



LEILAC

ROADMAP 2050





LEILAC Technology Roadmap to 2050

A cost-effective path to carbon neutral industrial production

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- Calix
- HeidelbergCement
- CEMEX
- Tarmac, a CRH company
- Lhoist
- ECN (later incorporated into TNO)
- Imperial College of Science Technology and Medicine
- Process Systems Enterprise Limited (PSE)
- Quantis Sàrl
- The Carbon Trust
- Solvay

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



Web: www.project-leilac.eu

LEILAC partners



Highlights



The Cement and Lime industries play a vital role in our society

Cement is used in our roads, buildings, homes, offices and almost all our infrastructure. Lime is used in a variety of applications including in the iron & steel, chemical, paper, pharmaceutical, drinking water, food, and farming industries. EU recognised these sectors as being ‘indispensable’ to the economy. Responsible for 8% of global CO₂ emissions, global cement and lime demand will increase due to the global population growth and the trend of further urbanisation. They play a vital part of our society and economy.



The Cement and Lime industries are dedicated to decarbonising

Cement and lime industries, both through their associations and individual corporate pledges, have made clear commitments to carbon neutral emissions production by 2050.



The LEILAC process is being designed for efficient, global roll out

A LEILAC module addressing 20% of a cement plant’s emission will begin constructed in 2022. The intent behind the commercial, global rollout of the technology is for the modular, scalable design to capture the process emissions from a plant of any size. The designs will eventually be ‘blueprinted’ and applied by engineering firms on a global basis to cement and lime plants, enabling localised expertise to be developed and used.



Appropriate long-term incentive frameworks and public financing for early movers are critical

Effective policy environments and incentive mechanisms are required globally to ensure that vital industries can continue to operate, while taking necessary decarbonisation steps. Public subsidies and investments are required to allow these technologies to continue to be quickly developed and installed globally. Support is required to enable and widely deploy transport and storage infrastructure, ensuring the captured CO₂ does not reach the atmosphere.



The LEILAC process (Direct Separation) represents a low cost, eco-efficient means of capturing process CO₂, and can be run on renewable energy

A variety of approaches and technologies are being developed to capture the CO₂ emissions from the cement industry, and they all need to be urgently developed and scaled up. Supported by industry and the EU, the proven LEILAC technology captures unavoidable process CO₂ emissions for minimal expense, as it as it does not need additional processes or chemicals. It can work in synergy with other technologies and approaches. It can also be fully powered by renewable energy and/or hydrogen, and all units will be ‘electrification’ ready.



These industries recognise that reaching carbon neutrality requires the use of carbon capture, utilisation and storage (CCUS)

Two-thirds of emissions from the production of cement and lime are unavoidable ‘process emissions’. While several approaches can be taken to reduce the volumes of CO₂ generated - and these should be pursued strongly - the most viable means of ensuring process emissions do not reach the atmosphere is by capturing and permanently safely storing the CO₂ typically in minerals or by sequestration. Using the CO₂, for example in the chemical industry and for creating synthetic fuels, may be an important enabler for capturing CO₂ from the cement and lime industry.



CO₂ transport and storage availability is vital to enable industrial decarbonisation, and without it the ability for our society to reach its climate change ambitions will be limited

The consortium considers the development and availability of transport and storage infrastructure to be vital for decarbonising the cement and lime industries. Unlike examples in the power and refining sector, the volume of CO₂ to be stored per plant is less. This opens local storage opportunities and industries. Given the very small size of most of the cement and lime players, steps must be taken to quickly develop storage sites of all sizes; ensure larger storage developments are appropriately sized for 2050 (particularly if using public money and only facilitating bigger players); and enable fair access.



Societal acceptance and Government support are essential

While pursuing every option available to decarbonise, the cement and lime sector needs the help and assistance of our society (as both project stakeholders and product consumers) as it decarbonises. On a local level, that can range from small increases in prices of cement, through to active support of decarbonisation projects so they remain competitive.



1 Executive Summary

The international community recognises that CO₂ emissions contribute to climate change.

The cement and lime industries serve an extremely important part in the functioning of our global society and economies. They are longstanding industries, highly optimised – providing low-cost products that underpin our daily lives. However, our societies, scientists, governments, and the industry have all acknowledged that the previous means of production cannot be sustained.

There is an enormous drive, and support, for addressing unavoidable process emissions derived from the production of cement and lime. Until very recently, there were not the technologies nor policy mechanism available to support wholesale decarbonisation efforts globally – but that has changed. Today the global cement and lime industries are both committed, and are developing the tools, to take dramatic steps in achieving net zero production.

LEILAC (Low Emissions Intensity Lime and Cement) projects aim to apply a breakthrough in low-cost carbon capture technology that will enable Europe's cement and lime industries to reduce their emissions dramatically, while retaining their international competitiveness.

Focused on addressing these industries' unavoidable process emissions using Calix's novel carbon capture technology – and supported by leading industrial players – the LEILAC projects are on track to deliver commercially relevant solutions by 2024.

LEILAC (both alone and alongside other decarbonisation methods) can enable net zero production of lime and cement at low cost, assuming:

- Policy support to ensure that global targets are met, and that there is a level-playing field for industrial producers.
- Sufficient transport and storage infrastructure are put in place, and regulated for fair access to small players, to ensure that society's unavoidable industrial emissions are not released to the atmosphere.
- The main technological challenges for capture continue to be addressed with support of the European Union and industrial partners.
- The roll out approach taken by Calix is intended to utilise the strengths and competences of existing global engineering houses, to enable a rapid rollout of low-cost process capture technology.

Should incentive frameworks and transport and storage infrastructure be in place, decarbonisation of industry is a very real possibility. Net zero emissions are required by 2050, and LEILAC is well placed to enable the cement and lime industries to contribute towards these targets in a timely, effective, and cost-efficient manner.



Photographed by: Paul Poels



2 Publication summary

Industry's decarbonisation vision

The adoption of the Paris Agreement, ratified by 175 countries, provided the clear objective of keeping a global temperature rise of well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to below 1.5 degrees Celsius.

In support of those ambitions, the very challenging goal of reaching carbon neutrality by 2050 has been set. These commitments are being made at a variety of levels. 127 countries, 823 cities, 101 regions, and 1,541 companies have committed to decarbonising their activities by 2050 (New Climate Institute 2021).

These commitments are being matched in the cement industry. The Climate Ambition Statement articulated by the members of the Global Cement and Concrete Association, and 2050 Roadmap by Cembureau, and the corresponding wave of individual corporate commitments, all have ambitions for neutrality by 2050.

This is not an easy commitment to reach for the cement or lime industry - responsible for 8% of global CO₂ emissions. Cement and lime provide vital services to our society, with essential products that are low cost and very efficiently produced. Since 1990, major efforts have been made to reduce emissions, including improvements to energy efficiency, use of alternative and waste fuels and clinker substitution.

However, complete decarbonisation of this industrial sector is far harder than many others, as most CO₂ emissions are released directly and unavoidably from the processing of the limestone. These “process emissions” are in addition to the CO₂ released from the combustion of fuels used to power the process (which represent around two-thirds of a plant's total emissions, depending on the fuel used).

Capturing unavoidable carbon

To reach the corporate emissions reductions targets by 2050, unavoidable process emissions must be addressed. The most effective means is to capture the CO₂, and ensure that it does not reach the atmosphere. Called Carbon Capture Use and Storage (CCUS), this general approach to decarbonisation has been used for decades in the hydrocarbon processing and recovery industries, further developed for the power sector. This will need to be applied to the majority of cement and lime plants due to those process emissions (Cembureau 2050 Carbon Neutrality Roadmap). As noted in the 2018 IPCC report, “CCS plays a major role in decarbonizing the industry sector in the context of 1.5°C and 2°C pathways, especially in industries with higher process emissions, such as cement.”

Capturing carbon from industrial processes and power generation plant has not yet been widely adopted due to the efficiency and cost penalties of traditional capture technologies, and a lack of meaningful (and universally applied) cost implications for emitting CO₂. However, changes are very rapidly being seen. Globally, 61 carbon pricing initiatives have been introduced covering 22% of all emissions (World Bank Group, 2021). The European Emissions Trading System (EU ETS), the largest carbon market in the world, reached a price of €57 per tonne of CO₂ in 2021.

The current collective objective facing industry and government (creating incentives) is threefold: to maintain economic prosperity, meet cement and lime market demand, while dramatically lowering CO₂ emissions.



Photographed by: Paul Poels



Carbon capture

The majority of initiatives to capture carbon are based, or adapted, from processes and techniques developed for the energy and chemical sectors, and are all based on separating gases. For 60 years solvents, such as amines, have been used to strip CO₂ from gases (particularly in refineries and natural gas processing plants), and a lot of work has been recently undertaken to apply them to the cement sector at increasingly lower cost. Sorbents (including calcium looping), membranes, and enhancements are being actively developed to reduce the volumes and/or energy required to separate CO₂ from flue gases. Other approaches, such as oxyfuel, separate gases in air, rather than at the stack. All these approaches must be developed as quickly as possible.

A new capture approach is being introduced. Calix's new process of 'indirect calcination' focuses solely on the cement, lime and magnesia sectors, ensuring that the relatively pure, unavoidable, CO₂ released from the limestone itself as part of the chemical reactions is not contaminated by either air or flue gases, and therefore available for direct capture.

The LEILAC process

The LEILAC (Low Emissions Intensity Lime And Cement) projects are developing a new technology, aiming to enable the cement and lime industries to capture those unavoidable CO₂ emissions emitted from the raw limestone.

The LEILAC process (also known as indirect heating, or direct separation) works within a normal cement plant's process. It is based on indirect calcination, by heating the limestone via a special steel tube within the 'precalciner'. This unique system enables pure CO₂ to be captured as it is released from the limestone, as the furnace exhaust gases are kept separate. Calcining raw meal by indirect heating (LEILAC) or by direct-heating (conventional calciner) can be done in principle with the same specific energy. The process does not involve any additional processes or chemicals, and simply involves a novel "pre-calciner" design (or new kiln, in the case of a lime plant).

This type of pre-calciner aims to use any type of fuel or heat source. This makes achieving a very efficient zero-emissions cement kiln, using biomass-rich fuels, green electricity, or hydrogen, a very real possibility with the same basic technology. If alternative fuels, biomass, or conventional fuels are used, any of the previously mentioned conventional carbon capture techniques can be applied to capture the combustion (heating) emissions. There would be synergies to such a combination, as the lowered energy requirements and capital of such a combined system would result in a very efficient means of achieving 'negative emissions' cement plants.

The LEILAC projects

Supported by the European Union, the LEILAC projects are applying this new type of pre-calciner. Applying the technology to the cement industry carries a large number of risks – and to quickly and effectively apply this technology, the European-Australian collaboration LEILAC projects include consortia of some of the world's largest cement, and lime companies, as well as leading research and environmental institutions.

The LEILAC1 project involved the construction of a Pilot plant at the HeidelbergCement plant in Lixhe, Belgium. Extensive research, development and engineering was necessary to design and construct the first-of-a-kind pilot – involving the dedicated, flexible, and professional inputs from all the project's partners, particularly the industrial users HeidelbergCement, Lhoist and CEMEX. This has enabled the construction of the pilot on time and on budget in 2019. Additionally, studies examining integration of the plant in different configurations, and confirmation of the sustainability of the process, and outreach activities have also been conducted by the other parties (Imperial, PSE, Quantis and the Carbon Trust).

The project has successfully demonstrated that both limestone and raw meal can be processed; that the CO₂ is successfully separated; and that (disaggregated from the entire system) the energy penalty for indirect calcination (LEILAC) should not be higher than direct (conventional) calcination. Other major findings are that there has been no build-up of material on the tube's wall; that the tube (despite the numerous runs) is exhibiting no significant negative operational deterioration; that there have been no negative impacts on the host plant, and no impact on clinker production; and that the pilot is safe and easy to operate, with no process safety incidents.



Photographed by: Paul Poels



LEILAC2: towards process integration

A follow-on project – LEILAC2 – commenced in April 2020, having been awarded €16m funding by the EU Horizon 2020 program with additional industry contribution. HeidelbergCement has kindly agreed to closely integrate the Demonstration plant into their operational plant in Hannover, Germany.

LEILAC2 will build a Demonstration Plant that aims to separate around 100,000 tonnes per year of CO₂ in a scalable module. The consortium, comprising Calix, HeidelbergCement, Cimpor, Lhoist, CEMEX, IKN, Certh, Polimi, BGR, GSB, Engie Laborelec, and Port of Rotterdam aims to demonstrate operational scale-up of the technology, as well as closer heat and process integration in an operational environment, to maximise the overall efficiency of the technology in a retrofit configuration, with minimal impact on clinker production and quality. The demonstration plant will also aim to show the applicability of less carbon intensive heat sources for the required calcination heat, i.e. the use of electricity and alternative (biomass rich) fuels.

The LEILAC2 plant is a first-of-a-kind retrofit. The CAPEX is expected to be around €16m. Further design, work and testing is required – but should the design work as planned - current estimates suggest the LEILAC2 may separate CO₂ at a cost of around €10/t CO₂ extra OPEX (above the host plant's operating costs). This excludes compression costs and CAPEX retrofit depreciation costs (including foundations, installation, structure), etc., which are expected to be in the region of an additional €10-€15/t CO₂.

Therefore, total CAPEX and OPEX costs of this demonstration-scale LEILAC plant is expected to be in the region of €20-25/t CO₂.

Full scale LEILAC

The intention with LEILAC2 is to start forming a robust, replicable module that can be simply scaled to capture 100% of a cement plant's process emissions (at any scale).

The LEILAC2 project is the first attempt at retrofitting the technology to a plant. At full scale, the LEILAC process conditions (and costs) will be improved from the current LEILAC2 projection through the following of steps in a future implementation, including: the use of the kiln gases; using the heat from the CO₂; enhanced preheat; the use of unprocessed RDF (reducing capture costs to €4/t CO₂); locating the units closer to the tower; skin loss reduction through module placement; and increasing the levels of insulation.

A full scale retrofit, depending upon the site in question and capital required to recover and utilise the heat, is expected to be close to BAT efficiency. On a greenfield site - when this type of pre-calciner is part of the planned installation - there is the opportunity for simpler integration, and minimal additional capital costs as a large proportion of the technology's costs are for foundations, structure, and installation.

A sustainable solution for the cement and lime industries

Every possible decarbonisation option needs to be urgently developed and deployed. In order to reach the required emission reductions by 2050, carbon capture will need to be applied to a vast majority of cement and lime kilns, and every technology option developed.

Once tested and scaled up, the LEILAC technology should provide an option for reducing the costs of carbon capture and accelerate the deployment in both the cement and lime industries using this new type of pre-calciner – enabling society to continue to benefit from these vital products without negatively impacting the environment.



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4 Aims & scope – carbon neutrality by 2050

The LEILAC1 (Low Emissions Intensity Lime And Cement) project has piloted a breakthrough technology that aims to enable Europe's cement and lime industries to capture their unavoidable process carbon dioxide (CO₂) emissions, for a minimal environmental or economic burden.

The adoption of the Paris Agreement, and its record-speed ratification by 175 countries, sets a clear global response to the threat of climate change. The Agreement's objective of keeping a global temperature rise of well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius, signals a clear intent to drastically reduce society's carbon emissions.

Cement is a critical requirement for our global society, with half a tonne of cement being used each year for every person on the planet [1]. Global cement demand will increase due to the global population growth and the trend of further urbanization. However, cement production is CO₂ intensive (8% of global CO₂ emissions), as the majority (typically over two thirds) of a plant's emissions are "process emissions" which cannot be avoided by replacing the use of hydrocarbon derived fuels.

Calix's LEILAC technology seeks to enable industrial carbon neutrality by 2050 by providing a novel carbon capture process that allows the low-cost capture of those unavoidable process emissions. The LEILAC technology re-engineers the existing process flows by indirectly heating the limestone. This unique system enables pure CO₂ to be captured as it is released from the limestone. This elegant solution requires no additional chemicals or processes. This innovation requires minimal changes to the conventional processes for cement, and simply replaces the calciner.

LEILAC1 has developed, built, and operates a pilot plant capturing around 5% of a typical cement plant's process CO₂ emission. Constructed next to the HeidelbergCement's plant at Lixhe, Belgium, the pilot has shown that over 95% of the process CO₂ emissions could be captured from cement or lime production without significant energy or capital penalty.

The LEILAC2 project aims to scale up the technology, with the objective of capturing 20% of a full-scale cement plant's (and 100% of a large lime kiln's) process emissions – capturing around 100 ktpa of pure CO₂ for minimal energy penalty (just compression). It will be built as a low cost, replicable and retrofittable 'module' at HeidelbergCement's plant at Hannover, Germany. It will seek to prove an effective retrofit solution with full integration; develop an easily replicable modular design; seek to demonstrate the use of alternative fuels (such as biomass) for the process; demonstrate the ability for fast ramp up/down times for the process using electricity (switching rapidly from fuel to electricity) allowing a cement plant to undertake load balancing of renewables on the grid – and enabling full electrification. It will seek to show how it can be used immediately, cheaply, and incrementally or fully retrofitted to all cement plants - enabling both cement and lime industries to dramatically reduce their unavoidable emissions while maintaining their international competitiveness.

From the outcome of the LEILAC1 pilot's results, and incorporating the pre-FEED results from LEILAC2, the intent of this document is to provide a Roadmap for the use of the LEILAC technology for the cement and lime industry.

In doing so, it will seek to incorporate the techno-economic modelling for the technology: including for the construction of new plants utilising the LEILAC technology and the retrofit to the LEILAC technology to existing plants. It will also elaborate on the costs and emissions from the use of different fuels, and the costs and emission from the combined use of the LEILAC technology with other carbon capture technologies: potentially enabling the most efficient and lowest cost carbon negative emissions process for the cement and lime industry.

The overall target for this roadmap will be in support of decarbonising lime and cement manufacture, and global objectives of achieving carbon neutrality by 2050.



5 Context

5.1 Climate change and decarbonisation

There has been an increasing global commitment to respond to the undisputable threat of climate change.

The Intergovernmental Panel on Climate Change has found that:

- Global emissions of carbon dioxide (CO₂) have increased by almost 50 per cent since 1990.
- From 1880 to 2012, average global temperature increased by 0.85°C. For each 1 degree of temperature increase, grain yields decline by about 5% (major crops have experienced significant yield reductions at the global level of 40 megatons per year between 1981 and 2002 due to a warmer climate).
- Emissions grew more quickly between 2000 and 2010 than in each of the three previous decades.
- Given current emissions, it is likely that by the end of this century, the increase in global temperature will exceed 1.5°C for all but one scenario.
- Major institutional and technological change will give a better than even chance that global warming will not exceed this threshold.[2]

The adoption of the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC), and its record-speed ratification by 175 countries, aims to hold the increase in the global average temperature to 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change.

To achieve these ambitious targets, fundamental changes are needed to reduce the CO₂ that we emit from industrial processes and energy generation.

The sets a clear global response to the threat of climate change – with Europe declaring it a ‘global climate emergency’.[3]



5.2 Cement and lime sectors

The widespread commitments to dramatically reducing our collective emissions by our nations’ governments has been matched by strong industrial commitments for carbon neutrality by 2050. However, for certain sectors – particularly cement and lime - this is not an easy commitment to reach.

Cement is the key ingredient in concrete, which is the most widely used man-made material on the planet - and is the safe, affordable bedrock of our civilisation: used in our roads, buildings, homes, offices and almost all our infrastructure. Cement is a critical requirement for our global society, with half a tonne of cement being used each year for every person on the planet [1].Lime is used in a variety of applications including in the iron & steel, chemical, paper, pharmaceutical, drinking water, food, and farming industries.

Global cement and lime demand will increase due to the global population growth and the trend of further urbanization. These industries therefore fulfil a very important service to our society, supporting our daily lives and underpinning our economies. Even taken in isolation, the cement and concrete industry directly employ more than 384,000 people in Europe, and combined with indirect jobs, more than 1,000,000, and 9% of the EU’s GDP.

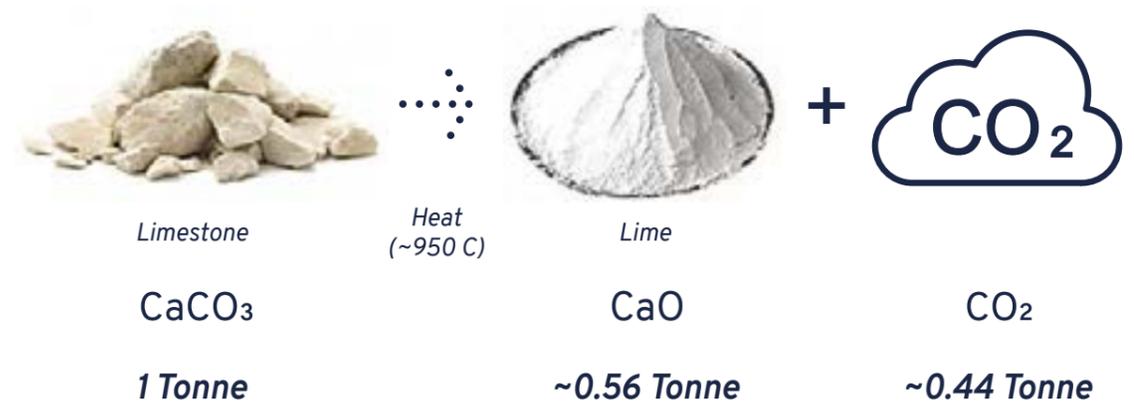
However, the production of both lime and cement is CO₂ intensive. For the cement and lime industries this is much harder as the majority (typically over two thirds) of a plant’s emissions are “process emissions” which cannot be avoided. Unavoidable process CO₂ emissions are released directly from the processing of the raw materials – not from the combustion of fossil fuels.

As a result, the cement and lime industry currently contribute to around 8% of global CO₂ emissions – and this may increase as sectors which can decarbonise easily and cheaply (such as power generation) start to take action.

Significantly, steps have been taken by the industry to reduce emissions where they can. The cement and lime industries have existed for thousands of years, produce very cheap products in support of our societies, and are extremely efficient. See section 7 regarding the different options that are being pursued. Despite these steps, the cement and lime industries cannot fully avoid the generation of process emissions.

In order to reach the EU’s emissions reductions targets by 2030, and global carbon neutrality ambitions by 2050, carbon capture technologies that stop CO₂ reaching the atmosphere will need to be applied to the majority of cement plants. Capturing this unavoidable CO₂, and ensuring that it does not reach the atmosphere, is the only means of stopping these emissions. As noted by the 2018 IPCC report, Carbon Capture Use and Storage (CCUS) “...plays a major role in decarbonizing the industry sector in the context of 1.5°C and 2°C pathways, especially in industries with higher process emissions, such as cement.”[4] However, to date CCUS has been expensive to implement.

LEILAC is being developed with Europe, with the LEILAC1 and 2 projects receiving grants from the European Union, the technology is being expressly developed to achieve our global targets in a timely, effective, and efficient manner. Doing so means developing a technology that is efficient, cheap, and can be rolled out globally.



5.3 Government policies, laws, regulations, and incentives

In reaching the global climate change targets outlined in the Paris Agreement, a number of countries have put in place detailed policies in support of these ambitions, and significant incentive and regulatory mechanisms in support of their climate change policies.

Europe: Policies and laws

The European Green Deal is a package of measures ranging from cutting greenhouse gas emissions to investing in cutting-edge research and innovation. The European Climate Law will write into law the goal set out in the European Green Deal – for Europe’s economy and society to become climate-neutral by 2050. The law aims to ensure that all other EU policies contribute to this goal and that all sectors of the economy and society contribute, and a new EU target for 2030 of reducing greenhouse gas emissions by at least 55% compared to levels in 1990.

Europe: Regulations and incentives

In enacting the European policy and legal framework, the EU has established a number of principle legislative and regulatory steps.

The primary tool is the EU Emissions Trading System (EU ETS), is a cornerstone of the EU’s policy to combat climate change and its key tool for reducing greenhouse gas emissions cost-effectively. It acts to limit and reduce greenhouse gas emissions from the power sector, industry, and flights within the EU in line with its emissions targets. This mechanism sets a cap on the total amount of greenhouse gases that can be emitted, with the total number falling each year.

Within the EU-ETS cap, companies receive or buy emission allowances, which they can trade with one another as needed. The current cost of emitting is around €64 per tonne of CO₂ (May 2021). [5] Between 2009 and mid-2018, the price was about €5 per tonne and never reached €20 per tonne. The dramatic increases in price are largely due to the stability reserves and increased emissions reductions made by the European Parliament.

In addition, to stop non-EU companies simply importing lower-cost products that emit CO₂, a border tax adjustment scheme will be introduced. This will be necessary to address ‘carbon leakage’, where industrial production is simply moved

to regions with less rigorous environmental standards and that do not have a penalty for emitting their CO₂. While not yet active, such a border adjustment needs to put in place to ensure that European industrial production and overall climate change ambitions are both protected. Without it, investments in decarbonisation activities will not be possible, and industrial production will leave the EU.

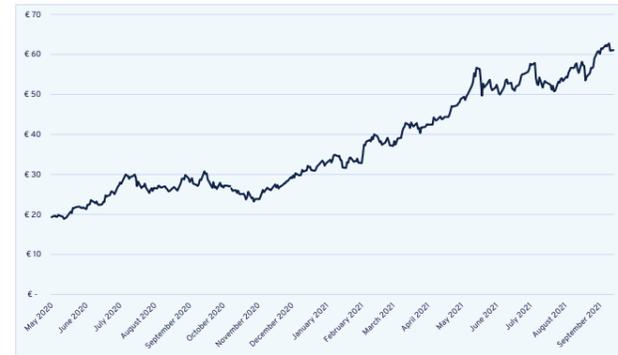


Figure 1 - Daily EU ETS carbon market price over the past 12 months (Euros) [5]

While cement plants currently receive ‘free’ allowances in Europe to reduce the potential for carbon leakage, this is a temporary derogation and are awarded based on benchmarked performance (which is continually being tightened).

CO₂ captured and safely stored according to the EU legal framework will be considered as “not emitted” under the ETS. Cement and lime plants that do not stop their CO₂ from reaching the atmosphere need to surrender allowances for each tonne of CO₂ released. This provides the primary incentive for the industry to ensure that they capture and permanently store their CO₂. It is likely that will be a Carbon Border Adjustment Mechanism (CBA), ensuring that European industry that invests in decarbonisation technologies is protected from imports that have not undertaken such environmental protection investments. However, such border adjustments also provide an incentive for decarbonisation activities for areas outside of Europe that seek to export clinker to the EU.

In addition to this mechanism, there is also a support fund for novel, large scale decarbonisation efforts in Europe. Called the “Innovation Fund”, and running from 2020, this aims to support 60% of the capital investments and operating costs for 10 years for selected decarbonisation projects.

National incentives

Specific EU Member States have their own policies and regulations, which enhance the ‘base’ rules provided by the European Parliament elected by European citizens. These notably include CO₂ emission costs (which vary, and some do not apply to industry) of up to €120 per tonne of CO₂ in Sweden and Switzerland.

Non-EU countries have introduced their own measures. The UK has its own emissions trading scheme, with a floor price of £22 per tonne of CO₂.

North America

The current administration of the USA has re-joined the Paris Agreement, and declared climate change the “number one issue facing humanity” and vowed a national transition from fossil fuels to renewable energy.

Existing CO₂ infrastructure is in place, developed in the 1970s, and there is an active market for enhanced oil recovery (EOR) and related CO₂ offtake agreements. The prices of such agreements are typically set at a per metric tonne price of about 40% of the price of oil per barrel[6].

Construction of CCUS facilities up to end 2023 (expected to be extended under the Biden Administration) is supported with the 45Q tax credits. Under this incentive regime new projects that store CO₂ at a rate that is greater than 100,000 tons per year qualify are given a tax credit of US\$35 / ton CO₂ if used for EOR, or US\$50 / ton if the CO₂ is permanently stored.

Local regulation and initiatives will have a significant impact on take-up of the technology, as in many markets a substantial proportion of manufacture is local (e.g. 99% in California). The importance of eliminating emissions in this sector is recognised, with significant efforts under way in California (the largest US market for lime/cement)

Canada has implemented a federal carbon tax, currently \$40/t (CAD) rising to \$170/t (CAD) by 2030. This tax serves as the floor for carbon pricing, in addition to stronger limits imposed by some provinces. The 2021 federal budget proposed to make up to \$1 billion available on a cash basis, in addition to other incentives, to draw in private sector investment. Similar to the USA, existing infrastructure and expertise is present for acid gas handling and injection.

China

The Chinese government has made a commitment to becoming a carbon-neutral nation by 2060.[7] This is very significant, and particularly for the outlook for cement decarbonisation. Around half of the world’s cement production being based in China. In support of such policy positions, a Chinese Emissions Trading Scheme has been introduced. While currently only covering emissions from the power sector, industrial emissions may be included in this – or similar – mechanism for ensuring the governing policies are followed. As some of the world’s largest cement producers are government owned, incentive mechanisms may not just be market-based.

India

While the country does not yet have a clear cement emissions policy, the country does include local companies that have clear corporate targets. UltraTech cement and Shree Cement are committed to the ambition of net neutrality by 2050. Dalmia Cement, in particular, has pledged it will achieve net zero emissions by 2040.

Asia Pacific, Africa and South America

While specific cement emissions policies are sometimes currently unclear in other regions, they are all served by numerous multinational production companies that have committed to net zero emissions targets.

Map of carbon taxes and emissions trading systems

Outlook

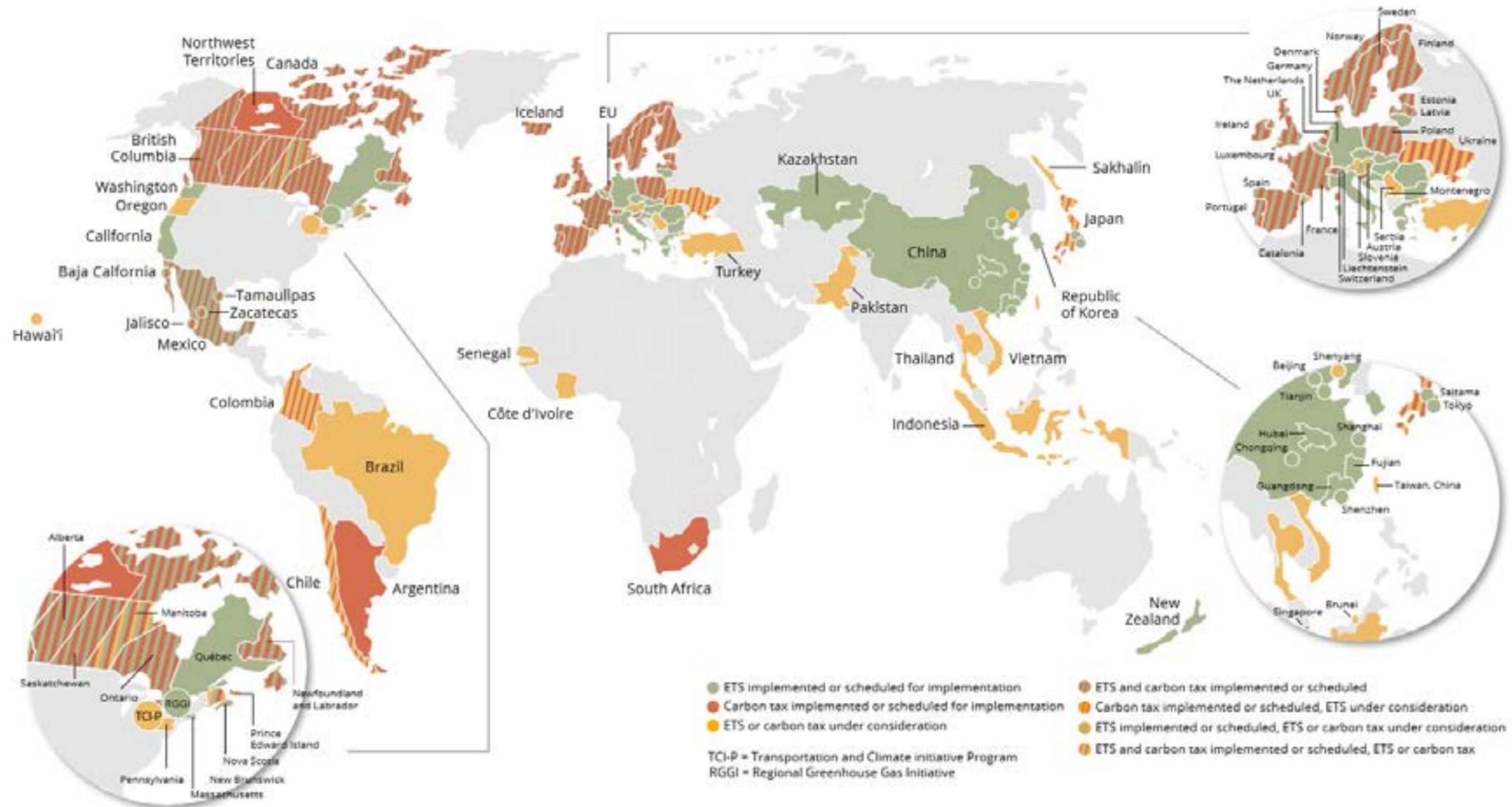
There is a clear trajectory towards a low carbon future and wide ranging support for meeting the targets decided upon by the world's governments in the Paris Agreement.

Different countries are moving at different speeds in how they seek to achieve those targets, and ultimately how to legislate such commitments.

Globally there are now 61 carbon pricing initiatives in place or scheduled for implementation, consisting of 31 ETSs and 30 carbon taxes, covering about 22 percent of global GHG emissions. Border tax adjustments to protect producers within these areas also provide a decarbonisation incentive for cement and plant producers that export to such regions. As noted, what these incentive mechanisms cover, their ambition, and how they function are all slightly different – but provide a clear view on the increasingly stringent global attempts to reduce and limit CO₂ emissions.



World Bank, State and Trends of Carbon Pricing 2021



5.4 Industrial association aspirations

While government policies are important to ensure that decarbonisation activities are possible – particularly to enable the development of transport and storage infrastructure, and allowing investable decarbonisation projects), the cement and lime industry are active in reaching our society’s emissions objectives.

The industry is conscious of its emissions, and central place within society. As such many of the primary cement and lime associations have ‘aspirations for carbon neutral concrete by 2050’, such as the Global Cement and Concrete Association (GCCA).[8] Cembureau, representing the European industry, is completely in line with the Green Deal, providing a detailed vision for how the cement industry can achieve carbon neutrality in Europe in 2050.

5.5 Industrial policy and incentives

In conjunction with governmental and trade body goals and aspirations – the commitments that have been made by individual cement and lime companies are extremely significant. In line with global climate change agreements and their own corporate commitments, many of the following companies use internal carbon prices to drive their investment strategies in their global portfolio. These internal carbon prices are often far more than current government-set carbon prices, and exist for companies operating outside of regions with current incentive schemes.

From within the LEILAC consortia:

HeidelbergCement has commitment to offer carbon-neutral concrete across their product portfolio by 2050 at the latest. [9] With operations in over 50 countries, many of which are not covered by existing regulations, this indicates a profound commitment – and great requirement for a global roll out of carbon capture technologies. As well as an internal carbon price, it provides all of its internal staff with incentives ensure its plants meet these objectives. Every employee now receives variable remuneration elements based on their individual performance and corporate CO₂ reduction targets.

CEMEX has committed to delivering a net-zero CO₂ concrete by 2050.[10] It also operates in over 50 countries.

Lhoist is committed to reducing emissions.[11]

CRH is striving for carbon neutrality along the cement and concrete value chain by 2050.[12]

CIMPOR is updating its commitments, aiming for neutrality by 2050.

Solvay is aligned to the Paris Agreement targets.[13]

Outside of the current LEILAC consortium, other large cement players are making either commitments or ambitions to net neutrality by 2050: in particular those that are signatories to the GCCA 2050 Climate Ambition: gccassociation.org/about-us/our-members/

LafargeHolcim operates in around 70 countries, signing the UNGC’s “Business Ambition for 1.5°C” initiative, with a 2030 SBTi-verified action plan, and objective of developing a net zero pathway for its ‘net zero by 2050’ pledge.[14] It has an internal carbon price.

Large Chinese manufacturers, such as Anhui Conch, China National Building Materials (CNBM), China Resources Cement Holdings will be part of Chinese government policy objectives.

Votorantim Cimentos, based in Brazil and operating in 11 countries, is committed to developing and implementing technologies that will enable it to deliver carbon-neutral concrete to society by 2050.[15]

Siam Cement Group (SCG), based in Thailand, is committed to supporting the Paris Agreement goals, and active in decarbonisation efforts.[16]

UltraTech cement and Shree Cement are part of the GCCA 2050 Climate Ambition for net neutrality.

Dalmia Cement, with a current carbon footprint that is 40% lower than the global average, has set the most ambitious target: being committed to becoming carbon negative by 2040. Doing so requires the use of electricity, and requires carbon capture and utilisation and carbon sequestration technologies.[17]

It is notable that outside of national carbon pricing schemes, the majority of these companies have internal carbon prices driving their investment decisions.

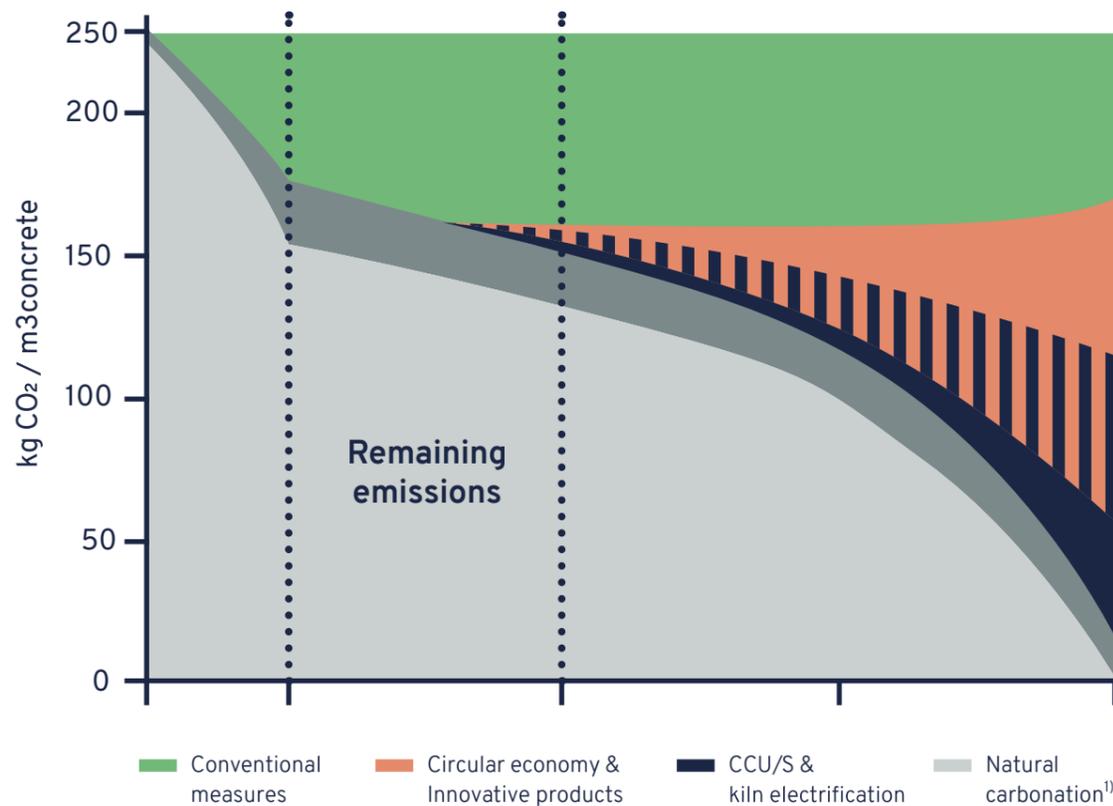


Figure 3 - HeidelbergCement’s roadmap to 2050

5.6 Technology outlook based on the current context

The cement and lime industries serve an extremely important part in the functioning of our global society and economies. They are old industries, highly optimised – providing low-cost products to us all. However, our societies, scientists, governments and industries have all acknowledged that the current means of production cannot be sustained.

There is an enormous drive, and support, for addressing unavoidable process emissions derived from the production of cement and lime. Until very recently, there were not the technologies nor policy mechanisms available to support massive decarbonisation efforts globally – but that has begun to change.

In 2021 the global cement and lime industries are both committed, and are developing the tools, to take dramatic steps in achieving net zero production.

The following sections will investigate the current ‘best available technology’ options available, the primary methods of decarbonisation, how LEILAC (both alone and with all other methods) can enable net zero production of lime and cement, and the associated economic and technological options per plant. The document will then investigate how LEILAC can be rolled out quickly, and efficiently, on a global basis in support of our shared 2050 goals.

6 Baseline production

6.1 Baseline production plant (BAT) Cement

Cement production could be seen as relatively simple, with the main processes being grinding, heating, and regrinding. Portland cement is a range of products which in Europe are defined by standard EN 197-1[18]. Clinker, which is produced in cement kilns, is present in all Portland cements and constitutes the majority by weight in most of these. CEM I, also known as ordinary Portland cement (OPC), is at least 95% clinker and not more than 5% other materials such as gypsum. Production of clinker is the most carbon- and energy-intensive activity in the manufacture of CEM I as other Portland cement products use supplementary cementitious materials (SCMs) to reduce the clinker-to-cement ratio. Examples are CEM II, which combines up to 35 wt% ground granulated blast furnace slag (GGBS) or pulverised coal fly ash (PFA) and CEM III, which combines up to 95% GGBS.

The best available technology (BAT) for the production of cement is a 'dry' process with a 5-stage preheater and a pre-calciner. Modern plants which employ this technology have a total specific electricity consumption of 80-100 kWh/t cement.[19] The process which is described below is designed for the production of (grey) Portland cement, which is the most common form of cement.

The mass balance presented below has been used as a basis for developing the mass balance of the BAT for cement production without CO₂ capture. Note that this mass balance produces cement with a cement-to-clinker ratio of 0.8, and therefore does not correspond to CEM I. Furthermore, it does not take flows of cement kiln dust.

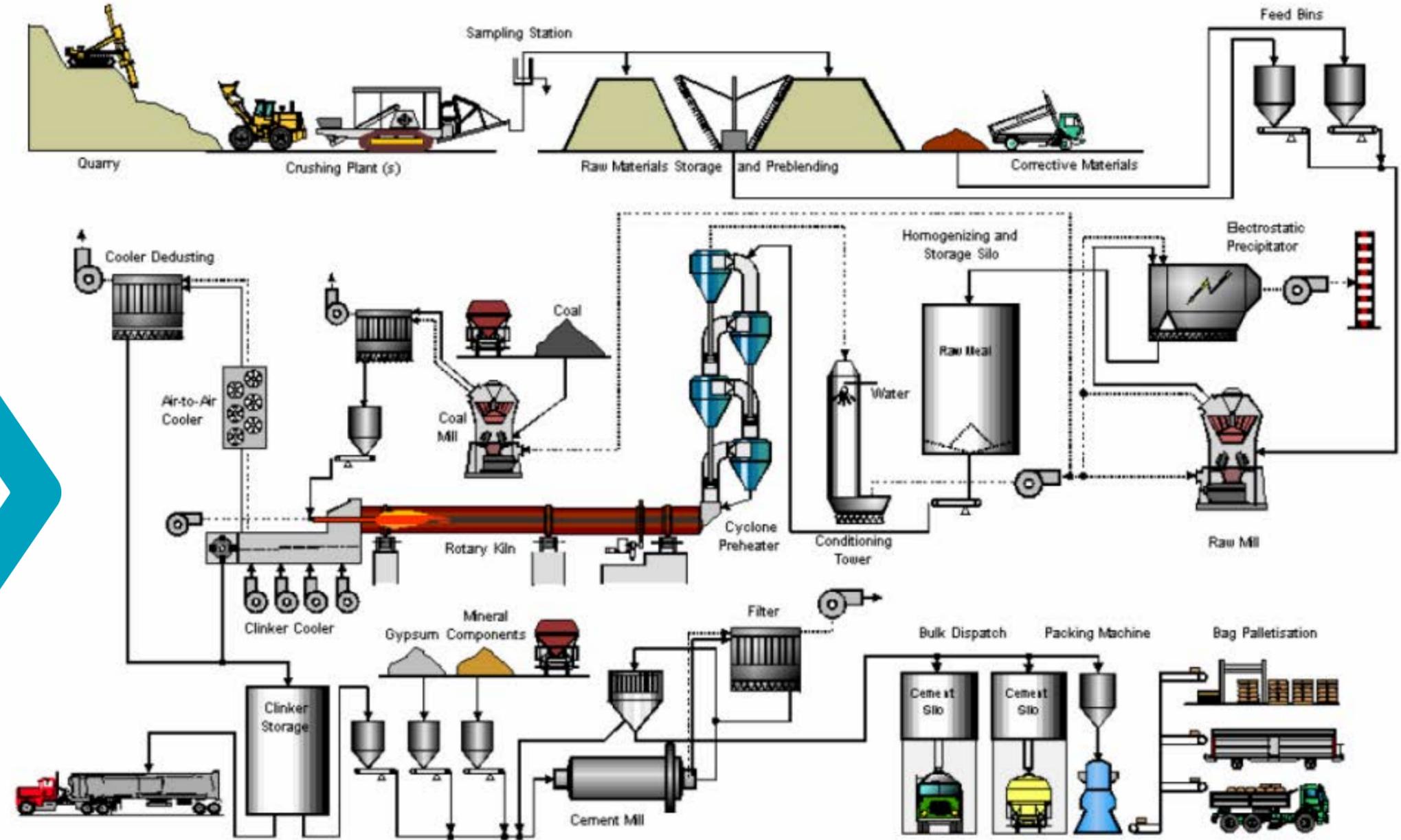


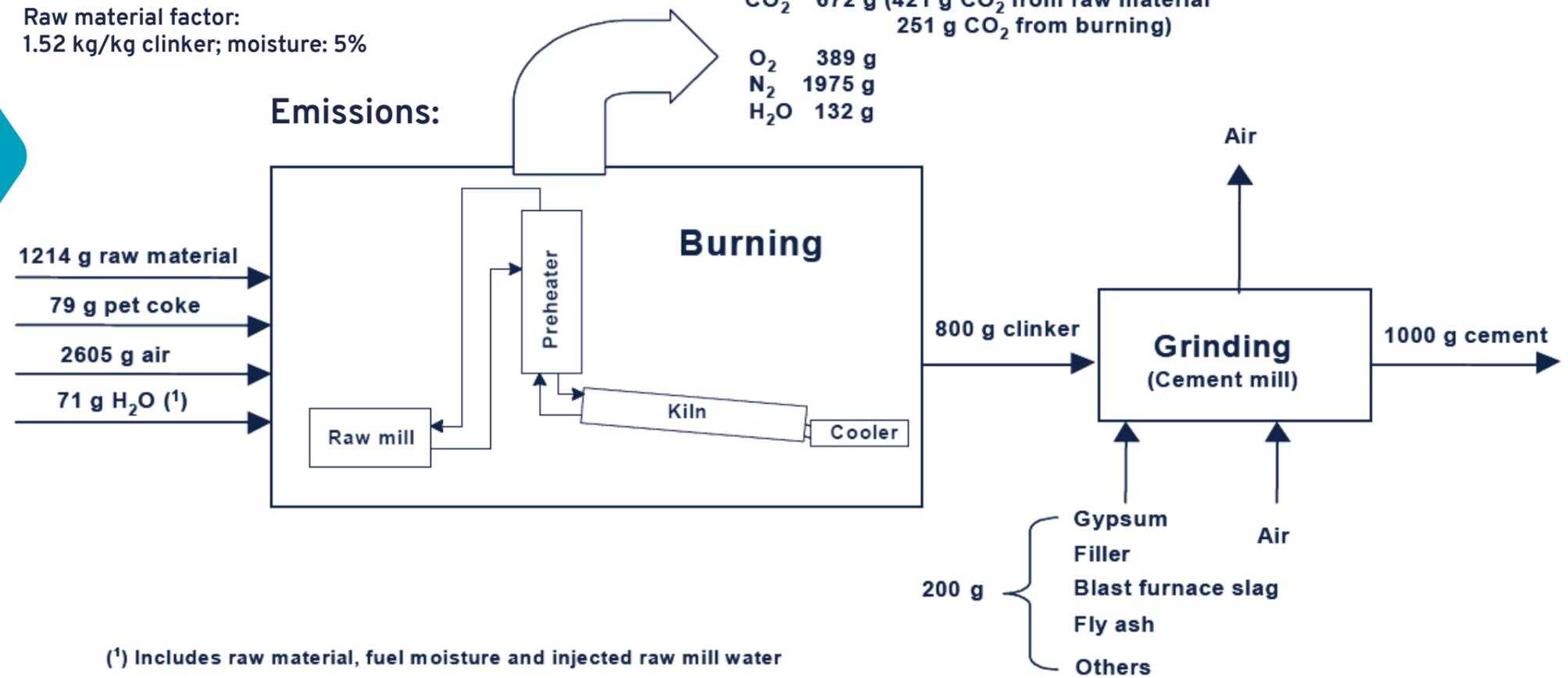
Figure 4 – Dry cement production process[20]

Mass balance for 1kg cement

Dry process; five stage preheater; precalciner; grate cooler; vertical raw mill
 Fuel: 100% petroleum coke
 Clinker factor: 0.75
 Air moisture: 1%
 Raw material factor: 1.52 kg/kg clinker; moisture: 5%

Kiln feed: 1.66 kg/kg clinker
 Heat consumption: 3300 kJ/kg clinker
 Petcoke NCV: 33500 kJ/kg fuel
 CLinker/cement factor: 0.8

Emissions:
 CO₂ 672 g (421 g CO₂ from raw material, 251 g CO₂ from burning)
 O₂ 389 g
 N₂ 1975 g
 H₂O 132 g



⁽¹⁾ Includes raw material, fuel moisture and injected raw mill water

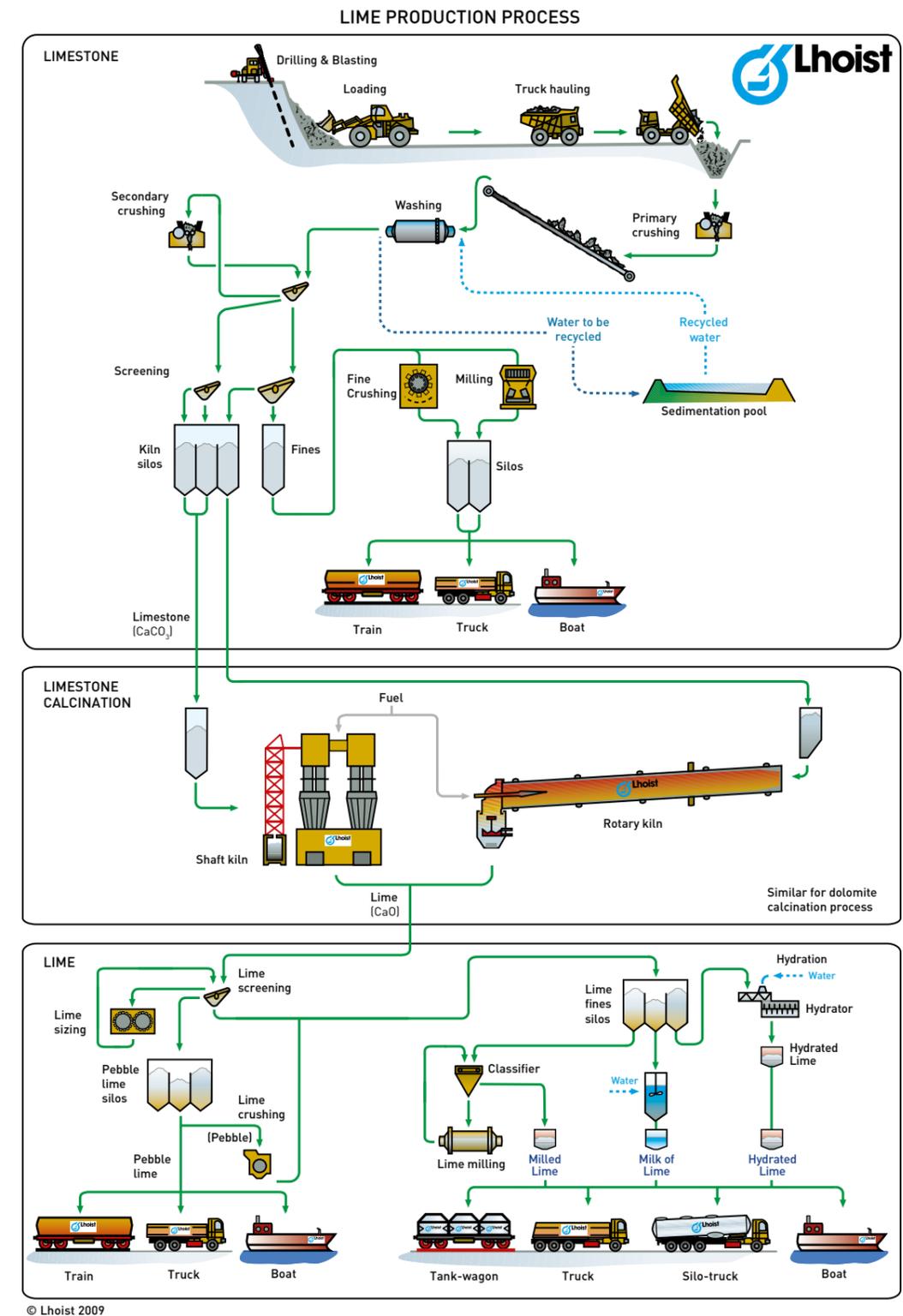
Figure 5 – Mass balance for the production of 1 kg of cement [20]

6.2 Baseline production plant (BAT) lime

There are a number of differences between the production of lime compared to cement:

- limestone is typically the only input material in quicklime production, i.e., no added clays or iron-rich minerals;
- the calcination of CaCO_3 is the key reaction, so there no requirement to have a kiln operating up to 1600 °C in order to effect the clinkering reactions,
- there may be some additional post-processing, depending on the lime product;
- the raw material does not require grinding to the same fine particle size;
- lime plants typically have a smaller throughput,
- there are many different types of lime kiln.

The lime production process from Lhoist below splits the lime production process into three stages: (i) the pre-processing of limestone, i.e., mining, transport, crushing, washing, screening and storage; (ii) calcination, i.e., heating of limestone (CaCO_3) in an appropriate kiln with an appropriate fuel to form quicklime (CaO); and (iii) the post-processing of lime, including screening and storage, to make pebble lime, milled lime (additional milling), milk of lime (additional milling and mixing with excess water) or hydrated lime (additional milling and hydration – only slightly above stoichiometric).



As indicated above, during the calcination of the limestone, a variety of different kiln types can be used, with varying feed qualities and sizes, efficiencies, fuels and products.



Kiln Type	Energy Use for lime and dolime manufacture		Commercial lime production per kiln type in EU-27 (2004)	Output Range (tonnes/ day)	Range of feed stone size (mm)
	Heat use (GJ/tonne product)*	Kiln electricity use (kWh/tonne)			
Long Rotary Kilns (LRK)	6.0 – 9.2	18 – 25	9%	160 – 1500	2 – 60
Rotary Kilns with Preheater (PRK)	5.1 – 7.8	17 – 45	10%	150 – 1500	10– 60
Parallel Flow Regenerative Kilns (PFRK)	3.2 – 4.2	20 – 40	46%	100 – 600	10 – 200
Annular Shaft Kilns (ASK)	3.3 – 4.9	18 – 35** or up to 50***	16%	80 – 300	10 – 150
Mixed Feed Shaft Kilns (MFSK)	3.4 – 4.7	5 – 15	8%	60 – 200	20 – 200
Other Kilns (OK)	3.5 – 7.0	20 – 40	11%	10 – 200	20 – 250

*Heat use/consumption represents about 80% of total energy consumption to produce lime

**For limestone grain sizes of 40-150 mm

***For limestone grain sizes of <40 mm

Table 1 - Energy consumption (per t product) of different kilns (2)

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Note that the enthalpy of reaction in forming solid CaO and gaseous CO₂ from CaCO₃ is unavoidable and is +3.20 GJ/tonne of product (assuming 100% purity of limestone, 100% calcination and standard conditions). Most kilns incorporate three zones: a preheating zone (often a separate unit in the case of rotary kilns), a burning zone and a cooling zone.

One important lime product quality is the specific surface area (SSA). The reactivity of the lime is proportional to the SSA. Reactivity is measured in a standardized t60 test. An amount of lime is added to water. The time required for the water's temperature to rise to 60°C is measured. Soft burnt lime are produced at relatively low kiln temperatures (~900-1000°C) and provide relatively high SSA. Soft burnt lime has t60 typically at 1 minute (between 0.5 and 2 minutes). This accounts for about 80% of production.

The main unit operation of the lime production process is the kiln. The Parallel Flow Regenerative Kiln (PFRK) is the most energy efficient (about 85%) and most common technology used in Europe. As such, PFRK is the preferred choice for benchmark. The operating scale will be defined as 600 tons per day of quicklime.

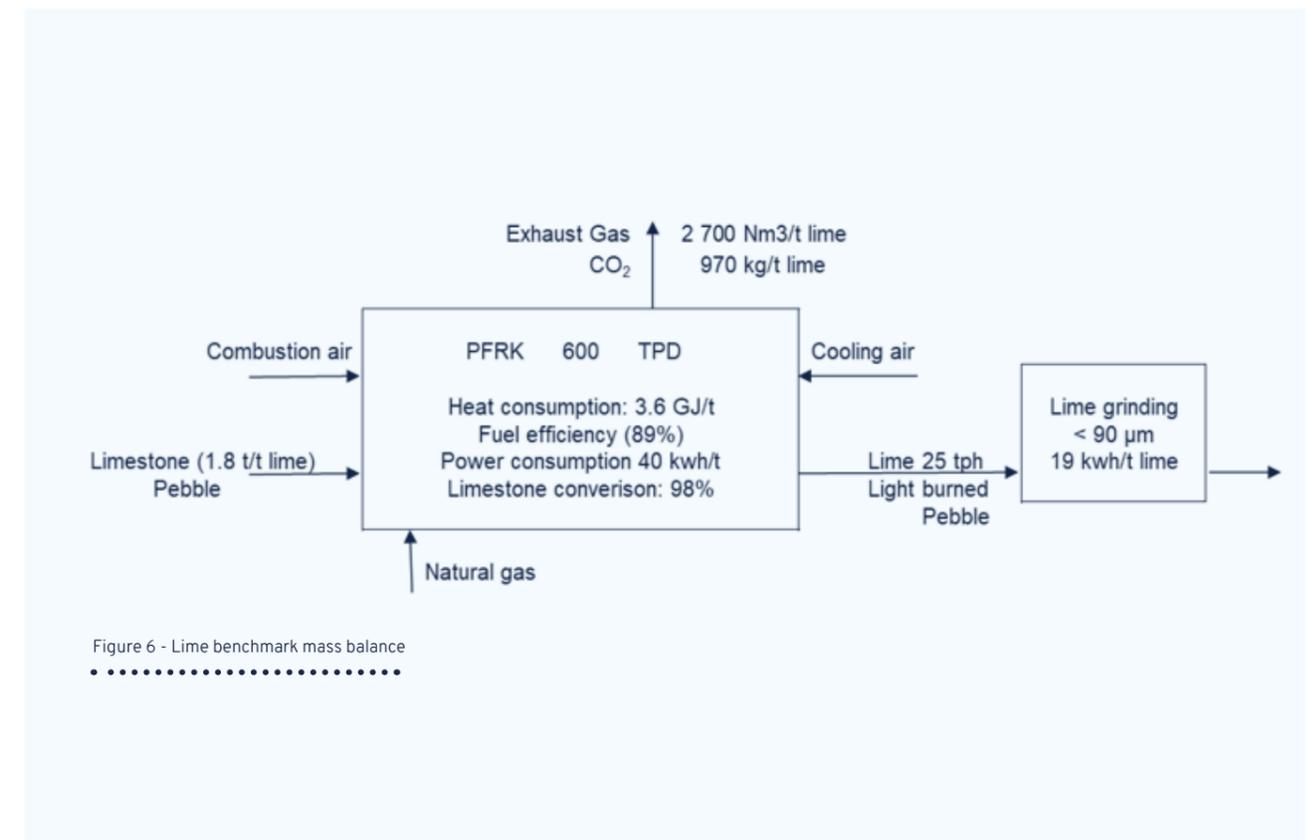


Figure 6 - Lime benchmark mass balance

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7 Routes towards net zero emissions lime and cement

7.1 Existing decarbonisation efforts

As noted, there are a number of main areas that the cement and lime industry can seek to decarbonise. Cembureau provide an informative graphic which shows the impact of each of the measures explained above; this is shown in Figure 7.

Of the 667 kg CO₂/t cement of decarbonisation efforts to be performed by 2050 to reach 'neutrality', modifications to clinker provide 160 kg; modifications to cement and its distribution provide 117 kg; modifications to concrete provide 59 kg; and carbonation of structures and demolition waste provide 51 kg, in total equivalent to 58% of those original emissions. This leaves 280 kg CO₂/t cement (42%), similar to the IPCC's 2014 estimate of 240–380 kg/t [22]. A recent study of deep decarbonisation of Norway's cement industry suggested that the industry could realistically abate up to 77% of its existing CO₂ emissions [23].

Roughly two-thirds of the direct CO₂ generated at a cement plant comes from the calcination of limestone and other calcareous minerals. This CO₂ is derived from the processing

of limestone itself and is unavoidable in the manufacture of Portland clinker, and most of its more innovative counterparts. If the Cembureau numbers are extrapolated to the world using the IEA's cement production estimate of 4032 Mt cement in 2050, these reductions would be 1.6 Gt CO₂/y, but a further 1.1 Gt/y would remain unabated. Even at 77% abatement, 0.6 Gt CO₂/y would be emitted. For context, the IEA model proposes that by 2050 all combustion emissions to atmosphere are 0.9 Gt CO₂/y, and that direct air capture removes 0.6 Gt/y [24].

The most practical solution to avoiding emission of this ca. 300 kg CO₂/t cement is to capture it at source, at the cement plant, and prevent it from reaching the atmosphere or oceans – carbon capture and storage. It is widely acknowledged that the success of CCS is particularly crucial for industry [25] and the cement sector in particular [24].

See section 6 regarding the resulting 'Best available technology', and section 12 regarding the Life Cycle analysis of current production emissions.

7.1.1 Demand reduction

Cement is sometimes over specified in construction projects and its consumption (and therefore manufacture) could be reduced by 'doing more with less'. Cembureau estimates that the cement content of concrete can be reduced by 5% by 2030 and 15% by 2050 through digitalisation, improved mix design and the use of new admixtures [21]. Further savings can be made by increasing the lifetime of buildings [26]. Despite these measures, the IEA expects demand for cement to be roughly stable between 2020 and 2050 [24].

7.1.2 Increased efficiency

The cement and lime industries have existed for thousands of years, produce very low-cost products in support of our societies, and are extremely efficient. Large changes occurred in the 19th century, with the introduction of the rotary kiln, and then continued to be optimised in the 20th century, including a transition to 'dry process' production, and pre-heater tower. For lime, a variety of novel, more efficient kilns have been introduced such as parallel flow regenerative shaft kilns. The European Union has few wet kilns left, although many relatively old pre-calciner kilns with relatively few preheater cyclones. As of 2004, three-quarters of kilns had energy intensities of 3300–4000 kJ/kg clinker (3.3–4.0 GJ/t clinker), with only 15% having values higher than this [20]. This indicates a relative lack of scope for further savings.

Nevertheless, the production processes continue to be optimised. Digitalisation, processes improvements throughout the production process, logistic optimisation, etc., are all actively pursued to reduce the energy requirements of production and therefore reduce emissions. Within Europe, it is hoped to increase efficiency by 14% by 2050.

7.1.3 Lowering fuel emissions

Significantly steps have been taken by the industry to reduce emissions where they can.

As indicated, CO₂ from the combustion of fuel typically contributes to around 1/3 of a plant's total emissions. The main area of CO₂ reduction has been through reducing combustion emissions, as the power sector has started to do. In particular, this involves moving from using fossil fuels to lower-carbon-emitting fuels, particularly alternative fuels (AF) that cannot be otherwise used by society.

Alternative fuels are effectively the recovery and use of energy from waste-streams, including and biomass wastes, and they play an extremely important part in waste management for local communities. This has been arguably the most successful decarbonisation action, at least in Europe where in 2017 46% of total thermal energy supply was provided by [21]. AFs may be 100% biomass or mixed fossil and biomass. 16% of European fuel was classed as biomass in 2017. Cembureau targets the use of 90% alternative fuels with 50% biomass by 2050.

It should be noted that fuel switching has an effect on thermal energy demand. Many AFs require higher air consumption per unit fuel than traditional fuels. This can lead to lower efficiency as more air must be heated up and subsequently emitted to the atmosphere.

Other parts of the world lag behind Europe in AF uptake (with a global average of somewhere between 5% [24] and 18% AF in 2020 [27]), but the gap is likely to shrink. Apart from the use of waste fuels, other ways to reduce combustion CO₂ are to use virgin biomass, blue or green hydrogen, or to electrify the process. The latter is generally considered difficult with limited uptake until 2040 because ordinary kilns are very difficult to electrify [24].

Fortunately, the LEILAC technology is particularly suited to partial or complete electrification, and for using biomass, or hydrogen – providing a potentially quick and effective route to fuel decarbonisation.

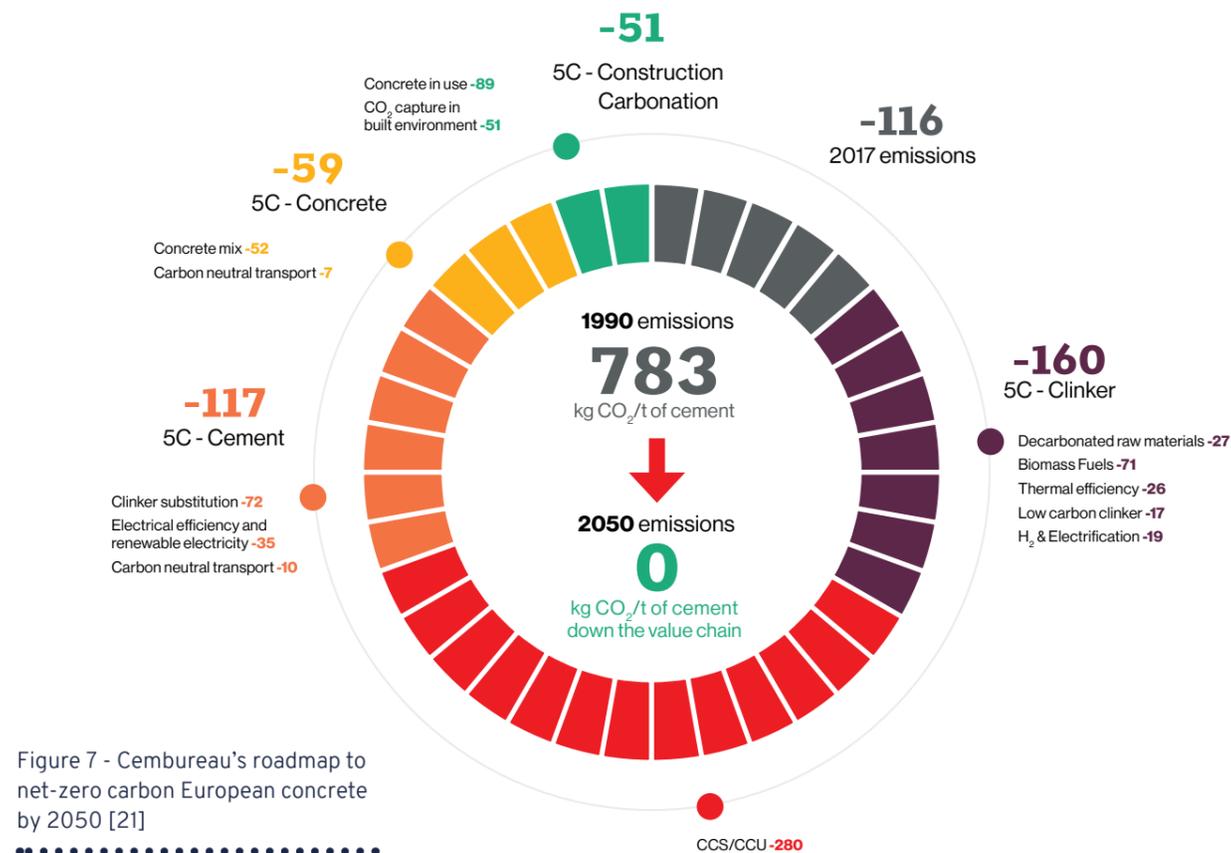


Figure 7 - Cembureau's roadmap to net-zero carbon European concrete by 2050 [21]



7.1.4 Reducing clinker content within Portland cement

Traditional Portland cement (CEM I) is 95% clinker and 5% gypsum and other additives. Clinker is particularly energy- and carbon-intensive to manufacture. However, other materials with a range of properties can be added to cement which do not significantly reduce its performance; in some cases their addition allows for easier construction.

Certain steps are being made – and should be fully pursued- to reduce the amount of lime required to make concrete. To date, supplementary cementitious materials (SCMs) have been used extensively to reduce the clinker-to-cement ratio, and are permitted in the current standards. Examples are CEM II, which combines up to 35 wt% ground granulated blast furnace slag (GGBS), a by-product of blast furnace ironmaking or pulverised coal fly ash from coal-fired power stations. In 2017 the clinker to cement ratio in Europe was 77%, and other companies (such as Dhalmia) use very low ratios.

Globally, the clinker-to-cement ratio (CCR) has fallen from around 84% in 1990 to 77% in 2020 according to some data [27] and 71% according to others [24]. However, the availability of such SCMs is starting to dramatically reduce as the power sector decarbonises and the steel sector reduces the volumes of available slag.[21] In addition the rate of increase of cement manufacture worldwide has outpaced both steel and coal power, meaning increasingly less GGBS and fly ash will be available per tonne of cement into the future.

Further steps can be taken (particularly in light of the reduced volumes of current SCMs) to use other materials. Natural pozzolans, limestone, and calcined clays can be used – should regulations and costs permit – but ultimately only reduce (not fully prevent) unavoidable process CO₂ emissions. Within Europe, the intent is to reach a ratio of 65% by 2050.

7.1.5 Novel cement

Portland cement performs well in most settings and has a two hundred-year track record of reliability. New cement clinkers are being actively developed to reduce the amount of limestone used in clinker, and therefore reduce the amount of CO₂ released per tonne of product – typically saving 20 – 30% CO₂ compared to Portland Cement. However, their use is restricted to specific purposes, as they are chemically different from Portland Cement – and need changes to regulations and building standards to enable wider use and roll out, and most importantly consumer trust.

An important consideration of Portland cements is the engineering experience that has been built up over many decades which provides professionals in the construction industry with confidence of their performance in creating safe, durable structures in a wide range of environments and applications. A concerted effort to introduce novel cement types could allow for lower carbon options for some applications, but take-up is likely to be a gradual process over several decades. As such, Portland cement and Portland blended cements are expected to remain dominant over the timescales relevant for decarbonisation, i.e. the next 10–30 years.

7.2 Carbon Capture

7.2.1 History and past economics

Carbon capture – as a basic technology – has been in commercial operation for a number of decades, and is a necessary processing step for many natural gas sites, fertiliser production plant, chemical and refining industries.

Most of the cement and lime industry’s emissions are largely unavoidable as they are process emissions – released from the chemical reaction of limestone necessary to manufacture the products. As a result, the global cement and lime industry recognises the importance of widespread deployment of carbon capture use and storage technology.

To reach the corporate and political emissions reductions targets by 2050, Carbon Capture technologies will need to be applied to the majority of cement plants. This is outlined in detail by the 2018 IPCC report, GCCA, and Cembureau – and all the major individual cement companies.

In the IEA’s 2050 “Key global milestones for CCUS” to reach 1.5°C, 1,355 million tonnes of CO₂ will need to be captured and stored from the cement industry by 2050.[24]

Regarding the production of cement, “After 2030 in the NZE, the bulk of emissions reductions come from the use of technologies that are under development today. CCUS is the most important, accounting for 55% of reductions in 2050 relative to today.”

While there are a number of large-scale Carbon Capture and Storage projects in the world, one of the main reasons that the technology has not been widely adopted yet (particularly in the power sector) is due to the complexity and costs of operations, which are not currently offset by the cost of emitting CO₂, nor easily passed onto the consumer due to the absence of a global carbon price. This is a particular issue for the cement and lime industries.

A major hurdle for cement plants is the cost of capture relative to their product. Comprehensive modelling undertaken by the project CEMCAP indicated that the production costs of clinker may double using amine or oxyfuel technologies.[28] This is clearly a major increase in the cost of manufacturing cement, much of which will have to be passed on to the customer. However, common with other hard-to-abate sectors, a significant increase in the price of the base commodity does not translate to a significant increase in the price of the final product bought by the consumer, which has value added to it by other material products, transport, and labour. This is primarily a case of carbon leakage, as the costs cannot be increased at all (passed onto the consumer) should the market include imported products that have not include the cost of decarbonising. In the case of plastics, the products can be bottles; for steel it can be cars; and for cement it is structures such as our houses.

Indeed, the increased cost to consumers of fully decarbonising the cement industry at 100 \$/t cement (approximately 150 \$/t CO₂ avoided) has been estimated at 3%, or \$15,000 on a \$500,000 house [29]. However, cement is a commodity product, and policy environment needs to ensure that decarbonisation costs can be passed on.



Photographed by: Paul Poels

7.2.2 Areas of development

Despite commercial application of carbon capture technologies in other industries, bespoke technology development steps – on top of the economics mentioned – are required for the cement and lime sectors.

No commercial-scale cement plants have yet been completely fitted with carbon capture technology. Most technologies still require one to two scale-up steps before being suitable for such application, and technical challenges, albeit mostly surmountable, still exist for all options.

Of the three traditional categories of carbon capture concept that have previously been developed for the power sector, two are suitable for application in the cement sector: post-combustion capture (solvent absorption and calcium looping) and oxy-fuel combustion. Both have been pursued by the cement and lime sector for over 10 years, with several pilots in operation (see the following sections). A recent comprehensive summary of these and other projects and technologies has been published by Plaza and co-workers [30].

The third type of carbon capture developed for the power-sector “pre-combustion” has not been traditionally considered by the cement industry, as it cannot capture the unavoidable process emissions. However, such an approach, as with all other types, can be used in conjunction with a LEILAC system.

A great body of work has been undertaken by the cement sectors assessing the technological and economic challenges of adapting and applying these technologies. ECRA, and later CEMCAP, have provided significant techno-economic studies. Chemical absorption with amines, the market leader in other markets such as thermal electricity generation, is considered a baseline against which others are measured. The CEMCAP project did exactly that, comparing absorption by MEA with calcium looping, oxyfuel, chilled ammonia, and membranes

[31]. Although it found that most of these technologies were cheaper than amines, it should be noted that MEA is rather old technology, and more efficient amine formulations exist. Recent project announcements, such as Brevik, all use newer ‘advanced amines’.

LEILAC – as a novel carbon capture technology – was not included in any of those assessments, as it is very new. It was only a concept in 2015, and has developed rapidly since with EU H2020 assistance.

Carbon capture technologies are typically based on separating gases (mainly CO₂ from a flue gas, but also O₂ from air to concentrate the CO₂ in a flue gas). All these technologies require additional chemicals, energy, and/or process steps. The LEILAC technology is quite different, as it simply stops the CO₂ released from a mineral being mixed with any other gases – as such it does not need additional chemicals, energy, nor process steps.

LEILAC aims to specifically address unavoidable process emissions, by demonstrating a technology that could replace an existing part of the cement and lime making process, and capture the pure process CO₂ emissions without significant energy or capital penalty. The low thermal energy penalty of LEILAC technology means that very little extra CO₂ is generated by this capture process. For other capture technologies, more energy is required to run their processes – and additional CO₂ is generated that also needs to be captured (creating a bigger difference between capture rates and avoidance rates). LEILAC can also work in conjunction with other capture and emissions reduction approaches, maximising the options available and minimising the resources required to decarbonise.

LEILAC will contribute to providing the community with a technology that can address the dual challenges of enabling European industry to sustainably thrive while significantly lowering CO₂ emissions.

Post-combustion capture

“Post-combustion capture” is a capture technology that is applied to the flue gas stream of a cement or lime plant, stripping the CO₂ from the process and combustion gas stream. Research activities that are currently on-going in the field of post-combustion capture include chemical solvents, solid media adsorption/absorption, and membranes.

7.2.3.1 Chemical Solvents

The most common technology is chemical solvents, which has been used commercially for a number of decades in several industries (natural gas processing, ammonia production, refineries etc) and high abatement efficiencies. Some pilot and demonstration plant projects are actively testing these processes (e.g. Norcem, Brevik, Norway; ITRI/Taiwan Cement Corp; Skyonic Corp).

Various solvents with high CO₂ selectivity are available, the most common being amines such as MEA, although a number of proprietary formulated amines exist that offer various benefits to reduce capital and operating costs. Other solvents include potassium carbonate, chilled ammonia, cryogenic methanol or formulating dimethyl ether mixtures. Each solvent will have its own advantages and disadvantages which require detailed evaluation on a case-by-case basis specific to the installed application. This includes: capture efficiency, product CO₂ purity including water saturation, solvent tolerance to oxygen, solvent losses, solvent corrosivity, process complexity, source of regeneration heat duty, among others.

Processes integration with a cement and lime plant would be minimal since the solvent would be installed as an end-of-pipe solution, thereby leaving the majority of the plant as is. Options for heat integration with the wider plant exist and sharing

of utilities would be available, but otherwise the chemical solvent process would be majority stand-alone.

Energy requirements for the stripping of the CO₂ using amines have dramatically improved over the decades, with MEA requiring in the order of 3.8GJ/tonne of CO₂ captured, to more modern formulations only requiring additional energy in the order of 2.4 GJ/tonne of CO₂ captured. There is an inherent thermal energy intensity of separation of around 1 GJ/t CO₂. [32]

Capture through chemical absorption is high, in the range of 90%+. Depending on the selected solvent the discharged flue gas can easily achieve less than 1 to 2% CO₂ v/v and in some cases be reduced to less than 500ppm levels of CO₂ if full capture is desired. The CO₂ produced from chemical solvents is typically very high 95 to 99% CO₂ (dry basis) with trace compounds remaining from the flue gas stream. Most chemical solvents such as amine are aqueous mixtures therefore produce a water saturated CO₂ that would require downstream dehydration before the end user.

Notable pilots include:

- Anhui Conch, China (capturing 50ktpa of CO₂, starting in 2018)
- Norcem’s trials with amine scrubbing [33]
- CO₂MENT LH Canada

7.2.3.2 Calcium looping

Calcium Looping performs the opposite reaction to the LEILAC Calciner to capture CO₂ using CaO to convert to CaCO₃ in a Carbonator. The CaCO₃ is then calcined back to CaO and recycled to the process, while the CO₂ is captured. Numerous options exist to integrate into a wider cement/lime plant with a Calix flash calciner or for post-combustion CO₂ capture only. The Carbonator is typically a fluidised bed type reactor.

Calcium looping can be installed either as an end-of-pipe solution or integrated with a cement or lime plant. In the former, the combined furnace flue gas and process CO₂ from the preheat system is sent into the carbonator where CO₂ reacts with the CaO and the remaining flue gas is returned to the preheat system. Carbonation is an exothermic reaction therefore heat is removed from the system by some medium such as steam generation which can offer beneficial use elsewhere in the plant. The CaCO₃ then travels to be calciner to be reacted into CaO the same as the LEILAC calciner, where the pure CO₂ stream is captured and the CaO is recycled back to the Carbonator in a closed-loop (if fact, a LEILAC calciner could be used in this step). This separate calciner will require its own heat source/furnace, and flue gas from this furnace will also be sent to the carbonated.

The integrated option is similar however the source of CaO comes from a fraction (~25%) of the total calciner product before the rotary kiln and is sent to a dedicated carbonator unit where it contacts the flue gas from the preheat system. The CaCO₃ is then recycled to the main plant's LEILAC unit and not an independent unit, and this excess process CO₂ is captured with the main process CO₂. In effect this means that the main plant calciner will be sized as 125% of the overall plant to accommodate this recycle stream, based on a 25% split to the Carbonator.

Notable pilots include:

- ITRI/Taiwan Cement (TWN) – with an end-of-pipe capture.
- CLEANKER for calcium looping [34] – with an integrated capture..

7.2.3.3 Membranes

Physical separation of the CO₂ from a gas stream is possible with membranes. While currently quite small in scale, and require development, they are in theory quite simple to operate. There would be a power requirement, but no thermal energy penalty.

7.2.3.4 Adsorption

Adsorption separation of the CO₂ from a gas stream is possible. With a potentially smaller footprint from chemical technologies, they rely on a pressure swing to regenerate the sorbent.

7.2.3.5 Post-combustion capture synergies with a LEILAC system

Should a carbon-containing fuel be used, the LEILAC technology (capturing the process emissions, at 2/3 of the plant's total emissions) could be used in conjunction with such post-combustion systems to capture the flue emissions (1/3 of the plant's total emissions). Used together, it is possible that the 'regeneration' requirements of the flue-gas plant could then be met by just the host plant's waste heat. When running on carbon fuels, this would enable a low-cost, zero emissions cement or lime plant – greatly reducing the capital costs, energy, and volume of CO₂ that would need to be capture from just using a post-combustion system alone. If a biogenic fuel is then used, it could enable a low-cost, negative emissions cement or lime plant. (see section 10)

7.2.4 Oxyfuel

Oxyfuel carbon capture is another method that can be applied to lime and cement plants. In this case, an 'Air Separation Unit', driven by electricity, strips oxygen from air. The oxygen is then burnt with the fuel, and the resulting flue gas has a relatively high concentration of CO₂.

Unlike post combustion capture, the use of oxyfuel requires adaptation of the cement clinker production process to address the change in process gases, process temperatures, and a need to minimise the amount of air ingress into the plant.

Studies of various parts of the oxyfuel system have been performed, with ECRA conducting physical testing at scale of key components (burner and clinker cooler) [35], but no complete pilot exists, but plans exist for one, including C14C.

7.2.4.1 Oxyfuel capture synergies with a LEILAC system

Should a carbon-containing fuel be used, the LEILAC technology (capturing the process emissions, at 2/3 of the plant's total emissions) could be used in conjunction with an oxyfuel system to capture the flue emissions (1/3 of the plant's total emissions). The LEILAC technology could use burners that can run on oxygen, as could the rotary kiln. Used together, this would greatly reduce the capital, complexity and risk of air-ingress compared to an-oxyfuel system alone. If a biogenic fuel is also then used, it could result in a low-cost, negative emissions cement or lime plant.

7.2.5 Pre-combustion capture

The third primary means of capturing carbon in the power sector was through 'pre-combustion capture', where the CO₂ is removed from the fuel prior to its use. These processes have been largely rejected by the cement and lime sectors because they do not address the unavoidable process emissions released by the limestone itself [52]. However, these technologies (as with all of the other types of capture developed with the power sector) have very strong synergies with a LEILAC configuration, should a fossil fuel be used.

7.2.5.1 CO₂ capture during reforming

It is possible to capture the CO₂ generated during the reforming of natural gas into hydrogen. Such a process is now called 'Blue Hydrogen', as a fossil fuel is decarbonised to create the hydrogen. This is distinct from 'Green Hydrogen' using just renewable power and electrolysis.[36] Blue hydrogen may provide a lower-cost decarbonised hydrogen supply in the near term, until fully-decarbonised green electricity is available. Blue Hydrogen can be produced either through conventional Steam methane reforming (SMR) or Autothermal reforming (ATR) – followed by a Water-gas-shift reaction and then Hydrogen separation (typically Pressure Swing Absorber) to create separate hydrogen and CO₂ streams. The Dutch report indicated a possible cost for separating CO₂ between 48 to 70€/t CO₂. [37]

SMRs and ATRs are in large-scale, commercial use.

7.2.5.2 CO₂ capture during gasification

It is also possible to produce hydrogen from the gasification of carbon containing solids. In this process, materials are converted at >700°C, without combustion with a controlled amount of oxygen, into a syngas (carbon monoxide, hydrogen, and carbon dioxide). There is then a water-gas-shift reaction and then Hydrogen separation to create separate hydrogen and CO₂ streams.

This process is being actively developed by a number of entities, including TNO, and could be used in conjunction with biogenic fuels or alternative fuels. See section 7.1.3.

7.2.5.3 Pre-combustion capture synergies with a LEILAC system

Using a decarbonised fuel stream with a LEILAC unit to capture the unavoidable process emissions is the simplest way to fully decarbonise a cement plant, with the lowest energy requirement and minimising the volume of CO₂ to be captured.

Using a renewable energy source (biomass or renewable electricity, see also section 7.1.3) is one option. Hydrogen is another:

Regarding reforming, the LEILAC technology is currently using burners that can run on hydrogen, and – using either Blue or Green Hydrogen – can be used with LEILAC to create a low-cost, zero emissions cement or lime plant.

Regarding gasification, the LEILAC technology is currently using burners that can run on hydrogen, and there are also opportunities for heat-integration of such a gasification unit with a LEILAC system. If a biogenic fuel is then used, it could create a low-cost, negative emissions cement or lime plant.

8 LEILAC vision

8.1 LEILAC as a core enabling pillar for decarbonisation of the cement and lime sectors

The lime and cement industry produce unavoidable ‘process’ emissions generated by the calcination of limestone and other carbonate minerals. Whilst this can be reduced, this process CO₂ must be captured by one means or another if the cement industry is to reach net-zero by 2050.

As previously observed, most carbon capture technologies proposed for the cement sector were developed for the electricity generation sector. A key difference between the sectors is the presence of the process emissions, which are not generated by combustion in an oxidising medium but simply by heating the raw materials. This opens up alternative approaches to adaptation of capture processes designed for other sectors. LEILAC is an example of this.

Calix’s LEILAC technology works within a normal cement plant’s process. It is based on indirect calcination, by heating the limestone via a special steel tube within the precalciner. This unique system enables pure CO₂ to be captured as it is released from the limestone, as the furnace exhaust gases are kept separate. Calcining raw meal by indirect heating (LEILAC) or by direct-heating (conventional calciner) can be done in principle with the same specific energy. The LEILAC process does not involve any additional processes or chemicals, and simply involves a novel “precalciner” design (or new kiln, in the case of a lime plant). This innovation requires minimal changes to the conventional processes for cement, and simply replaces the calciner.

LEILAC1 has developed, built, and operates a pilot plant capturing around 5% of a typical cement plant’s process CO₂ emissions. Constructed next to the HeidelbergCement’s plant at Lixhe, Belgium, the pilot has shown that over 95% of the process CO₂ emissions could be captured from cement or lime production without significant energy or capital penalty. LEILAC will deliver a techno-economic roadmap for the technology’s scale up and deployment. Comprehensive knowledge sharing activities have taken place, including at the pilot’s visitor centre and recently via virtual site visits during the pandemic (which can be provided at any time).

LEILAC will deliver a techno-economic roadmap for the technology’s scale up and deployment.

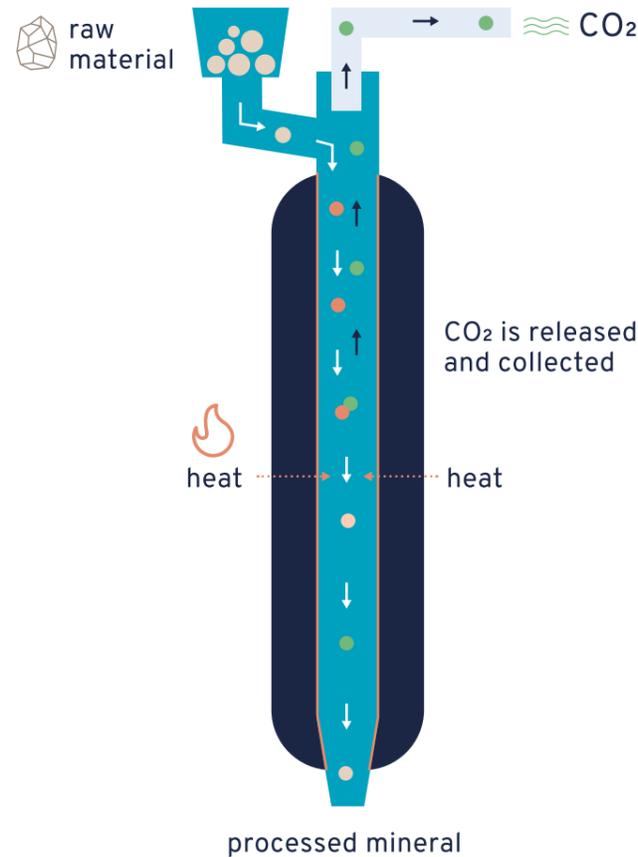


Figure 8 - Using Calix’s LEILAC technology the released process CO₂ is not contaminated. This carbon capture process does not require additional energy or chemicals.

The pilot has been run with limestone and cement raw meal, with the following major successes:

- The technology fundamentally works - indirectly calcining the input material;
- Separation of CO₂ (95% purity), with no air ingress or loss of containment;
- The LEILAC units can safely perform at the temperatures required;
- The energy requirements for the capture process are similar to those for a conventional cement plant, and no additional processing step or chemicals are required;
- There have been no negative impacts on the host plant, and no impact on clinker production.
- There is no significant ‘coating’ of the inner tube by the processed material (one of the highest risk associated with the technology’s application to the cement and lime industry).

Building on the success of the LEILAC1 project – LEILAC2 will develop, build and validate a module capturing 20% of a typical cement plant’s process CO₂ emissions, leveraging significant industrial funding. This module will be constructed and integrated into HeidelbergCement’s plant at Hannover, Germany. Construction is due to begin in 2022.

- Capture 20% of a full-scale cement plant’s (and 100% of a large lime kiln’s) emissions –around 100 ktpa of pure CO₂ for minimal energy penalty (excluding CO₂ compression).
- Prove the effective retrofit and full integration of the Demonstration Plant into the host cement plant’s operations.
- Prove the efficiency and stability of the complete cement-kiln process and resulting clinker quality when operating largely on LEILAC calcining technology.
- Prove that the Demonstration Plant forms an easily replicable modular design for scale-up – enabling the accelerated full-scale commercial deployment.
- Seek to demonstrate the use of alternative fuels (such as biomass) and electricity for the process, enabling a calciner/ lime kiln to be zero-emissions.
- Demonstrate the ability for fast ramp up/down times for the process using electricity (switching rapidly from fuel to electricity), allowing a cement plant to undertake load balancing of renewables on the grid – enabling the electrification of the cement industry and a resulting low cost, local, and effective solution for grid stability with high renewable use.

Once built the Demonstration plant will be trialed and validated under actual operating conditions, with a staged fuels commissioning programme and a variety of test campaigns over a 6-month period, to confirm the technologies performance and integration is as expected, paving the way for full scale demonstration. It will also provide a near-term, realistic business case for a transport and storage network in Europe’s main industrial region, using this low-cost capture plant as a catalyst for wider CCUS operations.

The LEILAC2 project, should it fulfil its design ambitions, assessed in its pre-FEED study, will – despite being a first-of-its-kind plant – potentially have an immediate solution that has a very low capital and operational expense (CAPEX / OPEX).

The Vision for the technology is to allow the lime and cement industries to capture their unavoidable process emissions for very low cost. For a plant using this technology, the main additional ‘cost’ would only be for compressing the CO₂ for further useful purposes (CCU) or safely storing it underground (CCS).

The roll out strategy is to develop a design that can be used widely, immediately, cheaply and incrementally or fully retrofitted to all cement plants - enabling both the cement and lime industries to dramatically reduce their unavoidable emissions while maintaining their international competitiveness.

Since 2020, Imperial College has been running independent process simulations assessing the thermodynamic potential for the LEILAC technology. This research has developed robust models that can successfully simulate both baseline and LEILAC (direct separation) plants with results in good agreement with existing literature, but with a model with significantly more granularity than current work, allowing, for example, understanding of the effects of different heating profiles across the stages of the LEILAC tube. The preliminary results for the flue preheating configuration suggests the technology offers energetic performance comparable to the current BAT (whilst also reducing emissions considerably). There is certainly considerable scope for further improvement (e.g. adjustment of heating profiles, waste heat recovery). The current analyses are being expanded and finalised for publication, with the first submission planned for Chemical Engineering Journal (Chem. Eng. J.).

8.2 Synergies between LEILAC and other decarb options & techs

8.2.1 Low and zero emissions fuels

The LEILAC technology, essentially requiring alloy tubes to be heated, can theoretically be fuel agnostic.

The LEILAC system can operate with traditional fuels (often natural gas). The LEILAC2 Demonstration plant will also aim to use a variety of alternative fuels, in alignment with the industry's roadmap for decarbonisation. This ensures that the LEILAC system can readily be retrofitted to existing lime and cement plants without changing the energy source.

As noted by Cembureau, the use of 'alternative fuels' will be very important component in decarbonising fuel emissions – as a large proportion of it is organic (and at an increasing percentage), and not a fossil fuel. Ideally, if captured, this can then lead to negative emissions.

As indicated in ICEF's 2020 Roadmap: Biomass Carbon Removal and Storage (BiCRS), waste which cannot be otherwise used (i.e. alternative fuels) should be seen as one of the primary means of creating 'negative emissions'. Waste, rather than forestry, should be the primary means of extracting CO₂ from the atmosphere. The ICEF roadmap indicates waste biomass could provide the majority of the 2.5 to 5.0 GtCO₂/y reductions foreseen[38].

The LEILAC system can also be operated using an electric heating system, hydrogen, or biomass. If electricity or hydrogen is sourced from a renewable energy source, this enables total decarbonisation of lime or cement production. Several LEILAC units are already powered by electricity, with proven operations also shown for natural gas. The LEILAC1 pilot's burners can utilise hydrogen.

These low-carbon sources of energy will be tested, and the LEILAC2 Demonstration plant will aim to show the applicability of these renewable energy sources for the required calcination heat for the cement sector, i.e. the use of electricity and alternative (biomass rich) fuels.

LEILAC2 will investigate the use of a hybrid system, using both conventional fuels and electricity. This has two benefits: it allows the optimisation of overall energy costs, and the potential for load-balancing of the grid – which can provide an additional source of revenue.

The act of load-balancing has very good synergies with the increased use of renewable energy on the grid. Currently, the uptake of renewable generation is, to some extent, limited by the peak demand of the system.

Taking an extreme example, if there is too much solar or wind supply at a given time – it is very difficult for those sources of power generation to 'stop' generating, causing grid instability.

It should be possible for a LEILAC installation be able to quickly 'use' the generated electricity, thereby increasing artificially demand to meet the uncontrolled generation. In this case a LEILAC installation would be providing a load balancing service (along with energy storage). This will be increasingly vital in stabilising the electricity grid, and potentially enabling higher proportions of renewable generation to come on-stream.

Projection for electricity prices, and the dramatically increased need for services vary, with projects of 'extreme' price events illustrating this:

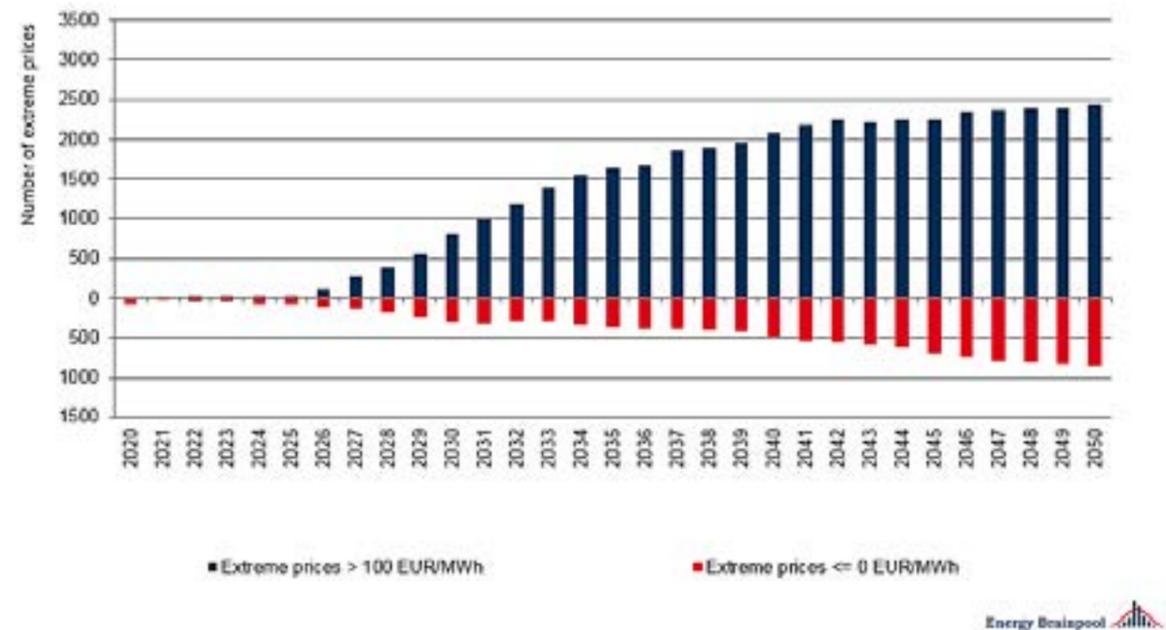


Figure 8 - Extreme price event forecast by Energy Brainpool[39]

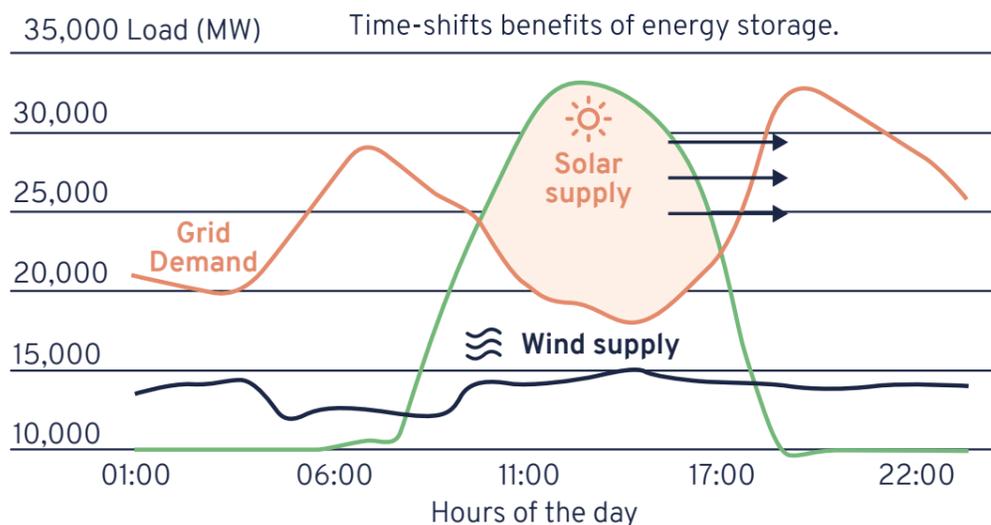
The costs of electrical elements may be higher than a simple combustion system, and in a hybrid system both the electric energy source and the gas combustion system would need to be installed. The design and feasibility of a hybrid system will also vary by fuel.

Nevertheless, it is anticipated that LEILAC plant will be made 'electrification' ready, even those intending to run a single more conventional fuel, allowing optionality for future deployment. This will allow future retrofits of such equipment with electrical elements later – future proofing a given installation.

The possibility of using LEILAC systems for load balancing – allowing more renewable energy generation on the grid – is a hugely positive finding that will be pursued vigorously.

8.2.2 Synergies with other carbon capture technologies

As mentioned, the LEILAC technology neatly complements all existing and future carbon capture systems, should a fuel source that emits CO₂ be used. See section 7.2 and the techno-economic section 10 regarding the cost-benefits of using LEILAC and another system for the lowest-cost, carbon-negative capture system.



Source: QIC

9 LEILAC technology and economic options

9.1 Configuration cement plant

There are a variety of methods for integrating a LEILAC capture system into a new or existing cement plant.

The technology is fundamentally simple in its implementation. The solution revolves around tubes which process a portion of the total cement meal flow. The tubes are of a relatively fixed size, and so while they may be adjusted slightly depending on the host cement plant's requirements, they will be of a size comparable to the tube at the core of LEILAC's furnace. It is by placing multiple tubes within a single furnace "module", and by installing a number of these modules in parallel into prospective cement plants, that the technology can address the specific retrofit needs of cement plants at any scale.

Greenfield

The simplest is a 'Greenfield' build, where the LEILAC system is 'the pre-calciner' for a new cement plant. Along with a scheduled major upgrade, this enables the system to be closely and efficiently integrated into the plant.

The technology is foreseen to be modularised, scaled up by installing multiple instances of groups (modules) of tubes. As such there is no maximum "size", and could even go beyond the existing equipment (and depending on rotary kiln type and configuration, may actually increase production clinker rates). The retrofitted equipment would be closely integrated into the host plant, thermally integrated using available high quality heat sources and returning products with a minimum of wasted energy.

Retrofit

For most cement plants, it is envisaged that a LEILAC system would need to be 'retrofitted'. This enables the plant to keep most of its current equipment, but allow its process emissions to be captured. For such a retrofit, there are a variety of options.

- A retrofit may be partial – for example installing a demonstration unit capturing 20percent of the plant's emissions – while the supporting financial mechanisms, transport and storage networks are put in place. See LEILAC2 as an example.
- A full retrofit may be 'low-impact'. The intent of such an installation is to allow the host plant to continue operating, while the LEILAC system is installed and commissioned alongside it. As with a partial retrofit, possibly less efficient than a more closely integrated retrofit, this has the potential for enabling low-cost capture of process emissions for minimal or no 'downtime' for the operational plant.

- A retrofit may completely replace an existing pre-calciner (or create one, in the case of older plants). This would necessitate significant changes to the host plant, but is similar to a 'Greenfields build'.

The footprint of the LEILAC technology is dependent on the number of tubes and modules. The footprint does not scale linearly with the number of tubes, as a module of 4 or more tubes within this same furnace provides a significant footprint advantage over multiple individual tubes. To provide perspective, a 200 TPD plant may be expected to have a footprint of 26 x 26 meters with a 60 meter tower height, or 13 x 26 meters with a 100 meter tower height, depending on whether the plant was to be optimised to minimise height or footprint.

A key benefit of the technology is the flexibility in which the LEILAC units can be installed, particularly where retrofit is required or limited space. LEILAC tubes may be positioned in banks of modules, stacked above each other, or even positioned in a circular pattern around the kiln to minimise distance for returning calcined meal.

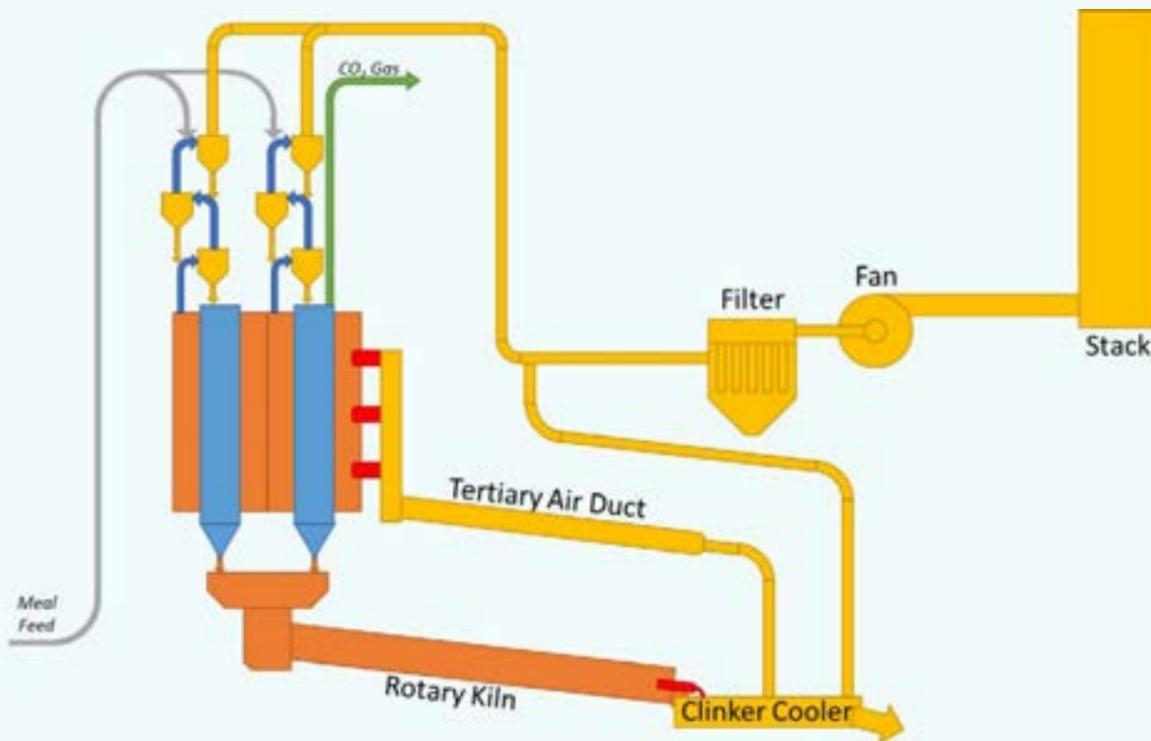


Figure 9 - Flow diagram of a full LEILAC installation.

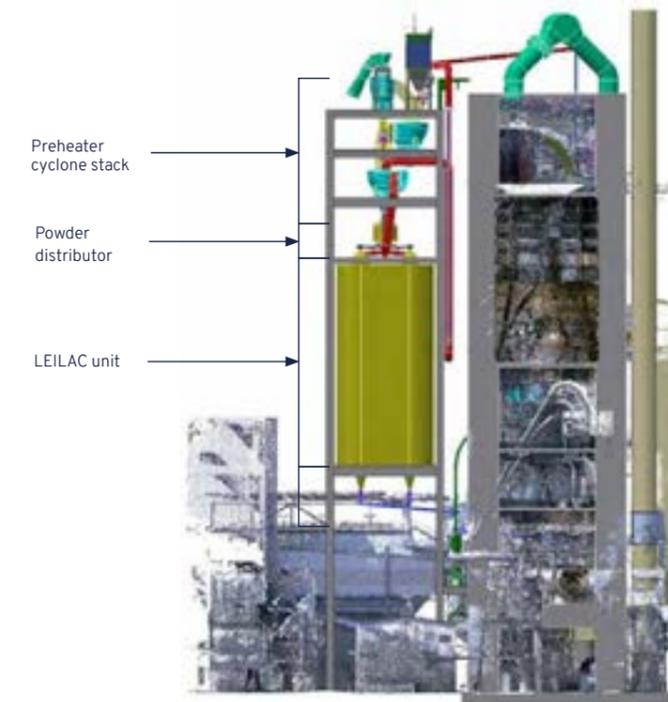


Figure 10 - an impression of the LEILAC2 plant to give a sense of scale, should it sit alongside the existing calciner tower (it will undertake 20 % of the duty of the current tower)



9.1.1 Low-Impact LEILAC Retrofit Integration

Two key advantages of the LEILAC technology are that it is able to be retrofitted within existing plants and that it is scalable, providing a system that can be utilised and implemented at various scales and levels of integration.

A key consideration for such a retrofit is that it can be build and commissioned without impacting the operations of the host plant, allowing the continuous production of clinker.

The LEILAC1 and LEILAC2 projects illustrate a partial retrofit to a cement plant. In both cases, they take a slipstream of raw meal, process it, and return the meal to the host plant. In the case of LEILAC2, the streams are more closely integrated with the host plant, with the intention of having an energy efficiency matching a conventional pre-calciner stack.

Such retrofits can be relatively simply carried out for either 20 to 30 percent of a plant's throughput, or 100 percent. Depending on the type and capacity of the host's rotary kiln, the production rate may be increased.

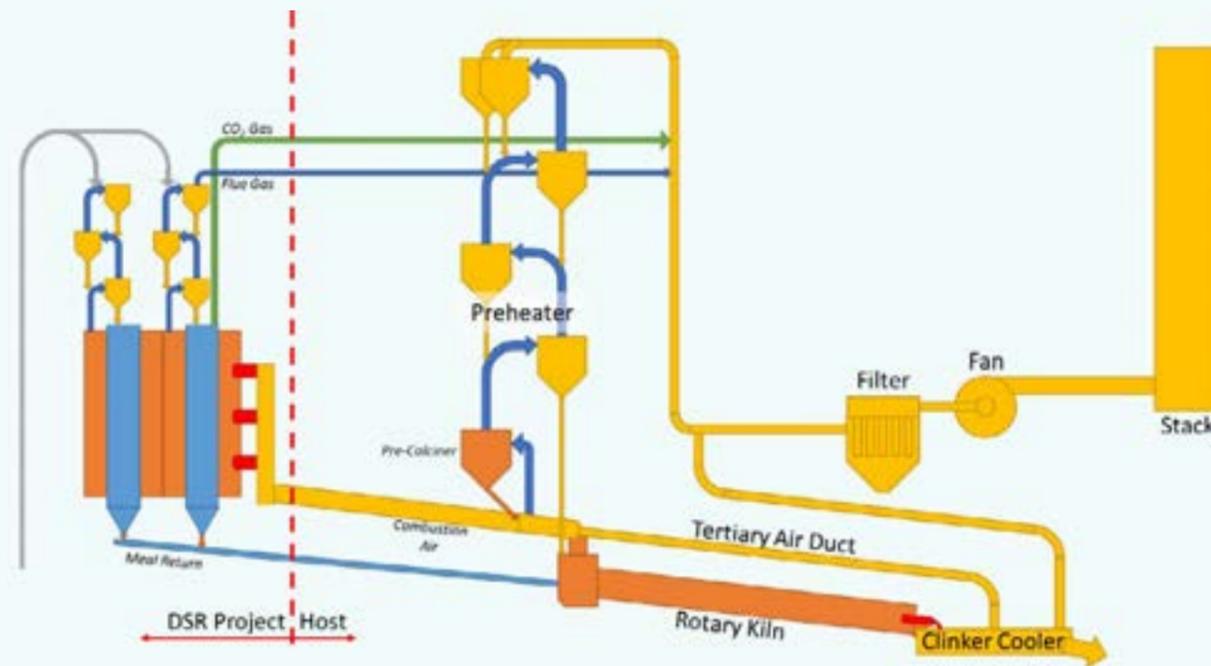


Figure 11 - Flow diagram of a partial LEILAC retrofit.

A 100% retrofit can be achieved without disruption to the host plant, through a complete or staged introduction of LEILAC modules that can be introduced gradually and then fully undertake the work of the previous pre-calciner tower system (as per the section below). Unlike a partial retrofit solution, a full retrofit would utilise the rotary kiln off-gases; this is discussed in the next section.

Each tube has a CO₂ cyclone to reduce the dust loading. The partially de-dusted CO₂ from the tubes' cyclones in a single module is combined and the solids are returned to the tube for reprocessing. A single CO₂ filter is used for the entire plant, regardless of the number of modules. If it is placed upstream of the cooling step (as shown above) it may need to be a ceramic filter; if it is downstream it could be made of conventional materials. A drawback of this method is likely

deposition of powder – and condensation of volatiles – on the cold surfaces of the heat exchanger.

Keeping the filter upstream of the heat exchanger removes the dust issue but does not avoid the condensation challenge.

Alternative methods of cooling the CO₂ may be used, for example evaporative cooling via water injection. This would have the added benefit of allowing simultaneous removal of the dust and condensates in a single, lower-temperature filtration step; however, it reduces the potential for waste heat recovery from this stream.

As a point of reference, the image below shows the technology applied to process 5% (left), 25% (middle) and 100% (right) of a typical cement plant's throughput.

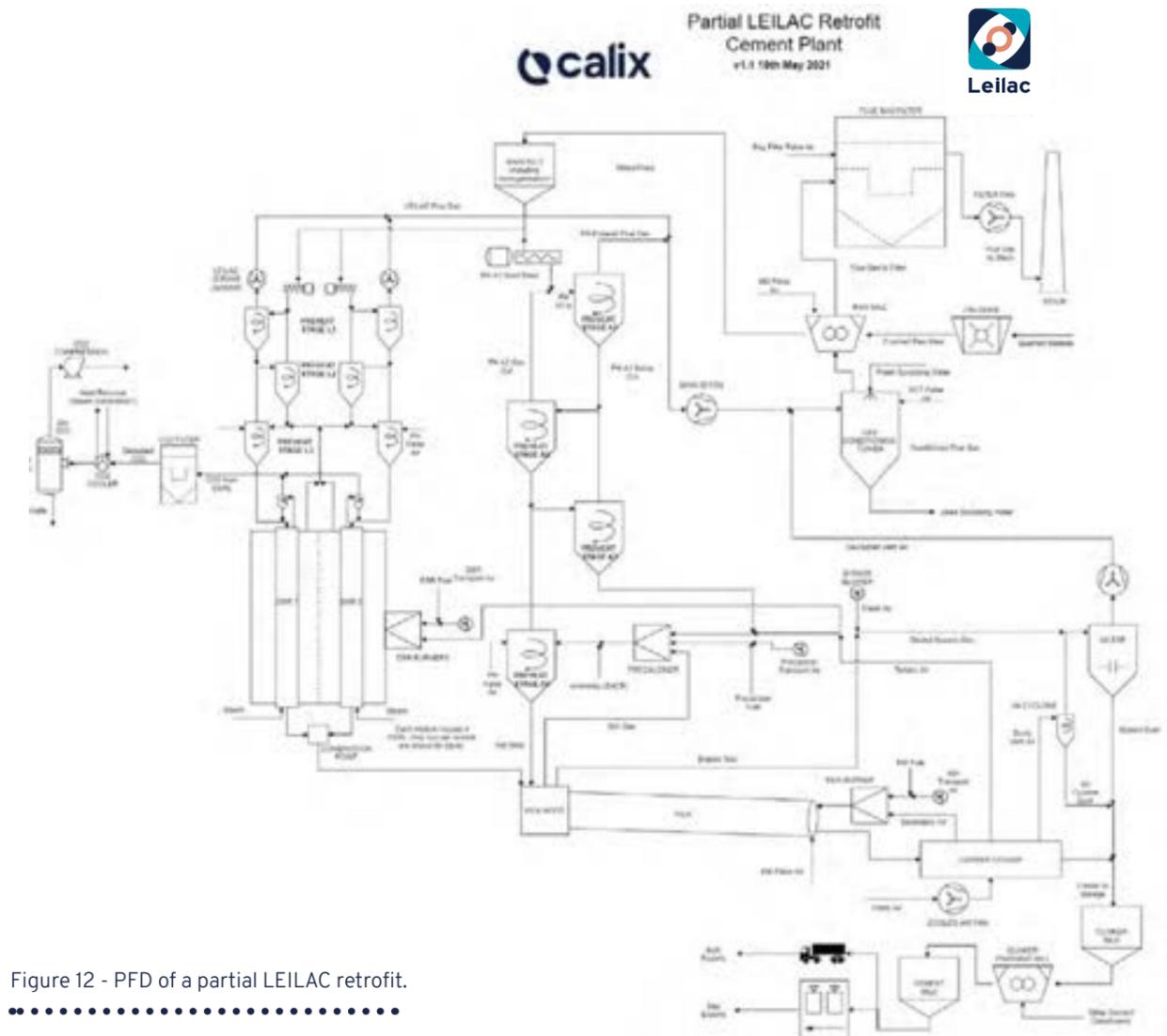


Figure 12 - PFD of a partial LEILAC retrofit.

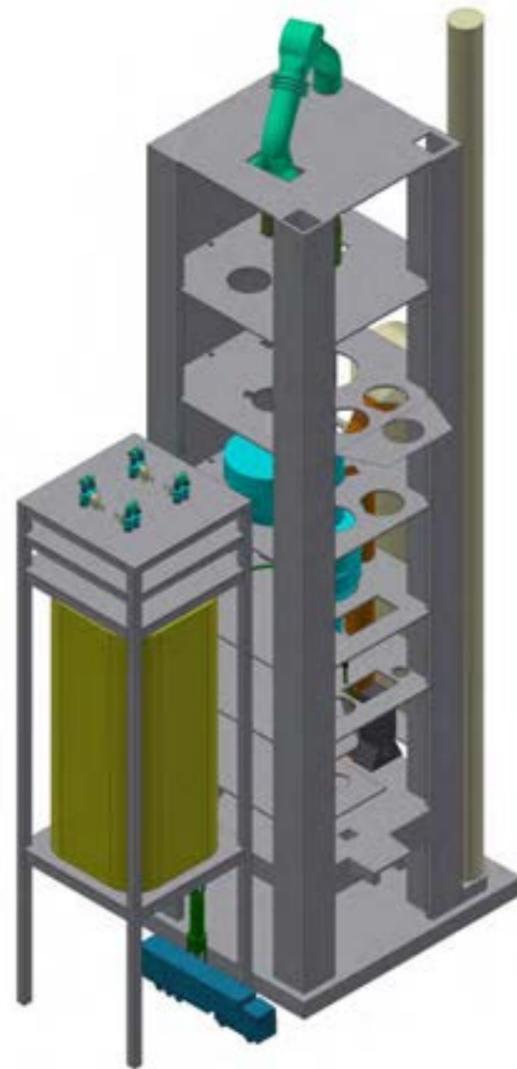


Figure 9 - The LEILAC technology applied to cement plants at various scales

Benefits of each solution:

Partial retrofit	Complete retrofit
Provides a substantial stream of process CO2 for a minimum of disruption.	Old and/or inefficient preheat/ pre-calciner stacks lines may be upgraded to match efficiency of BAT.
Allows all aspects of the technology to be trialled with the customer's specific requirements.	Enables capture of all process CO2 emissions.
Allows existing capital assets to remain in use.	Flexible in its implementation, may be culmination of partial retrofit steps, built alongside or replace existing preheat tower.
May be retrofitted in a relatively short timeframe – 12 months after feed study completion.	Lowest possible energy penalty, lower than that of the partial retrofit solution.
Less susceptible to variations in planning depending on site constraints.	

In either scenario, it may be possible to increase the capacity of the complete kiln line, in the case that the kiln is overperforming compared to the existing preheater / pre-calciner (if installed). This is articulated below in Figure 11 – the rotary kiln throughput may be up to the sum of the existing preheat / pre-calciner capacity and the LEILAC system's additional capacity.

It should also be noted that the precise configuration of the modules necessary to provide the full throughput may be adjusted according to the space constraints of the host plant. The images in Figure 11 below show two conceptual arrangements which both provide the same capacity, but with very different footprints / heights.

Each site will have its own constraints (geotechnical, height limits due to airport proximity, footprint availability etc) and this flexibility allows the solution to be tailored to those specific needs, while making use of the modular approach which makes the technology so simple.

The partial retrofit also provides a roadmap to complete retrofit, though it is best to have this planned possibility accounted for to ensure the necessary footprint is kept available. A partial retrofit may afford the customer with the ability to grow their customer base, logistics network and operational experience for the export of the CO₂ generated by the plant.

This may be done with minimal impact on the host plant's operations. A complete retrofit may be performed either with a new structure parallel to the existing preheat structure, or by refitting (or replacing) the existing preheat stack.



9.2.4 Lime product heat recovery – configuration

The product of the calciner exits the base of the tube at >900 °C in powder form and contains approximately 70% of the sensible heat. The product must be cooled before storage or use, and several heat recovery options exist.

Cyclone stack HX – Multi-stage cyclone heat exchangers are common in the cement industry for pre-heating the raw material. The raw material is directed heated using off gas from the clinker cooler and kilns in several co-current heat exchange cyclones arranged in series. Each step progressively increases the temperature of the raw material. Product cooling with cyclones is the reverse of this concept where a gas such as air progressively cools the product and in the process is heated. This heated gas is an energy source and can be directed to the top of the of the calciner for pre-heating the raw material in cyclone stack.

Fluidised bed HX – Multi-stage fluidised beds can achieve a similar result to the cyclone array assuming the material is in the right particle size range for fluidisation. The “preferred” PSD for lime calcination in the tube suits the use of this technology. The fluidised bed design separates the cooling gas from the powder eliminating carry over in this stream. A small amount of material is contained in the fluidising gas, but this is easily cleaned and returned to the product stream. The clean heated gas (likely air) can be used in the pre-heat cyclone stack or more widely in the host plant. For example, the plant may have a drying step or need for hot clean air elsewhere. Alternatively, steam can be raised via this method and used for heating or electricity production.

Other HX options – Other powder cooling options exist such as powder to powder/gas plate heat exchangers, powder to liquid screw heat exchangers and others. In most cases the flowability of the powder is an important consideration. The choice of technology will be case dependent with use of the cooling medium to be well understood.

9.2.5 Configuration – in-line (dry) hydration

Lime (CaO) is commonly converted to hydrated lime (CaOH₂). This is carried out in a slaking step where water is added. The resulting hydrated lime forms as a precipitated fine particle-sized product which is dried or sold as a slurry. Another approach is to use steam to “dry” hydrate the powder lime product that is produced through the LEILAC calciner. The energy recovered during this process may be used for pre-heat of the raw material, or if high pressure steam is produced, the energy can be converted to electricity through a turbine and used directly in the LEILAC process. The hydration energy is not commonly used so the addition of energy recovery should improve overall efficiency of the LEILAC process compared to other processes. In December 2014, a World Cement article titled, A Competitive and Efficient Lime Industry, made the following observations about energy recovery from lime hydration.

“The production of hydrated lime and dolime is an exothermal reaction, i.e. it generates heat. The heat resulting from the production of hydrated lime amounts to about 1.2 GJ/tonne of CaO. This heat could be used in industrial processes or heating buildings if there is such a demand in the remote areas where the plants operate. This option will require further R&D to work out how to extract the heat without affecting the production process and quality of the product.”



9.3 OPEX analysis - Energy Options

The LEILAC technology is based on indirect heating to separate the flue gases from the raw meal and CO₂. Thus, the capture efficiency is independent of the source of the fuel. As the LEILAC tubes just need to be heated, the process has the potential to be fuel agnostic. The aim is to enable the use of the host plant’s chosen fuel, but also holds the opportunity for using lower cost, and/or lower carbon, fuels.

These fuels can have their own emissions. For 100% capture using fuels that emit CO₂, the LEILAC technology may be paired with other CO₂ capture technologies, such as pre-combustion (oxyfuel, hydrogen), post-combustion (amines, MOFs, calcium looping). With such pairings, the modelling to date shows that the lowest costs of negative emission production is possible.

Alternatively, using fuels with limited CO₂ emissions, the LEILAC system should be carbon neutral by itself. It is already capable of using renewable sources of energy, such as electricity and hydrogen, and should be able to use biomass and waste.

A variety of possible energy sources are listed below.

- Conventional fuels
- Alternative fuels [26]
- Hydrogen [40], biomass and electricity. All LEILAC installations will be made ‘electrification’ ready, allowing optionality for future deployment.
- Hybrid solutions [41], with grid stabilisation / load-balancing. See section 8.2.1

The availability, and costs, of these fuels vary dramatically by both region and even plant. The techno-economic analysis is conducted on the basis of current general European average prices.

It is Calix’s ambition to enable the lowest-cost production of zero emissions lime and cement and provide an energy-agnostic solution.

9.4 Maintenance, Resourcing & Utilities

Maintenance

The general maintenance costs of a LEILAC installation are expected to be relatively low. The primary area of wear requiring regular inspection and periodic maintenance are the LEILAC tubes themselves. The length of service will depend on the meals used, the energy sources used, and the chosen alloy.

The operational tube in Australia has run for over seven years without being replaced. Tube life tests have been undertaken in LEILAC-1 and which will be continued in LEILAC. For the purpose of this modelling, a very high tube replacement rate has been assumed, and represents a large proportion of the expected capture costs in the modelling. These costs are not expected in reality, but represent an area of risk that has been costed into the projects. An easy, cost-efficient maintenance regime is a critical area of attention for the technology.

The current tubes are only a few percent of the total capital cost of an installation. They are designed in such a way that they can be very rapidly removed and replaced, minimising any downtime.

Additionally, separation of the CO₂ from the flue gas stream may result in a lower fan duties and flue gas clean-up costs; again this may represent an OPEX cost-down opportunity, but still to be quantified and has not been modelled.

Resourcing

The intent is that it is a simple replacement, or supplement, to a pre-calciner and should not require additional staffing to operate the unit.

The LEILAC1, despite being an R&D pilot, can be simply and safely operated.

Utilities

The LEILAC system does not required cooling water, make-up water, or any chemical make-up. It does require electricity for auxiliary equipment, as does an existing pre-calciner tower, and to drive a compression unit.

9.5 Capture cost summary

The capital and operational costings outlined within this section, and the subsequent techno-economic modelling in section 10, are based on nth-of-a-kind cost projections which are firmly based on the detailed engineering undertaken within LEILAC2 which is a first-of-a-kind plant.

The LEILAC Consortium have endorsed the LEILAC2 pre-FEED study. This was for a first-of-a-kind retrofit. Further design, work and testing is required – but should the design work as planned, detailed OPEX modelling within the pre-FEED study indicated that the LEILAC2 may separate CO₂ at a cost of around €10/t CO₂ extra OPEX (above the host plant’s operating costs). This excludes compression costs and CAPEX retrofit depreciation costs (including foundations, installation, structure), etc., which are expected to be in the region of an additional €10-€15/t CO₂. (Compression costs will vary depending on the fate of the CO₂).

LEILAC’s Energy and Mass Balance (EMB) for an nth-of-a-kind full scale retrofit using alternative fuels indicates a possible efficiency penalty of 0.6 GJ/t CO₂ – with options for near zero penalty (the model does not assume energy is recovered from the CO₂, and the degree of heat integration with the host plant that could be increased). With an electrically powered LEILAC, there would be an improvement of 0.7 GJ/t CO₂. Therefore, total costs of this first-of-a-kind LEILAC carbon capture plant is expected to be in the region of 20–25 €/t CO₂.

In future projects, we would expect the OPEX to reduce significantly, as the plants should be integrated more closely (for example the LEILAC2 Demonstration plant has minimal insulation, does not use kiln off gases, nor recovers energy from the CO₂ etc.)

In addition, the OPEX does not take into account income from load balancing grids. Should that work, the capture plant may receive an income of 10-20 €/t CO₂ eq. (a case study for Belgium in 2019 suggested an income of 11 €/t CO₂ eq.) The CAPEX for LEILAC2 is expected to be in the region of €16m.

Again, the positive findings of LEILAC2 engineering studies that have been conducted give a good degree of confidence of the anticipated potential cost improvements that are foreseen within the techno-economic modelling within this report.



As noted, independent verification of the thermodynamic potential for the LEILAC technology has been assessed by Imperial College. The preliminary results for the flue preheating configuration suggests the technology offers energetic performance comparable to the current BAT (whilst also reducing emissions considerably). There is certainly considerable scope for further improvement (e.g. adjustment of heating profiles, waste heat recovery). The current analyses are being expanded and finalised for publication, with the first submission planned for Chemical Engineering Journal (Chem. Eng. J.).

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10 Capture and storage techno-economic summary

10.1 Cement

10.1.1 Headline LEILAC Results

The techno-economic model is based on the findings of LEILAC1 and engineering of LEILAC2, and involves scaling and integration assumptions. The model incorporates capital costs and anticipated tube replacement schedule. – most of which have been outlined in section 9.

Several development and scale up steps are required to fit a complete LEILAC system to a cement plant, but in theory, as there is minimal energy requirements and relatively small capex, an Nth-of-a-kind capture costs may be low at around €22 per tonne of CO₂.

It is expected that a future, nth-of-a-kind full scale retrofit of a LEILAC installation may have a full chain CCS abatement costs (capture, transport, storage, including CAPEX costs) of around €39 per tonne of CO₂ avoided. Half of these costs relate to transporting and storing the CO₂.

Figure 15 below shows the results of the techno-economic study. It compares three options: Case A3, a LEILAC retrofit plant, Case A4, an advanced amine scrubbing retrofit plant, and Case A5, the two capture technologies combined.

It shows costs per tonne of CO₂ captured (i.e. how many tonnes are exported from the site) and costs per tonne of CO₂ avoided (i.e. the difference between emissions to atmosphere before

and after application of a decarbonisation process). For most capture technologies, there is a significant energy penalty, resulting in higher fuel consumption and therefore more CO₂ emissions. As the objective is to decarbonise, these additional emissions need to be captured in addition to those from the core process: increasing the volume of CO₂ to be captured and stored per unit of production. In the modelling of the advanced amines, it is assumed that as much waste heat from the host plant as possible has been used, beyond which point it is assumed that the same fuel as the host plant is used to generate the extra energy required. It is also assumed that the “extra” CO₂ generated is also captured and stored.

The low thermal energy penalty of LEILAC technology means that very little extra CO₂ is generated by this capture process; the amounts of CO₂ ‘captured’ and ‘avoided’ are much closer than for post-combustion capture process scenarios (the model does assume an amine plant would use available waste heat from a host plant).

As such, less CO₂ must be stored per tonne of CO₂ ‘avoided’ for a LEILAC system than for the amine system – which is why, for example, in the advanced amine scenarios the costs per tonne of CO₂ avoided (and volume of CO₂ to be stored) are significantly higher than those for CO₂ captured. Another point of note is that the compression costs for the amine system are cheaper. This is because process units – including compressors – are modelled to be cheaper per unit capacity as they increase in size.

The LEILAC plants show avoidance costs of around 38 €/t CO₂. However, 40% of this (€15.45) is assigned to transport and storage. Furthermore, electricity for compression is responsible for around €9; in total, these variable costs not associated with the core capture process are responsible for around 64% of the total costs of avoidance. Those core costs are 12–14 €/t CO₂ avoided.

See publication D5.1 Techno-economic model regarding a wide range of scenarios that have been modelled. The technoeconomic analysis report considers the following main cases– each with several models:

- Case A: Results for baseline, LEILAC, and advanced amines using alternative fuels
- Case B: Results for baseline, LEILAC scenarios by fuels and fully electrically powered
- Case C: Post-combustion scenarios
- Case D: Scenarios showing the synergies of LEILAC with other decarb options

The primary results are illustrated here, and section 15.

Note the difference between the “cost of capture” and the “cost of avoidance”. When using non-LEILAC technologies, there is a significant energy penalty, resulting in higher fuel consumption and therefore more CO₂ emissions. As the objective is to decarbonise, these additional emissions need to be captured in addition to those from the core process: increasing the volume of CO₂ to be capture and stored per unit of production.

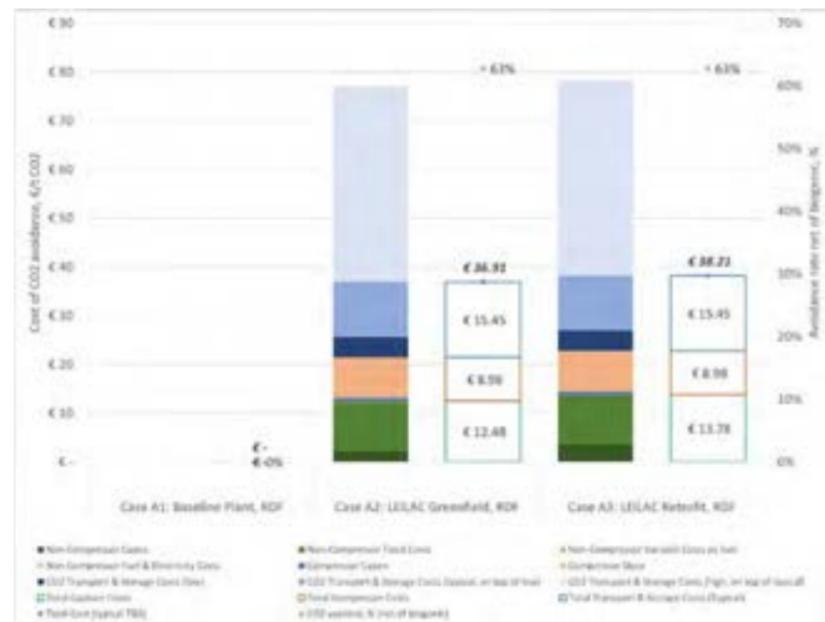
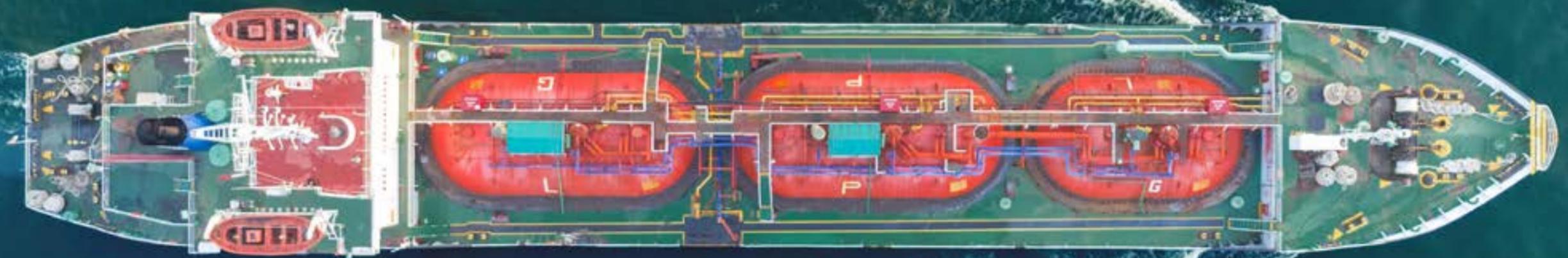


Figure 13 - Headline LEILAC Results for anticipated Greenfield and Retrofit nth-of-a-kind installation, including storage



Figure 14 - Headline technoeconomic results for RDF-fired cement plants (Case set A): Case A3 = retrofit LEILAC cement plant; Case A4 = retrofit advanced amine cement plant, Case A5: retrofit both LEILAC and advanced amines.

The cost of transport & storage per tonne avoided is significantly higher than for LEILAC because of the extra fuel that must be burned to raise steam for the amine stripper. Interestingly, it is cheaper to run the boiler on natural gas than RDF, presumably due to the lower CO₂ intensity per unit of energy.



A question of enabling low, fair cost transport and storage.

While a baseline case of around €15 per tonne of CO₂ is used, this is a major variable. This represents a 'low cost transport and storage scenario', (excluding initial compression).

However, it is expected that first movers, or areas with transport/storage operators with limited capacity, the costs may be much higher. For this reason, within the 'high cost transport and storage scenario', a transport and storage estimate has been made of €50/tonne of CO₂ (excluding initial compression).

The dramatic variance in these transport and storage costs illustrate the need of low-cost solutions, and governmental assistance in developing solutions at large scale – ensuring their free a fair access to smaller players.

Description		Case A1: Baseline Plant, RDF	Case A2: LEILAC Greenfield, RDF	Case A3: LEILAC Retrofit, RDF	Case A4: Advanced Amine Retrofit, RDF	Case A5: LEILAC/Adv. Amine Retrofit, RDF
Case		Case 1	Case 2	Case 2	Case 3	Case 4
Calciner Plant Fuel		RDF	RDF	RDF	RDF	RDF
Kiln Plant Fuel		RDF	RDF	RDF	RDF	RDF
Capture Plant Fuel		RDF	RDF	RDF	RDF	RDF
Location		Greenfield	Greenfield	Retrofit	Retrofit	Retrofit
Plant Capacity	kt/y clinker	1000	1000	1000	1000	1000
Emission reduction, fossil CO₂		0%	63%	63%	164%	148%
CO₂ captured	kt/y	0	498	498	1752	1410
CAPEX*	M€	0	27	34	98	99
CAPEX Annualised (over 30 years)	M€/y	0.00	1.3	2.0	5.6	5.7
Thermal Fuel OPEX	M€/y	1.8	1.8	1.8	5.3	3.7
Electricity OPEX	M€/y	10	14	14	31	25
Non-Fuel OPEX**	M€/y	27	40	40	73	65
Total Opex	M€/y	39	55	55	109	94
Total CCUS Cost	€/t CO ₂	0	36	37	44	43
Cost of avoidance vs. unabated base case A1 including storage	€/t CO ₂ avoided	0	37	38	94	67
of which capture processes	€/t CO ₂ avoided	0	12	14	49	32

Table 2 - Headline technoeconomic results for RDF-fired cement plants (Case set A); baseline, LEILAC and amine scrubbing when firing RDF

10.1.2 Variance by fuel, and near-zero emissions options

The main variance in cost for a LEILAC system is the choice of fuel. These vary over time and region

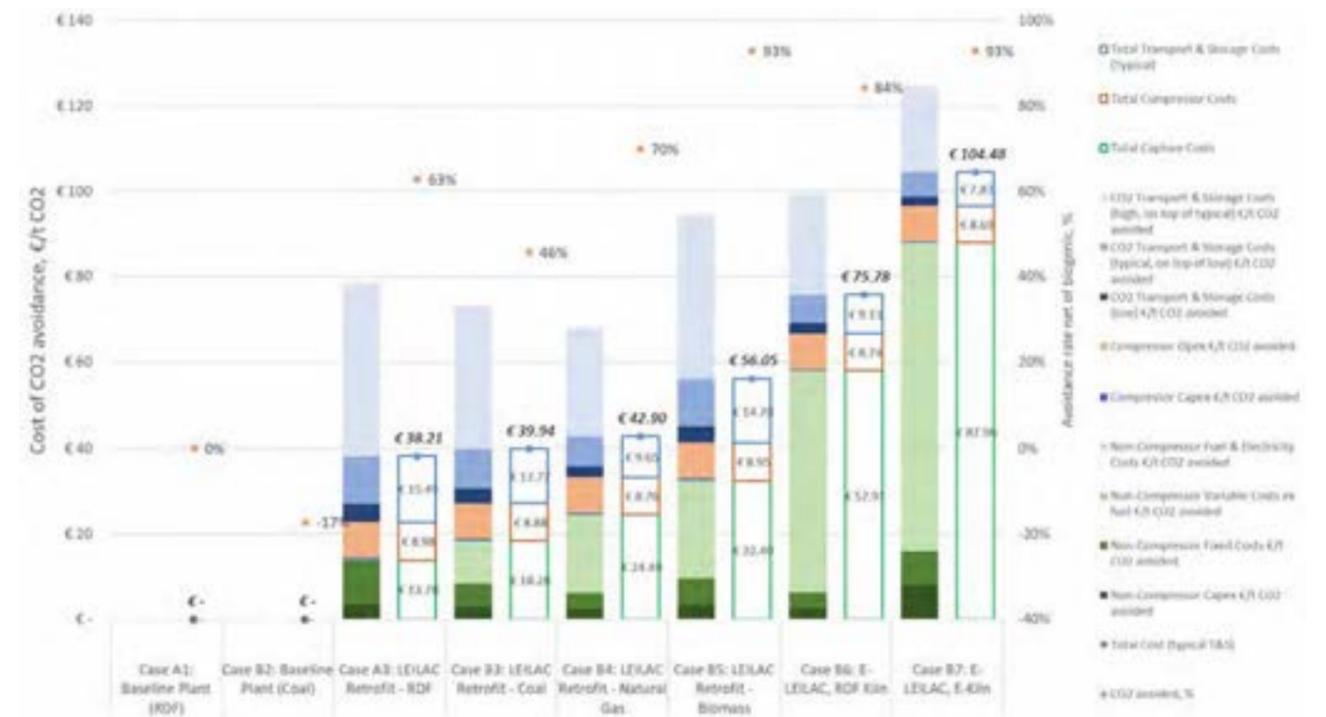


Figure 15 - Variations in expected cost, based on fuel use. Note that costs are per tonne of CO₂ avoided.

Near-zero emissions plants (B5 and B7) are possible with capture costs potentially in the region of 40 €/t CO₂ with biomass being used for both the LEILAC system and the rotary kiln.

10.1.3 Sensitivity to Capital Cost & Financing

The modelling undertaken has been designed to align with other techno-economic modelling that has been undertaken for the cement industry. The models used have been created from the findings of LEILAC1, and engineering of LEILAC2, and scaled to a full-size plant – representing nth-of-a-kind possible cost projections. Regional cost differences will change such projections. In the case of retrofit applications, such costs may be highly variable as infrastructure and ancillary systems need to be adapted. Examples of these extra costs are removing disused buildings, constructing new access roads, and adding soil improvements prior to construction. For any actual installation, an engineered feasibility study considering all of a plant-specific requirements are required to get an appropriate cost estimate.

However, for the purposes of illustrating some of the cost sensitivities that arise from a real-project application, the following graph shows some of the variables the projects need to contend with.

In Figure 16, using the scenarios outlined above, variations are made to reflect a 50% increase of the expected CAPEX to cover those extra non-capture unit expenses (Scenario 1). It also models changes to the cost of financing, for example by doubling the weighted average cost of capital (WACC) from 3% to 6% whilst reducing the payback period to 20 years from the baseline of 25 years (Scenario 2). (25 was used for consistency with the CEMCAP modelling). This is not particularly expected, given the increase in financing available to environmental technologies that are attempting to reach our climate change targets, but is used to illustrate the impact of such changes. A LEILAC system is expected to cost in the region of the CAPEX for a full scale (3000 tpd clinker), with an unscheduled stand-alone retrofit implementation may be in the region of 66–74 M€ (scenario 3 below). When considered as part of an otherwise planned upgrade of a site, the net cost may be around 33–44 M€ and is the upgrade assumption has been used in the “retrofit analysis”.

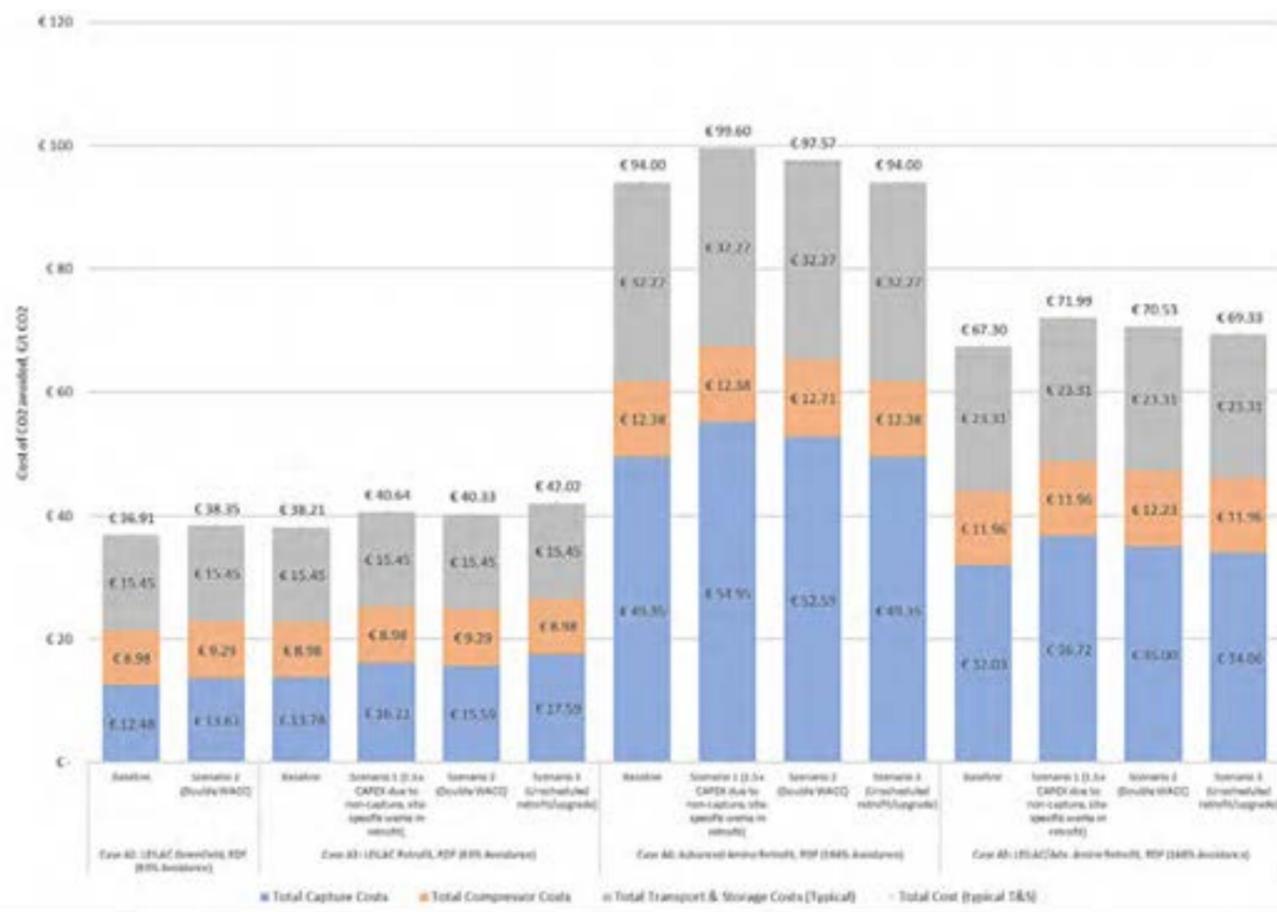


Figure 16 - Sensitivity Analysis: Increasing the CAPEX of the project by 50% (Scenario 1), doubling WACC & reducing payback period to 20 years (Scenario 2)

10.1.4 Routes to carbon neutral and negative cement production

Combining LEILAC and other capture technologies may provide the lowest-cost negative emissions.

The low thermal energy penalty of LEILAC technology means that very little extra CO₂ is generated by this capture process. For other capture technologies, more energy is required to run their processes - and additional CO₂ is generated that needs to be captured (creating a bigger difference between capture rates and avoidance rates). That is why the storage costs are higher for the advance amine scenarios using the same fuel.

A LEILAC system and rotary kiln using a renewable energy source (such as electricity, biomass or hydrogen), which enables a low-cost route to near carbon-neutral cement production.

For a carbon-negative solution, a LEILAC system works effectively when combined with any other capture technology. These strong synergies exist when a LEILAC system capturing unavoidable process-emissions is used with a small additional capture unit to capture CO₂ generated during heating. Compared to a stand-alone system trying to capture everything, overall far the less overall energy is required – and less additional CO₂ is generated.

As a result, a combined system may represent one of the most resource and cost-efficient means of carbon-negative cement production.

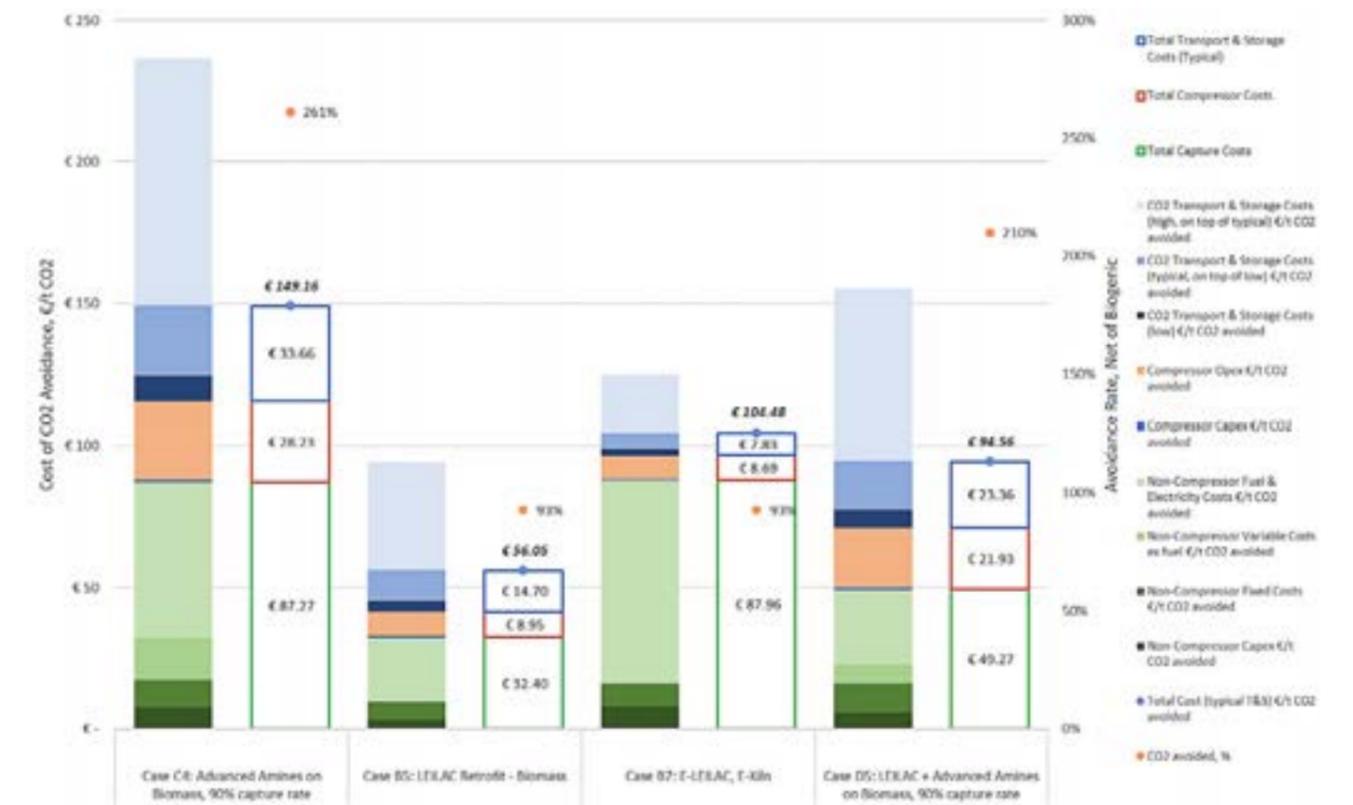


Figure 17 - Possible costs of low- and negative-emission configurations

11.1 Utilisation

As mentioned above, a wide range of uses for CO₂ are available across numerous industries. Some applications that already use CO₂ can be supplanted with captured CO₂, while other CO₂ sinks will be new developments based on incentive to utilise CO₂ that is now readily available. Unless specifically mentioned, all these carbon utilisation technologies could be implemented either in situ adjacent to the LEILAC CO₂ source, or installed elsewhere with the CO₂ transported via pipeline, rail, barge or truck in a liquefied or supercritical gas phase.

11.1.1 Fuels

The carbon in CO₂ can be utilised in the production of hydrocarbon fuels to displace hydrocarbons produced through conventional means. This allows the carbon to re-enter existing supply chains with minimal disruption. While offsetting the use of fossil fuels, the CO₂ is still emitted to the atmosphere unless it is captured for a second time at the point of combustion. The two primary pathways are:

- Synthetic natural gas produced by the Sabatier process, which produces CH₄ and H₂O from a reaction of H₂ with CO₂ via a nickel catalyst. The full production process is energy intensive (at 300–400 °C and ~3000 kPag) and requires a low-cost and carbon neutral source of hydrogen. However is an advantageous process since it can utilise CO₂ directly as a feedstock with no intermediaries.
- Longer chain hydrocarbons such as diesel can be produced via Fischer-Tropsch synthesis, which is a well-known and commercially proven technology. Again, the full production process is energy intensive and requires sourcing a low-cost and carbon neutral source of hydrogen. Additionally, this process conventionally requires conversion of CO₂ to CO (which is more chemically active than CO₂) or alternately would need specialised catalysts to use CO₂ directly.

In both cases the technology is at a relatively early stage; does not stop the CO₂ from ultimately reaching the atmosphere; and the volume of CO₂ required compared to the CO₂

generated by the cement and lime industries is likely to be limited. It may, however, be an extremely important means of lowering the emissions from certain sectors, and a source of revenue in regions without a price on emitting carbon.

11.1.2 Chemicals and Solvents

The carbon in CO₂ can be utilised in the production of various chemicals and solvents to allow the carbon to enter existing supply chains with minimal disruption, resulting in displacement of carbon intensive chemicals or solvents and potentially permanent sequestration depending on the material.

Two promising pathways are:

- Methanol can be produced by direct hydrogenation of CO₂ with H₂ in the presence of a catalyst. Methanol is an attractive product for CO₂ utilisation because it is both a direct fuel, or more commonly a feedstock for other commercial processes that already exist to convert methanol to petrol and other chemicals. Similar to the fuel synthesis, this process also requires a low-cost and carbon neutral source of hydrogen.
- The production of urea requires a supply of CO₂ to react with ammonia. Urea is a valuable product in its own right and also a feedstock for other chemical processes. However conventional urea production plants typically utilise CO₂ produced in situ from the manufacture of ammonia, therefore are unlikely to require CCUS-derived CO₂. Future novel processes to produce ammonia from electrolysis derived hydrogen and atmospheric nitrogen would then need an outside source of CO₂ to produce urea.

The volume of CO₂ stored, compared to the CO₂ generated by the cement and lime industries, is likely to be extremely limited. The CO₂ used does eventually reach at atmosphere in most cases, but may provide early projects with an economic incentive for capturing CO₂, and provides some avenues for lowering or offsetting the emissions in other sectors.

11.1.3 Biomass-Yield Boosting

CO₂ fixed via photosynthesis in biomass can be enriched or supplanted by captured CO₂, rather than atmospheric CO₂. Thereby allowing for beneficial use of the carbon or generation of value-added products. Uses of CO₂ in the biomass space are:

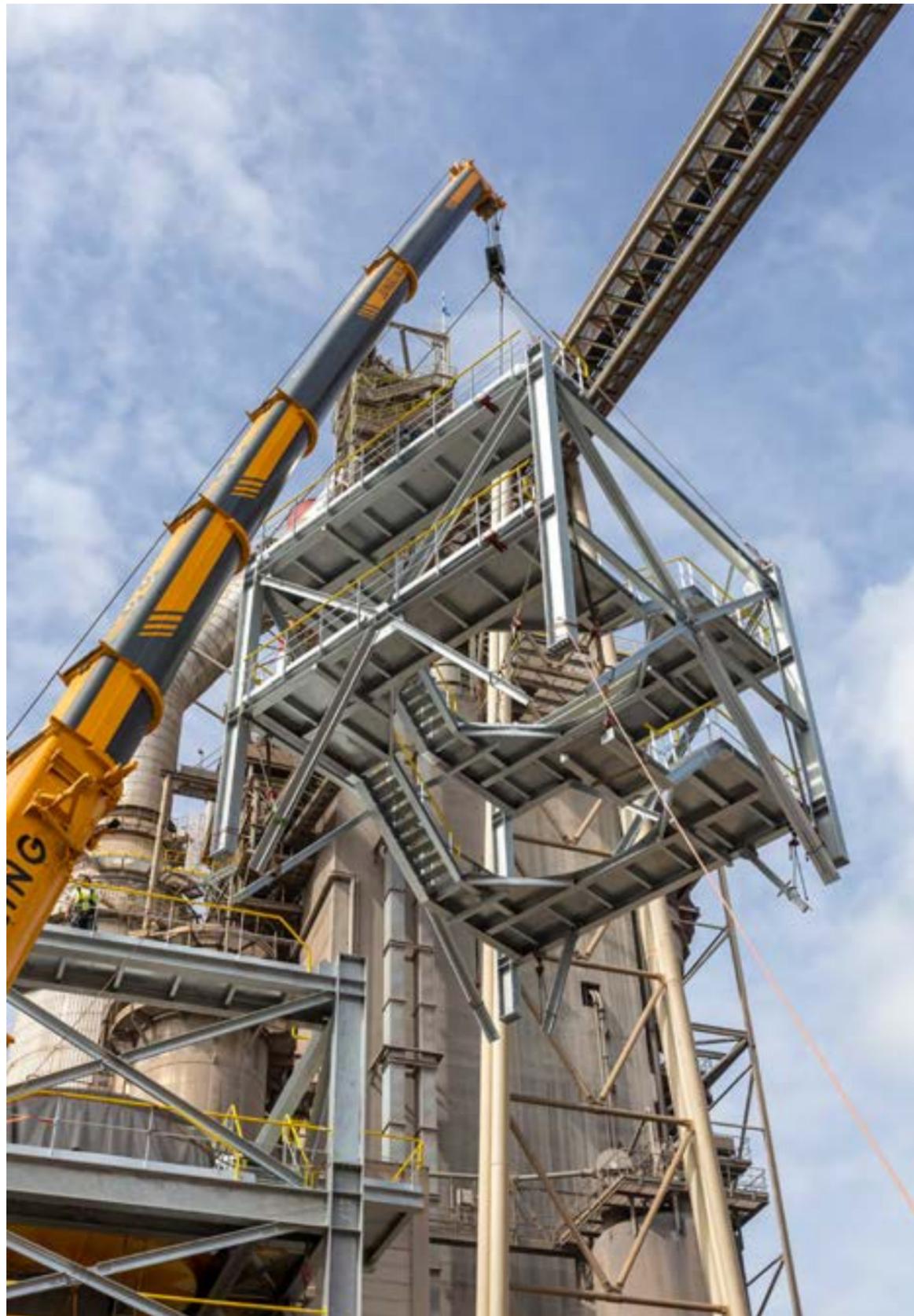
- Research into the carbon fertilization effect, which enriches atmospheric CO₂ to higher concentrations to boost photosynthesis in plants, has indicated that increased growth yields are possible with conventional or selectively bred crops. Commercially applied, this solution does pose potential downsides for biomass nutrient content and leaf transpiration. It should be noted that biomass grown with enriched CO₂ does not have to be solely for the food industry, both biogas and ethanol can be produced from foodstuffs as a method of fixing CO₂.
- Algae grown in an open or sealed bioreactor can be supplied with captured CO₂ and fixed via photosynthesis. This algae can then be processed into various value-added products such as animal feed rich in omega-3, fertiliser, biodiesel, or mixed with RDF to increase calorific value. The algal bioreactor process has advantages since it agnostic to a range of concentrations of inlet CO₂ and contaminants, which simplifies the upstream CCU process from the site of capture. Downsides are the high footprint per tonne of CO₂ and costs of maintaining the algae colony in cold ambient environments and solar energy requirements.
- Archaea, an organism similar to bacteria, can be used to produce biomethane under controlled conditions as a byproduct of its metabolic process. The process requires electrolytic hydrogen generation from water which is then combined with CO₂ in a bioreactor. The technology is still in the pilot phase of development but would be expected to have similar advantages and disadvantages to the algal bioreactor.

The volume of CO₂ stored, compared to the CO₂ generated by the cement and lime industries, is likely to be limited. The CO₂ used does eventually reach at atmosphere in most cases, but may provide early projects with an economic incentive for capturing CO₂, and provides some avenues for lowering or offsetting the emissions in other sectors.

11.1.4 Enhanced Hydrocarbon Recovery

Enhanced Hydrocarbon Recovery uses CO₂ as an active oil reservoir to pressurise, increase oil miscibility and displace “flood” entrained oil to increase production from adjacent oil well. This is considered a “tertiary” oil recovery technology and has been proven technically and economically, particularly in North America. Depending on how the EOR operation is run, while a percentage of the CO₂ will remain permanently sequestered, some will return to the surface with the oil needs to be captured and recycled back to the injection point. Historically, the percentage of CO₂ returned will be 30 to 40%, rising up to 90% as the reservoir is saturated with CO₂ and depleted of oil. It can take up to 5 years to see the first CO₂ breakout in this way, and over 10+ years before recycled CO₂ rises to 90% levels. As the reservoir is depleted, the oil recovery scheme can be converted to full CCS ensuring all the CO₂ injected is permanently stored.

While, by definition, being used for hydrocarbon production that is destined to be released into the atmosphere, such operations can permanently store the captured and used CO₂ and provide a commercial incentive for capturing and using CO₂ in regions without an incentive or price for emitting CO₂. Globally such EOR operations are geographically limited, and only sufficient to store a percentage of the CO₂ storage capacity requirements for our society.



11.1.5 Food and Commercial

The food industry has an established commercial history of using CO₂ for carbonation of beverages and in packaging to displace oxygen. High-pressure CO₂ is also used to produce decaffeinated coffee and processing products out of cannabis. Other commercial uses of CO₂ include: fire extinguishers/suppressants, dry ice, the medical industry, CO₂ derived lasers and research grades of near 100% purity CO₂. The CO₂ quality required by the food and commercial industries is extremely high relative to most CCU applications, and easily exceeds 99.5% purity. The volume of CO₂ stored, compared to the CO₂ generated by the cement and lime industries, is likely to be extremely limited, and is ultimately released to the atmosphere.

11.2 Storage

The primary means of ensuring that the CO₂ generated by industry does not reach the atmosphere is to permanently store or sequester CO₂. Multiple examples of this approach have been made (see section 15), and reports made on its environmental benefit (see in particular the IPCC Special Report on CCS)[4] The majority of CO₂ storage assessments are based on the use of saline aquifers.[42]

11.3 Subsurface Storage

11.3.1 Saline aquifers and depleted hydrocarbon reservoirs

Saline aquifers and depleted oil and gas reservoirs are a permanent, safe storage sites for CO₂.

Located several kilometres below the surface, and highly regulated, these sites are selected on the basis of having multiple ‘cap rocks’ to ensure CO₂ does not leak to the surface, and are closely monitored. Within the EU and other regions, such operations are highly regulated, and are covered by the EU Storage Directive.[43]

The use of subsurface storage is proven in industry and has been implemented in various locations worldwide. Depending on the reservoir type and geology, CO₂ is stored in a combination of structural, capillary, solubility (ex: saline water) and adsorption trapping. Depending on reservoir depth, permeability and other conditions, injection is usually completed in the range of 10-20 MPag at the wellhead in supercritical (or dense phase) operating conditions, however liquefied CO₂ or gas phase CO₂ may be utilised in some instances.

The quality of the CO₂ is typically greater than 95% both to achieve necessary dissemination into the reservoir and because higher concentrations of contaminants (CO, N₂, O₂, VOCs, etc) require more compression duty to maintain the required operating pressure envelope. At these high pressures the CO₂ rich stream is typically dehydrated below water saturation dewpoint to manage corrosion of the compression, transport and wellbore materials and thereby allow less-expensive steels to be installed. However in some cases where the reservoir is located nearby the CO₂ source, it is cheaper to use stainless steel materials and have no dedicated dehydration equipment. It should be noted that different reservoirs will have different limitations for CO₂ quality – and (under the EU Storage Directive) there are clear rules, indicating that there the CO₂ quality should not be inferior to the capture process.

A number of transport Hubs, and certain storage operators, place strict CO₂ quality limitations as a “de-risking” step, but many of which are tailored to certain capture or compression technologies, and are significantly more onerous than are required.

The global capacity for safe and permanent storage of CO₂ in saline aquifers is very significant – and far in excess of the global industrial CO₂ storage requirements. Ref IEA and IPCC and GCCSI

11.3.2 Offshore reservoirs

A particular subset of CCS is offshore subsurface CO₂ storage. The capacities of such off-shore structures are very significant, and Norway has safely operated such CCS sites since the 1990s.

Many onshore geographic areas do not have ready access to reservoirs that can be converted to CCS functionality either due to reservoir performance or risks for social/political/safety reasons near established population centres. Offshore reservoirs are simpler in this regard and the operators of them already possess the necessary technical expertise for safe transport, injection and reservoir modelling of high-pressure CO₂. Therefore it is likely that offshore CO₂ sequestration ‘hubs’ will be installed worldwide that will receive CO₂ from a variety of sources, charging a custody transfer fee as part of their business model.

Such offshore structures have the capacity to hold the entire global CO₂ generated by the cement and lime industries for many decades, is far in excess of requirements.



11.3.4 Sub-surface storage examples

There is extensive expertise and knowledge regarding sub-surface storage. Globally there are around 60 projects in operation, storing 40 million tonnes per year.[42]

- In the USA, the technology has been in use since the 1970s and is supported by extensive CO₂ transport pipeline networks. There are 12 operating commercial-scale CCUS sites in the US, primarily from natural gas and fertiliser plants, storing around 19million tonnes of CO₂ per year.
- Canada has 3 operating commercial-scale sites, each storing over 1 million tonnes of CO₂ per year.
- Europe has had extensive experience with storage operations. Sleipner has stored CO₂ since 1996, with systematic monitoring of its operations, which have now stored more than 20 million tonnes of CO₂. It was joined by Snøhvit (operating since 2008), and together capturing and storing around 1.7 million tonnes of CO₂ per year. Equinor is developing the Langskip project (aka “Longship”) and other large scale storage locations are under development. There are dozens of other storage projects in development.
- Australia’s Gorgon project is one the world’s largest, storing around 4 million tonnes per year

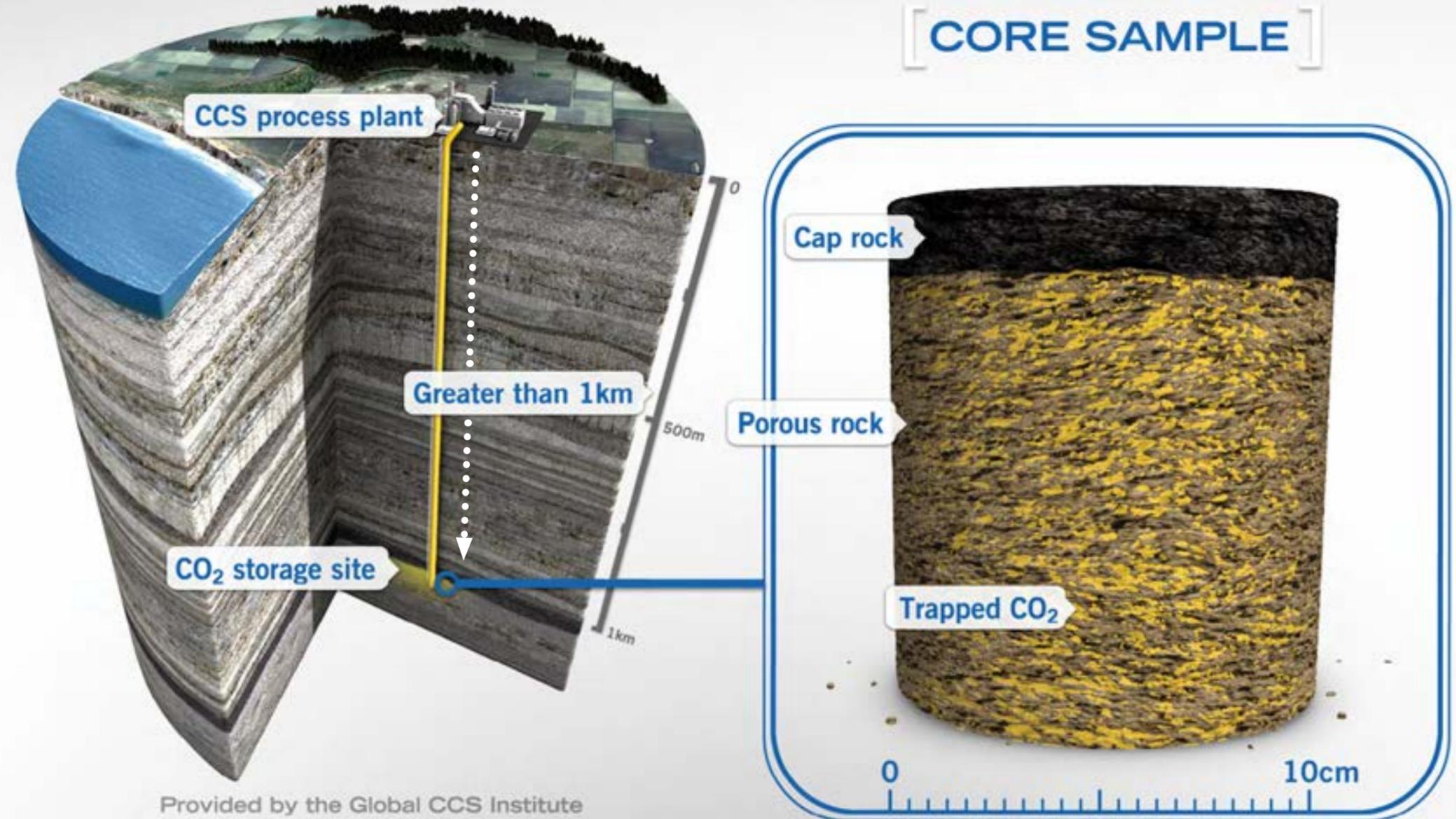
The storage capacity globally is significant. Based on geospatial data on sedimentary thickness and other parameters, total global storage capacity has been estimated at between 8 000 000 million tonnes and 55 000 000 million tonnes. While certain regions may have larger capacities than others, every region has more than enough permanent storage for its needs this century.

11.3.3 Enhanced geothermal power production

Enhanced geothermal production uses CO₂ as the thermal working fluid in a geothermal heating system, rather than conventional use of water. This scheme would allow targeting of certain reservoirs that are not well suited to water circulation and therefore would open up new areas to geothermal power, which is generally considered a reliable low carbon source of energy.

Alternatively, CO₂ is stored in nearby sub-surface formation to increase the pressure, and efficiency of water-produced geothermal energy. Downsides exist in the research regarding accurate modelling of the CO₂/reservoir interactions and has not been proven widely or deployed widely and at scale.

The volume of CO₂ stored, compared to the CO₂ generated by the cement and lime industries, is likely to be extremely limited – but is a means of increasing renewable power production. The CO₂ injected would be stored.



Reference

<https://www.globalccsinstitute.com/resources/ccs-image-library/>

11.3.5 Sub surface mineralisation

Enhanced mineralisation of CO₂ relies on the same calcination reaction used at LEILAC but in reverse to carbonate subsurface minerals. CO₂ injected subsurface into appropriate reservoirs will react with CaO, MgO and other materials to chemically fix and permanently sequestered CO₂ underground. This is analogous to the kind of mineral deposition seen at thermal hot springs where mineral rich water from subsurface react with atmospheric CO₂ to mineralise. This is a variation on the previously discussed oil and gas reservoir storage method, which is only physical or soluble storage in a reservoir, and not chemical. Concerns to be overcome with CO₂ mineralisation is preventing the blockage of flow paths for CO₂ to fresh minerals by those already carbonated.

11.4 Surface Storage

11.4.1 Building products and concrete enhancement

Using mineralised concrete products, CO₂ can be used in construction materials by dosing CO₂ into concrete during mixing and curing. The CO₂ binds to the calcium silicate clinker to form nano-scale CaCO₃ particles. This can reduce the amount of cement required to produce equivalent-strength concrete, and allows permanent fixing of the carbon as it is incorporated into the concrete. A likely application of this will be in precast concrete products where the CO₂ injection can be controlled and modularised. This is an attractive low OPEX way to fix CO₂, and the reaction kinetics favour the uptake of CO₂ carbonation in cement. However, ASTM and other standardisation organisations define the parameters/ characteristics of concrete mixtures rigidly and if CO₂ -based construction materials do not match those specific requirements, they may not be accepted for use, even when they exceed performance levels of traditional materials. Other future concrete mix designs may be developed that can hold even more CO₂ for the same performance if they can be accepted within the wider industry.

Such techniques need to be more fully developed, and will only be capable of storing a limited volume of the CO₂ generated by the cement and lime industries.

11.4.2 Recycled concrete fines – the circular economy

Similar to the above mineralised concrete products, the recycling of concrete fines back into the construction supply chain can reduce overall CO₂ emissions. Concrete from construction and demolition waste (CDW) is crushed and separated into aggregate, sand and cement paste. The aggregate and sand can go straight back to concrete production. The cement paste can be ground to a fine powder and returned to a cement plant for reprocessing. Some of the paste will have carbonated during the building's lifetime, with the remainder still being in hydrate form. These can be used as a raw material for clinker manufacture, with a lower embedded carbon content than virgin minerals, or carbonated to form new aggregates.

In the case of re-carbonation, the waste cement fines are carbonated with CCUS-derived CO₂ to fix the carbon and stabilise the mineral fines. This can be performed with cement fines from cement plants, too. The resulting carbonates are a valuable product in their own right that can be sold commercially. This is an attractive low OPEX way to fix CO₂, and the reaction kinetics favour the uptake of CO₂ carbonation in cement. Such techniques need to be more fully developed, but are extremely promising, and are critical for our society's circular economy. However, it is expected that they will only be capable of storing a percentage of the total volume of the CO₂ generated by the cement and lime industries.

11.4.3 Plastics

Plastics and polymers can also play a role in carbon storage through direct inclusion of CO₂ into the polymer matrix of various materials. Research and pilot plants are ongoing to develop a process that imbeds CO₂ within the polymer chain of polyols used in the manufacture of foams for products such as mattresses. Potential for newly developed metal catalyst systems allow efficient synthesis of CO₂ based polymers, polycarbonates and polyurethanes from copolymerization of CO₂ and epoxides. The physical and chemical properties of CO₂ based polymers may be tailored, which help to pave the way from lab-scale to practical applications, such as biodegradable disposal bags. Such techniques need to be more fully developed, and will only be capable of storing a limited volume of the CO₂ generated by the cement and lime industries.

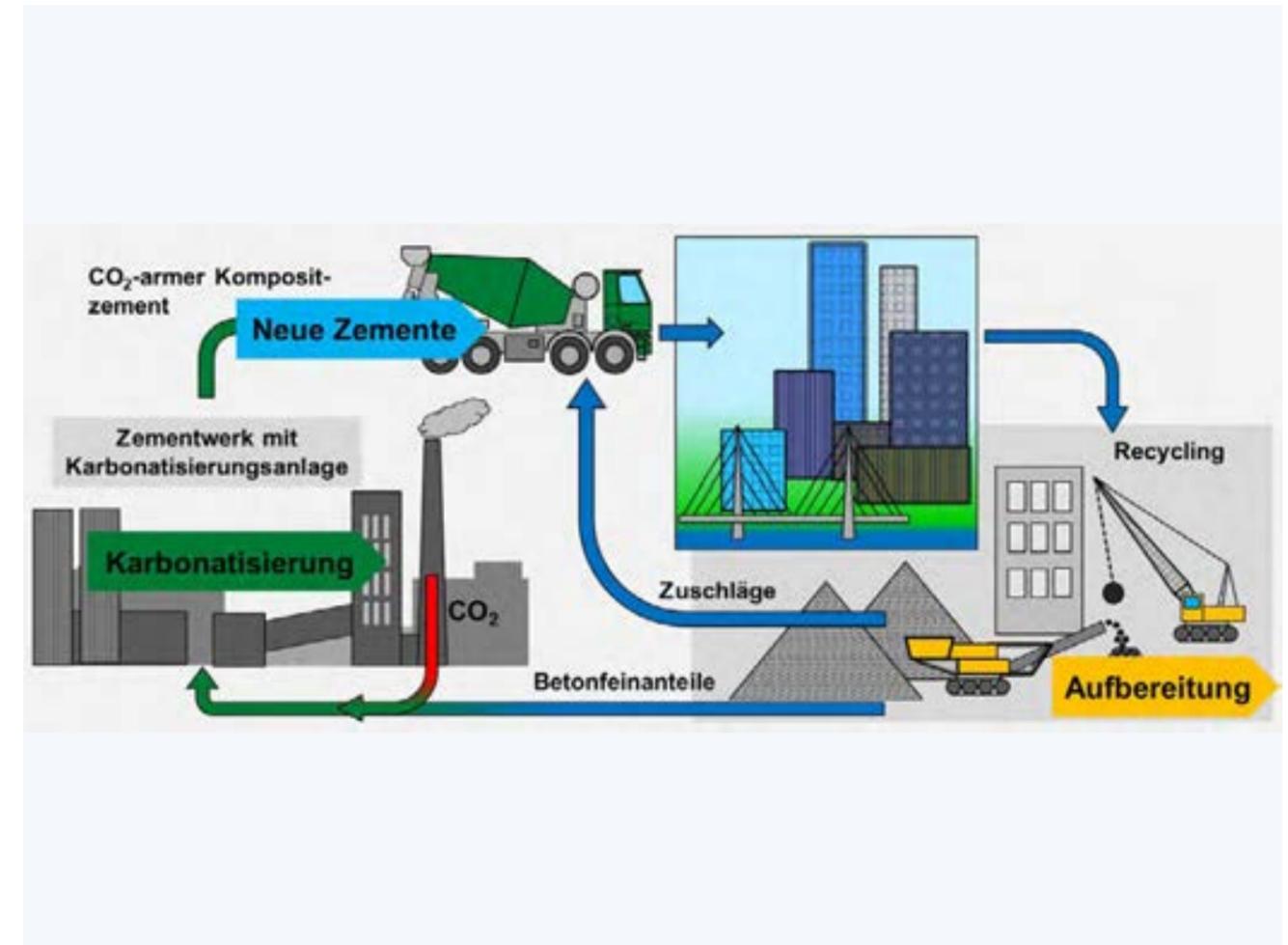


Figure 18 - Diagram regarding the C2inCO₂ project[44]

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11.5 Storage and use costs and outlook

As can be seen from the section above, there are a very wide range of variables that can impact the techno-economic assessment of a given CCUS operation.

Within this paper, the techno-economics of the various Usage options will not be assessed, as in those cases the CO₂ is treated as being 'emitted' under the current EU Emissions Trading System. While providing an extremely important source of income and transition for regions without a price on emitting carbon, given the volumes of CO₂ that need to be permanently sequestered – this study will focus on the current literature regarding subsurface permanent storage. It has the greatest degree of capacity, there is a lot of expertise and it is a well-known technology. In addition the IEA estimates that 70% of emissions are within 100 km of potential sub-surface storage in key regions.[45]

Costs

There have been a large number of significant studies regarding the costs relating to transporting and storing CO₂. In regions, such as the US, where pipeline infrastructure was put in place with public sector money in the 1970s to facilitate EOR, the prices for transport – and the income from offtake agreements – are relatively know and stable. For regions where infrastructure needs to be developed, these costs vary greatly. Even on the specific instance of purity and compression for injection, an overly onerous requirement can add many millions of euros of capital and operational expenses to move a tonne of CO₂ – which may restrict the ability of the industry to decarbonise.

While a baseline case of around €7 per tonne of CO₂ is used for storage, this is a major variable. This represents a 'low cost transport and storage scenario', (excluding initial compression). Major studies supporting this include an in depth assessment made by the Zero Emissions Platform in Europe, and the IPCC.[46][47]. They foresaw storage costs range from €1 to €20 depending on location and storage type.

However, it is expected that first movers, or areas with transport/storage operators with limited capacity, the costs may be much higher. For this reason, within the 'high cost transport and storage scenario', a transport and storage estimate has been made of €50/tonne of CO₂ (excluding initial compression).

The dramatic variance in these transport and storage costs illustrate the need of low-cost solutions.

The vital component for decarbonisation of the cement and lime industries is through the development, and availability, of storage infrastructure. Unlike other industries, the volume of CO₂ to be stored is minimal. This opens local storage opportunities and industries – but given the very small size of most of the cement and lime players, steps must be taken to quickly develop storage sites; ensure storage developments are appropriately sized for 2050 (particularly if using public money and only facilitating bigger players); and enable free and fair access.

11.6 Compression and transport Options

Once CO₂ has been captured, it is necessary to transport it to its destination.

The previous section has given an indication of how the CO₂ may be Used or Stored. The distance between a capture plant (source) and where the CO₂ is destined may be a matter of meters, through to thousands of kilometres.

There are several different means of moving CO₂ – primarily via pipeline, barge, ship, rail, or by truck. These transport options vary in their feasibility depending on the volume of CO₂ that needs to be moved, the distances and the geography involved.

These 'transport' options also have several different requirements, including purification and operational requirements.

All these variables have a profound impact on the impact and economics of a given CCUS project.



One of the key conclusions of this assessment is that CO₂ storage availability is vital to enable industrial decarbonisation, and without it the ability for our society to reach its climate change ambitions will be limited.

Governmental assistance is critical in developing solutions at large scale, and ensuring their free and fair access to smaller players – is essential.

Photographed by: Paul Poels

11.6.1 Pipeline transport

Pipelines can be extremely effective means of moving very large volumes of CO₂ over both short and long distances.

Should the distance between the captured CO₂ and its destination be short – potentially within meters – the sizing of such pipelines is largely immaterial and can be moved cheaply and simply at effectively atmospheric pressure.

Should the CO₂ need to be transferred be ‘offsite’, CO₂ pipelines are an extremely effective and safe way of moving substantial volumes of CO₂. An immediate analogy can be made to our society’s natural gas pipelines – and natural gas lines can even be recommissioned for use in transferring CO₂.

In order to ensure that the CO₂ pipelines are as small as possible, such systems typically require the CO₂ to be compressed to become supercritical or ‘dense phase’ fluid between 10-20 MPag. At these pressures the CO₂ retains the properties of gas (i.e. viscosity) but a density closer to a liquid, allowing transport of large volumes in small diameter pipelines.

CO₂ has been extensively transported safely and effectively since the 1970s, with the US having an extensive network of over 4,000 miles of CO₂ pipelines.

11.6.2 Shipping, barging and rail transport

Ships and barges can be extremely effective means of moving relatively large volumes of CO₂ over inland waterways and connecting to offshore storage sites.

11.6.3 Trucks

Trucks can be an effective means of moving small volumes of CO₂. While typically generating their own substantial emissions, they are often the only means of supporting certain applications – particularly when the CO₂ is being Used.

11.6.4 Blowing (Pipelines)

With CO₂ being generated at atmospheric pressure, one of the simplest (and cheapest) means of moving the CO₂ is by using low pressure (LP) boosting fans and blowers.

Such LP units are used primarily to induced draft or pressure boosting of the near atmospheric pressure CO₂ from the capture system via pipeline. By creating a slight positive pressure, the CO₂ can be transferred to the main CO₂ user (or HP compressor).

Such low pressure units are very cheap and effective, but are only relevant for movement of CO₂ over short distances.



11.6.5 Compression (Pipelines)

High pressure (HP) injection and transfer compressors are required where the destination of the CO₂ is either not nearby – or requires compression to enable its use or storage. Large HP compressors which are designed to discharge in the >10 MPag range do not perform well when also required to operate at vacuum at the suction side. The HP compressors tend to be multi-stage compression units, up to 8 stages depending on type and required discharge pressure needed for its transportation or storage.

Each compressor type has its own benefits and limitations so will be a case-by-case techno-economic analysis. Options include: high/low speed reciprocating, dry/oil flooded screw to centrifugal back-to-back/integral gear. As well, the compressor will need to be electric or steam drive from a renewable source to avoid additional carbon penalty of a gas/diesel driven engine.

Supercritical pressure can be achieved purely by compression, or once at supercritical density, a CO₂ pump. Higher concentrations of contaminants (CO, N₂, O₂, VOCs, etc) require colder temperatures and higher pressures to liquefy or higher pressures to achieve supercritical conditions and therefore negatively impact the performance of these systems.

11.6.6 Liquefaction (Shipping, train and trucks)

Liquefaction plant, which compressors and cools the CO₂ into a liquid phase at approximately -20°C and 1500 kPag. This greatly increases the density of the fluid, allowing large volumes to be transported. This would be analogous to the transport of LNG or CNG, which operate under similar philosophies and are both established and proven technologies.

If transported via ship, barge, train, or truck, the capture plant will most likely need a liquefaction plant, which compressors and cools the CO₂ into a liquid phase at approximately -20°C and 1500 kPag. This greatly increases the density of the fluid, allowing large volumes to be transported. This would be analogous to the transport of LNG or CNG, which operate under similar philosophies and are both established and proven technologies.

11.6.7 Purification requirements

For certain applications, particularly when a high CO₂ quality is demanded – for example food grade applications, urea production, or chemical uses - higher cost equipment may be required (for example to ensure no oil from the compression system contaminates the CO₂).

An algal bioreactor for example is already a water wet environment and operates at atmospheric pressure so is not concerned about dehydration. Therefore most 'wet' CO₂ systems operate with HDPE or fibreglass at low pressures.

HP multistage compressor will likely need to be dehydrated for operational and economic reasons. This is done primarily because water entrained in the CO₂ will condense into a free liquid which will form corrosive carbonic acid in a CO₂ rich environment. At high pressures it is more economic to dehydrate and use carbon steel than to use stainless steel everywhere (for example multiple kilometres of subsurface wellbore).

Any liquefaction system would have to remove water to prevent blockage from ice formation.

Dehydration technology is well-established in other industries such as oil & gas and would have to undergo a techno-economic analysis based on the specific dehydration requirements. Common technologies to remove water are: triethylene glycol circulation, refrigeration cooling and temperature swing adsorption.

11.6.8 Safety requirements

Safety is also concern when dealing with CO₂, especially in industries such as lime and cement which do not typically yet have experience with high-pressure gases. The installation of CO₂ capture, handling and transport storage will need to comply with both local regulations and industry best practices to ensure the safety of the site personnel and surrounding communities. Typical plant design practices such as HAZOPs can be used to identify and mitigate risks, with site installation location and appropriate safety systems installed for alarm and shutdown prior to or during a loss of containment scenario.

11.7 Compression and transport costs

As can be seen from the section above, there are a very wide range of variables that can impact the techno-economic assessment of a given CCUS operation.

For the purposes of an open, but meaningful, assessment a 'likely' scenario, and optimal 'low cost' scenario are presented below to given an indication of the possible range of costs that may be incurred from moving the captured CO₂. Even on the specific instance of purity and compression for transport, an overly onerous requirement can add many millions of euros of capital and operational expenses to move a tonne of CO₂ – which may restrict the ability of the industry to decarbonise.

While a baseline case of around €9 per tonne of CO₂ is used for transport, this is a major variable. This represents a 'low-cost transport and storage scenario', (excluding initial compression). Major studies supporting this include an in-depth assessment made by the Zero Emissions Platform in Europe, and the IPCC. They foresaw transport costs range from €4.50/tonne to €13/tonne CO₂ for pipelines and ships.[48][49]

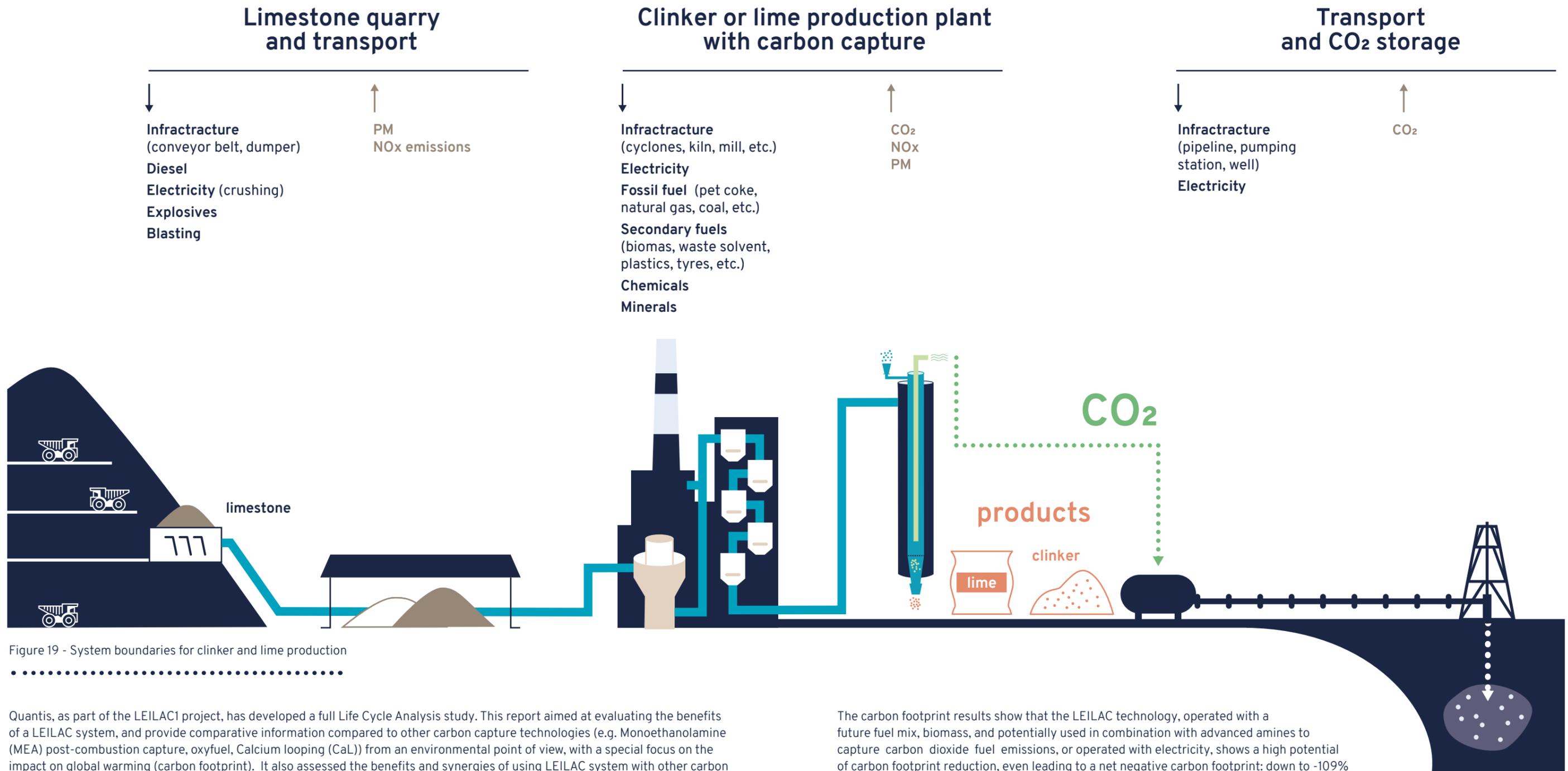
However, it is expected that first movers, or areas with transport operators with limited capacity, the costs may be much higher. For this reason, within the 'high-cost transport and storage scenario', a transport and storage estimate has been made of €50/tonne of CO₂ (excluding initial compression).

The dramatic variance in these transport and storage costs illustrate the need of low-cost solutions, and governmental assistance in developing solutions at large scale – ensuring their free a fair access to smaller players.

The vital component for decarbonisation of the cement and lime industries is through the development, and availability, of transport infrastructure connecting to storage sites. Unlike other industries, the volume of CO₂ to be stored is minimal, and may only contribute a portion of the CO₂ in a hub. This opens local storage opportunities and industries – but given the very small size of most of the cement and lime players, steps must be taken to quickly develop infrastructure; ensure CO₂ quality and transport developments are appropriately sized for 2050 (particularly if using public money and only facilitating bigger players); and enable free and fair access.

One of the key conclusions of this assessment is that CO₂ transport requirements and availability (particularly in the case of networks or hubs) is vital to enable industrial decarbonisation, and without it the ability for our society to reach its climate change ambitions will be limited.

12 Life Cycle Analysis (LCA)



Quantis, as part of the LEILAC1 project, has developed a full Life Cycle Analysis study. This report aimed at evaluating the benefits of a LEILAC system, and provide comparative information compared to other carbon capture technologies (e.g. Monoethanolamine (MEA) post-combustion capture, oxyfuel, Calcium looping (CaL)) from an environmental point of view, with a special focus on the impact on global warming (carbon footprint). It also assessed the benefits and synergies of using LEILAC system with other carbon capture techniques.

Through the use of LCA Life Cycle Assessment (LCA), the environmental performance of the LEILAC technology has been quantitatively compared to a technology without capture and other carbon capture technologies through several key indicators: Greenhouse Gas (GHG) emissions or carbon footprint, non-renewable primary energy use (energy footprint), water use (water footprint), but also impacts on human health and impacts on the ecosystem. This study assesses the life cycle of clinker and lime from the extraction and processing of all raw materials through the end-of-life of all components as well as future time horizons.

The carbon footprint results show that the LEILAC technology, operated with a future fuel mix, biomass, and potentially used in combination with advanced amines to capture carbon dioxide fuel emissions, or operated with electricity, shows a high potential of carbon footprint reduction, even leading to a net negative carbon footprint: down to -109% of the 2020 baseline production for clinker and to -113% for lime. Other environmental indicators such as non-renewable primary energy use (energy footprint), water use consumption, impacts on human health and impacts on the ecosystem confirm this trend, and show that LEILAC, as it uses few additional inputs, can reduce the other environmental impacts compared to the other assessed alternatives.



Key Conclusions

All carbon capture technologies enable the reduction in the carbon footprint of clinker and lime production compared to any clinker or lime production alternative without carbon capture. However, they differ in the quantity of energy required for carbon capture as well as the amount of carbon to be captured, i.e. MEA and calcium looping are more energy intensive to operate than other technologies.

The entire LCA report prepared by Quantis accompanies this report.



13 History, current state of the LEILAC technology

13.1 LEILAC1 results

The LEILAC1 project aims to apply a breakthrough low-cost carbon capture technology that will enable both Europe’s cement and lime industries to reduce their emissions dramatically, while increasing their international competitiveness.

The project’s first objective is to demonstrate that Calix’s LEILAC technology can be applied to the cement and lime industries, and that it can capture over 95% of the CO₂ process (carbonate) emissions (or ~ 60 % of a plant’s total CO₂ emissions if it is heated using coal) without significant energy penalty or capital cost. Doing this has required the development of, and testing on, a pilot plant designed to operate at up to 240 tonne per day input (tpd) and directly separating 85 tpd of process CO₂. The pilot is being hosted by Heidelberg Cement at Lixhe in Belgium.

The ‘Operational results’ paper includes more details, and depth about the issues faced, but the main conclusions are:

- The pilot was successfully and safely built to its original budget and on time;
- Proven operations with limestone and raw cement meal;
- Separation of CO₂ (>95% purity) directly from the LEILAC unit, with no air ingress or loss of containment;

- Heat transfer from the furnace to the powder in the tube, to achieve extents of calcination of more than 85% (98%+ demonstrated in Calix units, and expected with enhancements);
- The energy requirement for indirect calcination is not higher than direct calcination (disaggregated from the entire system) – thus the efficiency of the technology can approach current non-CO₂ capture BAT efficiencies, subject to successful heat integration.
- No additional processes or chemicals are required;
- There is no build-up of material on the tube’s walls, inhibiting the indirect calcination process;
- There have been no negative impacts on the host plant, and no impact on its clinker production;
- The LEILAC units can safely perform at the temperatures required.

The primary and most important technical risks associated with LEILAC technology were addressed. Further steps have been, and are, required to run the plant at its full designed capacity, but the process is working – heat is transferred to the raw material, and the pure CO₂ that is released through this calcination has been kept separate from the flue gases. The fundamental basis for this new carbon capture technology for the cement and lime industry has been proven.

13.2 LEILAC2 details and progress

The LEILAC2 project (Low Emissions Intensity Lime And Cement) is a 4 x scale up of the LEILAC 1 pilot, taking 20% of the host plants raw feed, and will be developed on a HeidelbergCement plant in Hannover, Germany.

LEILAC2 will develop, build, operate and test a 960 tonne per day demonstration plant at HeidelbergCement's plant in Hannover, Germany. The project objectives, as outlined within the H2020 Grant agreement, are to construct a Demonstration Plant to:

- Capture 20% of a full-scale cement plant's (and 100% of a large lime kiln's) process emissions – capturing around 100 ktpa of pure CO₂ for minimal energy penalty (just compression).
- Prove the effective retrofit and full integration of the Demonstration Plant into the host cement plant's operations.
- Prove the efficiency and stability of the complete cement-kiln process and resulting clinker quality when operating largely on LEILAC calcining technology.
- Prove that the Demonstration Plant forms an easily replicable modular design for scale-up – enabling the accelerated full-scale commercial deployment.
- Seek to demonstrate the use of alternative fuels (such as biomass) and electricity for the calcining process, enabling a calciner/lime kiln to be zero-emissions.
- Demonstrate the ability for fast ramp up/down times for the process using electricity (switching rapidly from fuel to electricity), allowing a cement plant to undertake load balancing of renewables on the grid – enabling the electrification of the cement industry and a resulting low cost, local, and effective solution for grid stability with high renewable use.

The project has recently passed its Preliminary Front End Engineering Design (pre-FEED) phase. As with LEILAC1, the methodology underpinning

the Pre-FEED phase and wider project, is based on the close collaboration between consortium partners and a number of different aspects (R&D, Engineering, business case development and social engagement) to develop a successful outcome.

The resulting basis of design was assessed in March 2021 in detail by an external Value Assurance Review panel of industry experts, over the course of two weeks. It was also reviewed and approved by the project's Executive Board. It was then finally reviewed and approved by the project's General Assembly.

13.2.1 LEILAC2's Pre-FEED cost estimates

The budget for the Demonstration plant design and construction is split across grant funding under the European Commission H2020 grant agreement, cash contributions from industrial partners and in-kind contributions for staff by all partners. The Demonstration plant build itself is expected to be around €16m.

A detailed process and techno-economic model has been developed, to provide OPEX analysis to feed into the options analysis work. This model has been validated against the process model.

This modelling provides details of the additional OPEX requirements over and above the Hannover host plant, both in terms of EUR/t.clk-e (euros per ton of clinker equivalent) and EUR/t.CO₂. This information has been modelled for a range of scenarios, and the results of the BoD scenario, and some alternative heating options.

Key Conclusions:

Detailed modelling has been undertaken, should the design work as planned, it is anticipated that the LEILAC2 would separate at a cost in the order of €10/t CO₂ extra OPEX (excludes compression costs and CAPEX depreciation costs, etc., which are expected to be in the region of an additional €10-€15/t CO₂).

13.2.2 LEILAC2's capture cost outlook

The LEILAC Consortium have endorsed the LEILAC2 pre-FEED study. This was for a first-of-a-kind retrofit. Further design, work and testing is required – but should the design work as planned, detailed OPEX modelling within the pre-FEED study indicated that the LEILAC2 may separate CO₂ at a cost of around €10/t CO₂ extra OPEX (above the host plant's operating costs). This excludes compression costs and CAPEX retrofit depreciation costs (including foundations, installation, structure), etc., which are expected to be in the region of an additional €10-€15/t CO₂. (Compression costs will change greatly depending on the fate of the CO₂)

Therefore, total costs of this first-of-a-kind LEILAC carbon capture plant is expected to be in the region of €20-25 /t CO₂.

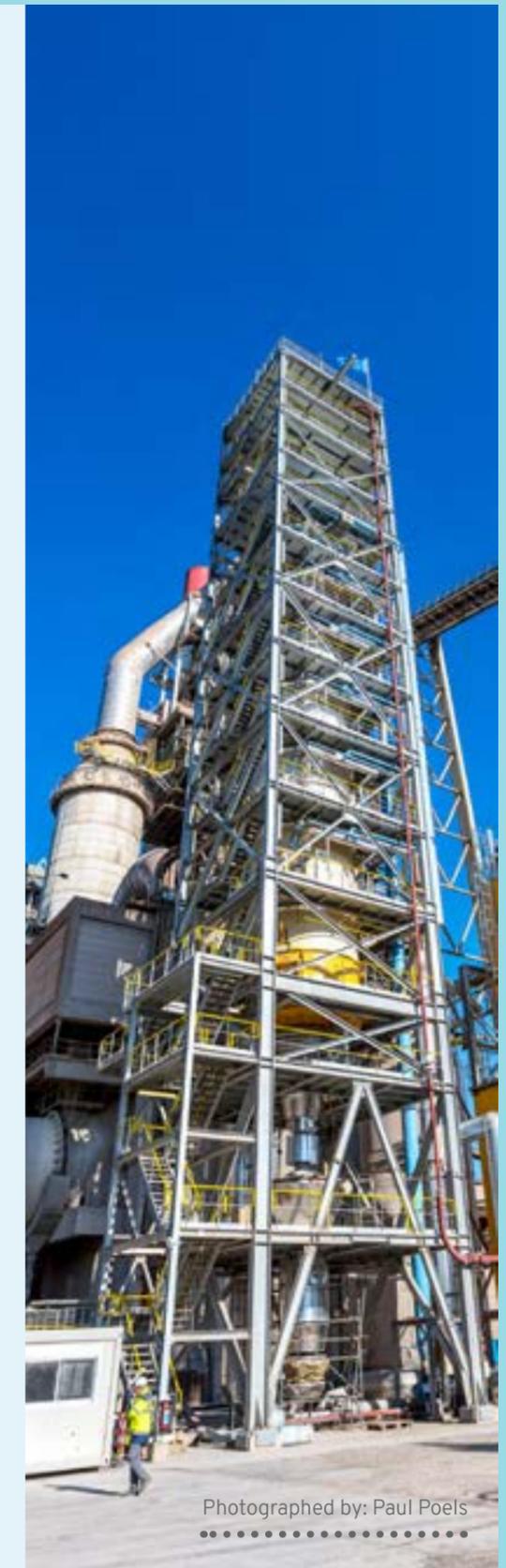
In future projects, there is opportunity for the OPEX to be reduced further, as better heat integration could be pursued (for example the LEILAC2 Demonstration plant has minimal insulation, does not use kiln off gases, nor recovers energy from the CO₂ etc.). A future retrofit would, for example, use the heat in the CO₂, and further reduce the cost.

In addition, the OPEX does not take into account income from load balancing grids. Should that work, the capture plant may receive an income of €10-20/t CO₂ eq. (a case study for Belgium in 2019 suggested an income of €11/t CO₂ eq.)

The CAPEX for LEILAC2 is expected to be in the region of €16m.

A LEILAC system is expected to cost in the region of the CAPEX for a full scale (3000 tpd clinker) retrofit implementation may be in the region of 66-74 M€. When considered as part of an otherwise planned upgrade of a site, the net cost may be around 33-44 M€ and is the upgrade assumption has been used in the "retrofit analysis". Both are illustrated in Figure 16.

On a greenfield site when it is part of the planned installation – net costs are expected to be in the range of 27-34 M€.



Photographed by: Paul Poels

14 LEILAC full scale implementation and rollout

14.1 Project development outline

The LEILAC technology is proven at 25ktpa CO₂ capture volume and scaling up to 100ktpa is underway to develop a module that should form the basis for commercial roll out – supporting cement and lime plants at any scale. Planning for a full-scale implementation, at 400ktpa CO₂ capture and beyond is already underway.

As can be seen from section 9.1, this type of capture technology is integrated into normal production process, the capital and operational expenses may vary by specific plant, level of integration, fuel use, and compression requirements. There are multiple options, ranging from fuel type to level of heat integration.

14.2 Roll out strategy – enabling rapid global deployment

To enable the roll out of the technology globally and as quickly as possible in support of the global climate change goals, Calix will not be the engineering provider for the majority of installations.

Technology will be licensed to customers and delivered by their preferred engineering company. These 'owners engineers' are anticipated to be the very large engineering companies behind many of the CCUS project developments being undertaken globally, and/or cement and lime plant design engineering companies.

With LEILAC1, a first of a kind pilot, it was clear that the LEILAC technology is relatively easy to build. As has been found with the LEILAC1 and LEILAC2 installations, the capital costs (CAPEX) are relatively small, and most of the costs relate to the structural steel, foundations, and installation. These costs are regionally specific, and may require locally adjustment from western European pricings. As such, the "LEILAC Technology" primarily centres on the tubes themselves, which are a minor cost and engineering component of a commercial build.

The intent is that the LEILAC modular design, largely developed for LEILAC2, is rolled out at scale over the first 5 projects. Initial planning for such full-scale installations is already underway.

The learnings from those deployments will form, effectively, a set of blueprints for such owners-engineers to use.

The approach to rollout is therefore in two stages: The first set of full scale projects will be used to finalise the first set of 'blueprints' for an easy-to-replicate module and find design solutions for the most likely integration options and issues. All subsequent projects should then use the technology just under licence, with owner-engineers being supplied with the necessary 'blueprints' and learnings to enable rapid and global deployment.



14.2.1 Project development strategy for initial full-scale application

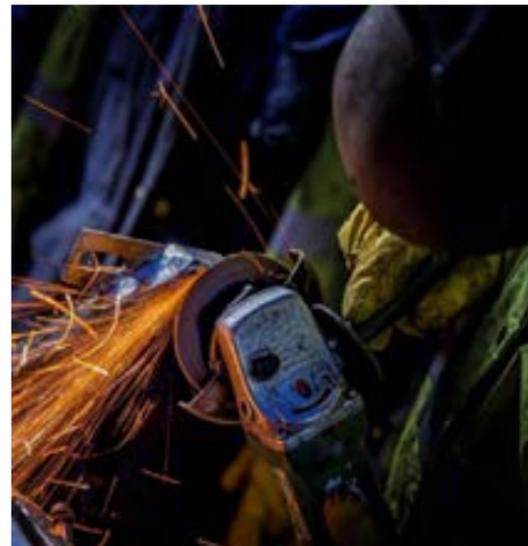
Following successful development of the LEILAC2 module, a full scale application will be primarily based on utilising a number of such modules. There are a wide variety of options for such full-scale application, including stacking such modules, increasing the number of tubes per module, arranging them around existing infrastructure etc.

Each implementation will require customization to the particular needs of the customer and location in question. To enable retrofitting in particular, the principal strategy is to ensure that there is minimal interruption of existing cement plant operations. As such, the modules are designed to be installed alongside existing pre-calciners, with tie-ins being created during conventional annual maintenance windows. The units will then be incrementally commissioned, ensuring that they work correctly, before being fully integrated.

As has been demonstrated with the LEILAC 1 and 2 projects, such full-scale applications will undertake standard engineering stage-gated processes to ensure that the technology can be successfully applied. There are a number of different configurations that can be used to retrofit a LEILAC installation, and a great number of options for transports, storing or using the captured CO₂ – and creating a full-chain solution is extremely important.

LEILAC projects are structured to follow standard engineering phases and stage gates to ensure that the engineering design and development provides the level of detail and accuracy required to fully understand how the Calix technology can support the implementation of decarbonisation, with confidence around development costs and time frames, as well as any technical risks. A significant amount of work will take place early within the project, during Pre-FEED, to understand and mitigate any technical challenges or project risks, with a focus on risk mitigation and technical validation.

For now, LEILAC team is closely involved in scoping work and providing support to pre-FEED and FEED studies. The engineering development stages, and indicative timings, are shown below. Development timelines will reduce as industry experience grows. As uptake increases, much of the requisite work can be undertaken by third party engineering consulting businesses.



Photographed by: Paul Poels
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Photographed by: Paul Poels
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14.2.2 Blueprinting to enable global rollout

The learnings from those deployments will form, effectively, a set of blueprints for such owners-engineers to use.

With LEILAC modules are designed to be relatively easy to build. By ultimately proving just blue-prints, this enables the use of any engineering company globally to construct LEILAC installations. This acts to disassociate the rapid rollout of the technology from any one company’s engineering staff, which is always going to be geographically limited. This approach to having a ‘blueprint’ for a wide range of companies to use (with a royalty rate based on installed capacity to Calix as the technology developer) is multifaceted:

- It is designed to enable all cement and lime plants to have a viable option for carbon capture technology installation easily without engineering staffing constraint.
- This approach therefore gives industry, and society, a chance at reaching our decarbonisation targets. It also allows local expertise, and know-how, to be fully used- rather than relying on Calix (which is an SME).

14.3 Technology conclusion

As mentioned, there is an effective strategy being developed for the rapid rollout of low-cost carbon capture. To reach our climate change ambitions, the IEA predicts that “the projected pace of deployment is equivalent to an average of 41 new 2 Mt annual capacity cement plants (existing or new-build)

around the world being equipped with CO₂ capture equipment every year – or nearly one every week – over the period 2030-70.”[50] This is a staggering requirement, and requires new means of low-cost, rapid deployment – that the LEILAC technology seeks to contribute to.

The LEILAC costs, both for OPEX and CAPEX, are relatively low for a carbon capture technology. Unlike other capture technologies which separate gases from gases, the LEILAC technology stops the CO₂ released from the limestone mixing in the first place – and does not require additional resources (chemicals, energy or processes) to do so. They can use a variety of fuels, and can work in synergy with other capture technologies. The LEILAC systems are being designed to be easy to use, safe, quick to deploy – using local engineers with a blueprint design, and not interrupt operations when being retrofitted to existing plant.

As has been indicated, even for the very initial projects – which are typically at higher cost than commercial deployment – the primary issues that are expected to inhibit rollout are external to the technology:

- that sufficient incentive mechanism are developed;
- that transport and storage infrastructure be put in place, that is low cost, of sufficient capacity, and accessible by all industrial emitters;
- that both governmental and non-governmental support be given for this environmental technology.

15 LEILAC Roadmap from 2025 to 2050

Should the LEILAC technology development go as planned, facilitated by global rollout by local engineering expertise, then capturing the unavoidable process emission from the cement industry may be achievable at low cost.

Some indicative costs for such capture are indicated within section 15. To facilitate rollout, creating viable business cases for individual projects, decarbonisation of the cement and lime industries will then be fully dependent on three elements:



Developing sufficient, low-cost, accessible CO₂ transport and storage infrastructure



Developing sufficient incentive mechanisms



Acceptance by society for these decarbonisation efforts



Support from regional and national governments

15.1 Summary of possible full chain LEILAC CCS costs

A nth-of-a-kind LEILAC system in Europe may be deployed, at full scale in Europe, for the numbers indicated in section 10. As indicated, there is further development required to apply the technology at full scale, and there are a wide range of costs associated with capturing the CO₂ from any given lime or cement plant using this technology, depending on the integration approach taken, region, and fuel. Primarily on the basis of the anticipated costs for a first-of-a-kind LEILAC2 retrofit installation, capture costs may be around 25 €/t of CO₂ including liquefaction and capital costs.

It is expected that such a system will produce CO₂ at relatively high quality (>97%). There are a very wide range of storage or use options (see section 13), and a variety of means of transporting the CO₂ to its destination. Should a facility mineralising the CO₂ be available near the capture plant, then there would be no requirement to further purify and compress the CO₂ – it could be simply blown to the factory.

Should a geological storage facility (for example a saline aquifer or depleted hydrocarbon site, etc.) be available, then the CO₂ could be simply compressed at low cost, and injected as required.

In the above examples, a full chain CCUS cost would be minimal – with the costs primarily comprising of the energy required for local compression, and operational costs such as for CO₂ monitoring and insurances. The costs may be in the region of €1-4/tonne of CO₂.

In most cases, it is anticipated that local storage is not possible. The costs will then be largely dependent on the transport means, its volume and state, tariffs associated with transport, and tariffs associated with storage. The costs of such transport and storage vary dramatically, particularly over time as the infrastructure and business models supporting this activity are developed and become established.

For nth-of-a-kind deployment at a reasonable scale:

- transport costs are anticipated to range from €4.50/tonne to €13/tonne for pipelines and ships.[48][49]
- Storage costs range from €1 to €20 depending on location and storage type.[46][47] The storage costs, for example in the case of EOR, can even be negative.

As such, within the ‘low cost transport and storage scenario’, a transport and storage estimate has been made of €15/tonne of CO₂ (excluding initial compression).

However, it is expected that first movers, or areas with transport/storage operators with limited capacity, the costs may be much higher. For this reason, within the ‘high cost transport and storage scenario’, a transport and storage estimate has been made of €50/tonne of CO₂ (excluding initial compression).

However, taking a reasonable case transport and storage scenario, and near-term LEILAC cost, it is currently anticipated that a LEILAC CCUS system may capture and store CO₂ for around €40/tonne of CO₂.



15.2 CO₂ reduction policies and incentives geographically

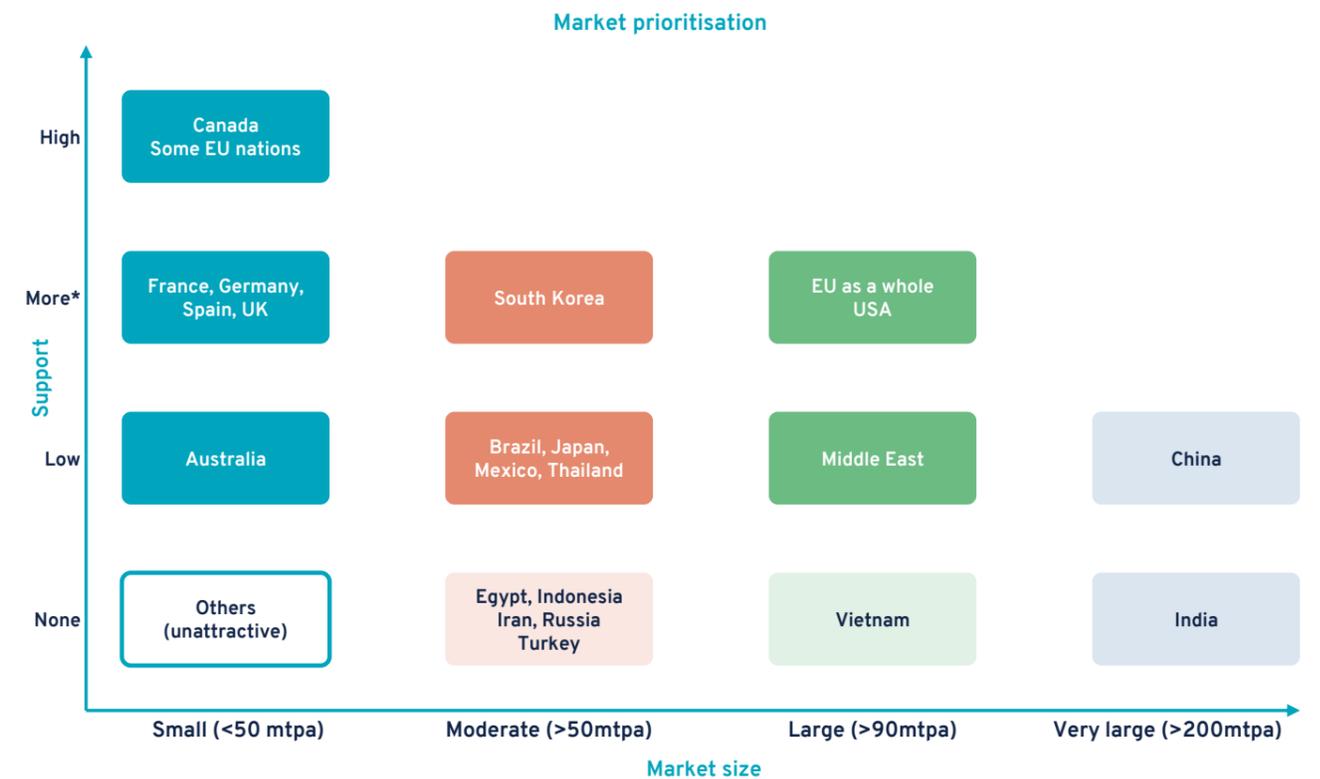
LEILAC's immediate focus is on large markets with established carbon pricing regimes and/or similar mechanisms. Not all of these mechanisms are, nor need to be, based on financial support or penalty, and it possible that in certain regions CO₂ capture and storage may just be mandated. Nevertheless, a number of measures are in place that are starting to set incentives at a rate that will enable CCUS projects to progress

Matching incentive mechanisms to the cement and lime production rates of those regions is of importance, and can serve to illustrate where the initial movers will be.

Global carbon pricing snapshot

Country/region	Cement production	Price at Apr '21*	Expected changes	Net zero**?	Basis of scheme
European Union	187 ktpa	c. €40	Rising to meet new 2030 targets	2050 (legislating for EU. In place in France, Germany)	Phase IV runs to 31/12/2030. Currently provided ETAs for 'free', they can be sold if the CO ₂ is stored. In Phase V, the ETS may just represent a liability to the industry
USA	106 ktpa	US\$35 (see note)	Increased funding support	2050 (announced)	US provides 45Q tax incentives worth US\$35-\$50/tonne
Brazil	65 ktpa	No regime	Measures under discussion	None	ETS scheme under consideration. Targeting 43% below 2005 levels by 2030
Japan	60 ktpa	¥289	Possible price of ¥5,000	2050 (announced)	De minimis carbon tax at present. 346 local governments committed to net zero by 2050
South Korea	55 ktpa	c\$17	Market-based scheme	2050 (announced)	World's second largest ETS
Mexico	47 ktpa	MXN39.8	ETS in pilot phase	2050 (announced)	Pilot ETS covers 300 entities, c 40% of national emissions
Thailand	40 ktpa	No regime	ETS under consideration	None	ETS under consideration. Intension to reduce emissions by 20% by 2030
Canada	14 ktpa	C\$40	C\$150 in 2030	2050 (legislating)	Price increases are legislated
Australia	12 ktpa	Nil	Market being investigated	2050 (indicated)	State-based commitments but no national commitment (yet)
UK	11 ktpa	c. €40	Expected to increase	2050 (legislated)	Membership of EU scheme to be replaced by new legislation. Current carbon price floor £15

*Total of lime and cement ** Nation committed to net zero emissions? † Price per tonne - source <https://icancarbonaction.com/en/ets-prices>



These markets are politically created, in order to reach our climate change ambitions, and can change very quickly. The EU and NA are currently areas of large political support and large market size, enabling early-mover CCUS projects in the cement and lime sectors.



15.3 Cement and lime sectors geographically

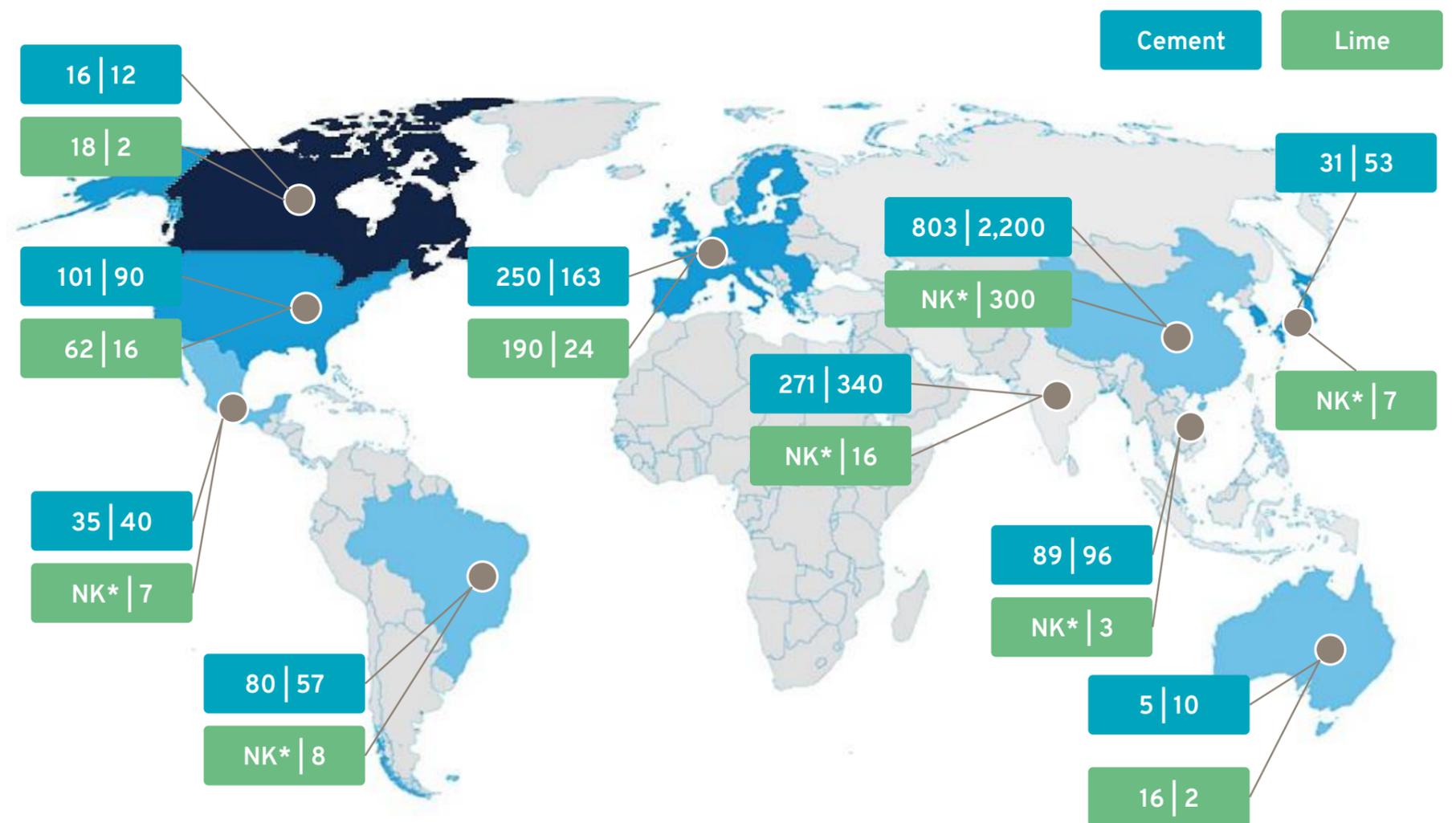
However, as noted within section y, almost all major cement companies have made pledges to achieve net-zero cement and lime production by 2050 – and are therefore taking action outside of political and market mechanisms. Combined with the approach being taken for the roll-out of LEILAC (allowing lime and cement companies to choose their preferred an EPC contractor, who implements the LEILAC technology under licence), mean that every sector should, in theory, be able to uptake LEILAC systems relatively quickly.

The immediate focus is on large markets with established carbon pricing regimes and/or similar mechanisms to enable early uptake of carbon capture technologies. These regions are likely to support early mover projects, the EU has significant incentive mechanisms and support schemes to address the full chain CCUS costs associated with decarbonising the cement sector.

Key markets for lime and cement production:

Number of plants | millions of tonnes produced*

Lime and cement production: number of plants – millions of tonnes produced[51].



15.4 CO₂ storage geographically (large scale storage capacity exists in almost all major target markets)

There are a very wide range of either using or storing CO₂ (see section 11). Given the long- term objective of full decarbonisation, permanent geological storage options are expected to be the primary means of ensuring CO₂ generated from the production of lime or cement does not reach the atmosphere, and is the critical enabling step for large-scale emissions reductions.

According to the IEA, under their net-zero emission pathway scenario, CO₂ transport and storage industry will develop, handling and storing 5000 Mt/year of CO₂.

There have been extensive studies regarding the global storage capacity, with assessment improving in their accuracy over time. At a global level, it is anticipated that there is more than enough storage capacity to address all of the world’s industrial emission for centuries.

Ensuring that such activities are safe is of great importance. Regulations are in place in many areas, particularly in the EU with the Storage Directive which has been transposed into all Member States’ legislation.

Essentially, CO₂ that has been captured (e.g. through a LEILAC system) is compressed, and then injected to a great depth below the earth’s surface. The CO₂ is then ‘stored’ in a reservoir of porous rock located under a ‘cap rock’ made of multiple layers of impermeable rock. This ‘cap rock’ ensures that the CO₂ cannot escape. As noted, there are multiple types of sub-surface reservoirs capable of permanently trapping the CO₂, with deep saline formations and depleted oil and gas reservoirs having the largest capacity.

A wide range of experiences with CO₂ storage has been developed on a global basis, and significant scale.

- In the USA, the technology has been in use since the 1970s and is supported by extensive CO₂ transport pipeline networks. There are 12 operating commercial-scale CCUS sites in the US, primarily from natural gas and fertiliser plants, storing around 19 million tonnes of CO₂ per year. Canada has 3 operating commercial-scale sites, each storing over 1 million tonnes of CO₂ per year.
- Europe has had extensive experience with storage operations. Sleipner has stored CO₂ since 1996, with systematic monitoring of its operations, which have now stored more than 20 million tonnes of CO₂. It was joined by Snøhvit (operating since 2008), and together capturing and storing around 1.7 million tonnes of CO₂ per year. Equinor is developing the Langskip project (aka “Longship”) and other large scale storage locations are under development. There are dozens of other storage projects in development.
- Australia’s Gorgon project is one the world’s largest, targeting storage of around 4 Mt per year

Currently, there are around 60 projects in operation around the world, storing 40 million tonnes per year.[42]

The storage capacity globally is significant. Based on geospatial data on sedimentary thickness and other parameters, total global storage capacity has been estimated at between 8 000 000 Mt and 55 000 000 Mt. While certain regions may have larger capacities than others, every region has more than enough storage for its needs this century. The IEA estimates that 70% of emissions are within 100 km of potential storage in key regions.

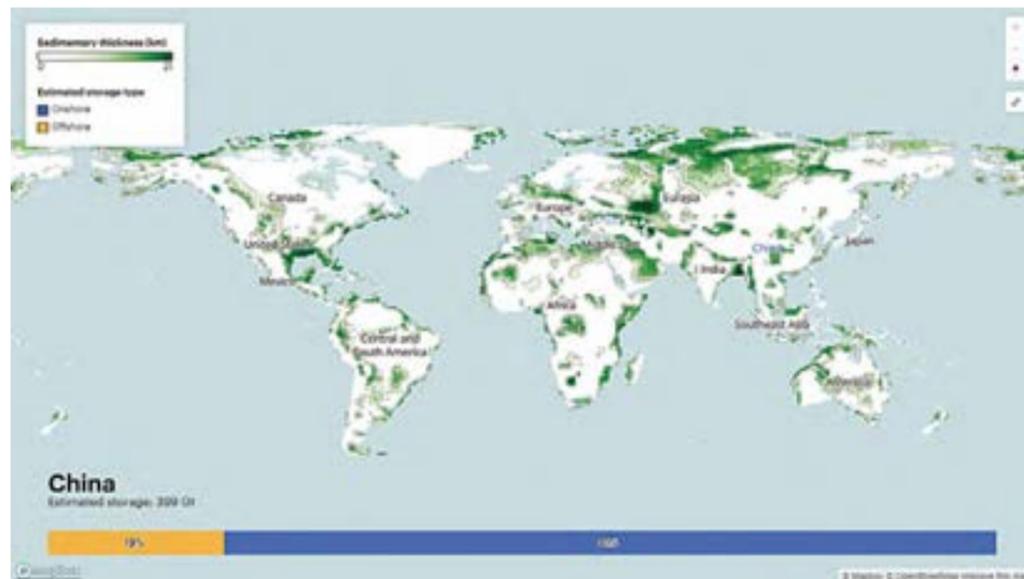


Figure 22 - IEA, Theoretical CO₂ storage capacity by region[45]

15.5 Societal acceptance and governmental support

While incentive mechanisms, and low-cost capture systems, and available storage options are all important, the primary enabling factor for cement decarbonisation is via societal support.

As has been seen, technologically capture at low cost is possible with a LEILAC system. CO₂ storage is viable, at very large scale, in most regions. Incentive mechanisms are being put in place, and even today CCUS projects in the cement and lime sectors are potentially viable.

However, cement and lime production are an integral part of our society – providing both the material that we all use (directly or indirectly) in our daily lives, and a critical part of our economies.

Decarbonising these critical industries is necessary if we are to reach our climate change ambitions and stop global heating. Communicating the necessity of such decarbonisation, and the benefits, is not easy and cannot ever be assumed.

On a project-level basis, clear and open communication, and a say in the project’s development, can be important in facilitating societal acceptance of these decarbonisation approaches. Governments have a key role, promoting the environmental, economic benefits (particularly employment) – and can facilitate deployment through permitting, coordination and public procurement rules.

On a more general basis, clear and consistent support for the decarbonisation steps being taken from all sectors – industry, government and society – is a key enabling step.

15.6 Expected potential uptake geographically

The LEILAC technology is commercially viable without subsidy of up-front capital costs, so long as there is an adequate carbon pricing regime to cover with minimal operating costs of the capture unit and the transport and storage costs for dealing with the captured CO₂.

With the EU ETS and substantial support for CCS installations in the 2020s, it is expected that Europe will host the majority of LEILAC installations in the 2020s. With generally high acceptance of society and governments for the need to decarbonise industry, the option for reaching net-zero is feasible. Getting there will require CCUS, and an increasing acknowledgement that the cement and lime sectors have no other option is starting to be made.

These enabling steps are critical, and increasingly common. There are good prospects of projects progressing in locations outside Europe, including the Americas, Japan, China and other countries in the APAC region.

15.7 Potential CO₂ reductions through to 2050

As illustrated in section 7, in order to reach ‘net zero emission’ by 2050, a wide range of actions need to be taken to decarbonise the cement and lime sectors.

Globally, the IEA’s ETP anticipates that in order to reach our climate change ambitions, “by 2070, 80% of clinker production is equipped with CCUS, and a total of over 40 GtCO₂ is captured cumulatively.”[50]

Combining the anticipated contribution of different roadmaps (Cembureau, ECRA, IPCC, IEA etc.) the following route to 2050 can be illustrated:

Decarbonisation requirements to get to 2050



Figure 23 - Illustration of Cembureau’s expected decarbonisation efforts for cement production by 2050

The Cembureau has produced a 2050 roadmap, to enable net zero emissions by 2050 in Europe. This includes all of the methods possible to reduce emissions throughout the lifecycle of the product; including transportation of product, novel cements, and re-carbonation. In order to reach zero, it envisages Carbon Capture and storage being required to contribute approximately 42 percent of the decarbonisation efforts required.

As it is the intent that LEILAC uses low carbon fuels – as it is part of the production process, and is not an addition – then the expected contribution may be around 55 percent (280kg CO₂/t cement for capture and 90 kg CO₂/t cement from the fuel emissions through the use of biomass, electricity and hydrogen).

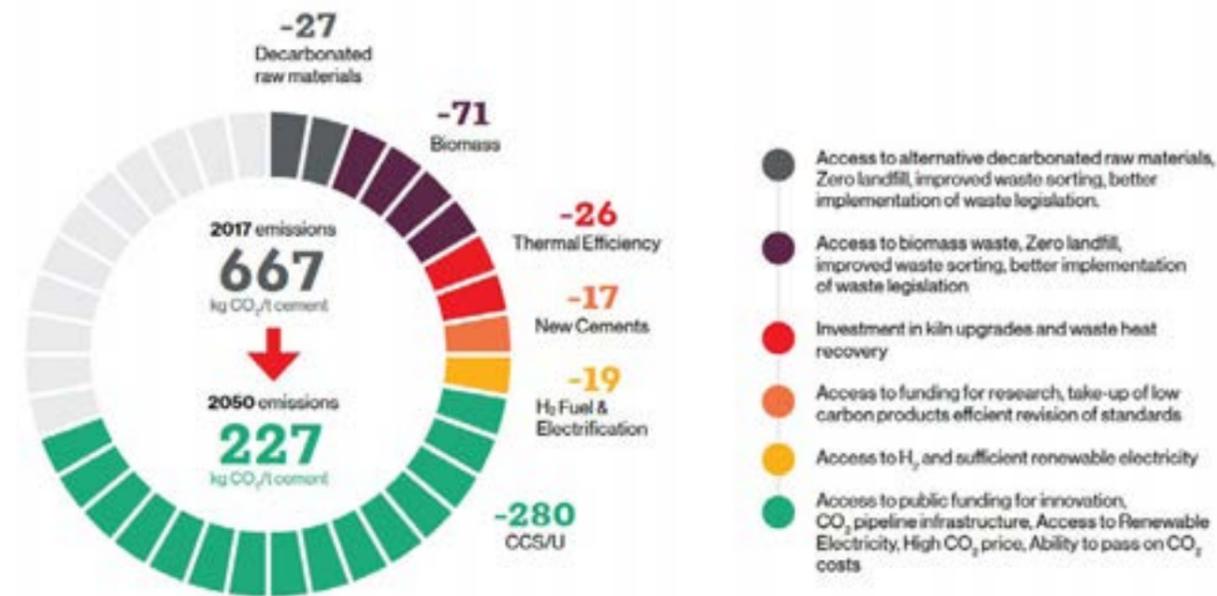


Figure 24 - Cembureau's expected decarbonisation efforts for clinker (only) production by 2050[21]

Restricting the decarbonisation effort to the production plant alone, a cement plant produces clinker. Within that scope, carbon capture and storage is anticipated to contribute 63 percent of the decarbonisation efforts required, and 84 percent of the required effort when combined with the use of alternative fuels, electrification, and hydrogen use.

LEILAC can play an important role in addressing this requirement for the cement and lime sectors:

- A low-cost effective means of capturing unavoidable process emissions,
- Ability to use biomass, hydrogen, and electricity,
- Ability to work in synergy with other capture technologies to enable negative emissions, including re-carbonation.

These scenarios are for the entire European fleet, requiring a variety, and greater, emissions reductions per 'type' of decarbonisation activity on a plant-by-plant basis.

In regards to a specific plant basis, as articulated there a great variety of ways that a LEILAC system could be used – with the emissions profile and costs all varying by configuration and fuel.

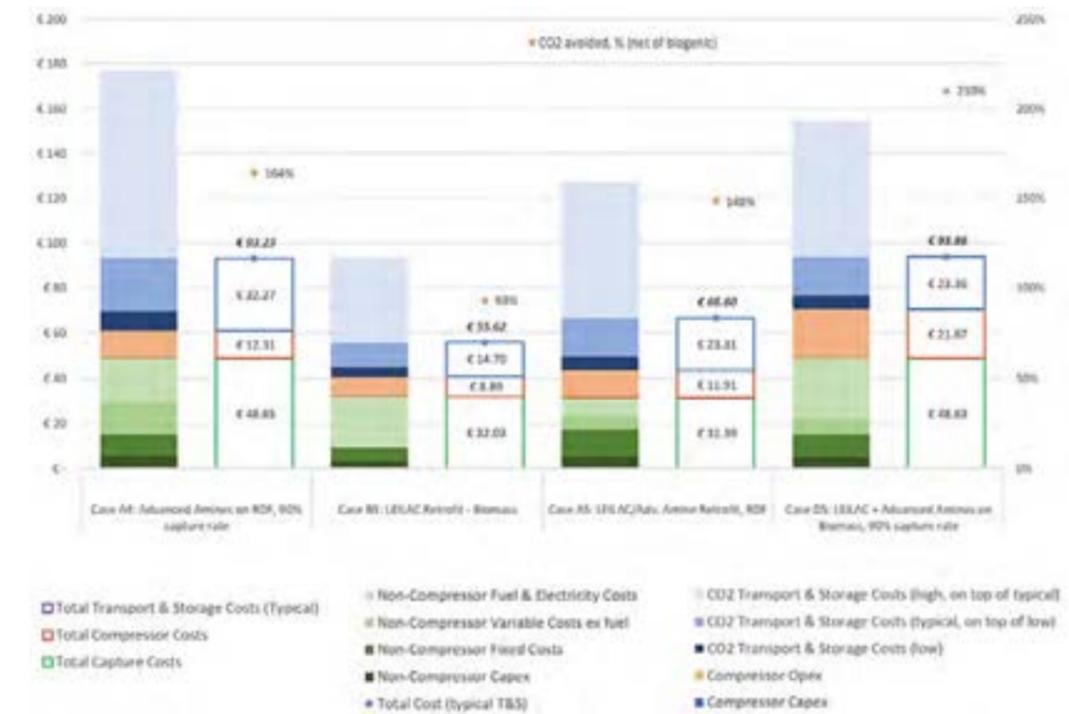


Figure 25 - Possible costs for low-cost carbon negative emissions

On a simplistic basis, taking the case B5 -LEILAC Retrofit – Biomass, a zero-emissions plant could be envisaged, for a total CCS cost of €56 per tonne of CO₂. (The LEILAC capture costs, including capex and compression, would be approximately 41 €/t)

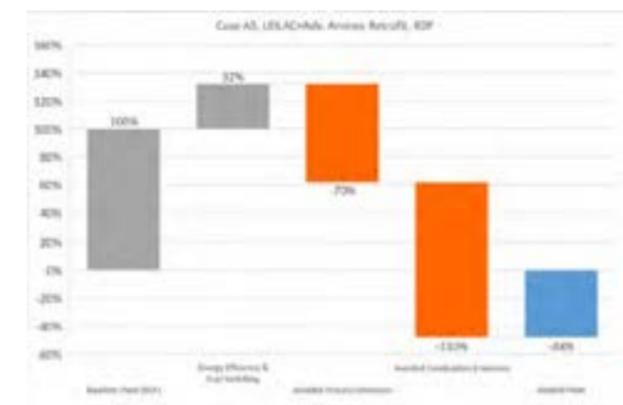
Figure 26 - Use of a LEILAC system with biomass for low-emissions cement production



With a LEILAC system capturing for very low cost the unavoidable process-emissions, the strong synergies with a small additional capture unit are pronounced. A stand-alone advanced amine unit attempting a negative emissions, may have avoidance costs of 94 €/t CO₂ (Case A4).

When used in conjunction with a LEILAC system (case A5) the costs reduce to 67 €/t CO₂, as less energy is required, and less CO₂ needs to be stored.

Figure 27 - Use of a LEILAC system with a small advanced amine unit, with biomass, for negative-emissions cement production



Includes financing and depreciation of capex at approximately €37million, compression, transport and storage costs.



Photographed by: Paul Poels

16 Conclusions: LEILAC is a high potential cost-effective path to zero and negative carbon emissions lime and cement production

There has been a demonstrable global commitment to respond to the threat of climate change. To achieve the ambitious target of minimising global heating to 1.5°C, fundamental changes are needed to reduce the CO₂ that our society emits.

Cement and lime are essential elements of our society, providing the basis for our infrastructure, homes and underpinning our economies. However, due to unavoidable process emissions, and the energy needed to drive these processes, these industries are currently responsible for 8% of global CO₂ emissions.

In order to reach the required emission reductions by 2050, carbon capture will need to be applied to a vast majority of cement and lime kilns, and every technology option should be developed to de-risk this task.

Once tested and scaled up, the LEILAC technology should provide an option for reducing the costs of carbon capture and accelerate the deployment in both industries using this new type of pre-calciner.

The techno-economic forecast for the technology is very promising. It is feasible that the LEILAC process can be applied to a cement and lime plant in the near future at full scale, capturing their unavoidable process emissions for minimal cost. Comprehensive life-cycle analysis studies have been carried out on a wide range scenarios and options, illustrating that dramatic emissions cuts in cement and lime production are possible using the low-cost LEILAC process.

Decarbonising industry is difficult, and must fulfil three criteria in every region of the world:



To maintain economic prosperity



Meet cement and lime market demand



Dramatically lowering CO₂ emissions

Ultimately, the cement and lime sectors have clearly articulated their desire to have neutral emission by 2050, through individual corporate commitments and association roadmaps, and the technology – such as LEILAC – is starting to rise to the challenge.

The technology is feasible and is approaching the point of being commercially applied under the incentive mechanisms in certain regions. A continued and strengthened support from policy makers, government and society are required to enable decarbonisation at scale: particularly to facilitate transport and storage options to address these unavoidable industrial CO₂ emissions.

Our shared and collective aim is to enabling society to continue to benefit from vital products that benefit us all, without negatively impacting the environment.

This project's techno-economic modelling and roadmap report supports our view that LEILAC can play a significant role in our collective endeavours to reach net-zero by 2050.

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