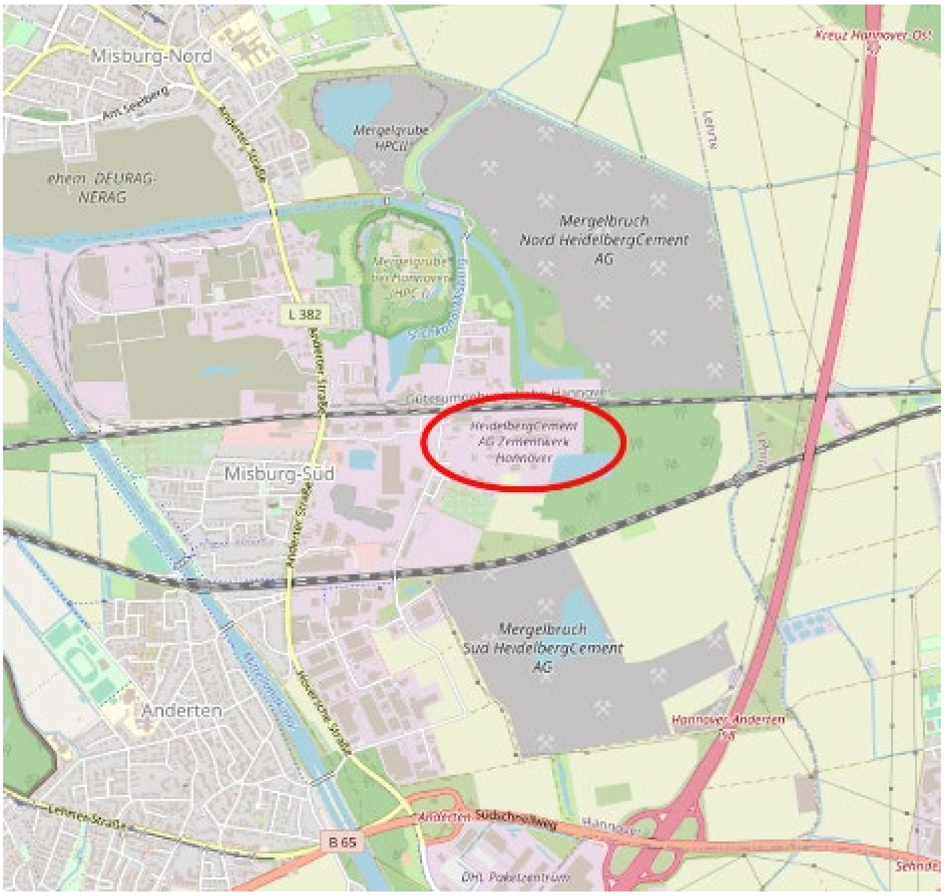

Figure 9: Map of western Misburg-Anderten

Several unused structures can be found within the plant, due to the production history of the plant (Berthold Lange founded the Teutonia Misburg Portland-Cementwerk in 1897). For example, the bare concrete structures of the former preheater towers number 5 & 6 are dominating the visual impression of the plant, once seen from the close by highway. The active kiln line number 7 (Ofenanlage 7) and its much higher preheater tower are thus partly hidden behind those empty concrete structures.

SITE LAYOUT

10 shows how Leilac-2 will integrate with the existing cement plant. In this figure, the demonstration plant is shown to the south (left) of the preheater tower WT7. The combustion air ducting is shown in yellow, and the Leilac-2 flue gas duct is shown in teal. The rotary kiln is shown below (east) of WT7.

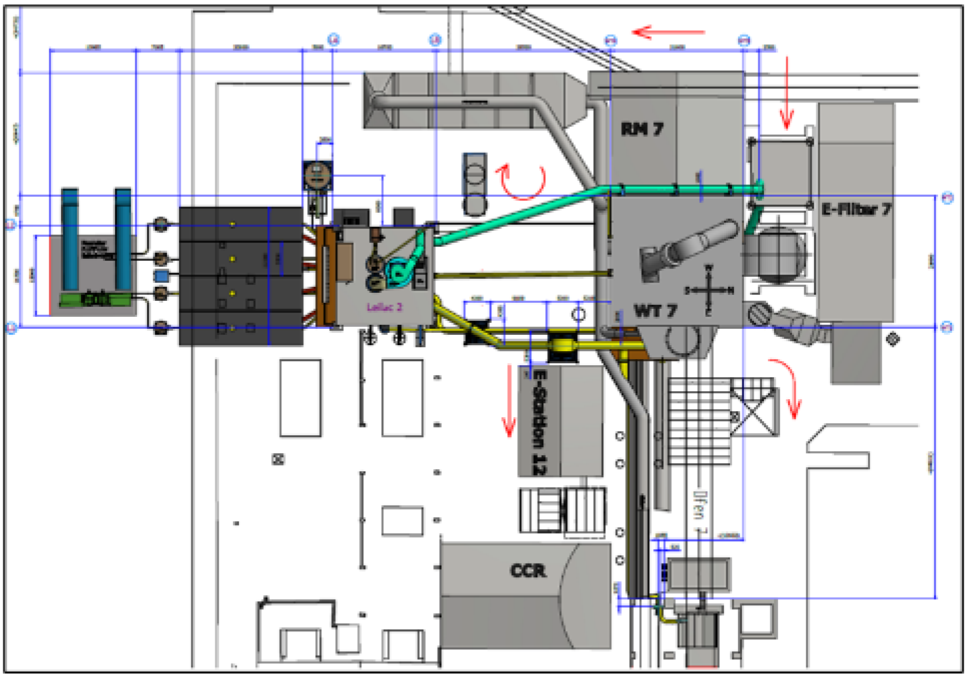

Figure 10: Hannover site layout, with Leilac-2 and its tie-ins shown. The layout is facing West.

Figure 11: Hannover site layout impression, with site demolition and Leilac-2 and its tie-ins shown.

6 LEILAC-2 DEMONSTRATION PLANT - DESIGN

The Leilac-2 plant is split into different subprocesses which are designed to complete a set task to achieve the main goal of calcining raw meal and capturing high purity CO_2. These subprocesses, and the equipment they use, are outlined in the chapters below. Most of this equipment is already being used in the cement industry and it can be operated in a comparable manner.

INTEGRATION

6.1.1 Integration Philosophy

The demonstration plant will be subjected to the operating conditions of the Hannover plant, given its close integration, allowing the Leilac-2 system to be observed in an operational environment to identify its technology readiness level (TRL) 7[5]. The Leilac-2 plant will have numerous integration points with the Hannover plant. The integration points from the Hannover host plant to Leilac-2 include

1. Raw meal feed
2. Tertiary Air and Cooler Vent Air
3. Process Water
4. Mains Water
5. Ammonia injection
6. Electricity connection
7. Natural gas connection

The integration points from the Leilac-2 plant to the Hannover host plant include

1. Calcined meal return
2. Furnace Exhaust Gas
3. CO_2 Pipeline

6.1.2 *Staged Operations and Start Up Plan*

One of the key requirements of the Leilac-2 project is to ensure that the integration of the new demonstration plant poses minimal risk for the main host plant. The design team have developed a **staged integration approach** that allows for scaled commissioning, reducing disruption risks. This plan has been signed off by the Executive Board and will be developed into a detailed commissioning and operations plan during detailed design.

PROCESS OVERVIEW

Leilac-2's process design was completed during the early pre-FEED phase of the project, as a collaborative exercise between industry partners Polimi and Leilac Limited. The configuration chosen was one which supported the longer-term ambitions for the technology, while providing a stepwise approach to reaching this solution. Leilac-2 therefore contains more optionality than will be provided in an "n-th of a kind" (NOAK) implementation of the Leilac technology. Each design configuration was analysed to assess the process parameters, impact on the host plant, technology risk and the data which was sought from that configuration.

The plant layout can be broken down into the following key blocks:

- Hannover Cement Plant – Interfaces with Leilac-2
- Meal Distribution & Preheating
- Calcination tubes & hot meal conveying
- Combustion air supply
- Combustion & Furnace

[5] As defined by the European Commission for Horizon2020 projects: https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

- Flue Gas Handling (post-furnace)
- Flue Gas Handling (post-preheat)
- CO_2 process gas handling

6.1.3 Process Overview

Key features of Leilac-2's design include

- Four calciner tubes within one furnace chamber
- A preheater string for heat transfer from flue gas
- Fuel flexibility, with staged operations for natural gas, through to biomass and ambition of full alternative fuel use.
- Full heat integration with the plant, with safe material conveying
- Use of typical cement plant equipment allowing for easy integration, operation, and maintenance

The control system design is being developed in collaboration with Heidelberg Materials, including a controls expert, and the Hannover plant operations team.

MODELLING & TECHNICAL VALIDATION

Process Modelling is a key tool for understanding the relationship between the inputs, outputs, and key processes within a plant, whether they are chemical, physical, or thermal. It aims to provide an accurate representation of how changes in one of these elements affects the others. This whole-plant approach reduces the chance of serious knock-on effects being overlooked prior to the finalisation of design and operation. This reduction in the risk of the overall process being unfit for purpose or necessitating the modification or replacement of process units after commissioning, is the motivation for process modelling. Another key motivation is that the process model can be used to optimise the process conditions to maximise or minimize key performance indicators, for example CO_2 capture efficiency, or thermal energy demand. This improves the overall economic viability of the process.

Politecnico di Milano (Polimi) used Aspen Plus, a well-established process simulation tool, to develop an integrated model of the combined host plant + Leilac-2 system. This was calibrated using real process measurements, and then applied to a range of scenarios. The results have been used in the rest of the plant design and in the OpEx modelling.

Aspen Plus is used to calculate mass and energy balances based on the specific design of the process, consisting of raw materials, unit operations, and their given composition and operating conditions. First, a process model of the existing plant is built in Aspen environment to calibrate equipment and operational parameters. Then, the integrated system is developed based on the PFD including Leilac-2. The overall model is completed using informed and agreed assumption, particularly for the operation of the unit operations in the new plant. The model has been verified to ensure agreement between the data from the simulation of Hannover's process and the measured data reported by the plant.

CERTH undertook a Computational Fluid Dynamics (CFD) study to review and further improve the key assumptions and boundary conditions of the model. This work improved the rate of convergence for subsequent Leilac2 CFD modelling in the FEED phase and supported the final arrangement and sizing of the calciner tubes.

6.1.4 Model Scenarios

Numerous scenarios have been run to simulate the expected conditions of Leilac-2, and some hypothetical alternatives helped assess the operation and impacts on Hannover's process. These were aimed at analysing the effect of changing the fuel source and the combustion air.

The goal of this scenario analysis is to compare key performance indicators (KPIs) of different process operational states, such as temperature of flue gases, fuel consumption, or volumetric flow rates, and anticipate their impacts on the whole operation.

Campaigns were performed in existing Calix calciners to measure the thermal behaviour of Hannover meal. External consultants were also engaged to undertake several R&D programmes., utilising both the Leilac-1 Pilot plant in Belgium, and the Calix electric calciner in Australia.

6.1.5 Environmental – Gaseous Emissions Modelling

An emissions model was developed to forecast the concentrations of regulated species in Leilac-2 and the main stack to provide assurance that the combined emission stream of Hannover with Leilac-2 will remain below the legal limits set by the regional and federal authorities.

The model is a mass balance in Microsoft Excel. Its inputs include

- Fuel and meal compositions
- Experimental results of preheater and Leilac simulations
- Injection rates of abatement consumables
- Overall energy and mass balance developed by Polimi
- Historical emission rates from the existing Hannover plant stack.

7 REGULATORY CONTROLS AND APPROVALS

ENVIRONMENTAL & POLLUTION CONTROL

The following gas species are regulated and must be controlled on the Hannover site, including in Leilac-2:

Species	Formula
Chlorine (as hydrogen chloride)	HCl
Sulphur Oxides	SO_x
Carbon Monoxide	CO
Total Organic Carbon	TOC
Ammonia	NH_3
Nitrogen Oxides	NO_x
Dust, HF, Hg, heavy metals, PCDD/F, benzene	

By integrating Leilac-2 into the process, all the components are forecast to be below limits, with abatement and operations plans in place.

PERMITTING & PLANNING APPLICATION REQUIREMENTS

The Hannover plant must conform to emission limits of regulated species set by the local authorities. An external expert will undertake emissions modelling of the combined process, in addition to the modelling completed by the project team, as required by standard permitting requirements in Germany.

The engineering documents will be prepared by June 2023 and planning application will be submitted late 2023.

8 PROCUREMENT

As in the Leilac-1 project, grant funding and partner cash contributions will be used to purchase equipment packages and services.

The procurement plan will be signed off by the Executive Board, ensuring all industrial partners providing funding and involved in procurement, have agreed to the plan. The procurement plan provides the Executive Board with forecast spend profile over the EPC phase to completion.

A list of recommended suppliers has been developed. These suppliers are a combination of suppliers known to Calix, Heidelberg Materials, IKN or Cemex. The aim of the FEED stage procurement was to gain the most accurate costs for estimate, not to select final vendors.

Based on early and developing design, the following package list was established:

1- Furnace System
2- Burner
3- Process Pipework
4- Duct and Cyclone Refractory
5- Gas treatment
6- Alternative fuels transport and storage System
7- Kiln Feed
8- Reactor Package
9- Ancillary Package
10- Mechanical Installation
11- Electrical Installation
12- Structure
13- Civil Package
14- Construction Services
15- Erection Package

A detailed procurement plan has been developed, outlining lead times, supplier quotes, dates equipment is required on site for construction, and required purchase date. This will be further developed in early detailed design.

9 CONSTRUCTION

A construction manager has been engaged by Leilac, and a detailed construction plan prepared. The construction plan includes:

- Site preparation
- Civil works and foundations
- Tower construction
- Storage management
- Materials management
- Security
- Detailed construction programme
- Forecast spend analysis
- Safety

10 COST ESTIMATE

The originally agreed budget split including grant funds and in-kind cash contributions:

European Commission Grant Funds, including plant and R&D	€16m
Industrial partner cash contributions	€8m
In-kind contribution for personnel costs (FTE) by all partners	€10m
TOTAL of budget allocation	**€34m**

Cost plan development was a key focus during the FEED study and through Value Engineering. Following the pandemic, supply chains and market conditions have increased the challenge of confirming equipment and package prices. The effect of COVID-19 on the building and supply industry has been substantial. Increased global demand in the construction sector, combined with the multiple and complex impacts of the pandemic on supply chains and logistics, have resulted in unprecedented shortages, delays and, increased prices of materials and labour across the economy.

Significant reductions in capital costs were achieved through value engineering. The final cost plan, at the end of the value engineering phase, including all methods listed above, forecasts a capex cost of EUR27m, excluding any contingencies.

OPEX COSTS

A cost model of operations is in development and will be evaluated and finalised during the operations phase of the project. OpEx modelling considers

- Fuel consumption in Hannover
- Consumables use in Hannover
- Fuel consumption in Leilac-2
- Major electrical duties in Leilac-2
- Consumables use in Leilac-2

11 FEED RESULTS AND NEXT STEPS

The Executive Board approved the final design for the Leilac-2 demonstration plant following value engineering. This design includes

- Combined pre-heat stack
- Multi-tube furnace with 4 tubes
- Conveying systems

Costs have significantly increased during and after the COVID-19 pandemic. The original budget also did not include parallel energy systems. The change to include capacity for 95% alternative fuel (with 5% natural gas trim) was added to the Basis of Design, in response to the increased natural gas prices, and the European Commission's call for projects to move away from natural gas usage.

OVERVIEW OF THE FEED STUDY PHASE

- FEED study completed March 2022 – with a technically viable design for a LEILAC Demonstration Plant that would capture around 100 000 tonnes of CO2 per year of pure CO_2. Furthermore, a well-developed, staged retrofit design and start up/ operations approach developed.
- Milestone 2 – Financial Investment Decision was successfully passed in March 2022.
- A Value Engineering phase from April to September 2022 significantly reduced the cost of the Demonstration Plant.
- The Executive Board approved the final revised (Value Engineered) Basis of Design in September 2022.
- Leilac-1 Pilot Plant upgrade works were undertaken to de-risk the preheat cyclone and new conveying system. Initial operations showed good flowability through conveying systems and Pre-heat systems.
- Governance structure remains in place with additional resources added by Calix (design management and EPC Project Manager) and Heidelberg Materials (permitting & site upgrade works).

NEXT STEPS

The project moved into detailed design in October 2022, with final PFD frozen in April 2023. The critical path moving forward is to ensure construction can proceed as soon as possible and minimise the overall impact of delays to the project.