Leilac

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TO: Industrial Efficiency and Decarbonization Office, U.S. Department of Energy
FR: Leilac, U.S., Inc.
RE: DE-FOA-0003363: Request for Information on Transforming Industry – Strategies for Decarbonization

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Leilac thanks the Industrial Efficiency and Decarbonization Office (IEDO) at the Department of Energy (DOE) for the opportunity to help identify cost-effective strategic pathways to achieve thriving U.S. industries with net-zero greenhouse gas emissions by 2050.

For cement, a combination of low-cost process emission capture, the use of lower carbon fuels and feedstocks, and electrification provide cost-effective pathways for the industry to reduce its emissions, retain its international competitiveness and support sustainable U.S. manufacturing.

Leilac aims to deliver a breakthrough decarbonization technology for the cement and lime industries. Unlike conventional carbon capture technologies that require an additional, energy intensive process to separate gases from gases, Leilac employs a “process modification” to cement and lime production to efficiently capture unavoidable process emissions. This modification simply prevents CO_2 emissions released from the raw material from being contaminated by exhaust gases and air, thereby enabling their capture as high-purity CO_2, without additional chemicals or solvents and for minimal energy penalty. It is also energy agnostic and fully compatible with alternative and clean fuels, including electrification.

Leilac is encouraged by accelerating policy support in the U.S. that will enable the rapid expansion of sustainable cement and lime and, ultimately, full decarbonization. We are highly supportive of the steps DOE is taking to identify pathways to decarbonize industrial processes and mitigate challenges and appreciate the opportunity to respond to this Request for Information (RFI). Leilac welcomes the chance to participate in additional conversations with the agency and all interested parties on this crucial topic to provide further information about our solutions and answer any questions that may arise.

Yours faithfully,

Daniel Rennie
Chief Executive Officer

Category 1A: Questions on Primary Challenges and Barriers to Decarbonization

1A.1 What feedback do you have on the primary industrial decarbonization challenges and barriers summarized above? Please list any additional barriers that you think are important.

Thermal Systems Emissions: High temperature industrial heating processes typically involve the combustion of fossil fuels to generate the required process heat. New technologies, however, have the potential to enable fuel switching to low and zero emissions fuel sources, including hydrogen and, importantly, full electrification.

Leilac has proven at pilot scale its electric and renewably powered calcination technology for cement and lime production. Leilac's parent company, Calix Limited, has also applied the same core electric calcination platform technology to the production of calcined clays, green iron, alumina and lithium.[1] Electrification of mineral processing offers several advantages over combustion approaches and the use of fossil fuels, including significant emissions reduction, more efficient energy use, more precise and controllable delivery of process heat, load balancing of renewably powered energy grids, and local environmental and health benefits.

Recommendation 1: Electrification can now be considered as a primary pathway for emissions reduction in mineral processing. Fully electric solutions for industries such as cement, lime, iron and steel can be supported by further deployment of low-cost renewable electricity generation, suitable grid infrastructure, and subsidy of demonstration and first-of-a-kind commercial electrification projects.

Process Emissions: In 2015, process-related CO_2 emissions from cement calcination accounted for 58% of total direct cement industry CO_2 emissions, while energy-related emissions accounted for 42%.[2] As the industry transitions to lower carbon fuels, process CO_2 will account for an increasing proportion of greenhouse gas emissions. Addressing process emissions is therefore a critical step, and Leilac commends the DOE for the focus given to the abatement of process emissions in the development of its industrial decarbonization pathways.

The Leilac technology is specifically designed to enable the efficient capture of unavoidable process CO_2 emissions at low cost. It is retrofittable, can be integrated into the host plant with minimal to no downtime, does not alter or impact product (cement, lime) quality, and can enable switching to lower cost and/or lower carbon fuels.

Despite these advantages, the abatement of process emissions still comes with an additive cost compared with an unabated cement plant, and much of this cost results from the need to compress, transport and store the captured CO_2. This additive cost is ubiquitous to all carbon capture and storage projects, regardless of the carbon capture technology employed. As

[1] https://calix.global/sustainable-processing/
[2] Department of Energy, Industrial Decarbonization Roadmap, September 2022.

described in the following sections, transport and storage costs are also highly variable and provide significant sources of risk and uncertainty to CCUS projects. As a result, current incentives, such as those provided under Section 45Q of the U.S. tax code, are often insufficient to drive adoption of CCUS in the cement industry.

Special consideration of process emission abatement within the available decarbonization incentives schemes could help focus CCUS investment towards hard-to-abate sources of industrial emissions with little to no alternative decarbonization pathway.

Recommendation 2: Consider a separate incentive under Section 45Q for the capture, use and/or storage of industrial process emissions that provides a higher tax credit for process emissions relative to other fossil sources of emissions.

Constraints within Industrial Entities: The adoption of new technologies, or alternatives to traditional manufacturing processes, represents a business risk for industrial facilities such as cement plants. While tax credits and other incentives provide significant and welcome upside for prospective decarbonization projects, they do not force adoption in the way a carbon price or emissions trading scheme would, nor provide downside cushioning to help derisk new technology adoption.

Given the complexity of many industrial decarbonization solutions, as illustrated in the following section, producers may understandably be reluctant to take a risk that could disrupt their production or impact their competitiveness. The lure of upside incentives can be balanced by downside cushioning mechanisms that help derisk technology adoption and promote the establishment of first-of-a-kind projects. Such mechanisms could include production insurance schemes or similar guarantees of support that protect producers from the potential economic risks of new technology adoption.

Recommendation 3: Consider additional policy support for industrial decarbonization projects that provides downside cushioning to derisk early adoption of new technologies.

Carbon capture and storage projects typically involve multiple partners to deliver the capture, compression, purification, transportation and storage of CO_2. For many industrial facilities, local CO_2 storage may not be possible, necessitating CO_2 transport across large distances to its eventual storage destination. Such projects are highly complex, requiring stakeholder management with many partners and communities and regulatory compliance possibly across multiple jurisdictions. This complexity is a significant barrier to the establishment and progress of CCUS projects.

Industrial sources of emissions, such as cement plants, are unlikely to have the appropriate resources to successfully develop and manage large-scale CCUS projects. Governments can provide valuable support beyond financing, including project coordination and the establishment of suitable collaborations, stakeholder management and regulatory advice, and streamlined permitting procedures for priority projects.

Recommendation 4: Provide access to industry-wide advisory support for the development of complex industrial decarbonization CCUS projects, including stakeholder management, matchmaking with appropriate partners, regulatory compliance, and fast-tracking of permitting.

Decarbonization Infrastructure: The lack of adequate CCS infrastructure in the U.S. is perhaps the greatest barrier to widespread project deployment and deep decarbonization of cement production. In October 2023, Leilac released a techno-economic analysis[3] of the technology at full commercial scale (based on central European costs) and found that the cost for process emissions avoidance would be approximately €33 per ton of CO_2 and the cost for near-zero emissions cement would be €39 per ton of CO_2. This cost includes the CAPEX and OPEX to capture and compress the carbon emissions from a full-scale cement plant. It does not, however, include CO_2 transport and storage costs.

CO_2 transport and storage costs are highly variable, dependent on local geographic and geological considerations, distance to existing infrastructure, local regulation and several other factors. The availability of carbon management infrastructure is typically the primary consideration when assessing the feasibility of CCUS projects for cement, and accessible and low-cost CCUS infrastructure is essential for the project economics of carbon capture solutions across industrial subsectors.

Cement is a low margin, dispersed commodity product that plays a vital role serving society and supporting local economies. In a decarbonizing economy, the highly variable and regional nature of the costs associated with carbon management risks the viability of cement production in some regions.

Carbon management infrastructure will underpin the decarbonization of multiple industrial subsectors, particularly those with high levels of process emissions, in addition to the likely growth in Direct Air Capture for carbon dioxide removal. Wide-spread access to appropriate carbon management infrastructure across regions will also be essential to enabling an equitable decarbonization of industry and the maintenance of sustainable local manufacturing bases. As such, shared carbon management infrastructure developed through careful planning and coordination and used across industrial subsectors will be critical in enabling the lowest-cost and most equitable decarbonization pathways.

Governments can and should play a central role in developing carbon management infrastructure and managing access to it. By leading the development of suitable CO_2 hubs, pipelines and sequestration sites, governments can drive down the cost of decarbonizing hard-

[3] Leilac, Decarbonising Cement: Leilac at Full Commercial Scale | Leilac, October 2023.

to-abate industries, protect against monopolies gaining control of essential infrastructure, improve regional equity in decarbonization outcomes, and improve the return on public investment through more efficient infrastructure development and its broader use by industries.

Through a central role in developing and managing access to carbon infrastructure, governments can also support cost-effective deployment through market creation initiatives, such as platforms to match carbon sources with transporters, users and storage sites, competitive auctions or similar approaches to drive down costs, and measures to prevent monopolies and cost increases that take advantage of increased incentives to industry through 45Q and other public subsidies.

In the same way an industrial energy user does not have to develop the infrastructure required for generating and transmitting electricity, it should not have to solve the downstream transport and sequestration of captured carbon dioxide. Government support and coordination should be targeted at ultimately enabling carbon management infrastructure to become an accessible utility service for industrial facilities.

Recommendation 5: Governments should lead the development of CO_2 hubs and other carbon management infrastructure to help ensure their most cost-effective deployment and equitable access across multiple industry players, subsectors and regions.

To help reduce risks and drive adoption of CCUS, particularly for process emissions, and to promote industry-wide access to solutions, governments could also consider funding support that limits the exposure of individual projects or companies to highly variable costs associated with carbon management. As opposed to large-scale funding for selected individual projects, a cap on carbon transport and storage costs would promote equitable adoption of solutions, and derisk projects by removing a significant source of uncertainty and variability.

Effective decarbonization solutions can also deliver significant local community benefits. These include job creation and the broader protection of regional economies reliant on local industrial activity and improved local environmental and health benefits. Equitable access to carbon management infrastructure, regardless of where a plant happens to be located or its underlying geology and geography, will help ensure community benefits from decarbonization are available nationwide, and local manufacturing can be sustainable across the U.S.

Recommendation 6: Consider placing a short to medium term cap on the cost exposure of industrial decarbonization projects to transport and store CO_2, particularly those targeting hard-to-abate process emissions.

Clear, consistent, and appropriate regulations on CO_2 specifications required for access to carbon management infrastructure can also help derisk and accelerate decarbonization projects. Carbon transport and storage operators should not have penalizing requirements on carbon capture plants or industrial facilities. Instead, the emphasis should be on ensuring safety through the lowest cost specifications required for CO_2 purity and tolerance levels for given impurities.

Currently, some transport and storage operators place onerous requirements on capture plants. This can include requirements for CO_2 purity levels higher than food grade or beyond detectable limits. Through increased government coordination and regulation of carbon management infrastructure, appropriate standards can be introduced to promote total lowest-cost solutions across the carbon value chain.

Recommendation 7: Introduce consistent and safe standards on CO_2 specifications for transport and storage that promote lowest cost carbon management.

Market Demand: Though not listed in the primary barriers DOE has identified, one of the largest challenges we see in the U.S. is a lack of sufficient demand signals for low-carbon alternatives. Leilac is very encouraged by recent legislation, like the Bipartisan Infrastructure Law and the Inflation Reduction Act, and its potential to support significant advances in lower-carbon industrial processing.

Despite this landmark funding, Leilac is still seeing less willingness from industry members to move forward with projects in the U.S. compared with European counterparts. We believe this is largely due to the lack of demand drivers and regulatory requirements for carbon abatement.

Adequate demand signals are essential to commercial liftoff of decarbonization projects. We are encouraged by federal and state efforts, such as the Buy Clean and Low-Embodied Carbon programs, that seek to support demand generation for low-carbon products; however, a disconnect remains between industry players and policy, as most facilities remain hesitant to invest in decarbonization solutions without regulatory requirements or a degree of certainty that there will be demand for their low-embodied carbon products. Stronger demand signals are necessary to derisk nascent technologies and establish a robust market for lower-carbon products.

Measures that stimulate demand for low-carbon-intensity products can complement the various available incentives and drive adoption of industrial decarbonization solutions. The government is one of the largest procurers of cement – establishing robust procurement policies would create a strong market signal (e.g., low-embodied carbon requirements, auctions for low-embodied carbon products). In addition to government procurement requirements and incentives for lower embodied carbon products, policy concepts such as a carbon contract for difference (CCfD), as seen in Germany and other European countries, could help bridge the cost gap between business-as-usual products and low-carbon products until customers are ready to pay a green premium. Ultimately, a carbon border adjustment mechanism can provide an effective means of enabling the regulation of low-carbon products and protecting local industry from any disadvantage from international competitors.

Recommendation 8: Continue to implement policies that drive demand for, and promote stricter regulation of, low-carbon intensity products.

1A.2 Which barriers do you feel are most important to address first? and,
1A.3 How would you recommend government engage to address these (or other) industrial decarbonization barriers?

For inherently carbon intensive industries with high levels of process emissions, such as cement, access to low-cost carbon management infrastructure is critical to enabling industry-wide decarbonization. Rapid action in the U.S. to address these needs and complement carbon capture projects with expedited permitting and construction of pipelines and sequestration sites will be central to the overall success of carbon management in the industrial sector.

Government coordination and subsidy would be an effective way to deliver equitable solutions, with a pathway to future CCUS projects that leverage this infrastructure being economically viable without further public subsidy. Additionally, for CCUS projects to be broadly successful, transparent permitting timelines, technical support from federal agencies, and effective community engagement will all be required.

1A.4 Aside from cost, what vulnerabilities/challenges do facilities face when adopting new technologies?

Public acceptance is one of the greatest sources of risk for CCUS projects. Governments and policy makers generally regard CCUS as an essential technology for society to meet its global climate commitments, and particularly for abatement of process emissions in cement production. Public acceptance of CCUS, however, has been problematic, complicated by the variety of types of CCUS proposed, their cost and technical viability, and the perception that CCUS was being deployed to prolong the use of fossil fuels. These concerns have led to some skepticism and cynicism in public attitudes towards CCUS.

The public is therefore an essential stakeholder group for any CCUS project, and their engagement and support provide the project's social license to operate. It is important that community benefits are embedded into every CCUS project to support broad public acceptance, including significant wealth creation and sharing with local economies. In particular, the focus should be on retaining jobs and supporting existing economic activity to become sustainable in a low-carbon economy. This is opposed to the sometimes spurious promotion of 'green jobs', that at best may not lead to permanent roles, or worse reflect inefficient operations and technologies that require significant additional labor resources and are therefore detrimental to sustaining competitive industrial operations in the long term.

Embedding local community considerations into decarbonization projects can also help to deliver environmental and health benefits. When community benefits are considered as part of a holistic assessment of a project's merits, the chosen technical solution can deliver benefits beyond reducing greenhouse gas emissions. For example, switching industrial heat sources from coal to renewably generated electricity can deliver improved air quality to the neighboring communities. Similarly, carbon capture projects that carry a real risk of negative local environmental or health impacts, for example, through the release of chemicals to the environment, should not be funded. This both helps to protect the local community and supports broad public acceptance of CCUS.

Recommendation 9: Continue to embed community benefits and the promotion of public acceptance as a critical consideration in the support for projects.

Category 1B: Questions on Cross-Cutting Decarbonization Strategies

This category is focused on cross-cutting technologies and strategies that apply across industry. Responses regarding subsector-specific decarbonization technologies and strategies should be submitted in Category 4.

1B.1 What are the most impactful cross-cutting and systems-wide strategies needed to decarbonize industry and why?

The primary limiting factor facing the deployment of decarbonization technologies for US industry is the lack of appropriate, industry-wide (i.e., non-competitive) incentives or penalties.

There are many risks associated with the development and scale up of new technologies. These can be partially mitigated through financial backing to minimize – at least for a few early movers – the associated risks and performance issues with both new technologies and new business cases. Full chain, integrated, multi-actor CCS developments can be complex; factors for consideration include offtake agreements, timing and dependencies of the separate capture, transport and storage developments, and financing of the relevant components.

Outside of the policy mechanisms discussed above, cost and knowledge sharing of large demonstration/near commercial units would be of substantial benefit. This is an approach Leilac has successfully implemented in Europe through the EU funded Leilac-1 and Leilac-2 projects, each of which involved a consortium of partners from industry, research institutes and academia. As well as derisking early-stage projects, a consortium based approach promotes knowledge sharing and the development of industry-wide solutions.

1B.2 What approaches are useful to allocate and structure investments for cross-cutting technologies vs. industry-specific technologies?

Customers willing to pay green premiums for low-carbon products are unlikely to always be located in proximity to the products they are seeking to procure. In the case of industrial products like cement, it is difficult to transport certain products long distances. Voluntary programs and reporting schemes that allow for a book-and-claim system for low-carbon products would enable investments from customers willing to pay a green premium to support projects.

1B.3 Given the breadth of available and emerging technologies, which cross-cutting technologies are most in need of RD&D funding?

First, the development and deployment of carbon capture technologies that are low-cost and do not introduce new chemicals or pollutants to the facility or local community are critical for widespread industrial decarbonization at the speed needed to meet our climate goals. While industry will require an all-of-the-above approach to decarbonization, it is important to ensure there are no negative local impacts that could ultimately stall projects or harm communities. Additionally, the connection of projects to safe, low-cost CO_2 transport and storage options is critical for reaching final investment decision.

Secondly, to implement electrification of industrial processes or decarbonization technologies at facilities, additional funding for renewable energy storage or low-carbon hydrogen that integrates with these technologies at the scale needed for industry is key. Today, most carbon capture technologies must operate on natural gas or commercial alternative fuels.

1B.5 Which barrier(s) do you think is most important to address?

The development of low-cost, accessible and equitable carbon management infrastructure, as outlined in recommendations 5 and 6.

1B.7 What approaches are needed to reduce or overcome the risk of deploying new crosscutting technologies, catalyze uptake, and accelerate technology adoption?

As described earlier and outlined under recommendation 3, policy support that provides downside cushioning, in addition to the upside incentives now available, can help derisk early adoption of new technologies and processes. This is particularly important in the absence of a carbon price or other regulatory measures that drive action in risk-averse, low-margin and conservative industries.

Category 2: Questions on Framework for Industrial Decarbonization Pathways

2.1 How does your organization approach planning for different pathways to decarbonization?

Leilac's technology is fuel agnostic and compatible with a wide range of energy sources, including electricity and renewables, hydrogen, natural gas, and alternative fuels. This unique feature for a carbon capture technology enables multiple viable pathways to decarbonization, including the avoidance, rather than capture, of fuel related emissions.

Leilac's partners can select the pathway(s) that work best for them at a facility level and on the timescale that matches their decarbonization ambitions and access to necessary supporting infrastructure, such as the availability of CO_2 transport and storage and low-cost renewable electricity generation. Additionally, the CO_2 captured by Leilac's technology is highly pure (+98% purity), which allows a facility to sell their carbon for multiple uses or storage types without significant additional purification steps. Leilac can also be deployed as a retrofit and via a modular design approach, allowing for flexibility in installation of the technology at different sites, including through a phased integration if desired.

2.5 How can we differentiate "bridge" investments that produce emissions savings in the near/medium-term but are at least neutral for the path to net-zero emissions (e.g., installing new electrified equipment) versus the "dead-end" investments that produce emissions savings in the near/medium-term but delay or deviate from the path to net zero emissions (e.g., efficiency improvements to fossil-fuel based systems), often causing stranded assets?

Leilac's technology is designed to efficiently capture unavoidable process emissions, and enable the transition to lower carbon fuels, such as hydrogen or renewable electricity, over time. Process emissions are an inherent part of the cement making process and abating them is a challenge that all cement plants must address. As such, investment in CCUS infrastructure for cement is necessary.

Fuel emissions for cement, however, are not unavoidable. While we must decarbonize as quickly as possible, it is important to also facilitate flexible and low-cost pathways to decarbonization. This can be achieved by focusing on the capture of unavoidable process emissions and a flexible transition to lower carbon fuels that accounts for local constraints such as variable availability.

Local environmental impacts from decarbonization technologies should also be strongly considered. Unlike some carbon capture technologies that increase emissions (e.g., NOx, toxic chemicals) in the local area by introducing new chemicals into a facility, Leilac does not use additional chemicals or solvents, and ensures no negative impact to the local area.

2.6 How can we build timelines into the pathways (e.g., how can we project when those major decarbonization investments will be possible/needed)?

It is critical that industrial decarbonization projects move from the announcement and assessment stage to final investment decision as soon as possible. It will be possible to build in timelines into decarbonization pathways by supporting markets with policies that drive demand, as outlined in our responses above. In particular, large-scale investment in carbon capture projects for cement will be directly dependent on the availability of local carbon management infrastructure.

2.7 What factors are important to include in projecting long-term investment needs or technology transition needs?

The source of carbon emissions and the potential for avoidance is a key consideration when designing carbon management infrastructure. For example, as other industries decarbonize through avoidance pathways, such as switching to renewable generation and batteries in the power and transport sectors, industries with high levels of process emissions will account for an increasingly large share of greenhouse gas generation. In this scenario, cement plants are likely to become the largest point sources of CO_2. Carbon management infrastructure should therefore be designed with cement plants as a focal point, while also considering the needs of, and leveraging synergies from, the carbon management requirements of the emerging Direct Air Capture industry.

2.10 Are there current policies or interventions that are hindering implementing different decarbonization pathways?

Whilst highly supportive of developing CCUS projects, the incentives available under 45Q promote capture of CO_2, rather than avoidance. For cement plants that require CCUS to abate their process emissions, this risks also locking in CCUS as the only solution for fuel emissions. Similar incentives to switch to low carbon fuels and avoid fuel related emissions should be available to help promote flexible decarbonization pathways and ultimately lowest cost emissions avoidance.

Recommendation 10: Promote and incentivize CO_2 avoidance equally with CO_2 capture from industrial facilities.

2.11 What additional data and information is needed to support data-based decision making within a pathway framework?

Transparent, credible and publicly available techno-economic analyses of a range of decarbonization options can help inform and improve decision making. Leilac has published detailed techno-economic analyses of its technology and its application to cement and lime decarbonization[4]. We would also welcome the opportunity to provide inputs to government or third-party led analyses that can help provide a robust platform for data-based decision making.

Category 4A: Cement Questions

The following questions are focused on cement manufacturing decarbonization. Responses on cross-cutting technologies (applicable to multiple manufacturing subsectors) should be submitted in Category 1.

4A.1 How do you expect the U.S. demand and production of cement to change by 2050 and why?

We agree with the DOE's estimate that cement production will increase by ~43% by 2050. To move the cement industry toward decarbonization, we encourage demand driving policies. Funding for decarbonization projects through grants is extremely valuable for scaling new and emerging technologies. Once scaled, these technologies will require demand for low-embodied carbon cement or regulations to decarbonize industry for widespread decarbonization and investment.

[4] Leilac, Decarbonising Cement: Leilac at Full Commercial Scale | Leilac, October 2023.

4A.2 What do you think of the net-zero subsector emissions by 2050 pathway described above and detailed in the pathways analysis summary document (if reviewed)?

Leilac agrees with the cost, infrastructure, and technical challenges identified by DOE in the pathways analysis summary document for cement. Decision-making for CCS projects is highly location-specific, based on suitable geology or other access to transport and storage options, along with state and local support for such technologies. Costs of fuel and electricity are also significant considerations for facilities.

We would encourage DOE to consider multiple types of CCS projects in establishing programs to support deployment of this pathway. Traditional, post-combustion capture technologies will be important, but solutions that can also address the inherent process emissions and enable fuel switching are likely to provide lower cost long term pathways to net-zero subsector emissions.

In particular, we advocate for a transition towards a staged approach to cement decarbonization. Leilac recognizes and commends the significant DOE support for first-of-a-kind commercial deployments of CCUS for cement, and this will continue to be an important requirement to derisk projects and drive commercial demonstration of novel approaches. In the medium to longer term, however, a move away from large funding for individual projects and towards support for wide-spread emission abatement can provide more flexible, equitable, and cost-effective decarbonization pathways.

For example, the availability of large public grants for individual projects can drive producers to consider decarbonization on plant-by-plant basis, seeking maximum public subsidy per project before moving onto the next. Alternatively, a gradual approach to decarbonization that considers the whole of industry, rather than individual facilities, creates the flexibility to deliver the most cost-effective decarbonization pathways. For cement, this can include first transitioning as much as possible to low carbon clinker substitutes, then capturing unavoidable process emissions, and ultimately switching to low carbon energy sources such as electricity, biomass, and waste fuels.

When considered at a fleet-wide or industry-wide level, these decarbonization levers can be pulled in a staged approach as and when the supporting infrastructure or inputs become available, or suitable demand is created. Similarly, this approach can help deliver a greater return on investment of public subsidy by avoiding early projects locking in high-cost solutions simply to secure a large public grant. Ultimately a phased approach considered at an industry-wide level can support the deployment of lowest-cost approaches and provide a pathway for projects to become economically viable in the absence of large public grants.

Recommendation 11: Following successful first-of-a-kind commercial demonstrations, consider transitioning public support from a project level towards the deployment of industry-wide enabling infrastructure.

In the near to medium term, switching to lower cost and lower carbon waste-derived fuels can reduce costs and emissions and provide waste-disposal benefits. Waste-derived fuels often generate CO_2 emissions from both fossil and biogenic carbon sources. In this case, the biogenic CO_2 could be treated as being non-emitted or neutral on a life cycle assessment basis, thereby providing a cost-effective means of reducing emissions associated with heating and energy use.

Recommendation 12: Consider biogenic sources of carbon emissions as being non-emitted and incentivize fuel switching from fossil to biogenic fuels where appropriate.

In the longer term, electrification + CCUS for process emissions is viable, and may ultimately deliver a lower cost, more sustainable, and more equitable solution. In particular, hybrid fuel use of large plants can enable matching of energy sources to spot pricing and grid stabilization. Similarly, electric calcination can be applied to produce calcined clays with near zero emissions. Electrification can also deliver greater local community benefits, including improved air quality and health outcomes, promote additional renewable generation and its integration in the grid through load balancing, and avoid overall CO_2 emissions. Fully realising the potential of this decarbonization pathway, however, requires further support, including for R&D, early commercial demonstration, and access to sufficient low cost renewable generation.

Recommendation 13: Support R&D and commercial demonstration of electrification + CCUS decarbonization pathways for cement.

4A.3 What do you think are the primary production routes needed to decarbonize the cement subsector between now and 2050? For each route for which you have knowledge or expertise, please share the following information. Please also provide any supporting references (if available).

4A.3.1 What are the primary solutions/technologies necessary for that production route?

As DOE identifies on page 21 of the pathways analysis summary, Leilac anticipates CCUS solutions to play an essential role in decarbonizing both the cement and lime industries.

The Leilac technology is a carbon capture solution that captures unavoidable CO_2 emissions in the processing of limestone. Our process aims to do so without impacting product quality, operating cost, or efficiency (as there are minimal additional operating expenses) – with an overall low capital spend. Because of the flexibility our design and approach allows, we believe the technology will play a necessary role in CCS deployment in the U.S.

As outlined above and summarized in recommendations 12 and 13, switching to lower carbon fuels, including electrification and hybrid fuel use scenarios, can deliver significant emissions reduction, economic and local community benefits.

4A.3.2 What is the likely utilization of that route in the near-term (now-2030), mid-term (2030-2040), and long-term (2040-2050) (such as the percent of cement production)?

Carbon capture and storage is likely to be the predominant decarbonization option for the cement industry in coming decades. Other solutions that require cement quality standards to be updated, risk cement quality, or require stranding existing assets and require dramatic scale up are less likely to be deployed widely in a timeframe that meets the decarbonization commitments of industry or the U.S.

In the near-term, CCS solutions are likely to be fueled by natural gas or other commercially available low-carbon fuels. In the medium- to long-term, hydrogen and electrification may provide an even lower carbon CCS solution for a cement production facility.

4A.3.4 What are the primary barriers/challenges faced by this route and how can they be overcome?

At present, the primary barriers faced are related to a lack of demand drivers to derisk investments and uncertainties related to carbon transport and storage.

4A.4 What technical and/or technology solutions does the subsector need that are not currently available?

To implement electrification and further decarbonization of industrial processes, additional funding for proving and scaling renewable energy storage or low-carbon hydrogen that integrates with these technologies will be important. Today, most carbon capture technologies must operate on natural gas or commercial alternative fuels.