A techno-economic analysis of the Leilac technology at full commercial scale

October 2023

Leilac2

Partners

Heidelberg Materials, ENGIE Laborelec, IKN, CERTH Centre for Research & Technology Hellas, LEAP, BGR Federal Institute for Geosciences and Natural Resources, CEMEX, Politecnico Milano 1863, CIMPOR, calix, Lhoist, Port of Rotterdam, Geological Survey of Belgium, museum

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Disclaimer:

Decarbonising cement | Leilac at Full Commercial scale[1]

The Leilac technology

- No additional chemicals or processes
- Scalable modular design
- Low-impact retrofit
- Future-proof fuel optionality
- Flexible layout and integration
- Targeting the lowest cost

Techno-economics

~€33/tonne CO_2
Cost for process emissions avoidance.[2]

€39/tonne CO_2
Cost for near-zero emissions cement[4]

~€16/tonne clinker Cost increase for process emissions capture

€53m worth of CO_2 captured[3] for **€20m**

~€90-135m
Leilac CAPEX requirements[5]

~10€/tonne CO_2
Leilac operating cost[6]

>98% Expected captured CO_2 purity

92% Direct CO_2 emissions avoided with e-Leilac

Illustrative figures based on central European costs. Regional and plant specific analysis is provided through a scoping study. For more information please email contact@leilac.com.

[1] A technoeconomic analysis of a full-scale implementation of the Leilac technology at a typical 1.2 million tonne clinker per year cement plant with a capture capacity of 590 ktpa of CO_2.

[2] Typical CO_2 process emission capture cost on a per tonne of CO_2 avoided basis. Includes CO_2 compression, maintenance, and CAPEX repayment. Excludes CO_2 transport and storage.

[3] Annual value of CO_2 captured, and associated capture cost. Assumes an average EU ETS price of €90. Excludes CO_2 transport and storage.

[4] With the addition of a small post combustion capture unit for fuel emissions.

[5] For a typical, 1.2 million tonne clinker per year plant, excluding CPU CAPEX. Range includes optionality on fuel and preheater replacement / reuse.

[6] Excludes compression and CAPEX repayment. Assumes use of 95% alternative fuel at negative prices.

Decarbonising Cement

Leilac at Full Commercial Scale

A retrofit and integration techno-economic analysis of the Leilac technology at full commercial scale.

An impression of a full-scale Leilac plant. Capable of capturing 590 ktpa of CO_2, this plant has a footprint of 54 x 27m (similar to the existing tower) and height of 90m.

Contents

Executive Summary

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 will be able to be replicated and applied at any scale.

This study, in support of the Leilac-2 project, provides a techno-economic analysis of the application of the Leilac technology at the full-scale of an illustrative cement plant located in central Europe. The study had two key objectives: to ensure that the Leilac technology could provide a low-cost option for full commercial-scale implementation, and to ensure that Leilac-2 is testing and developing a design that supports that full-scale vision.

The study indicates that the Leilac technology could be successfully retrofitted to a typical cement plant at a scale to capture up to 95% of its process emissions at low cost. The study finds that an optimised plant design based on the Leilac-2 module and running on 95% alternative fuel could capture 590 000 tonnes per year of CO_2 for €33/tonne of CO_2 avoided, including CO_2 compression, maintenance, and CAPEX repayment.[1] The study also concluded that full-scale installation does not require significant downtime, with the Leilac technology able to be built alongside ongoing plant operations and connected during routine maintenance.[2]

At an EU ETS price of €90, full-scale implementation of the Leilac technology at a typical cement plant considered in this study could capture CO_2 emissions worth €53 million per year for an annual cost of €20 million, excluding CO_2 transport and storage.

The study assessed the capture rate and costs for full-scale Leilac plants based on duplicating the current Leilac-2 design (4-tube modules), representing the simplest approach to applying the design at full-scale. Future module designs, containing more tubes per module, could provide improved design solutions that can be implemented at lower cost, but are not considered in this analysis.

Additional scenarios studied include the use of alternative fuels, electrification, and a post-combustion system for capture of fuel emissions and residual process emissions. Other abatement solutions for fuel emissions, including calcium looping, are feasible, but are not included in this study. All scenarios studied have different costs and emissions profiles, through to being carbon negative. Implementation of the Leilac technology also allows for a transition to clean fuels or the addition of a post-combustion capture unit at a later date.

The results of the scenario analysis include:

- €30–33/t CO_2 avoided – using five Leilac-2 modules in various configurations.
- Near-zero emissions for €39/t CO_2 avoided, with the addition of a small post-combustion system, set as an amine unit in this study.

The study assumes that a typical cement plant is not due for significant upgrade, and therefore includes the cost of taking the plant offline to complete the installation, should additional time beyond routine shutdowns be required. This cost should also be considered in any comparative analysis.[3] Leilac's capture of process CO_2 at >95% purity (but likely >98%) has been considered, enabling smaller CO_2 compression units, and reducing additional post-capture CO_2 processing steps than many equivalents.

Electricity and natural gas costs are based on European prices projected for the late 2020s. As electricity costs vary significantly by location and are expected to be extremely volatile for the foreseeable future, particularly in Europe, the operating costs for the full electrification scenario (and other technologies that rely heavily on electricity) should be treated with caution. A sensitivity analysis on electricity price has been performed and is presented in Section 4.3.1. Low-grade alternative fuel is assumed to be the reference fuel, and is assumed to attract a negative price due to the opportunity costs associated with disposal. This is another significant cost driver, and so a sensitivity analysis on the fuel's gate fee has been performed.

The study presents a vision for a low-cost, retrofittable and scalable capture solution for unavoidable process emissions from cement production. There is room for further optimisation. Strong synergies with post-combustion capture of fuel emissions provide immediate and economical pathways to near zero emissions cement, while the prospect of full or partial electrification and the use of low CO_2 footprint fuels such as biomass or hydrogen provide future-proof solutions for a full-scale Leilac installation.

[1] For a cement plant with a capacity of 1.2 million tonnes of clinker per year. That cost includes a Leilac CAPEX of around €137m (excluding compression) and Leilac OPEX would be approximately €10/tonne of CO_2 avoided (excluding compression). Compression CAPEX is approximately €19m, and OPEX €13/tonne of CO_2.

[2] This scenario is based on an installation that, should it be non-operational for any reason, would not impact clinker production rates as it is a semi-independent unit.

[3] Cost, where applicable, includes required downtime: calculated using the annual production value of clinker, based on a clinker price of €55/tonne and an annual production volume of 1.2 million tonnes.

1. Introduction

1.1. The Leilac Technology

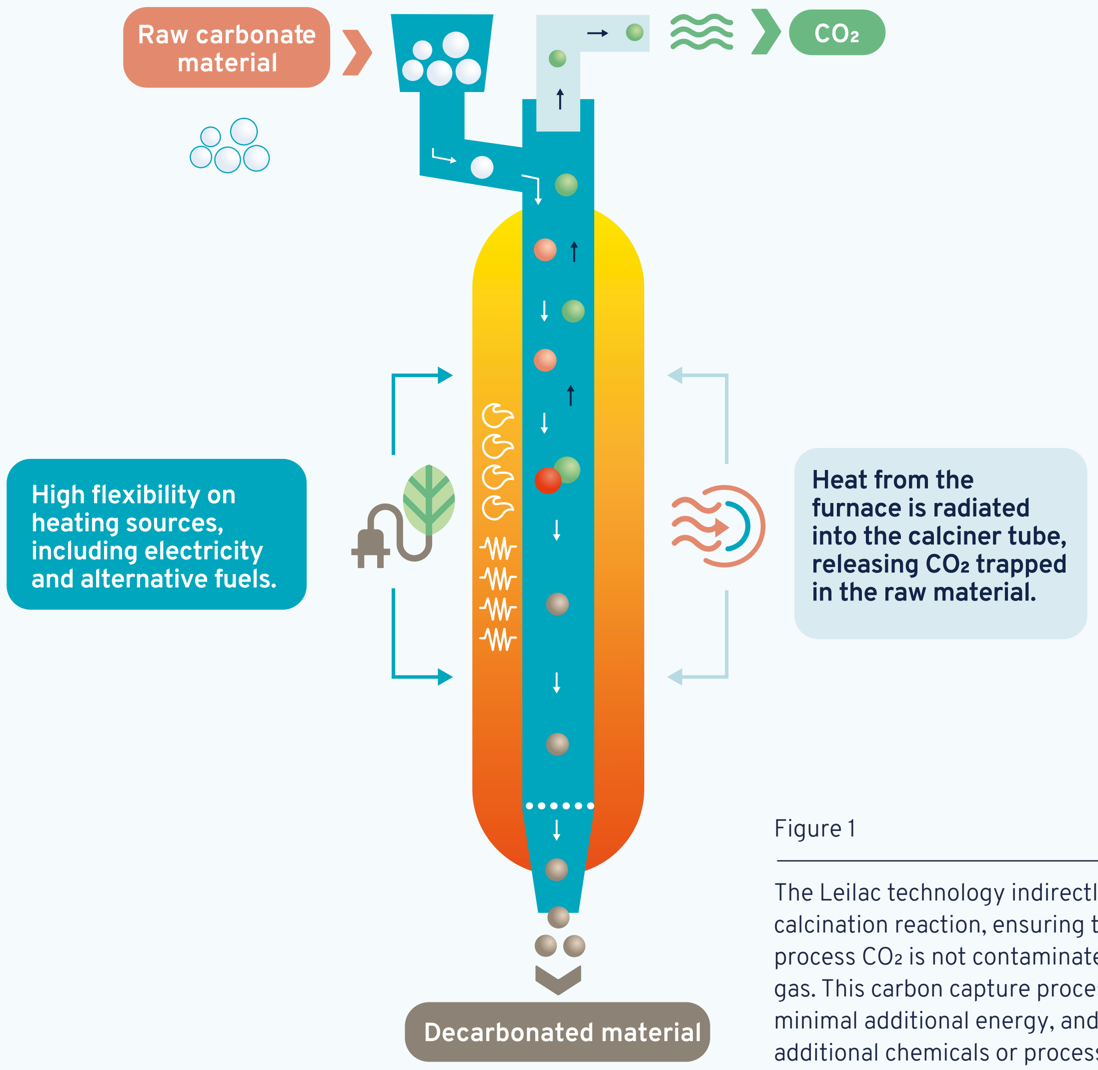


Figure 1

The Leilac technology indirectly heats the calcination reaction, ensuring the released process CO_2 is not contaminated by flue gas. This carbon capture process requires minimal additional energy, and no additional chemicals or processes.

Leilac Limited aims to enable the efficient and affordable abatement of unavoidable process emissions from cement and lime production. The Leilac technology is shown in Figure 1. 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 $CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$. 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%.

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 the unavoidable process emissions from calcination to be efficiently captured as high purity CO_2 (>95% as confirmed at the Leilac-1 pilot plant), without dilution or contamination from combustion byproducts, and with no additional chemicals, solvents or processes

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 direct CO_2 emitted from a cement or lime plant. Leilac's technology is being developed to run on a variety of energy sources, including electricity, alternative fuels, biomass, and hydrogen.

As such, it provides 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 solvents, and by using a proportion of the plant's own product, CaO in a process known as calcium looping.

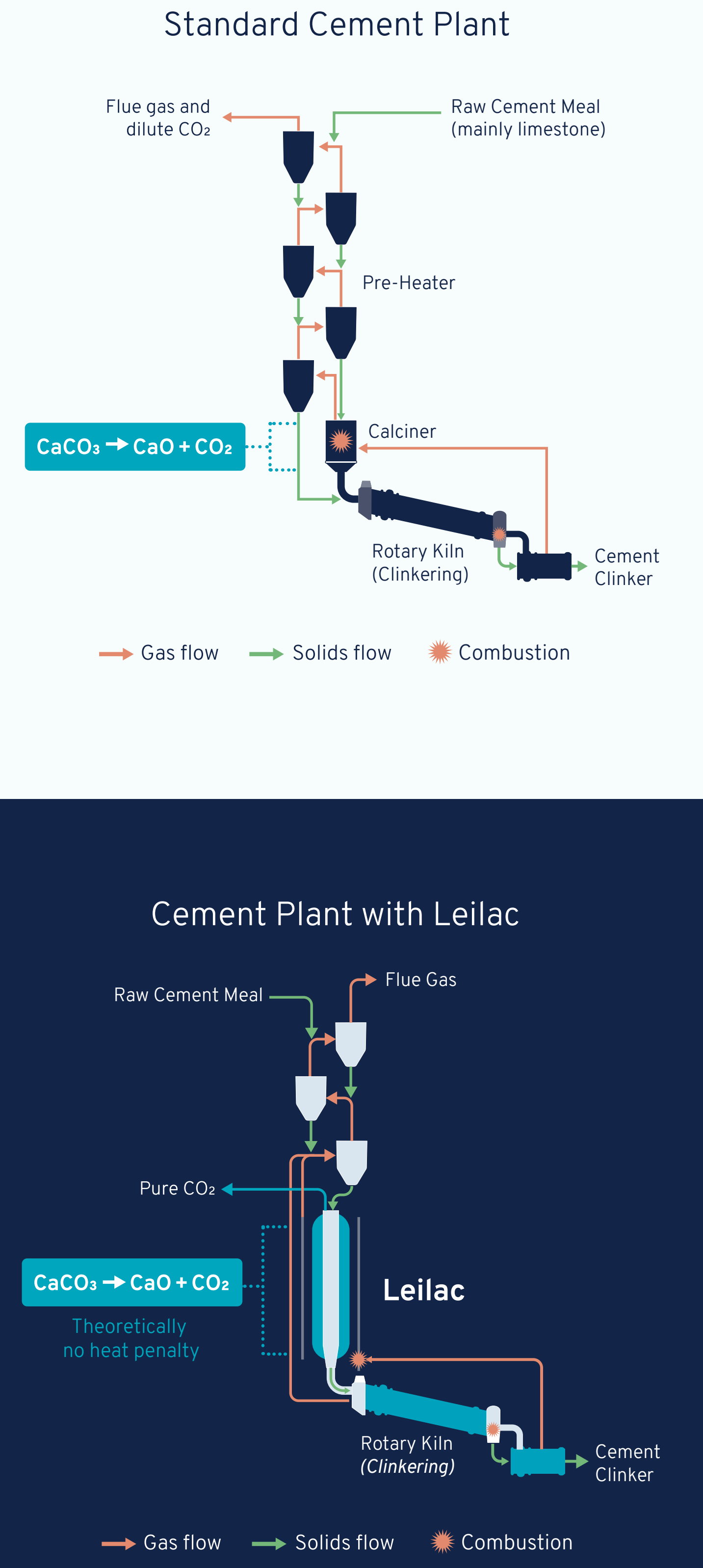


Figure 2

Leilac's efficient process modification approach.

1.2. The Leilac Module

The Leilac technology has been developed as a retrofittable, modular design to provide a flexible layout that minimises Leilac's footprint and enables full scalability to capture up to 100% of the process emissions from any plant.

Within the Leilac-2 project, the furnace module is being developed as a multi-tube furnace with four Leilac tubes within one furnace. This module size provides a strong basis to scale from, with each module capable of separating in the order of 100 000 tonnes per annum of CO_2 at >95% purity. This design will enable the demonstration of a commercially relevant module and near-term commercial roll out of the technology. Its relatively straightforward engineering means that local firms should be able to perform most of the engineering, procurement, and construction.

Further design development and optimisation, however, is underway within Leilac. Future designs will include a larger module with more tubes (6+), enabling a further reduction in cost, reduced energy requirements, minimised conveying needs and a reduced footprint, amongst other benefits.

The flexibility of the Leilac technology allows scale-up in a number of different configurations. The Leilac plant can also be built over existing equipment (even the kiln), within existing structures, or attached to, or even replacing, the existing pre-calciner tower. Furthermore, it can be adapted to accept a range of fuels and to work with technologies for capturing combustion CO_2 emissions.

The final optimised footprint of the Leilac plant will depend on the layout and any restrictions of the host site, configuration of the modules, and the fuel type.

[4]ktpa = thousand tonnes per annum.

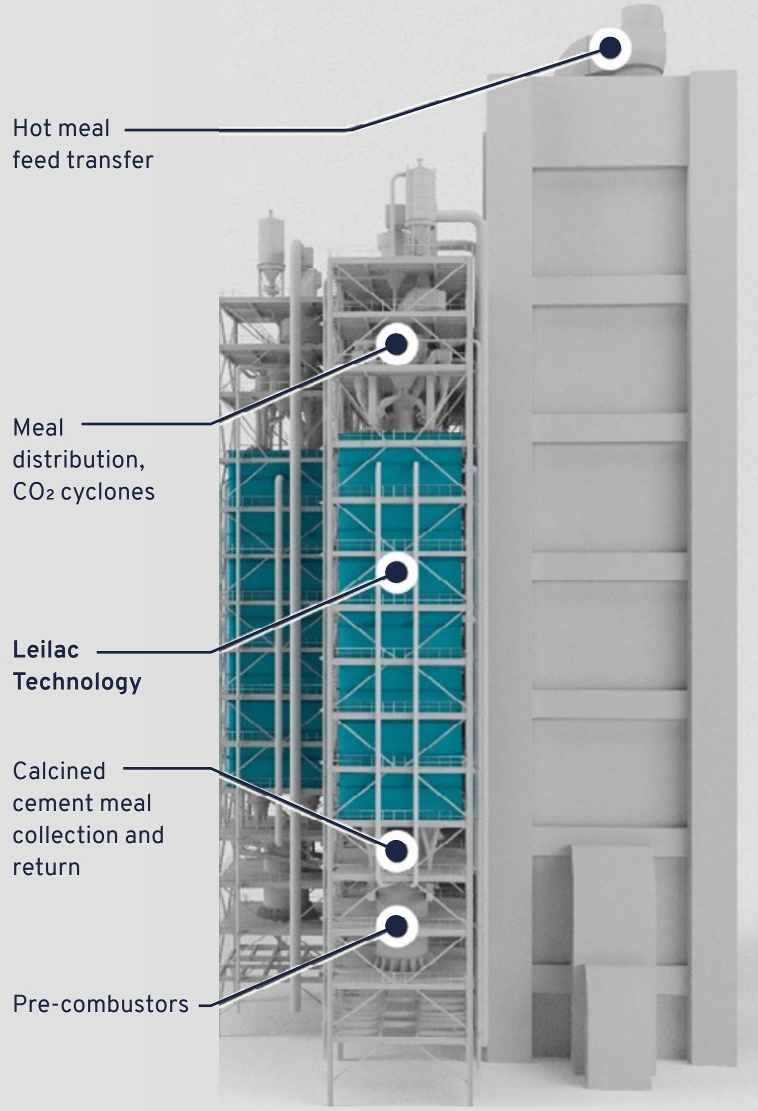


Figure 3

Basis of Design (tower layout) – Commercial scale, preheater replacement and hot air slide return.

1.3. Scaling Up and the Leilac Projects

As this study details, the Leilac technology offers a low-cost carbon capture solution to support the decarbonisation of the cement and lime industries. The technology is proven at pilot scale at the Leilac-1 site, technology development and optimisation programmes continue, and a demonstration scale plant is in development under the Leilac-2 project.

The Leilac-2 design, following its Value Engineering Activity, and in support of full-scale implementation, has changed since March 2022. It includes:

- a significantly simplified furnace which is lighter, cheaper and smaller;
- a next-generation combustion system at ground-level and clustered);
- simplified conveying, allowing shortened tower height; and
- a shared pre-heater stack, reducing the number of cyclones and control complexity.

Full-scale design based upon the new Leilac-2 approach is underway, offering a near-term, commercially relevant solution.

In parallel, the technology development and optimisation programmes run by Calix Limited and Leilac continue both in Australia and at the Leilac-1 pilot site. These programmes include:

- Development and optimisation of combustion systems for a range of fuels – including physical testing with CEMEX at a plant in Germany, as well as at stand-alone testing sites, and parallel development of next-generation systems;
- Furnace design and optimisation;
- Proving multiple conveying system designs to cover a wide range of plant & process layouts;
- Flow control within the Leilac tubes to improve heat transfer, residence time and calcined meal quality;
- Scale-up of electrification solutions for calcination using the Leilac technology;
- Development of integrated net-zero solutions, such as Leilac + post combustion capture units and Leilac + calcium looping;
- Cost-effective flue and process gas clean-up; and
- Efficient maintenance and tube replacement regimes.

Leilac-1 | Pilot plant

Lixhe, Belgium 2019
25,000 tonnes / year CO_2
160 tpd clinker equivalent
~5% throughput

Leilac-2 | Demonstration plant

Hannover, Germany
100,000 tonnes / year CO_2
640 tpd clinker equivalent
~20% throughput

Leilac-3 | Full commercial scale

The Future
500,000+ tonnes / year CO_2
3000+ tpd clinker equivalent
100% throughput

Figure 4

The evolution of the Leilac technology.

Figure 5

An impression of the commercial-scale Leilac plant, situated on a cement plant next to the existing preheater tower.

2. Leilac: A Commercial-Scale Study

2.1. Leilac at Full Scale

Leilac's modular technology is designed to be replicated and applied at any scale. As an illustrative example, the designs featured in this study focus on the full-scale implementation of Leilac (Leilac-3) at a typical cement plant, with a capture capacity of 590 000 tonnes of CO_2 per year.

The proven Leilac-1 pilot and designed Leilac-2 demonstration plant, capturing up to 100 000 tonnes per annum, remove much of the risk associated with the development steps required for full-scale deployment of the Leilac technology. As the approach is effectively a process modification and does not theoretically require additional energy to separate gases from gases, it has the potential to be the lowest cost means of addressing unavoidable industrial process CO_2.

The ability to install low-cost carbon capture capacity without significant downtime is another differentiating feature of the Leilac technology. This study examines a core scenario, followed by a number of alternative design scenarios. This includes different integration methods – particularly reusing the existing preheater tower (but with an associated down-time of the host plant) versus a stand-alone installation that would not interrupt operations, and which could allow different modules (or the whole capture installation) to be taken offline without stopping clinker production. Other design scenarios include different return methods and resulting variances to the heights of the Leilac installation, and CAPEX/OPEX requirements.

Other designs and scenarios described in this document include:

- Simple x5 duplication of the Leilac-2 module as designed today (i.e., no improvement or development from Leilac-2).
- Impact of key modelling assumptions, such as the cost of electricity.
- Full decarbonisation via electrification, with the same plant process emissions (i.e., those from the raw meal).
- Full decarbonisation via an additional post combustion capture plant for the capture of fuel emissions.
- A counterfactual, with post-combustion capture used for all CO_2 emissions.

These scenarios include the full abatement costs to the point of export[5], and costs associated with taking the host plant offline, detailed to a pre-FEED level of engineering – and cost and design reassurance from making only a x5 scale-up step.

2.2. Study Objectives

The Leilac at Full Commercial Scale study was developed to provide an analysis of the application of the Leilac technology at the full scale of a typical cement plant.

The study aims to:

1. Assess the technical and economic viability of a full-scale Leilac plant installation and confirm that the Leilac design can provide a low-cost option for abatement of process CO_2 emissions in a typical cement plant.
2. Ensure that the Leilac-2 design is testing and developing a design that supports that full-scale vision.

[5] This includes any purification and compression or liquefaction, but excludes transport and permanent storage/use of the CO_2.

2.3. Summary of Study Outcomes

The results of the study provide confirmation of the technical and economic viability of the technology at full commercial scale. As such, the study provides a firm basis upon which cement and lime producers can make both near-term decisions on new carbon abatement projects, and further develop business strategies on the pathway to carbon neutrality.

The study provides an overview of the basis of design for a full-scale Leilac plant, as well as process and integration options, and summary of the expected capital and operating costs.

This study has confirmed:

- The basis of design for a Leilac full-scale plant, including footprint and tower layout, process and integration options – building on the scale-up steps taken with the Leilac-1 pilot and Leilac-2 demonstration plant designs – to separate unavoidable CO_2 emissions at low cost.
- The advantage of a good quality CO_2 stream, particularly in comparison with other technologies that require significantly higher gas clean-up costs.
- The advantage of a modular design and of flexible options for a low impact retrofit or new build.

In addition, the study has confirmed the following benefits of the Leilac technology:

1 Low cost.

2 Near-term solution at full commercial scale.

3 Similar footprint to existing pre-heater tower.

4 Optionality on the capacity of capture and maintenance.

- The capture capacity can be increased from 590 000 tonnes of CO_2 per year at a later date. For example, a post-combustion capture unit can be added to capture emissions associated with carbon containing fuels.
- Leilac's design can enable maintenance on individual modules, only requiring the plant to only be taken partially offline.

5 Fuel optionality.

- The Leilac technology provides a high degree of flexibility on fuel sources, enabling lower cost or less carbon-intensive fuels to be used over time, including full electrification.
- If desired, a retrofit of the furnace side could be undertaken to switch fuel source or electrify, while leaving the process side unaffected. The cost of this is outside the scope of this study.

6 High purity CO_2.

- CO_2 quality is expected to be high (tests on Leilac-1 confirm 95% purity), reducing CO_2 processing unit (CPU) equipment size and costs.

7 Minimal down time.

- The Leilac technology can be built alongside ongoing plant operations, enabling minimal downtime of the host plant.

8 Accessible blueprint model.

- A blueprint model is designed to maximise the speed of adoption and impact of the technology and ensure that decarbonisation solutions can be delivered by local companies using local resources.

9 Core technology proven.

- The technology was proven with the Leilac-1 pilot, and Leilac-2 will de-risk remaining technology development. Leilac's modular approach means that scaling up will be achieved by duplication of known modules, reducing design uncertainty and increasing standardisation across the industry.

10 Cheaper cost of CO_2 avoided, both for process emissions and a net-zero plant.

- The Leilac-2 demonstration unit at Heidelberg Materials' plant in Hannover, Germany, is designed to address remaining scaling and implementation risks. Full-scale installations of the Leilac technology offer the potential to be the lowest cost, most flexible, and future-proof decarbonisation solutions available to the cement and lime industries.

3. Full Scale Study Overview

3.1. Site Layout, Assumptions and Requirements

The Leilac technology can be applied to greenfield or brownfield installations, a large variety of fuels, and in theory any cement plant type. This study considers the retrofit of a full-scale Leilac system to an operational cement plant. A cement plant that is well suited to the Leilac technology will have options for CO_2 transport and space for the new installation.

For the purposes of this study, the following assumptions regarding the configuration of a cement plant requiring a retrofit have been made (the technology can be applied to greenfield installations, a full variety of fuels, and in theory any cement plant type):

- Clinker capacity of approximately 3600 tonnes per day (tpd);
- A dry process with a single preheating string comprising five preheaters and one precalciner;
- No current supply of mid air from the clinker cooler, only secondary, tertiary and vent (aka exhaust) air;
- A fuel mix of roughly 90% alternative fuel, with an aggregate biogenic content of 60%[6];
- Available fuels: coal, two grades of alternative fuel, pure biomass and natural gas;
- The kiln uses a 40/30/30 mixture of coal, pure biomass and high-grade alternative fuel, and the precalciner uses an 80/20 mixture of low-grade alternative fuel and pure biomass.
- For a typical retrofit installation, the construction of the new modules would be able to take place during normal cement production operations in the preheater replacement option, with only the final tie-ins necessitating a shutdown. This will reduce the total downtime required for the retrofit.

Similarly, the CPU site layout would be optimised for a given plant layout. Typically, the initial de-dusting, cooling and ID Fan will be located adjacent to the Leilac tower for fine pressure control at the lower operating pressures in the system. The position of the CPU plant has much more freedom than the Leilac modules, and can be installed near the CO_2 export location. This has the added benefit of allowing its location to consider improved safety in the case of leaks or spills when transporting or storing high-pressure gas or cryogenic liquid CO_2.

3.1.1. Leilac plant 3D model

The Leilac technology can be arranged in several ways. The Leilac technology's modular configuration means that the plant layout is flexible and can be tailored to the host plant with which it will be integrated. Figure 5 depicts one such configuration.

3.2. Leilac Process Development & Integration

As the Leilac unit is a process modification to a part of a cement plant, it must connect to other units. Whilst the general location within the process is fixed – it is a calciner upstream of the kiln – there is optionality around the exact arrangement.

There are three main aspects of Leilac integration: process integration concept, fuel, and conveying technology. These are addressed in the following three sub-sections, and some combinations are summarised in Section 3.2.5.

[6] This is roughly in line with the Cembureau target of 90% alternative fuel and 50% biomass by 2050: https://cembureau.eu/media/kuxd32gi/cembureau-2050-roadmap_final-version_web.pdf (page 16).

3.2.1. Process Integration Options Summary

There are two integration concepts for a solid fuel-fired Leilac retrofit: preheater replacement and preheater re-use. The key differentiators between these are shown in Table 1.

This report predominantly considers the preheater replacement option. The replacement option aims to minimise down-time by building all-new preheaters directly above the Leilac unit, with one preheater string per module. As such, the replacement option can allow the majority of construction work to occur alongside continued operation of the existing cement plant. More details about the preheater re-use option, together with a PFD, are available in Appendix 4 in Section 4.2.

Preheater replacement (Option 1)	Preheater re-use (Option 2)
Built adjacent to the plant with minimal downtime for pre-heater replacement and commissioning	Reuses structures and equipment, requiring significant downtime for adaptation
One string of preheaters per module	Reuse of some existing preheaters in existing tower, with one new preheater directly above each tube
Calcined meal flows into preheater 5 for re-heat	Calcined meal flows into preheater 5 for re-heat
Kiln gas combines with Leilac flue gas prior to preheater 3	Kiln gas combines with Leilac flue gas prior to preheater 2

Table 1

Key Differentiators of preheater replacement (Option 1) and preheater re-use (Option 2)

3.2.2. Process Description – Preheater Replacement (Option 1)

One arrangement of the preheater replacement concept shown in Figure 6. It aims to minimise disruption to the existing plant during construction. New preheaters above each Leilac module are installed, enabling the plant to continue operation until physical integration is required. Other arrangements of the concept are possible and may be preferable in certain circumstances.

Leilac Cement Plant

(Option 1: Preheater Replacement)

February 2023

Leilac 2 | Leilac

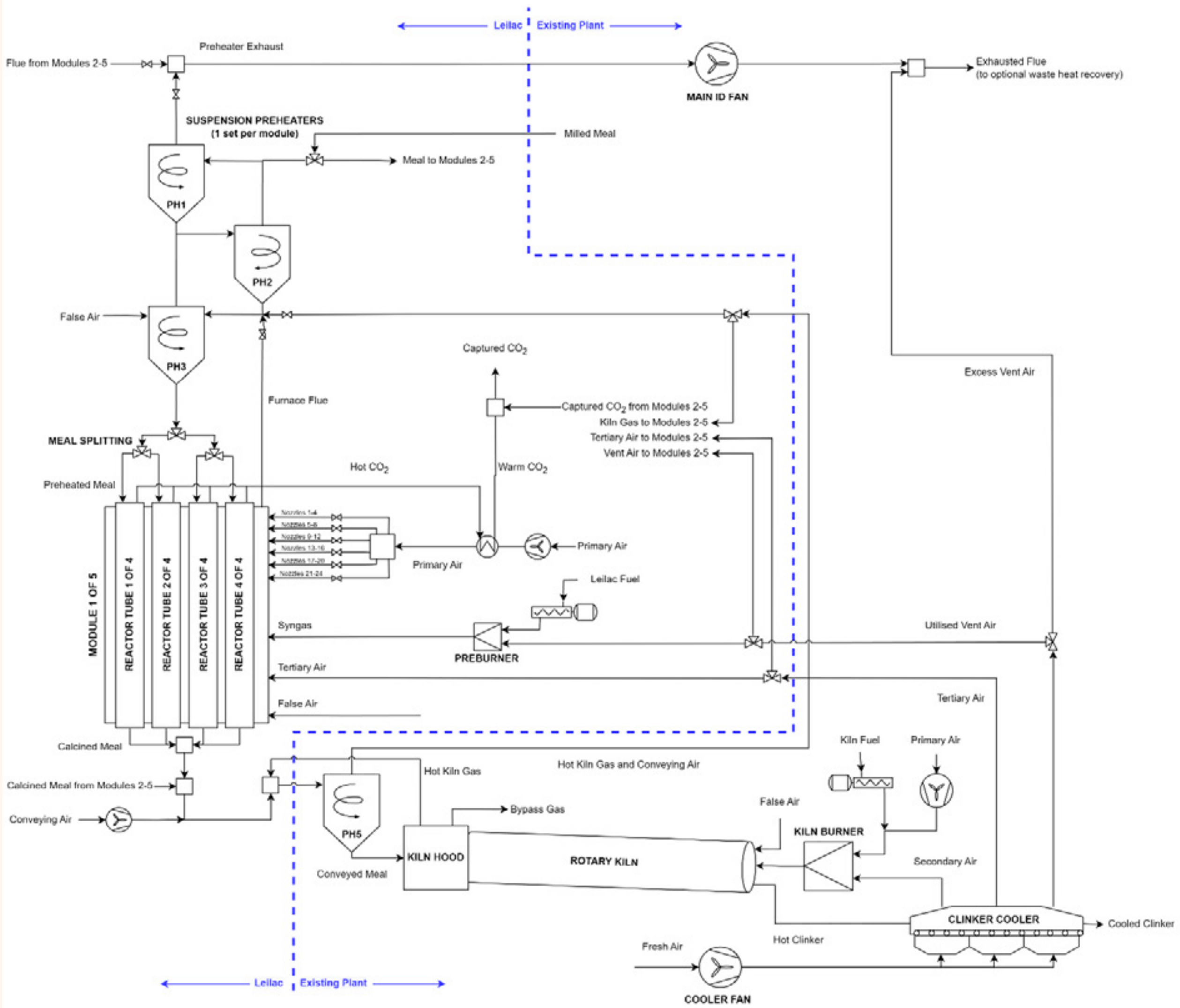


Figure 6

Process flow diagram for the preheater replacement option

Preheaters

Meal from the plant's main silo is split equally between each Leilac module. Within each module, the meal is then dosed into the riser connecting preheaters 1 & 2. It passes through all three preheaters, contacting a mixture of kiln gas and Leilac flue gas, preheating the meal and cooling the flue gases. The meal is then distributed to the inlet of each tube within the module.

Calcination

The preheated meal passes into each calciner tube from the top, whereupon it falls under gravity. As it falls down the hot tube it is heated above 900 °C via radiation from the calciner tube walls. The meal's carbonate constituents then thermally decompose to oxides and CO_2. The CO_2 rises against the meal and exits from the top. This facilitates some heat transfer from the CO_2 to the meal and increases meal particle residence time. The calcined meal leaves via the conical section at the bottom of the tube and enters a collection and conveying system.

Conveying

The meal from each tube passes into a system which conveys the calcined meal to the kiln. In the layout analysed in this study, it enters a hot air slide (HAS) which conveys it to a central mixing point for each module, and then to a central mixing point for all modules. The meal then enters an entrained flow conveyor (EFC) which transports the meal to the existing preheater 5 where it contacts the kiln gas before passing to the kiln via the existing chute and splash plate. This increases the meal temperature entering the kiln and reduces the kiln gas temperature prior to its ducting to the upper preheaters. In this manner, both the concentration of volatile salts passing to those upper preheaters and the kiln thermal duty are reduced.

Combustion

In the case of alternative fuels, the fuel is partially combusted in a central pre-combustor for each module, and the resulting high-temperature syngas is ducted to ports on the furnace surrounding the Leilac tubes. Similarly, tertiary air from the clinker cooler is split and ducted to other ports on the furnace. Full combustion occurs in the furnace, releasing the heat which transfers to the meal via radiation from the tubes. Some heat trim is achieved using natural gas for fast response, which is also used for start-up.

Waste Heat Recovery

The amount of heat transfer between the meal and flue gases in the preheaters should be kept lower than in unabated Best Available Technology (BAT) plants[7], to ensure that most calcination occurs in the Leilac technology and a high process CO_2 capture rate is realised. This lower rate of heat transfer is the main reason for the modest energy penalty of Leilac, with that heat leaving in the flue gas instead of being absorbed by the meal. Thus, the flue gas is hotter than in a typical plant and its heat should be recovered. Waste heat recovery can be used to raise steam for either electricity generation or the regeneration of post-combustion capture solvents such as amines.

CO_2 Management

The CO_2 passes out of each Leilac tube and into a cyclone which returns most of the entrained powder to the tube. This partially de-dusted CO_2 from all the tubes in a module then passes through a heat exchanger where it heats the primary air used in the furnace. Next, it combines with the CO_2 from other modules and enters the CPU.

[7]European Commission. (2013). Reference Document on Best Available Techniques in the Cement, Lime and Magnesium Oxide Industries. European Commission DG Environment. https://eippcb.jrc.ec.europa.eu/sites/default/files/2019_11/CLM_Published_def_0.pdf

3.2.3. Fuel options

Leilac intends to provide no limitation to fuel selection for the Leilac unit, enabling a future-proof solution that is compatible with fuels that may become lower in cost and/or lower carbon fuels. If desired, a retrofit of the furnace side could be undertaken to switch fuel source or electrify, while leaving the process side unaffected. The cost of this is outside the scope of this study however. The fuel options considered are as follows:

- **Alternative fuel.** As explained in section 3.2.2, the core process configurations use a pre-combustor to partially combust the fuel (in the case of solid fuels) before ducting it to the furnace. The partial biogenic content allows for a net reduction in fossil CO_2 emissions. By converting the alternative fuel to syngas in the pre-combustor, the syngas can then be processed as needed by conventional or novel gas treatment techniques to remove contaminants or increase its heating value. This study does not take credit for these syngas optimisation techniques or their associated costs.

- **Pure biomass.** Processed in a similar fashion to alternative fuel, pure biomass would reduce the overall amount of fossil carbon on the plant. If biomass were used to replace all fuel on-site (i.e., both Leilac and the rotary kiln), the only fossil emissions of CO_2 would be the small amount of process CO_2 that is emitted from the raw meal in the preheaters and the kiln. Pure biomass will have lower levels of chlorine and sulfur than most grades of alternative fuel. This is investigated in Section 4.3.2.

- **Electricity.** In an electrified Leilac process, calcination heat is supplied by electrical elements, with no combustion. Some process rearrangement is required; for example, the kiln gas and tertiary air are combined and sent to the preheaters, rather than the tertiary air going to the furnace to facilitate combustion. However, roughly two-thirds of the fuel burned in a generic cement plant is in Leilac itself, so total CO_2 emissions (fossil + biogenic) will fall to around one-sixth of that from an unabated plant. This could be combined with relatively modest amounts of low CO_2 footprint fuels to heat the kiln and reduce fossil emissions to near-zero.

- **Natural gas.** This is a common primary fuel in some regions such as North America, but unlikely to be economic in others such as Europe. Leilac-1 and Calix's CFC 15000 in Australia run on natural gas; Leilac-2 will initially run on natural gas before transitioning to solid alternative fuels. When using natural gas, Leilac does not require a pre-combustor and can perform full combustion in a single step within the furnace. The option of regenerative heating offers alternative process layouts to increase efficiency and reduce operating costs.

- **Hydrogen.** Future low CO_2 footprint fuels such as sustainable hydrogen can be burned by Leilac in a similar manner to natural gas, as a full or supplemental energy source, but without the resulting carbon emissions.

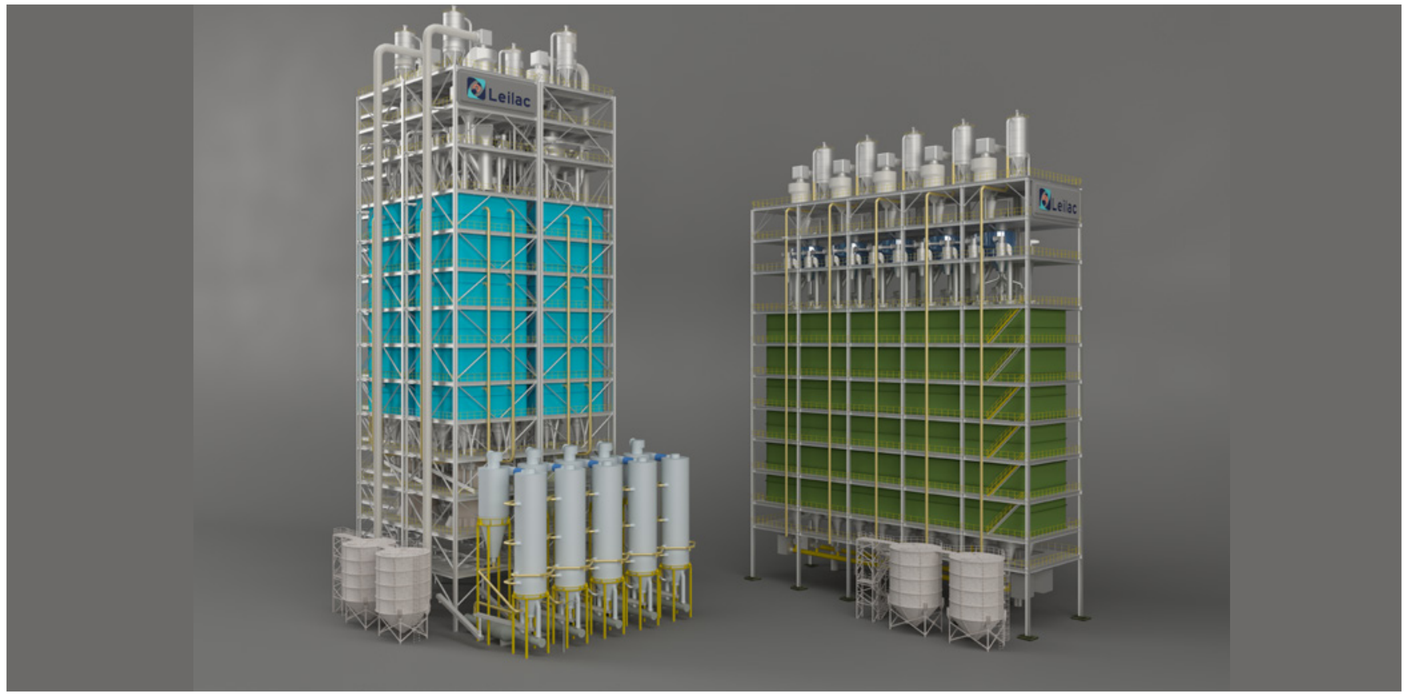


Figure 7

An impression of the Leilac technology at full commercial scale using alternative fuel combustion (left) and electricity (right).

3.2.4. Calcined material conveying options

The final main process optionality is the conveying of solids. Within the study, three options have been considered:

i. Hot air slides only (HAS). This requires the base of the Leilac technology to be installed at an elevation higher than the kiln entry point because the calcined meal is required to flow at a steady vertical gradient into the kiln entry point.

ii. Hot air slides plus entrained flow conveying (EFC). In this configuration the hot air slides move the meal from under the modules, where it is picked up vertically and passed to the kiln entry point via an inclined chute. This removes the requirement to have the Leilac technology base higher than the kiln entry point. However, it requires more air and electricity to operate than the HAS-only system.

iii. Conventional lean phase conveying (LPC). This uses more air than HAS+EFC and has height flexibility like the HAS+EFC, but it is a more mature technology.

The chosen fuel and conveying options effect the process layout, CO_2 capture/avoidance performance, capital cost and operating cost. More analysis and discussion is provided in Section 4.

3.2.5. Examples of integration option combinations

Table 2 shows the key properties of several integration options based on a number of potential configurations.

Scenario	Powder conveying (Leilac to kiln)	Total tower height (m)	Footprint (m)	Anticipated CAPEX (core process, ex. compression, M€)	Anticipated OPEX (inc. core capex, ex. compression, €/t CO_2 avoided)
1A. Preheater replacement	(i) Hot air slides	90	54 x 27	137	20
1B: Preheater replacement	(iii) Lean phase pneumatic conveying	71	54 x 27	137	20
2. Preheater re-use	(i) Hot air slides	67	54 x 27	122	19
3. e-Leilac: Preheater replacement, using electric heating	(i) Hot air slides	48	54 x 27	87	154

Table 2

Summary of example integration options for Leilac.

There are differences in the CAPEX and OPEX values, especially when comparing electric plants with their combustion counterparts. The lower CAPEX for electric plants is due to the simplified design, and the higher OPEX is mostly due to the significantly higher cost of electricity versus typical thermal fuels on a cement plant. More detail can be found in Table 7 and Section 4.2.2.

The difference in CAPEX between preheater replacement and preheater reuse is mainly due to the increased number of new preheater stages, and kiln gas handling equipment.

More detail about the CAPEX cost model is provided in 4.1 and more detail about the OPEX cost model is provided in Section 4.2.

3.2.6. Options for different decarbonisation rates (and over time)

Leilac captures the process CO_2 generated from the calcining meal but does not directly mitigate the combustion emissions. As such, the Leilac process using alternative fuel achieves abatement/avoidance of approximately 76% of total fossil CO_2 emissions (equivalent to 60% fossil + biogenic CO_2 capture[8]) relative to a baseline plant with no abatement.

The flexibility and compatibility of Leilac's technology with multiple energy sources enables various configurations towards zero or even negative emissions. These configurations include Leilac operating with biomass, hydrogen, electricity, or an additional carbon capture unit (e.g. an amine system) to reduce or eliminate emissions associated with fuel use. Figure 8 shows these routes.

Such deeper decarbonisation can be taken in incremental steps, reducing initial CAPEX and OPEX requirements and allowing CO_2 transport and storage infrastructure to continue to develop.

For example, a low-cost Leilac system can be installed at the earliest opportunity, abating approximately two-thirds of CO_2 emissions. As decarbonisation efforts continue to intensify, conventional fuel use can be fully decarbonised commensurate with the emissions targets of the plant. This can be achieved either by fuel switching to low CO_2 footprint fuels such as sustainable biomass or hydrogen, electrification of the entire Leilac installation, or the addition of a relatively small conventional post-combustion capture (PCC) unit if using a fuel with carbon emissions. Such a staged approach would postpone the relatively greater expenses until a later date, allowing a two-step business case (with varying decarbonisation rates) to be made.

[8]The significant difference between these values is addressed in Section 3.2.7.

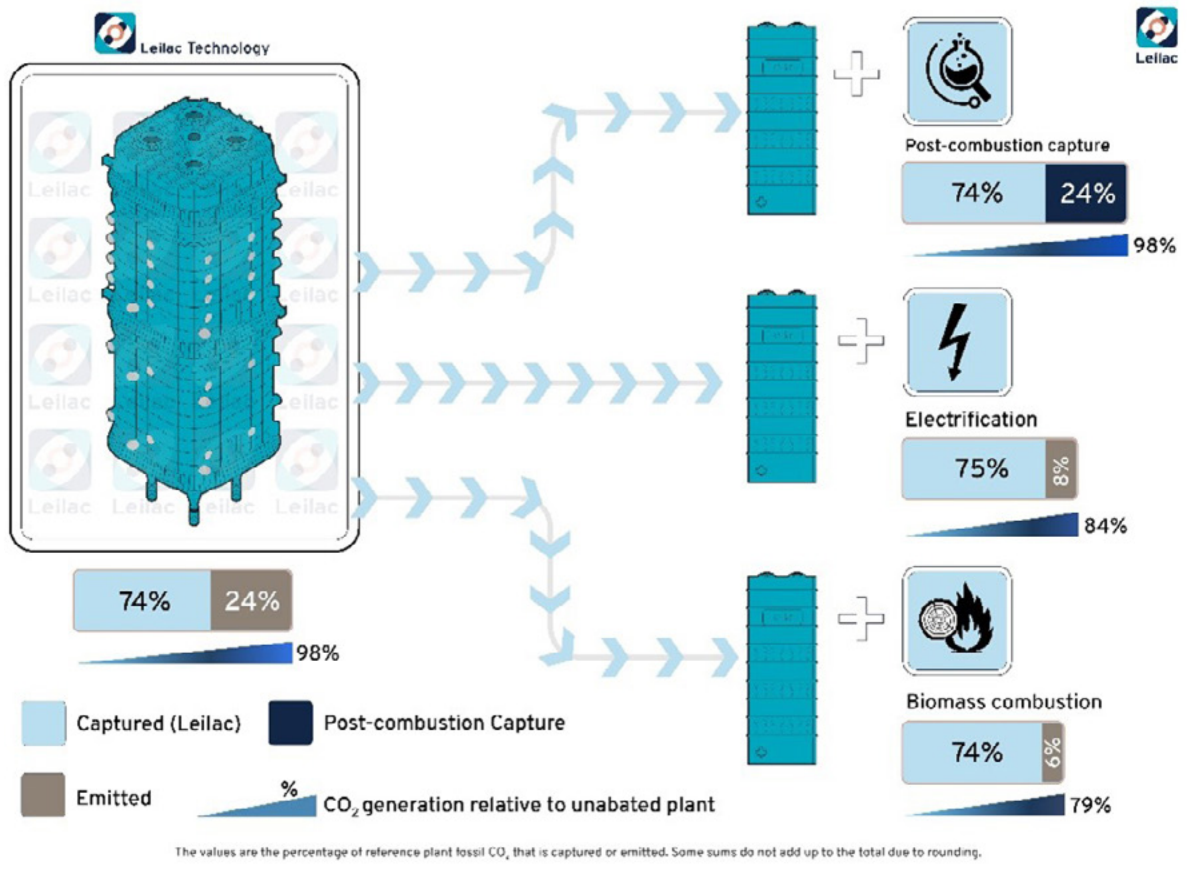


Figure 8

Routes to Leilac net zero: post-combustion capture, electrification and biomass combustion.

To exemplify this, the techno-economic analysis includes one scenario to model the addition of a PCC plant to capture enough CO_2 so that the plant is net-zero in terms of fossil carbon. To provide an example, the model assumes the use of a formulated amine solvent technology, since it is a relatively proven and well understood technology in post-combustion capture. However, there are several other post-combustion capture options which are compatible with Leilac, such as calcium looping (CaL), hot potassium carbonate looping, and solid amine systems which have potential to enable net zero at similar or lower cost.

Leilac and solvent scrubbing are a good fit for each other, because most of the thermal energy penalty of Leilac can be recovered to make steam to drive the PCC's solvent regeneration/desorption column. However, since PCC is a separate system installed on the back end of the host cement plants exhaust system, the Leilac technology is fundamentally agnostic to the PCC technology. The Leilac technology can be adapted to provide the best fit for the host plant to reach net zero. More details are provided in Section 3.3.

The PCC system is assumed to have its own CPU separate to the Leilac technology to produce a different grade of CO_2. However, this is a high-cost option, and simplifying compression and transfer by a single export point would enable significant cost savings; more details are available in Section 3.4.

Figure 9

An impression of a fully electric installation of the Leilac technology at full commercial scale.

3.2.7. Process Modelling – Scenarios & Results

Leilac has developed rigorous process models of the various process layouts in Aspen Plus modelling software. These process models focus on the energy and mass balances around each unit and the system as a whole. The main scenarios presented in this document are shown in Table 3, and the results of the process model are shown in Table 4.

Scenario code	Plant type	Fuel	Preheater concept	Conveying technology
Baseline	Baseline Plant	Existing Mix	Not Applicable	No conveying
1a	Leilac Plant	95% alternative fuel + 5% natural gas	Replacement	(i) Hot Air Slide
1b				(iii) Lean Phase Pneumatic Conveying
2			Re-use	(i) Hot Air Slide
3	e-Leilac	Electricity	Replacement	(i) Hot Air Slide

Table 3

Summary of main technoeconomic scenarios in this document.

Scenario		Unabated	1. Preheater Replacement		2. Preheater Re-use	3. e-Leilac
Conveying			HAS	LPC	HAS	HAS
INPUTS	Unit					
Raw meal	t/h	240	240	240	240	240
Kiln fuel	t/h	5	3.8	4.3	3.6	3.8
Calciner fuel	t/h	15	17.0	17.0	17.0	104.5 MW
OUTPUTS						
Clinker	t/h	152	150	151	150	151
Captured CO_2	t/h	0	73	73	74	75
Captured CO_2 Purity (dry basis)	mol%	28%	99%	99%	99%	99%
PERFORMANCE						
Thermal duty	GJ/tclk	3.2	3.5	3.6	3.4	3.3
… of the calciner	GJ/tclk	2.3	2.7	2.7	2.7	2.5
… of the kiln	GJ/tclk	0.9	0.8	0.9	0.7	0.8
Cement Plant CO_2 Generation (Scope 1)	tCO_2/h	118	121	122	121	87
… of which captured by LEILAC	tCO_2/h	0	73	73	74	75
… of which emitted	tCO_2/h	118	48	50	47	12
Net Fossil Emissions from Cement Plant only	tCO_2/h	100	24	26	24	8
Fraction of CO_2 captured	%	0%	60%	59%	61%	86%
Net emissions intensity (Fossil & Bio)	tCO_2/tclk	0.78	0.32	0.33	0.32	0.08
Net emissions intensity (Fossil Only)	tCO_2/tclk	0.66	0.16	0.17	0.16	0.06
Direct CO_2 avoided	tCO_2/tclk	0.00	0.50	0.49	0.50	0.60
… fraction of fossil CO_2 avoided (ETS applies)	%	0%	75%	74%	76%	91%
Specific Primary Energy Consumption for CO_2 Avoided (SPECCA)	GJ/tCO_2	0.00	0.48	0.71	0.42	0.02

Table 4

Key results from the process models for the unabated (reference) plant and Leilac-enabled plants.

The fossil avoidance rate for Leilac is significantly higher than the overall capture rate. This important difference is explained below.

Table 5 shows summary data for the unabated (i.e., reference) and Leilac 1a scenarios. In both scenarios the same amount of CO_2 enters with the meal, mostly in the form of calcium carbonate[9]. This carbon, embedded in minerals, is counted as fossil CO_2 in the same manner as the CO_2 generated from burning fossil fuels.

The fuel mixes used in the two scenarios are combinations of different fuels. Some fuels are completely fossil (e.g., coal) and others are completely non-fossil, also known as biogenic. Some, such as alternative fuels, are a mixture of both[10]. The breakdown into fossil and biogenic is shown in Table 5, too. This means that in the unabated scenario, while approximately 0.28 tonnes of fuel-related carbon are emitted per tonne of clinker (t CO_2/t clk), only 0.11 tonnes are from fossil sources. As such, approximately 83% of the fossil CO_2 is from the meal, and 17% from fuel.

The different fuel mix used by Leilac means that the fraction of fossil CO_2 in the fuel in Leilac is higher than in the reference, unabated scenario. Furthermore, the modest energy penalty of Leilac means that the absolute generation of fossil fuel CO_2 is higher than the unabated scenario. The overall effect is a decrease in the avoidance rate of Leilac.

When Leilac captures the vast majority of the fossil-derived, meal-related CO_2, the total fossil CO_2 emissions drop by 75% (0.66 to 0.16 t CO_2/t clk) despite the slightly higher fuel requirement.

[9] The slight difference is due to preheater efficiency assumptions.

[10] In this work, natural gas is assumed to be a mixture of fossil-derived natural gas and some biomethane that is added to the grid. The biomethane is biogenic, and so the natural gas blend is only around 91% fossil.

	Unit	Unabated	Leilac (1a)
CO_2 from meal	t CO_2/t clk	0.52	0.53
...of which captured by Leilac		0.00	0.49
Total CO_2 in fuel		0.28	0.31
...of which fossil CO_2		0.11	0.14
...of which biogenic CO_2		0.17	0.17
Aggregate fuel biogenic content	% C	60%	55%
Net CO_2 Emissions (generated minus captured, minus biogenic)	**t CO_2/t clk**	**0.66**	**0.16**

Table 5

Breakdown of sources of CO_2 in the unabated (reference) scenario and when using the Leilac technology to replace the preheater (scenario 1a).

3.3. Post-Combustion Capture (PCC) for Net-Zero Applications

A post-combustion capture plant is required in the case of fossil hydrocarbon combustion if net-zero CO_2 emissions are desired. The fossil hydrocarbons can come from conventional fossil fuels (coal, natural gas, fuel oil), unconventional fossil fuels (petroleum coke, solvents), or alternative fuels which contain both a fossil and biogenic component (alternative fuel, tyres). This post-combustion plant will capture the combustion CO_2, plus the small remaining process CO_2 emissions due to minor amounts of calcination in the preheaters and rotary kiln. This unit is approximately 25% of the size of the post-combustion plant that would be required if it were installed as the only technology for capture. It can also be installed at a later date from the main Leilac unit if desired.

The Leilac technology is compatible with any viable post-combustion capture technology. For a given project, the most suitable post-combustion capture technology will be chosen on a project-by-project basis. For the purposes of this illustrative study, the use of a formulated amine solvent is assumed. Formulated amines offer a similar, yet more efficient approach to traditional amines, as the solvent is specifically designed for post-combustion CO_2 removal. Formulated amines offer several advantages for use in cement decarbonisation, including additives that increase resilience to oxygen and other contaminants in the mixed gas phase that are common in cement applications.

CO_2 emissions associated with fuel use is mixed with the bulk flue gas, kiln gas and tertiary air from the plant at a concentration between 20 and 30% CO_2 by volume. For a cement plant using the Leilac technology, this concentration will be significantly lower (less than 10-15% by volume) due to the previous capture of over half of the total plant CO_2.

Analogous to the CO_2 from the Leilac process, the amine plant will need upstream cooling, de-dusting and pressure boosting, and a SNCR and FGD to remove NOx, SOx and HCl from the gas, which would otherwise poison the amine solvent. Other diluents such as N_2, O_2 and CO will not be selectively absorbed by the amine solvent and will instead predominantly stay in the CO_2 lean gas leaving the system. The captured CO_2 will contain trace amounts of these components, along with some amine entrainment and water. The contents of this CO_2 from an amine solvent system, or any other post-combustion capture technology will need to be considered in the CPU design.

Due to the high availability of waste heat in the cement plant, low pressure (LP) steam will used in the solvent regeneration reboiler, with steam generated from the Leilac plant to supply as much of the LP steam as practical, and the balance made up by fuel combustion. Steam condensate is recycled in a closed loop to generate more steam.

Importantly, this hybrid capture scenario would require only a relatively small post-combustion unit with energy requirements for amine regeneration that could be sourced predominantly from waste heat, including some recovery of the modest energy penalty of a retrofit Leilac plant. These synergies offer a potential low-cost and near-term solution for net-zero cement.

3.4. CO_2 Compression & Clean Up

The CO_2 compression and post-capture system design consists of a CPU which handles the CO_2 captured by the Leilac technology. This equipment will be present in all options and scenarios. The Leilac technology is flexible to any downstream CCUS process at the battery limit of the system, with two main technical solutions presented, both of which are industry standard for CCS:

1. CO_2 liquefaction for purification and to allow export in liquid phase to any combination of truck, rail or ship/barge.
2. Compression up to supercritical pressure >100 barg, which requires a high-pressure pipeline for transport.

3.4.1. Leilac CO_2 Processing Unit (CPU) - Liquefaction

The liquefaction process increases CO_2 density by over 200 times relative to the gas phase at atmospheric pressure, enabling more economical transport by truck, rail or barge and subsequent export to markets for use or storage, depending on local or regional availability.

For liquefaction, the key equipment and processes for the CPU are listed below. For full details on liquefaction options, please refer to Appendix 1.

1. Inlet cooling, de-dusting and ID fan – Process CO_2 from the calciner should be cooled, de-dusted and pressure boosted by the ID Fan before the main CO_2 compressor. This allows low design temperature equipment to be used and increases the reliability and performance of the CO_2 compressor.
2. CO_2 compression – A multistage compressor is used to compress the CO_2 up to a pressure (22-25 barg) suitable to flow through the downstream processing equipment and maintain pressure for storage in liquid state (20-22 barg).
3. CO_2 dehydration – Dehydration of the CO_2 down to ppm levels is used to meet CO_2 specifications and prevent ice/hydrate formation in the cryogenic liquefaction unit.
4. CO_2 liquefaction – Liquefaction of the CO_2 gas increases its density suitable for transport via truck, rail or barge to a use or storage location. Trace contaminants such as O_2, N_2, CO, NOx, SOx present in the CO_2 remain in gas phase and can be separated during this process. As the high purity CO_2 output from the Leilac process remains free of any combustion contaminants, this option does not require significant removal of non-condensables.
5. Liquid CO_2 storage and export pumps – buffer storage and loadout pumps of liquid CO_2 is required to allow continuous CPU operation when export only occurs during normal working hours.

3.4.2. Leilac CO_2 Processing Unit (CPU) – Supercritical Pressure

Alternatively, the CPU can compress the CO_2 to a supercritical pressure rather than liquefying. This option can be considered providing suitable pipeline infrastructure is accessible for CO_2 export.

Compression of CO_2 to a supercritical pressure is achieved by raising the pressure of the CO_2 to above its critical point of 74 barg and 31°C, at which point the CO_2 is regarded as being in a supercritical phase or dense phase. At these conditions the CO_2 flows at a density approaching that of the liquid (600-700 kg/m^3), but with the viscosity still of a gas. This allows economical transport of large volumes of CO_2 across long distance pipelines with low pressure drop, analogous to transport of high-pressure natural gas.

For supercritical pressure, the key equipment and processes for the CPU are listed below. For full details on the supercritical pressure option please refer to Appendix 1.

1. SNCR and wet FGD – As this CPU option is 100% gas phase, NOx, SOx and HCl removal will be necessary from the raw process CO_2 before the CPU. In this study we assume this is performed by SNCR and Wet FGD.
2. Inlet cooling, de-dusting and ID fan – Process CO_2 is then cooled, de-dusted and pressure boosted by the ID Fan before the main CO_2 compressor. This allows low design temperature equipment to be used and increases reliability and performance of the compressor.
3. CO_2 compression – A multistage compressor is used to compress the CO_2 up to a pressure (40-50 barg) suitable to flow through the downstream processing equipment. This pressure is targeted since the CO_2 has a higher operating density and therefore can use smaller processing equipment that is not yet considered high-pressure equipment.
4. CO_2 Treatment– Dehydration of the CO_2 down to ppm levels is used to meet CO_2 specifications and prevent free water phase formation in the pipeline, which is known to be corrosive in a high CO_2 environment. If additional CO_2 treatment is needed to meet the export CO_2 specification (e.g., desulphurisation or oxygen scrubbing) the necessary equipment would be installed here to complete the purification step.
5. CO_2 Compression – Dry CO_2 is then returned to the same compressor for final pressurisation > 100 barg. Total compression stages will vary between 4 and 12 depending on compressor type and selection.

4. Cost Model

4.1. CAPEX Cost Model

4.1.1. Model Structure

The CAPEX model gives the different costs for the three scenarios described earlier:

1. Preheater replacement, with alternative fuel combustion

2. Preheater re-use, with alternative fuel combustion

3. Preheater replacement, with electrical furnace

The model is essentially a list of cost line items which are expected within a project to build Leilac technology at a cement plant. A cost has been assigned to each of these items, at a given scale. These costs are either taken from real quotes or invoices, or are estimates based on experience and market conditions.

The model takes the original cost for a line item and scales it appropriately for the plant in question to produce a unit price. This uses a scaling ratio with a scaling factor, which is set in advance for each line item based on its nature. The unit price is multiplied by the expected quantity of units required to produce an overall cost of that line item. These are summed to get the total cost.

4.1.2. Model Assumptions

The assumptions taken for the CAPEX are:

- 5 Leilac modules with 4 tubes each
- Does not include :
  - special extra works on site (demolition, moving of large equipment…)
  - new electric and natural gas links to Leilac towers
  - additional heat recuperation
  - contingency
  - temporary CO_2 storage on site
  - compression/liquefaction and any CO_2 polishing (these costs are shown below the line)
  - permitting
  - transport of equipment to site.
- Prices used are from 2019 i.e., pre-COVID-19 except for electric bulks, and electric furnace systems
- Downtime cost:
  - Preheater replacement: Close to zero, with the tie-ins performed during the annual shutdown period
  - Reuse of existing preheaters: 1–2 months
- The management and engineering cost factor considered is 6%. This is relatively low due to the modular nature of the Leilac technology.

Table 6 gives the CAPEX for the three main scenarios. The core process cost is around 137 M€ for the scenario with alternative fuel combustion and all-new preheaters. Re-using the existing preheaters reduces cost by around 14 M€, or 10%. This is due to reduced requirements for new equipment.

Switching to electric heating reduces core process capital costs by around 36%, as shown in Scenario 3.

	1a. Preheater replacement + alternative fuel	2. Preheater reuse + alternative fuel	Scenario 3. Preheater replacement + electric
Total for core Leilac plant (M€)	**136.6**	**122.5**	**87.2**
Leilac CPU (M€)	18.7	18.6	18.7
Total for Leilac + CPU (M€)	**155.2**	**141.1**	**105.9**
Post-combustion capture plant for net-zero (M€)	119.2	117.3	16.4
PCC CPU (M€)	11.0	11.2	1.9
Total, Leilac + post-combustion capture	285.4	274.8	124.2

Table 6

Leilac CAPEX for 5 modules of 4 tubes each.

This study provides illustrative figures based on central European costs. Regional and plant specific analysis is provided through a scoping study. For more information please use contact@leilac.com.

4.2. OPEX Cost Model

An operational expenditure (OPEX) model was developed to support this study. It aims to forecast the extra costs of running the cement plant once Leilac has been installed.

The scenarios studied are those shown in Table 3, and uses inputs from the process model as shown in Table 4. It also requires some assumptions, the most important of which are shown in Appendix 3.

Further to those core scenarios, there are two other aspects that are investigated: combination with post-combustion capture (Section 4.2.3), and a sensitivity analysis (section 4.3).

The OPEX model includes the use of higher-grade tube alloys and more frequent replacement for Leilac scenarios where low-grade fuel such as alternative fuel is burned, due to the sulphur and chlorine content in the fuel, and presence of tars and ashes. The cost of these replacements includes only the tube material and fabrication, not the installation; this is assumed to be covered within the main maintenance budget. The actual replacement rate will become more certain over time as more Leilac tubes are operating and exposed to a range of atmospheres, including during the Leilac-2 project. Equally, the costs of the alloys, and the range of options, will evolve over time and economies of scale in multi-tube modules.

While not considered in the OPEX model, it should be noted that the modular arrangement of furnaces considered within this model would allow for tube replacement and other module specific maintenance to take place on a module-by-module basis. As an example, one module being taken offline in this five-module plant would reduce the total plant throughput by 20%, allowing the cement plant to continue operations at 80% capacity, spreading the maintenance duration over a longer period of time in exchange for maintaining a higher total uptime. This option may be attractive to plants that are under-subscribed at certain times of year. Otherwise, maintenance and tube replacement in all modules can be performed in parallel to minimise down-time.

The model also accounts for emission abatement consumables. This currently comprises calcium hydroxide. While many plants use a range of consumables such as ammonia and $Ca(OH)_2$, we assume that Leilac will lead to no overall significant change in these consumables except for $Ca(OH)_2$. This is based on the model for Leilac-2, with a reduction associated with existing use and also an expectation that the injection rate will be less than the maximum rate assumed for Leilac-2, given a) it is a conservative design and b) a lower chlorine content compared to the assumed Leilac-2 fuel. Leilac is also investigating the possibility to recycle a small proportion of the calcined meal to the preheaters to provide some abatement for significantly lower cost.

The Leilac technology replaces the existing precalciner and has few extra processes. While the pilot and demonstration plant require extra attention due to their first-of-a-kind, experimental nature, the technology is designed to be within the capacity of existing operators and as such no extra operational staffing costs are forecast.

4.2.1. The Carbon Cost of Capture: Capture vs Avoidance

The cost of the Leilac process is expressed in a range of metrics. While mostly self-explanatory, the difference between CO_2 captured and CO_2 avoided is important and is explained here via a thought experiment.

Assume an unabated process emits 1000 kg CO_2/t clinker, and that the objective is to reduce this plant's emissions by 90% - i.e., to 100 kg/t. This can be done by capturing that 900 kg CO_2/t clinker.

However, capture processes tend to require energy input, and this energy is often provided via combustion of fuel, which itself generates CO_2. The amount of extra CO_2 varies according to the fuel and capture process, but for the purposes of this experiment let us assume that, for every 10 tonnes captured, an extra 1 tonne is generated by the capture process.

Therefore, if the capture plant captures those 900 kg/t clinker, it will emit another 90 kg/t – bringing emissions up to 190 kg/t. That means that, whilst 900 kg CO_2/t clinker is captured, the net reduction, known as the amount avoided, is only (1000 – 190 =) 810 kg CO_2/t clinker.

Thus, the capture rate – relative to the new plant's total emissions – is 83%, but the avoidance rate – relative to the original plant – is 81%.

In practice, capture plants can capture their own emissions, too. This does not change the method of calculation. The calculation is recursive; in this case, the capture plant ends up generating 100 kg CO_2/t clinker in total. Thus, the CO_2 captured is 1000 kg/t and the total emitted is 100 kg/t – a capture rate of 100% but an avoidance rate of only 90%.

4.2.2. OPEX Cost Model – Results

The key results are shown in Table 7 in various units, and Figure 10 as Euros per tonne of CO_2 avoided. Tables and figures showing the costs in €/t clinker, €/t CO_2 captured, and €/t CO_2 avoided are presented in Section 4.3.3.

Capture costs are around 31–34 €/t CO_2, and avoidance costs are within the 30–33 €/t CO_2 range. In general, preheater re-use costs are expected to be lower due to lower capital requirements, and those with hot air slides are more thermally efficient and therefore have lower operating costs than pneumatics, which is less efficient.

The cheapest and most expensive core scenario, excluding electric, only vary in cost of avoidance by 6%. This means that Leilac is feasible and cost-competitive across a range of configurations.

Across the preheater replacement (1a and 1b) and preheater reuse (2) scenarios, the main cost drivers are the compressor OPEX + CAPEX (≈14 €/t capture), non-compressor CAPEX (≈10 €/t capture), and maintenance (≈4 €/t capture). Compressor OPEX is mainly the electricity required to run the compressor and other CPU units.

Electrification has fundamentally different cost drivers. It shows a capture cost of 168 €/t CO_2, approximately five times the cost of the other cases. The major cost is electricity for heating, at 144 €/t CO_2 relative to the baseline unabated plant. There are comparatively modest reductions in the capital repayment cost, abatement consumables, and tube replacement compared with the increase in thermal fuel costs.

A major benefit of electrification is that it avoids significantly more CO_2 than it captures, due to fuel switching. This avoidance rate of >90% compares with avoidance rates of around 75% for Leilac when operating on alternative fuel (scenarios 1 & 2).

		1a. Preheater replacement + HAS	1b. Preheater replacement + LPC	2. Preheater reuse + HAS	PCC Only	Leilac (1a) + PCC	3. e-Leilac
Capture Rate (Fossil + Biogenic Carbon)		60%	59%	61%	86%	81%	86%
Avoidance Rate (Fossil Carbon Basis)		76%	74%	76%	100%	100%	92%
Financial Costs	€/t clinker	€ 16.53	€ 16.21	€ 15.58	€ 49.89	€ 26.45	€ 83.88
	€/t CO_2 captured	€ 33.89	€ 33.53	€ 31.85	€ 67.55	€ 43.03	€ 167.56
	€/t CO_2 avoided	€ 32.98	€ 32.90	€ 30.92	€ 74.72	€ 39.66	€ 138.19

Table 7

Summary of CO_2 capture costs for all main scenarios in this study. Capture Rate is all carbon emissions (i.e., fossil plus biogenic), Avoidance Rate is a fossil carbon only basis. Costs include CO_2 compression, maintenance, and CAPEX repayment, and exclude CO_2 transport and storage.

This study provides illustrative figures based on central European costs. Regional and plant specific analysis is provided through a scoping study. For more information please use contact@leilac.com.

4.2.3. Combination with post-combustion Capture

The thermal and electrical energy demand of the complementary post-combustion capture plant has been determined for the preheater replacement and HAS option, presented as 'Leilac (1a) + PCC'. Where the Leilac system is unable to provide sufficient waste heat to meet the requirements of the post-combustion plant's regenerator and enable the complete system to reach net zero, extra natural gas is combusted. This is included in the cost framework and the model accounts for the associated CO_2 emissions.

However, synergies that result from the combination of the two capture technologies mean the extra cost of the amine system is relatively low. With the Leilac technology capturing the majority of total CO_2, only a relatively small post-combustion capture plant is required to reach net zero. The energy requirements of the smaller post-combustion plant can be largely sourced from waste heat, minimising the costs of a combined net-zero capture solution. Some additional CAPEX is required for the waste heat recovery (WHR) heat exchangers which convert heat from the cement plant's flue gas to drive amine regeneration.

The CAPEX of the overall amine post-combustion capture plant is based on scaling the costs (421 M€[11]) and size (0.4 Mtpa CO_2[12]) of the Brevik post-combustion capture plant, minus 25% due to first-of-a-kind effects. This is a reasonable example project to use for this comparison, because as with the Scenario 1 + PCC scenario, it will recover the vast majority of the heat from the flue gas as opposed to using boilers.

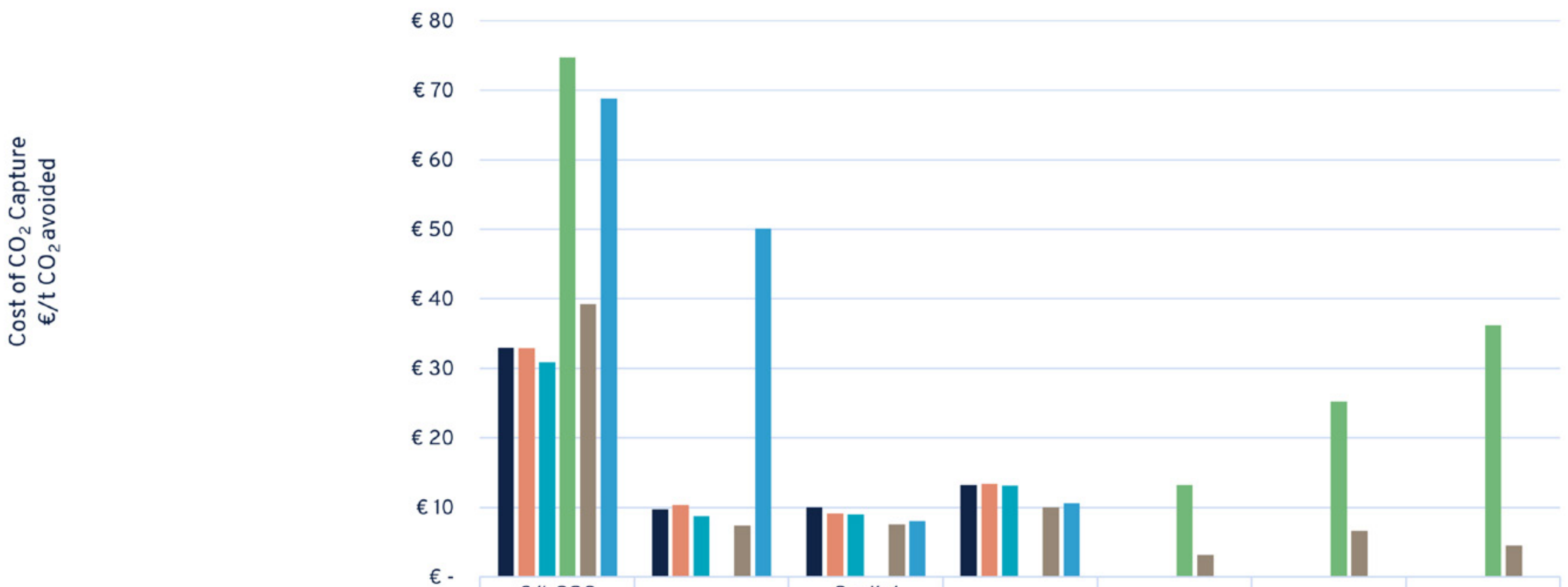
The combined Leilac/amine system shows an increased avoidance cost versus the Leilac only scenario, being around 19% (€6.3) more expensive per tonne of CO_2 avoided. On a tonne of clinker basis, it is 60% higher.

A counterfactual scenario, which shows the costs of capture for a post-combustion capture plant alone, is shown as 'PCC only'. Here, the cost of capture per tonne of clinker is 49.89 €/t, two times the cost of the Leilac only case and 89% more expensive than when Leilac and PCC are used together. Over 40% of the PCC only cost is capital repayment.

There is an increase in the amount of CO_2 generated, for the reasons described in Section 4. 2. 1. This additional CO_2 generated by the PCC plant must also be transported and stored, increasing the costs per tonne of CO_2 avoided.

[11] https://energywatch.com/EnergyNews/Cleantech/article13445570.ece
[12] https://unece.org/sites/default/files/2022-04/Brevik%20HeidelbergCement.pdf

Leilac Marginal Opex incl. Capex Repayment - Leilac Limited Estimates
€/t CO_2 avoided



	€/t CO2 Avoided (Fossil Basis)	Core Process Sub-total	Capital Repayment (Core)	CPU - LEILAC	CPU - Amine	Amine Capex	Amine Opex
1a. Preheater replacement. Alternative fuel. HAS.	€ 32.98	€ 9.73	€ 10.03	€ 13.21	€ -	€ -	€ -
1b. Preheater replacement. Alternative fuel. LPC.	€ 32.90	€ 10.37	€ 9.15	€ 13.38	€ -	€ -	€ -
2. Preheater reuse. Alternative fuel. HAS.	€ 30.92	€ 8.80	€ 8.95	€ 13.17	€ -	€ -	€ -
PCC Only	€ 74.72	€ -	€ -	€ -	€ 13.27	€ 25.26	€ 36.19
Leilac + PCC	€ 39.25	€ 7.35	€ 7.58	€ 9.98	€ 3.19	€ 6.62	€ 4.54
Preheater replacement. Biomass. HAS.	€ 68.77	€ 50.10	€ 8.06	€ 10.61	€ -	€ -	€ -

Figure 10

Marginal OPEX incl. CAPEX repayment for main Leilac scenarios (97% calcination leaving Leilac) – Leilac estimates, €/t fossil CO_2 avoided. e-Leilac (scenario 3) is omitted from this chart due to its significantly higher cost, but the values can be found in table 10.

4.3. Sensitivity Analysis

4.3.1. Electricity Price

The impact of electricity price on the cost of CO_2 avoidance was investigated. The two main aspects are the impact on the cost of capture when other thermal fuels are used, and the impact when electricity is used as thermal fuel.

Several electricity prices were chosen, specifically: 0, 40, 80, and 120 €/MWh. (The baseline scenario has a price of 80 €/MWh.) Preheater replacement (scenarios 1a) and e-Leilac (scenario 3) were selected for analysis for the combustion plants' and electric plants' sensitivity analyses, respectively. The results are shown in Figure 11.

Combustion Plants

The dependency of cost of avoidance on electricity price is linear, as would be expected. In the case of plants using alternative fuel, the cost of avoidance increases by 1.4 €/t CO_2 with each 10 €/MWh increase, a relatively small influence.

Electric Plants

Here, we see a linear dependency again. The cost of avoidance ranges from 44 €/t CO_2 for electricity at 20 €/MWh to 168 €/t CO_2 at 100 €/MWh. The cost of avoidance increases by approximately 16 €/t for every 10 €/MWh of electricity price increase. The cost of avoidance remains positive even with free electricity due to the other costs incurred throughout the plant, mainly capex repayment (>80%).

4.3.1.1. Natural Gas Price

Figure 12 shows that the natural gas price has no effect on the cost of Leilac technology when burning alternative fuels. This is because we assume that, in the long-term, no natural gas will be required in the combustion system. There is a moderate effect on the cost of post-combustion capture processes, where natural gas is continued to be burned. Advances in combustion for post-combustion capture would reduce the impact of this parameter on the cost of avoidance.

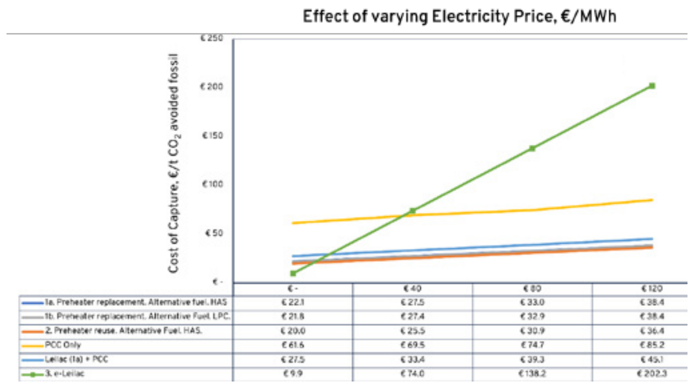


Figure 11

Sensitivity analysis showing the cost of avoidance of fossil CO_2 (€/t CO_2) with varying price of electricity (€/MWh).

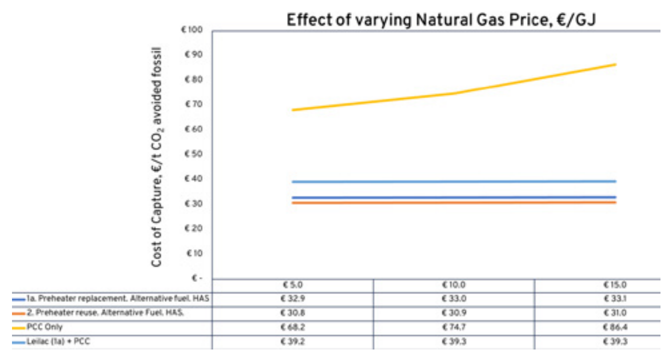


Figure 12

Sensitivity analysis showing the cost of avoidance of fossil CO_2 (€/t CO_2) with varying price of natural gas (€/GJ). Switching from HAS (1a) to LPC conveying (1b) produced very similar results that could not be distinguished on this graph.

4.3.2. Fuel Switch to Pure Biomass

The core Leilac scenarios including both preheater replacement (1a and 1b) and preheater reuse (2) assume that the plant runs on 100% low-grade alternative fuel. This is not the only viable fuel, and one alternative is to use pure biomass. With no fossil carbon content, this greatly reduces the fossil fuel-related CO_2 emissions of the cement plant.

The 'CO_2 avoided' metric takes these reductions in fossil CO_2 emissions into account alongside those of the captured CO_2. Figure 13 shows the results when the plant is modelled running on biomass fuel with a cost of 8 €/GJ, compared with the other main scenarios in the report.

This scenario delivers a cost of 69 €/t CO_2 avoided, a significant increase relative to the Leilac alternative fuel scenario. It also delivers fossil CO_2 avoidance of 94%, a significant increase to alternative fuel and similar to the electrification scenario.

The results suggest that combining Leilac and biomass could lead to a near net-zero plant for a slightly lower cost than post-combustion capture on its own. This may be attractive for cement plants that have limited space or capital budgets, or where CO_2 avoidance is strongly preferred to capture. For example, if CO_2 transport and storage costs are high or there is limited availability of low-cost alternative fuel.

4.3.3. Calciner Alternative Fuel Price

The gate fee paid upon delivery of alternative fuel can vary quite significantly depending on location and quality. The baseline assumption is a price of -3 €/GJ. Two other prices were investigated, 0 and -6 €/GJ. The results are shown in Figure 14. The impact on avoidance cost is relatively minor. This is due to the similar fuel properties assumed for Leilac and the calciner it replaces. Furthermore, these long-term performance estimates for Leilac assume energy penalties below 1 GJ/t CO_2 captured, which moderates the impact of the fuel price.

4.3.4. Capital Repayments

The impact of reduced and increased capital repayments was modelled by varying the weighted average cost of capital (WACC). Reducing the WACC from 3% to 1.5% reduced capital repayments by 57%, whereas a WACC of 8% increased capital costs by 107%. Changing the WACC from 3% to 8% had a relatively large impact on the cost of CO_2 avoidance of Leilac, with typical costs increasing by 12 €/t CO_2 to 45 €/t CO_2. The increased WACC had a larger impact on the post-combustion capture scenario, with capital costs increasing by 30 €/t CO_2 to 104 €/t CO_2 avoided.

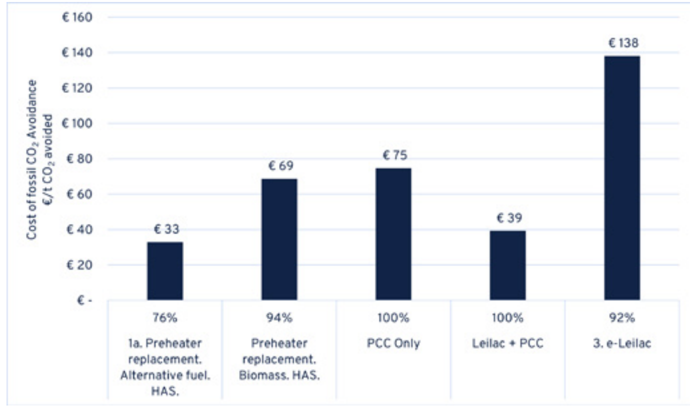


Figure 13

Fossil CO_2 avoidance rate (per cent) and cost of fossil CO_2 avoidance for multiple abatement scenarios.

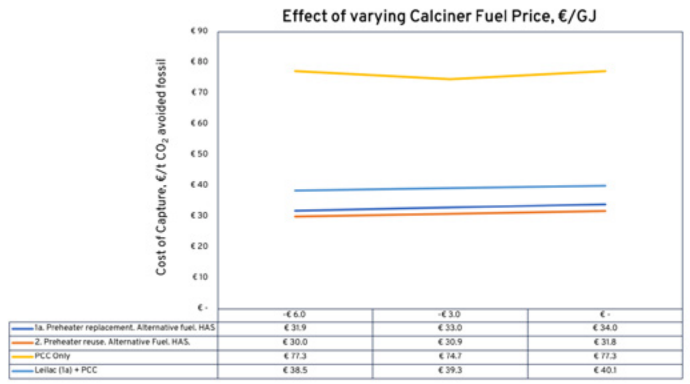


Figure 14

Sensitivity analysis showing the cost of avoidance of fossil CO_2 (€/t CO_2) with varying price of calciner alternative fuel (€/GJ). Switching from HAS (1a) to LPC conveying (1b) produced very similar results that could not be distinguished on this graph.

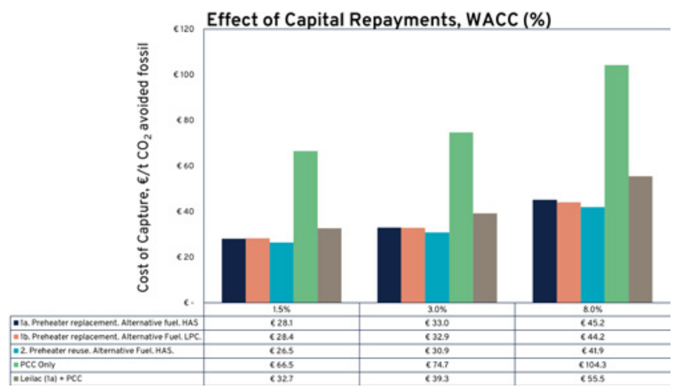


Figure 15

Sensitivity analysis showing the cost of avoidance of fossil CO_2 (€/t CO_2) with varying the cost of capital repayments by variation of WACC (%).

5. CO_2 Transport and Storage

Although a detailed analysis of CO_2 transport, use and storage options is beyond the scope of this study, CO_2 transport and storage infrastructure will be essential to the successful decarbonisation of any cement plant, and the cost of this infrastructure will be a significant driver of the overall economic viability of carbon capture for cement. As such, it is important to include the impact of transport and storage in any summary of anticipated total CO_2 avoidance costs for cement.

5.1. CO_2 Transport Options

Once captured, CO_2 must be transported to its destination. The distance between a capture plant (source) and the ultimate destination of the CO_2 may be anywhere from a matter of meters to thousands of kilometres. Additionally, the volume of CO_2 and location of its capture will be a major factor in determining the appropriate mode of transport. As such, CO_2 transport costs vary dramatically, and must be considered on a plant-by-plant basis.

CO_2 transport options include pipeline, barge, ship, rail, and truck. These transport options vary in their feasibility depending on the volume of CO_2 that needs to be moved and the distances and the geography involved. They also have different requirements, including purification and operational requirements. All these variables have a profound impact on the economics of a given CCUS project.

5.2. CO_2 Utilisation and Storage Options

There are many options for dealing with the captured CO_2. These range in their levels of technical maturity, geographical availability, level of economic benefit, level of purification requirements, and vary in environmental benefit.

Carbon utilisation

Carbon utilisation consists of a range of technologies that use or convert CO_2 to make valuable fuels, feed, chemicals, building materials or other products. For some existing applications, captured CO_2 can replace conventional CO_2 feedstocks, while new applications can be developed based on incentives to utilise CO_2. The market for CO_2 utilisation, however, will likely remain small relative to the volume of CO_2 that will need to be captured from industry.

Carbon storage

The primary means of ensuring the CO_2 generated by industry does not reach the atmosphere is to permanently store or sequester it. Geological storage reservoirs are the only volumes that can permanently store CO_2 at a sufficiently large scale.

Geological storage of CO_2 has been safely undertaken for many years. From storage in deep saline aquifers, to depleted hydrocarbon fields, to mineralisation, where the CO_2 is bound to rocks, geological storage of CO_2 uses well established, regulated, effective and safe practices.

The International Energy Agency (IEA) estimates that 70% of CO_2 emissions are within 100km of potential subsurface storage reservoirs in key regions. For cement and lime, the decentralised nature of production opens opportunities for local storage solutions. This can help reduce transport costs and provide local incentives for storage infrastructure development.

5.3. Estimated CO_2 Transport and Storage Costs

Given the high level of variability in CO_2 transport, use and storage options, it is reasonable to use an indicative range of expected costs.

For transport, assessments by the Zero Emissions Platform in Europe, and the IPCC estimate costs in the range €4.50–€13 / tonne CO_2 for pipelines and ships.[13, 14] From this, a baseline transport cost of €9 per tonne of CO_2 is assumed.

For storage, estimated costs range from €1 to €20 depending on location and storage type.[15, 16] Taking a baseline storage cost of around €7 per tonne of CO_2, a total average cost for transport and storage of €16 per tonne of CO_2 is assumed. This represents a low-cost transport and storage scenario.

As CO_2 transport infrastructure is developed, however, first movers or areas with limited capacity may experience much higher costs. Therefore, a high-cost transport and storage scenario is estimated at €50/tonne of CO_2.

The variance in these transport and storage costs illustrate the need for low-cost solutions. Government support will be essential in developing the required infrastructure and ensuring it is accessible, of sufficient scale, and available at the lowest possible cost to the cement industry.

[13] ZEP. The Costs of CO_2 Transport Post-demonstration CCS in the EU. European Technology Platform for Zero Emission Fossil Fuel Power Plants, Zero Emissions Platform; 2011.

[14] R. Doctor et al. IPCC Special Report on Carbon dioxide Capture. 2018. Ch. 4. Transport of CO_2

[15] ZEP. The Costs of CO_2 Transport Post-demonstration CCS in the EU. European Technology Platform for Zero Emission Fossil Fuel Power Plants, Zero Emissions Platform; 2011.

[16] R. Doctor et al. IPCC Special Report on Carbon dioxide Capture. 2018. Ch. 4. Transport of CO_2

5.4 Total Estimated CCUS Costs

The CO_2 capture options and costs outlined in this techno-economic study provide flexible, scalable and cost-effective carbon capture solutions for cement. CO_2 capture, however, is only a part of the solution. Once captured and compressed, the CO_2 must be transported for use or permanent storage.

Using a likely potential range of transport and storage costs of €16–€50 / tonne of CO_2, a summary of total CO_2 avoidance costs, including capture, compression, transport, and storage can be given for the main scenarios described in this study.

As shown in figure 16, CO_2 transport and storage costs are a major driver of the overall economic viability of CCUS for cement. When transport and storage costs are at the high end of the estimated range, they account for more than the total cost of capture and compression when using the Leilac technology and alternative fuel. For low-cost carbon capture technologies to deliver impactful emissions reduction, CO_2 transport and storage infrastructure that is accessible, of sufficient scale, and available at the lowest possible cost will be essential.

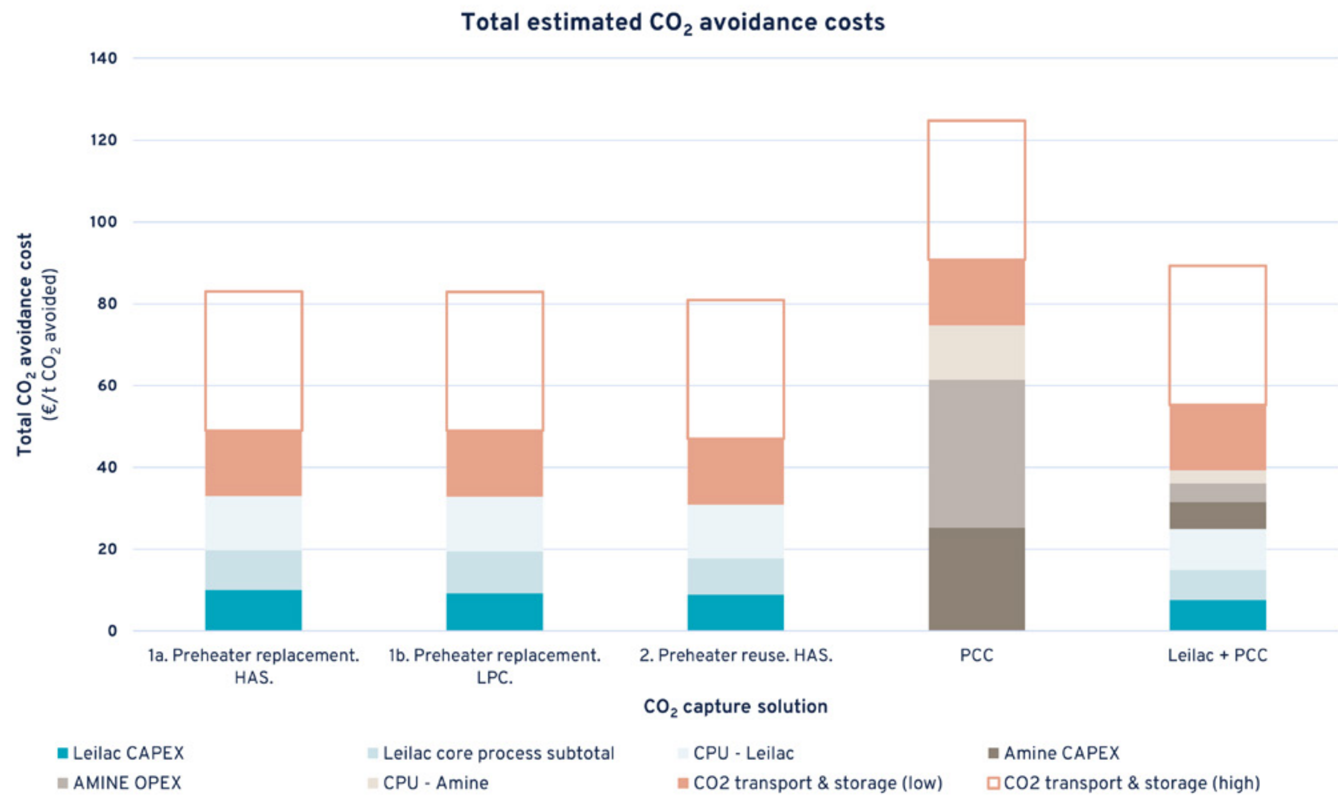


Figure 16

Total estimated CCUS cost summary for Leilac capture options operating on alternative fuel, post-combustion capture (PCC) using amines, and a combined Leilac and PCC solution. Total CO_2 avoidance increases from ~76% for the Leilac only scenarios to 100% for options with a PCC unit.

This study provides illustrative figures based on central European costs. Regional and plant specific analysis is provided through a scoping study. For more information please email contact@leilac.com.

6. Study Conclusions

1. **Application of the Leilac technology to the full capacity of a typical cement plant is feasible.**

   The Leilac technology can be implemented in flexible configurations with significant optionality on layout, integration, and fuels. This flexibility will enable the retrofit of Leilac at full-scale to most cement plants, with designs optimised for each individual plant's properties and requirements. The installation of Leilac at full-scale will use known technologies thanks to the future technological development achieved by the Leilac-2 project.

2. **Application of the Leilac technology to the full capacity of a typical cement plant is cost-effective.**

   The core CAPEX is around 135 M€ and OPEX, excluding compression and CAPEX repayment, is ~10 €/t CO_2 captured.

3. **Application of the Leilac technology avoids ~75% of fossil CO_2 emissions.**

   Importantly, most of these fossil CO_2 emissions are released directly from the raw material as an inevitable by-product of cement production. Switching to Leilac and 0% fossil carbon fuel increases the fossil avoidance rate to 94%.

4. **The Leilac technology unlocks low-cost net-zero cement manufacture.**

   Leilac can be combined with post-combustion capture technologies that use the excess heat from the existing cement plant and Leilac to regenerate the solvent, leaving very little extra heating requirement. This solution all but eliminates the largest operating cost of post-combustion capture, greatly reducing its cost of CO_2 avoidance. A combined Leilac + amine system could reach net zero for ~€39/t CO_2 avoided (~26 €/t clinker).

5. **The Leilac technology continues to improve.**

   Aside from Leilac-2, Leilac is developing new techniques, methods and partnerships to continuously reduce the cost and complexity of CO_2 capture while scaling up its application.

6. **Accessible and economical CO_2 transport and storage infrastructure is essential.**

   CO_2 transport and storage costs are highly variable and account for a significant proportion of the total CO_2 avoidance costs. The development of low-cost, large-scale infrastructure will be essential for carbon capture solutions to deliver impactful emissions reductions for the cement industry.

7. Appendices

7.1. Appendix 1: CO_2 Compression and Clean Up

The CO_2 compression and post-capture design consists of two main units:

1. The CPU for CO_2 captured by the Leilac calciner. This equipment will be present in all options and scenarios and will treat the CO_2 to a nominal specification. Exact CO_2 specifications vary depending on the CO_2 endpoint for CCS or CCU, and within those options depending on transport options or even reservoir modelling. This Appendix considers a nominal level of gas handling, which can be tailored to suit the application. Three technical solutions are presented, all of which are industry standard for CCS:
   a. The base case is CO_2 liquefaction for treatment and to allow export in liquid phase by any combination of truck, rail or ship/barge.
   b. An alternate option for compression up to supercritical pressure, which requires a high-pressure pipeline for transport.
   c. Local compression and treatment only, remaining in lower pressure gas phase. This would be suitable only for local CCU to supply CO_2 to a downstream process, or CCS through re-use of an existing pipeline.

2. The post-combustion capture plant is used to capture the remainder of the CO_2 from the plant, including combustion flue gas from the calciner furnace, CO_2 generated from pre-calcination in the PHT, CO_2 generated from final calcination in the rotary kiln and combustion flue gas from the rotary kiln. This post-combustion capture plant is only needed in the net-zero scenario where CO_2 capture needs to be equal to CO_2 generated from 'fossil' sources that fall under the ETS penalty. This study assumes the use of a formulated amine solvent; however, any suitable post-combustion capture technology can be used in this service.

7.1.1. Leilac CO_2 CPU – liquefaction

Process CO_2 from the top of the calciner flows to the compression and post-capture processing equipment to meet the pressure and CO_2 quality specifications for export. The hot and dusty CO_2 will be cooled, de-dusted, pressure boosted by the ID fan and cooled again (<60 °C) to remove water and dust and increase gas density to maximise compressor throughput.

The first cooling loop will utilise waste heat recovery (WHR) to generate steam for use by other system(s) or to preheat primary combustion air used by the calciner. The second cooling loop will be part of the compressor interstage cooling and will use either a cooling water circuit or ambient air in an aerial cooler, depending on compressor vendor selection. De-dusting will be by a conventional baghouse. Pressure boosting by the ID fan is also conventional equipment and would be common to the Leilac calciner with or without a CPU. The pressure boosting has the benefit of allowing the CO_2 compressor to operate at a marginal positive pressure, which increases performance, reliability, and eliminates air ingress.

The raw CO_2 composition from the calciner is derived from the calcination of a cement meal powder with no exposure to combustion of alternative or other fuels. Therefore, contaminants typically seen from combustion such as residual VOCs, NOx, SOx, HCl or CO are greatly reduced. The contaminants from the cement meal exposed to the calciner and CPU are reduced further by pre-heating the cement meal in an oxygenated environment prior to entering the calciner, which is proven to volatilise, or otherwise react and remove contaminants from the system within the PHT overheads. Some trace volumes of NOx, SOx and HCl, however, will still be generated, in addition to N_2 and O_2 from trace air leakage in the system. Moisture will be present, but its content will also be minimal since most of the water in the cement meal is also driven off in the PHT.

The CO_2 operating pressure entering the CPU will be slightly above atmospheric; therefore, compression will be necessary to add pressure to overcome the pressure drop through the system and deliver a CO_2 product at export pressure. Controlling compression in a single multistage unit, rather than installing multiple compressors in series on either side of the post-capture processing equipment, reduces cost and complexity. The CO_2 compressor is typically electric motor drive (EMD) to avoid generating additional CO_2 from a gas or diesel turbine/engine. Use of EMD also allows better speed control, less vibration and lower maintenance.

At least two stages of compression are required, with the post-capture processing to be installed after the second stage. It is best to complete the post-capture processing (excluding dehydration and liquefaction) at the higher pressures after compressor discharge, since this allows for smaller systems where pressure drops can be easily overcome and where there is sufficient CO_2 partial pressure driving force for absorption/adsorption. Throughout the CPU process, interstage cooling down to <45 °C can be achieved using ambient air or cooling water in a heat exchanger.

Based on the raw CO_2 composition, the main contaminants that need to be removed are water (H_2O) and trace non-condensables such as oxygen (O_2) and nitrogen (N_2).

The moisture content of the CO_2 from the Leilac process will be minimal since most moisture will be driven off in the PHT. Given the requirements of the downstream system, however, it will be necessary to remove moisture down to ppm levels.

Condensed water in a CO_2 rich environment is corrosive due to CO_2 solubility in water forming carbonic acid, which requires more expensive corrosion resistant materials such as stainless steel. It is therefore critical to remove water to a moisture level below concentrations that any combination of operating pressures and temperature could drop the CO_2 stream to below its dewpoint conditions. Removal of water also prevents formation of solid water/gas hydrates or ice in the system, which lead to blockages in the cryogenic liquefaction process. A free liquid water phase can occur as the CO_2 is cooled during exposure to low ambient, or pressure let-down during start-up under J-T effect.

As the raw CO_2 from calcination is cooled, compressed, and cooled again, its position along the phase envelope will shift to a point where free water will condense out of the CO_2 gas as a separate liquid phase and can be removed in conventional gas/liquid separator vessels. This water separation has the additional benefit that water soluble contaminants will be partially removed from the system during this step.

After water is removed during compressor cycles, a further dedicated 'deep cut' is needed to force moisture below saturation. Technical solutions for dehydration or dewpoint control include Joule-Thompson or Refrigerant cooling, glycol or other liquid absorbents and membrane separation and/or adsorption in solid media beds (activated alumina, silica gel or molecular sieves).

For the CPU, the preferred technical solution to reach 50-250 ppm levels of water is adsorption in solid media beds, which is consistent with technology selection by specialised vendors. The solid media beds use temperature swing adsorption (TSA), where gas flows into one of a series of pressure vessels containing a packed bed of solid media, water is adsorbed into the media, and dry gas exits the vessel. Once the media is saturated with water, a manifold of on/off switching valves isolate the vessel and open to flow to the fresh vessel ready for adsorption.

The water saturated vessel is regenerated by a high temperature regen gas that flows through the media, liberating the water. The regeneration cycle runs on a timer to cycle between 2 or more vessels, and once regenerated the switching valves automatically open the vessel back to adsorption mode and send the next vessel into regeneration mode. The regen gas will be a 10-15% slipstream of the dry CO_2 discharge, and once water saturated, will be cooled and recycled upstream where the water condenses and is removed. Depending on adsorbent type, the regen gas will be heated to 150-300°C.

The use of solid media adsorbent vessels offers advantages: they are chemically inert, have no moving parts and have no electrical or fuel load outside of the regeneration cycle, and no steady-state chemical losses or makeup. Start-up is instantaneous, turndown infinite, and they can be operated in standby or flow-through mode as a guard bed indefinitely. Routine maintenance is minimal, mainly servicing of the on/off valves to ensure they cycle properly, and inspection/cleaning of downstream dust filter(s) to prevent carryover of the solid media into the downstream piping. Major maintenance will involve complete or partial replacement of the solid media, which is typically done every 5 years based on OEM recommendations. This maintenance cycle depends on the load seen by the media and number of cycles, with performance tracked using the downstream CO_2 quality analyses to observe decay ahead of replacement. Therefore, the performance, reliability and availability of the solid media adsorbent treatment system is high.

The dry CO_2 then enters the liquefaction system. The liquefaction process serves two main purposes:

a. Liquifying the CO_2 increases its density by over 200 times relative to gas phase, making it suitable for bulk transport by truck, rail or barge to downstream users. This enables CO_2 export to markets for use or storage, depending on local or regional availability. Alternatively, gas phase or supercritical phase CO_2 export is typically only feasible through long term agreements for pipeline infrastructure.

b. Removal of trace non-condensable containments such as O_2, N_2, or CO. Depending on the final CO_2 specification, minimal removal may be needed to stabilise the phase envelope of the CO_2 and provide a safe buffer to remain in liquid phase at all operating pressures and all operating temperature ranges during transport. More strict CO_2 specifications will require a deeper cut for HS&E limitations in the event of exposure (excluding food grade CO_2), or for wellbore metallurgy/reservoir permeability limitations, which vary significantly depending on operator maturity.

The CO_2 entering the liquefaction system is cooled in a heat exchanger by a closed-loop refrigeration circuit to -20 to -30°C, where the CO_2 condenses to liquid and the other non-condensables (O_2, N_2, CO) stay in the gas phase. The refrigeration circuit is typically powered electrically and will use a suitable refrigerant to meet regional environmental regulations. Depending on the final CO_2 specification, the non-condensable containments can be vented off in a simple gas/liquid flash vessel or sent to a distillation column (often called the stripper tower) which performs the fine gas/liquid distillation through use of a reboiler and/or reflux. A distillation column will be able to produce up to food grade CO_2 if desired, although at additional CAPEX and OPEX cost. Design options can be progressed to produce different grades of CO_2 if desired. Small amounts of CO_2 are always lost to the off-gas overheads, and could equal roughly 2-3% of the total CO_2 by volume. The off-gas overheads can be directed to existing or new vent systems as needed. If CO_2 recovery is crucial, additional processing of this off gas could be undertaken.

The produced liquid CO_2 is now of suitable quality for long distance transport (truck, rail or barge), injection and storage, or utilisation. Liquid CO_2 storage will be held in insulated pressurised vessels to provide the desired buffer storage time to allow CO_2 export during a nominated export schedule.

A full plant recycle is available in the design, which provides functionality to recycle off-spec gas from the export area back to compressor suction and allow re-processing of the CO_2 through the adsorbent units. This will ensure no off-specification CO_2 is exported during either a process upset or during start-up while the system is brought online. During the time the system is in recycle, the Leilac calciner could remain running unabated, and this design will be able to quickly return to specification (<1 hour) and will lead to a net reduction in the need to blowdown, vent or otherwise run the Leilac calciner unabated. Through this visibility and feedback of the CO_2 quality the operational monitoring and quality control of the process is high.

7.1.2. Leilac CO_2 CPU – supercritical pressure

The alternate CPU arrangement is to compress the CO_2 to a supercritical pressure rather than liquefy. This is achieved by raising the pressure of the CO_2 above it is critical point, around 7.4 Mpag and 31 °C, at which point the CO_2 is referred to as supercritical or dense phase. Under these conditions the CO_2 flows at a density approaching that of the liquid (600-700 kg/m³), but with the viscosity still of a gas (~0.06 cP). This allows economical transport of large volumes of CO_2 across long distance pipelines with low pressure drop, analogous to transport of high-pressure natural gas.

The supercritical pressure option is known to be lower CAPEX and OPEX than the liquefaction base case, primarily due to the lower complexity of gas compression versus liquefaction equipment and no energy demand to cool to cryogenic temperatures. This option, however, requires access to a high-pressure pipeline.

To achieve supercritical pressure, the CPU differs from the main base case CPU design in two key ways:

1. Following inlet cooling, compression and dehydration (which are unchanged) the CO_2 flows back to the compressor for an additional number of stages of compression and cooling cycles, identical to the first two stages of inlet compression, until it reaches > 10 MPag (green line in figure 16). This will be achieved in a single multistage compressor combined with the initial stages, with the dehydration done interstage at around 40-50 barg.

   Total compression stages will vary between 4 and 12 depending on the selected compressor type, and would be confirmed by the compressor vendor. This reduces cost and simplifies operation as a single large compressor is preferable to two smaller compressors in series. Compressors of this type are common in industry for this application and at this scale. After dehydration, there is no longer any risk of formation of the liquid phase, therefore the compressor can transition from stainless steel to normal carbon steel, reducing cost.

2. The removal of some contaminants will require additional processes, as there is no liquefaction step to drive off the other gases. In this compression case, contaminants removal is key to meet the downstream specification, but also to manage the pressure/temperature phase envelope of the CO_2 mixture to avoid formation of a liquid phase that can damage compressor internals. Namely, NOx, SOx and HCl should be removed via SNCR and FGD upstream of the compressor, since this is a practical method in cement plants to remove these contaminants in gas phase.

If using, an amine plant will already have a SNCR and FGD, so this is not a significant addition to the overall design. Dilution by N2 and O2 from false air will be more economically managed by stopping false air at the source rather than removal from the gas, but if necessary additional processing units can be added to the CPU. The Leilac process operates at positive pressure, unlike conventional cement plants, so air ingress is expected to be minimal. Other contaminants such as CO are minor and not a priority under EOR specifications.

The remainder of the CPU for the supercritical pressure design regarding control strategy, safety and recycle is unchanged. Note that this option does not store any CO_2 buffer capacity since the pipeline is always available during normal operation.

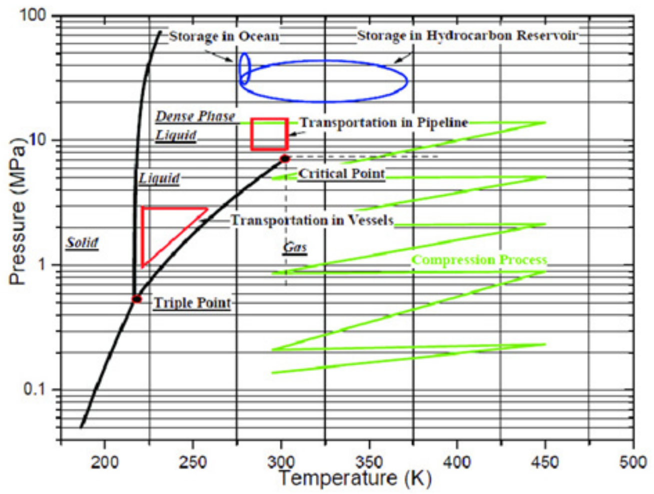


Figure 17

CO_2 phase diagram for dense phase compression.[13]

[13]Coquelet, Stringari, Hajiw, Gonzalez, Pereira, Nazeri, Burgass & Chapoy. (2017). Transport of CO_2: Presentation of New Thermophysical Property Measurements and Phase Diagrams. Energy Procedia. 114. 6844-6859. 10.1016/j.egypro.2017.03.1822.

7.1.3. Leilac CO_2 CPU – Local CCU

The last CPU arrangement is minimal gas handling to supply a downstream CCU system or technology. The CO_2 would remain in gas phase and delivered at the appropriate pressure and temperature as required. This would be suitable for CCU in-situ at the cement plant or to a nearby adjacent facility due to the low density of the CO_2 requiring large pipe diameters or storage points for transport. This option is also attractive for cases that re-use existing pipeline infrastructure that has lower pressure limits than the supercritical option.

The potential downstream CCU system or technology is highly variable, as is the potential market for CCU at the CO_2 capture rates of a full-scale cement plant, so is not addressed in detail in this study.

This option however would represent the lowest Capex and OPEX cost for the CPU is the required equipment will be minimised. Following inlet cooling, compression and dehydration (which are unchanged) the CO_2 flows to the compressor for an additional number of stages of compression required, which could be as low as one stage for low pressure operations. If a final CO_2 temperature above typical ambient is required, options for waste heat integration with the host plant could be applied to add additional heat back to the CO_2 stream. Contaminant removal will largely be minimised but can be applied case-by-case as needed. In some applications the presence of water or CO could be advantageous to the CCU process and therefore would not be removed at all.

7.2. Appendix 2: Alternative Process Description – Preheater Re-Use (Option 2)

Here, only differences with the Preheater Replacement option are described. The process flow diagram is shown in Figure 18.

Preheaters

The complete meal flow passes into the existing preheater 1 via the riser between preheaters 1 & 2. The meal is lifted and heated by the kiln gas and Leilac flue gases, which are combined immediately prior to their entering preheater 2. The partially preheated meal is then conveyed to the Leilac modules where it is split per module, and then per tube prior to entering the preheater 3s, of which there is one per tube. Each preheater 3 receives an equal fraction of the flue gas from that module – in this case, one quarter each. After this final preheating stage, the meal passes into the tubes. The flue gases from the preheater 3s are combined and pass to the point at which they merge with the kiln gas.

Calcination

As per preheater replacement.

Conveying

The meal is conveyed from preheater 2 to preheater 3 by entrained flow conveyor. The calcined meal is conveyed in the same manner as the preheater replacement option.

Combustion

As per preheater replacement option.

Waste Heat Recovery

As per preheater replacement option.

CO_2 Management

As per preheater replacement option.

Leilac Cement Plant

(Option 2: Preheater Re-use)

February 2023

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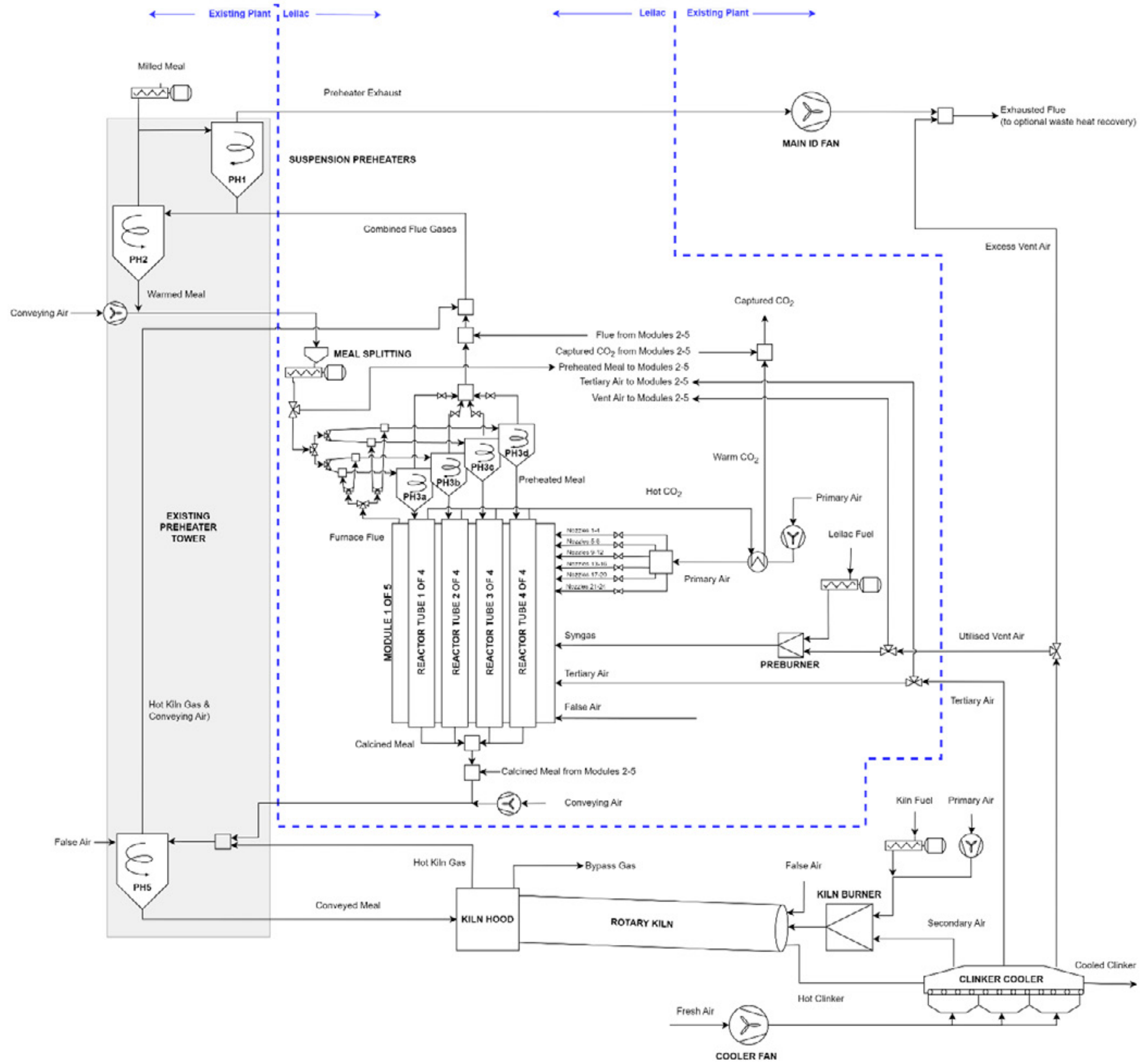


Figure 18

Process flow diagram for the preheater re-use integration option.

7.3. Appendix 3: Assumptions and Calculations in the Cost Model

7.3.1. Key Assumptions in the Cost Model

Parameter	Value	Units	Comments
Plant lifetime	25	Years	
WACC	3%	Per Year	Based on known coupon rates for sustainable bonds[14] and standard bonds[15] issued by cement multinationals. This rate is higher than either.
Operational hours	8000	Per Year	
Electricity price	80 22	€/MWh €/GJ	Expected long-term electricity price post-2025. Note that 2025 central European futures are significantly higher (ca. 130 €/MWh) as of mid 2023[16].
Natural gas price	36 10	€/MWh €/GJ	Natural gas price assumed to be in the 30–40 €/MWh in the long-term (i.e. beyond price rises caused by the war in Ukraine)
Calciner ('low-grade') alternative fuel price	-3	€/GJ	Leilac assumption, based on aggregated data sources and valid for regions with high levels of recycling and waste management such as the European Union. Gate fee slightly increased (i.e. more negative 'cost') as alternative fuel reduces in quality due to improved recycling, and landfilling becomes more expensive.
Extent of calcination exiting Leilac	97%	Mol/mol	Typical extent of calcination leaving Leilac
Extra electricity demand of Leilac vs Unabated Plant	0	kWh/t clk	Assumption assumes moderate efficiency gains from improved equipment and integration methods.
Assumed EU ETS Price	90	€/t CO_2	

Table 8

OPEX Model Assumptions. Leilac Limited assumptions based on 2019/2020 data, unless otherwise specified.

[14]https://www.holcim.com/media/media-releases/holcim-launches-first-sustainability-linked-bonds-in-Swiss-franc-market
https://www.holcim.com/media/media-releases/first-sustainability-linked-bond-eur-850-million
[15]https://www.heidelbergcement.com/en/pr-02-04-2020
[16]https://www.cmegroup.com/markets/energy/electricity/german-power-baseload-calendar-month.html

7.3.2. Mathematical Definition of Avoidance Rate

CO_2 generated, $m_{CO_2,gen}$

$$m_{CO_2,gen,TP} = m_{CO_2,gen,MP} + m_{CO_2,gen,CP}$$

Fossil CO_2 generated, $m_{CO_2,FC,gen}$

$$m_{CO_2,FC,gen,TP} = m_{CO_2,FC,gen,MP} + m_{CO_2,FC,gen,CP}$$

CO_2 emitted, $m_{CO_2,em}$

$$m_{CO_2,em,TP} = m_{CO_2,gen,TP} - m_{CO_2,cap}$$

$$m_{CO_2,em,ref} = m_{CO_2,gen,ref}$$

CO_2 avoided, $m_{CO_2,av,TP}$

$$m_{CO_2,av,TP} = m_{CO_2,gen,ref} - m_{CO_2,em,TP}$$

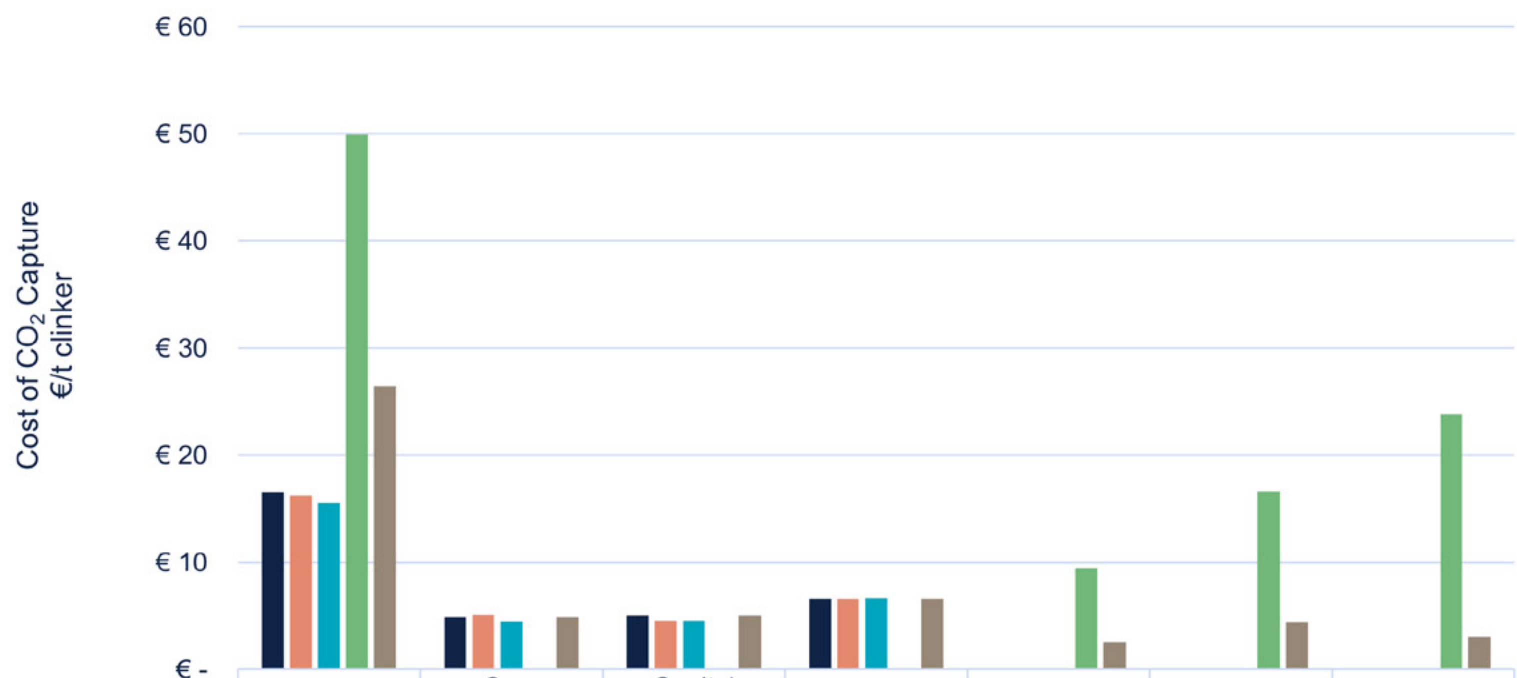
Fossil CO_2 Avoided, $m_{CO_2,FC,av,TP}$

$$m_{CO_2,FC,av,TP} = m_{CO_2,FC,gen,ref} - m_{CO_2,FC,em,TP}$$

Symbol	Name	Typical units
$m_{CO_2,av,TP}$	Total CO_2 avoided per tonne of product after CCS is applied.	tCO_2/t product
$m_{CO_2,em,TP}$	Total CO_2 emitted to the atmosphere per tonne of product after CCS is applied	tCO_2/t product
$m_{CO_2,em,ref}$	Total CO_2 emitted to the atmosphere per tonne of product in the reference plant	tCO_2/t product
$m_{CO_2,gen,TP}$	Total CO_2 generated per tonne of product after CCS is applied	tCO_2/t product
$m_{CO_2,gen,MP}$	CO_2 generated per tonne of product in the main plant only once CO_2 is applied	tCO_2/t product
$m_{CO_2,gen,MP}$	CO_2 generated per tonne of product in the capture plant only once CO_2 is applied	tCO_2/t product
$m_{CO_2,gen,ref}$	Total CO_2 generated per tonne of product in the reference plant	tCO_2/t product

7.3.3. Supplementary OPEX Model Result Tables & Charts

Leilac Marginal Opex incl. Capex Repayment - Leilac Limited Estimates
€/t clinker



	€/t clinker	Core Process Sub-total	Capital Repayment (Core)	CPU - LEILAC	CPU - Amine	Amine Capex	Amine Opex
1a. Preheater replacement. Alternative Fuel. HAS.	€ 16.53	€ 4.88	€ 5.03	€ 6.62	€ -	€ -	€ -
1b. Preheater replacement. Alternative Fuel. LPC.	€ 16.21	€ 5.11	€ 4.51	€ 6.59	€ -	€ -	€ -
2. Preheater reuse. Alternative Fuel. HAS.	€ 15.58	€ 4.43	€ 4.51	€ 6.63	€ -	€ -	€ -
PCC Only	€ 49.89	€ -	€ -	€ -	€ 9.49	€ 16.61	€ 23.80
Leilac (1a) + PCC	€ 26.45	€ 4.88	€ 5.03	€ 6.62	€ 2.52	€ 4.39	€ 3.01

Figure 19

Marginal OPEX incl. CAPEX repayment for main Leilac scenarios operating on alternative fuel (97% calcination leaving Leilac) – Leilac estimates, €/t clinker.

	1a. Preheater replacement. Alternative fuel. HAS.	1b. Preheater replacement. Alternative fuel. LPC.	2. Preheater reuse. Alternative fuel. HAS.	PCC Only	Leilac (1a) + PCC	3. e-Leilac
Capture Rate (% of all carbon)	60%	59%	61%	86%	81%	86%
€/t CO_2 Captured (All Carbon)	€ 33.89	€ 33.53	€ 31.85	€ 67.55	€ 43.03	€ 167.56
Core Process Sub-total	€ 10.01	€ 10.56	€ 9.06	€ -	€ 9.84	€ 146.72
Capital Repayment (Core)	€ 10.31	€ 9.33	€ 9.22	€ -	€ 7.74	€ 7.33
CPU - LEILAC	€ 13.58	€ 13.64	€ 13.56	€ -	€ 10.19	€ 13.51
CPU - Amine	€ -	€ -	€ -	€ 12.84	€ 3.88	€ -
Amine Capex	€ -	€ -	€ -	€ 22.49	€ 6.75	€ -
Amine Opex	€ -	€ -	€ -	€ 32.22	€ 4.63	€ -

Table 9

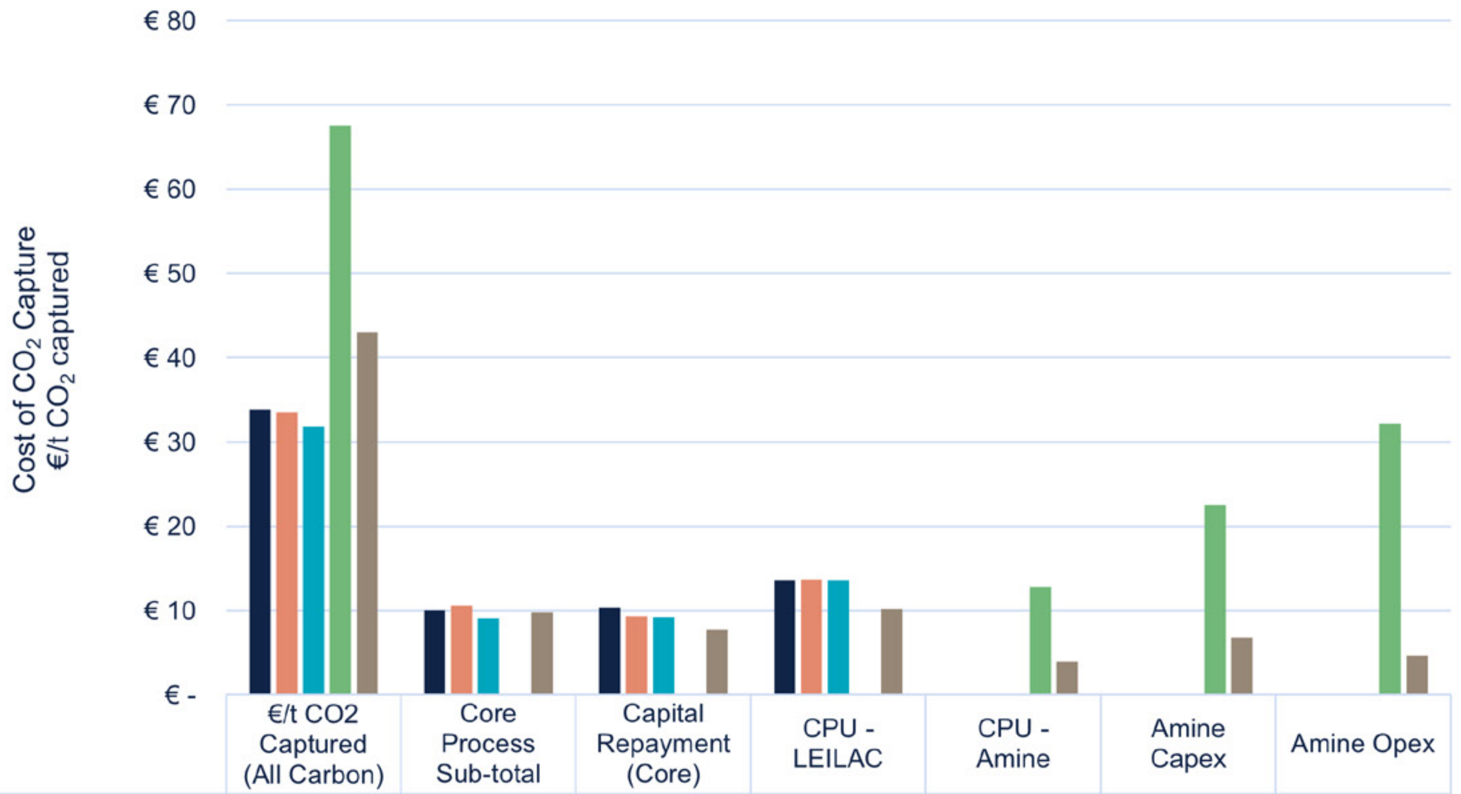
Cost of CO_2 capture for all Leilac scenarios (97% calcination leaving Leilac).

	1a. Preheater replacement. Alternative fuel. HAS.	1b. Preheater replacement. Alternative fuel. LPC.	2. Preheater reuse. Alternative fuel. HAS.	PCC Only	Leilac (1a) + PCC	3. e-Leilac
Avoidance Rate (Fossil)	76%	74%	76%	100%	100%	92%
€/t CO₂ Avoided (Fossil Basis)	€ 32.98	€ 32.90	€ 30.92	€ 74.72	€ 39.25	€ 138.19
Core Process Sub-total	€ 9.73	€ 10.37	€ 8.80	€ -	€ 7.35	€ 119.05
Capital Repayment (Core)	€ 10.03	€ 9.15	€ 8.95	€ -	€ 7.58	€ 6.04
CPU - LEILAC	€ 13.21	€ 13.38	€ 13.17	€ -	€ 9.98	€ 11.15
CPU - Amine	€ -	€ -	€ -	€ 13.27	€ 3.19	€ -
Amine Capex	€ -	€ -	€ -	€ 25.26	€ 6.62	€ -
Amine Opex	€ -	€ -	€ -	€ 36.19	€ 4.54	€ -

Table 10

Cost of CO_2 Avoidance (Fossil Carbon Basis) for all Leilac scenarios (97% calcination leaving Leilac).

Leilac Marginal Opex incl. Capex Repayment - Leilac Limited Estimates
€/t CO₂ captured



	€/t CO2 Captured (All Carbon)	Core Process Sub-total	Capital Repayment (Core)	CPU - LEILAC	CPU - Amine	Amine Capex	Amine Opex
1a. Preheater replacement. Alternative Fuel. HAS.	€ 33.89	€ 10.01	€ 10.31	€ 13.58	€ -	€ -	€ -
1b. Preheater replacement. Alternative Fuel. LPC.	€ 33.53	€ 10.56	€ 9.33	€ 13.64	€ -	€ -	€ -
2. Preheater reuse. Alternative Fuel. HAS.	€ 31.85	€ 9.06	€ 9.22	€ 13.56	€ -	€ -	€ -
PCC Only	€ 67.55	€ -	€ -	€ -	€ 12.84	€ 22.49	€ 32.22
Leilac (1a) + PCC	€ 43.03	€ 9.84	€ 7.74	€ 10.19	€ 3.88	€ 6.75	€ 4.63

Figure 20

Marginal OPEX incl. CAPEX repayment for main Leilac scenarios (97% calcination leaving Leilac) – Leilac Limited estimates, €/t CO_2 captured

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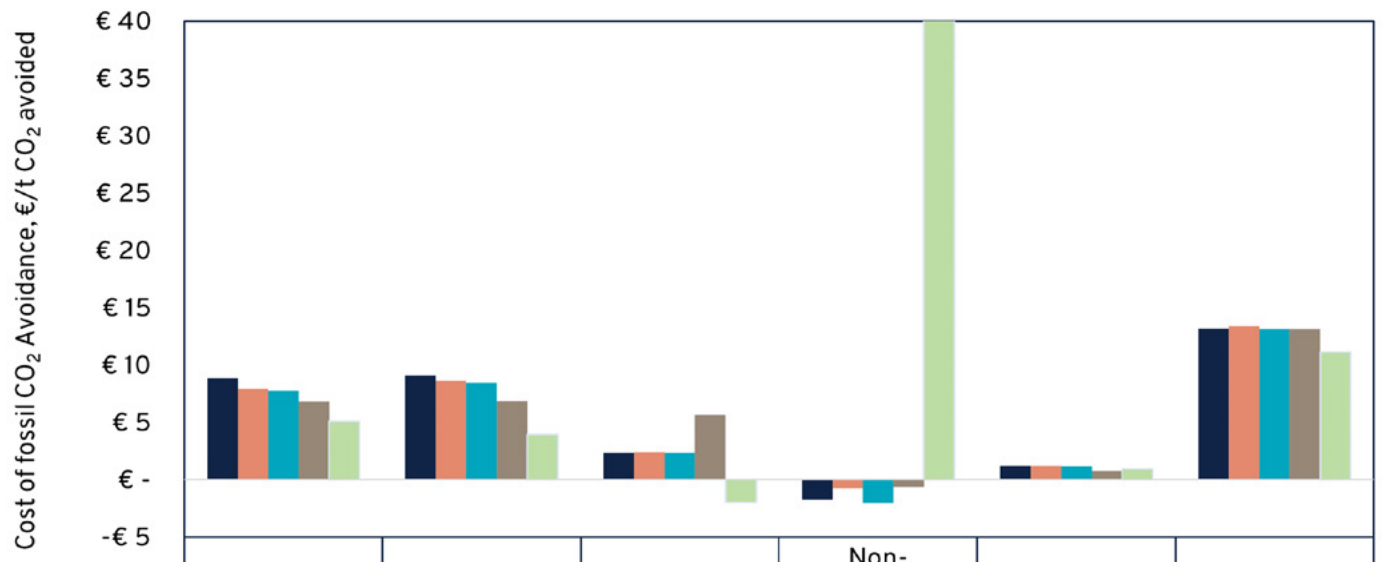
An alternative, more traditional categorisation of costs is shown in Table 11 below. This is used in Figure 20.

System 1 (main report)	System 2 (Traditional categories)	Core process/ other
Fuel (thermal)	Non-compressor fuel & electricity costs	Core process
Electricity – main plant		Core process
Amine plant electrical demand		Other
Amine plant fuel (natural gas)		Other
Emissions abatement consumables	Non-compressor variable costs (excl. fuel & electricity)	Core process
Amine replacement		Other
Tube replacement	Non-compressor fixed costs	Core process
Other maintenance		Core process
Operational labour		Other
Capital repayment	Non-compressor capex	Other
	Compressor capex	Other

Table 11

Comparison of categorisation systems for this study.

Leilac Marginal Opex incl. Capex Repayment - Leilac Group Estimates €/t fossil CO_2 avoided



	Non Compressor Capex	Non-Compressor Fixed Costs	Non-Compressor Variable Costs ex Fuel	Non-Compressor Fuel & Electricity Costs	Compressor Capex	Compressor Opex
1a. Preheater replacement. Alternative Fuel. HAS.	€ 8.83	€ 9.11	€ 2.39	-€ 1.76	€ 1.21	€ 13.21
1b. Preheater replacement. Alternative Fuel. LPC.	€ 7.95	€ 8.67	€ 2.43	-€ 0.73	€ 1.21	€ 13.38
2. Preheater reuse. Alternative Fuel. HAS.	€ 7.77	€ 8.48	€ 2.37	-€ 2.05	€ 1.18	€ 13.17
Leilac (1a) + PCC	€ 6.79	€ 6.88	€ 5.63	-€ 0.62	€ 0.79	€ 13.17
3. e-Leilac	€ 5.09	€ 3.92	-€ 1.97	€ 119.05	€ 0.95	€ 11.15

Figure 21

Marginal OPEX incl. CAPEX repayment for main Leilac scenarios (97% calcination leaving Leilac) – Leilac estimates, €/t fossil CO_2 avoided. Scenario 3 (electrical) is included but note that the values for total cost and non-compressor fuel & electricity costs go beyond the chart scale.

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