The Economic Case for Two Emerging Decarbonization Options for Cement Production

Evaluating LEILAC's Direct CO2 Separation Pre-Calciner and Rondo's Thermal Energy Storage

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Summary

We evaluated the business case for two emerging decarbonization options for cement production, LEILAC's direct CO_2 separation pre-calciner and Rondo's thermal energy storage. We assessed the economic viability of these two technologies, taking two example case cement plants A and B (based on the Redding and Mojave 2019 production figures), with differing cement output and CO_2 emissions (Annex 1). Based on the capital expenses, energy requirements and savings, the total CO_2 abated by the two technologies and the cost of transporting and storing CO_2 if required, we calculated the CO_2 abatement costs ($/ton) for plants A and B for a one-year time period.

We compared this cost against the financial benefit from avoided GHG emissions permit purchases under California's cap-and-trade scheme ($27/ton), and the benefit of the federal 45Q tax credit for CO_2 sequestration ($85/ton). The net benefit (i.e., benefit minus cost) improves over the life of operations as the cost for a GHG permit goes up. The findings we present in this paper are based on some key assumptions; a change in any of these assumptions could significantly alter the economics for these cement decarbonization technologies.

Key points:

- There is a convincing business case for both plants A and B for the LEILAC and Rondo combination when the price of renewable electricity is low.
- Rondo, as a standalone decarbonization energy for calciner heat, can be financially viable as long as there is access to local renewable electric resources.
- The business case for LEILAC as a standalone decarbonization technology capturing and sequestering process CO_2 emissions is the weakest. At both plants A and B, the net benefits of abatement of LEILAC are negative.
- In all cases, net benefit is highly dependent on access to low cost, renewable electricity. We modeled $0.02 and $0.05 per kWh as a range for a power contract for a dedicated, adjacent renewable electricity resource. We also modeled $0.20/kWh for purchase of renewable electricity from the California grid. Since a Rondo system can operate with intermittent power (i.e., it can provide 24 hours of continuous heat from 6 hours per day of electric power), it is possible that power contracts could be lower than $0.20/kWh if renewable electricity pricing is based on the lowest cost during the day or night.

Findings & Observations

Overall, our results indicate that there is a convincing business case across both plant A and B for the LEILAC and Rondo combination, and Rondo as a standalone decarbonization technology as long as there is access to local renewable electric resources. Plant B is more than double the output of Plant A and thus fixed costs are amortized across a large CO_2 abatement so there is a larger net benefit due to this cost efficiency. In the calculations below the 45Q federal tax credit is $85/ton CO_2, avoided CO_2 permit is $27/ton CO_2, natural gas price is $8 per MMBtu and transport plus sequestration of CO_2 is $23/ton.

Plant A: 627,000 tons cement/year

Abatement Technology	Total Abatement (tCO_2)	Renewable Electricity Prices ($ per kWh)	Capital Investment ($M)	Abatement Cost ($ per ton CO_2)	Abatement Benefit ($ per ton)	Abatement Net Benefit ($ per ton)
LEILAC + Rondo	285,631	0.02	104	55	90	36
		0.05	104	93	90	-3
		0.20	104	284	90	-194
Rondo	73,463	0.02	50	1	27	26
		0.05	50	147	27	-120
		0.20	50	877	27	-850
LEILAC	285,631	0.20	54	270	90	-180

Plant B: 1,600,000 tons cement/year

Abatement Technology	Total Abatement (tCO_2)	Renewable Electricity Prices ($ per kWh)	Capital Investment ($M)	Abatement Cost ($ per ton CO_2)	Abatement Benefit ($ per ton)	Abatement Net Benefit ($ per ton)
LEILAC + Rondo	850,433	0.02	262	54	93	41
		0.05	262	86	93	8
		0.20	262	251	93	-157
Rondo	187,465	0.02	125	0	27	27
		0.05	125	146	27	-119
		0.20	125	875	27	-848
LEILAC	850,433	0.20	137	239	93	-146

The net cost of CO_2 abatement for the LEILAC+Rondo combination at plant B ranged from a profit of \$8/tCO_2 to \$41/tCO_2 depending on an electricity price of \$0.05/kWh or \$0.02/kWh respectively. The strength of the business case for the LELAC+Rondo decarbonization technology is sensitive to the cost of electricity. This relationship between the economic viability of the LEILAC+Rondo combination and power prices is even more evident in the case of plant A. Here, a lower electricity price of \$0.02/kWh yields a net cost of abatement of \$36/tCO_2, but a higher electricity price of \$0.05/kWh turns the net cost negative and undermines the economic viability.

For Rondo as a standalone decarbonization technology displacing natural gas combustion to heat a conventional pre-calciner, the business case is the strongest and abatement costs the lowest across both plants when electricity is cheaper. Power prices at \$0.02/kWh result in an abatement net-benefit of \$26/tCO_2 and \$27/tCO_2 for Rondo as a substitute for natural gas combustion (to heat the pre-calciner) at facility A and B respectively. However, the economic viability of Rondo as a replacement for natural gas combustion does not sustain when power prices increase to \$0.05/kWh, and the net benefits at both plants turn negative.

The business case for LEILAC as a standalone decarbonization technology capturing and sequestering process CO_2 emissions is the weakest. At both plants A and B, the net benefits of abatement of LEILAC are negative, thus costing an additional \$146 to \$180/tCO_2 abated after accounting for the revenue from 45Q and avoided GHG allowance purchases. LEILAC's economic viability is mostly undermined by the high grid power prices to run the pre-calciner and the CO_2 compressor. Rondo and the Rondo+LEILAC combination emerge as more economically feasible options because Rondo can operate continuously even with intermittent electricity from adjacent, dedicated renewable power generation on site.

Because these figures are based on a set of strictly defined assumptions, we are not claiming that these numbers are definitive. To calculate the total CO_2 abatement and simplify our model, we took natural gas as the only status-quo fuel. However, the actual fuel mix of cement plants varies. It is predominantly made up of more carbon intensive fossil fuels. Thus, our model underestimates total CO_2 avoided and subsequently the CO_2 abatement cost when LEILAC and Rondo displace more CO_2 intense fossil fuels and not just natural gas[1]. In addition, the fuel costs to provide heat for California cement facilities are likely lower than our assumption of all natural gas and thus we overestimate the fuel costs.

Furthermore, there are several parameters, such as CO_2 storage, transport costs and logistics, and cost of renewable electricity which are uncertain and/or unknown. Changes in any of these parameters could alter our net benefit calculations and the business case for LEILAC and Rondo's cement decarbonization technologies. The purpose of this paper is to invite further inquiry and investigation into our primary idea that cement decarbonization is financially beneficial with technologies available in the next few years and policy supports that exist today.

The following sections will describe the two decarbonization technologies under consideration, the equations we have used to calculate their CO_2 abatement costs, and the assumptions and conversion that go into those calculations.

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[1] https://www.climateworks.org/wp-content/uploads/2019/02/CA-Cement-benchmarking-report-Rev-Final.pdf

Explaining the Two Technologies: LEILAC & Rondo

Low Emissions Intensity Lime And Cement (LEILAC)

Calix's LEILAC technology abates the process emissions from cement production through a direct separation carbon capture technology[2]. LEILAC re-engineers the traditional cement production process flows to replace the conventional pre-calciner with a module capable of direct CO_2 separation[3]. LEILAC's pre-calciner is heated indirectly by an array of steel tubes to help carry out the calcination reactions and CO_2 separation. The limestone $CaCO_3$ that passes through LEILAC's direct CO_2 separation unit, before entering the kiln, breaks down in the heat to release a pure stream (>95%) of CO_2[4]. Because the CO_2 is obtained from the decomposition of the limestone heated indirectly in LEILAC's pre-calciner, additional equipment and processes associated with conventional carbon capture techniques are not required. The design of LEILAC's direct separation technology makes it energy efficient, "retrofit ready", and cheaper than conventional forms of carbon capture[5]. These characteristics position LEILAC's direct separation technology as a cost-effective option to decarbonize the process emissions from cement production.

Key Techno-Economic Aspect for The CO_2 Abatement Cost Model:

Theoretically, there is no additional energy penalty associated with integrating LEILAC's pre-calciner for the direct separation of CO_2 from limestone because the additional energy penalty for the direct separation of CO_2 is offset by the energy saved in the kiln[6]. However, there could be a ±10% margin of error in estimating these energy use of LEILAC's module and the equivalent savings in the kiln.

Rondo's Heat Battery

Rondo's thermal energy storage system involves using electric resistance heaters to superheat firebricks with the help of an air blower to circulate the heat to the brick structure for convective heat transfer. The superheated air can then be delivered to the cement facility for heating LEILAC's pre-calciner (with direct CO_2 separation) or a conventional cyclone pre-calciner. Rondo's heat battery has the potential to abate all of the heat-energy-related emissions for the calciner if the electricity for superheating the firebricks comes from renewables like solar and wind. Because the battery can charge during periods of excess solar and wind generations and deliver zero-carbon heat when power generation is carbon intensive at night, it can take advantage of the diurnal power generation of renewables and their intermittency.

Key Techno-Economic Aspect for The CO_2 Abatement Cost Model:

Using dedicated renewables, the energy costs of providing zero-carbon heat for LEILAC's direct separation unit, the kiln or both can be provided at lower prices due to low costs of solar and wind power generation.

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[2] https://www.leilac.com/report/leilac-techno-economics-report-summary-2021
[3] https://cordis.europa.eu/project/id/654465/reporting
[4] https://www.leilac.com/whitepaper/capturing-co2-in-cement-precalciners
[5] https://www.leilac.com/report/leilac2-pre-feed-report
[6] https://www.leilac.com/conference/carbon-capture-from-cement-lime

CO_2 Abatement Cost Model

To model the cost of cement decarbonization technologies and their combinations, we borrow some key elements from the levelized cost of carbon abatement concept[7].

$$Cost\ of\ CO2Abatement = \frac{+(EnergyExpenses - EnergySavings)}{TotalNetAbatedCO2Emissions} + CO2TransportStorageCostsPerTon$$

It is important to note that our CO_2 abatement cost estimates are only based on a one year long time period and the CO_2 produced. A levelized cost metric would require more assumptions about power prices, depreciation rates, future discount rates, and maintenance costs. To simplify, we have used the CO_2 abatement cost estimates just for one year.

The opportunity cost of capital, represented as capital recovery, is computed based on a capital recovery factor of 8% multiplied with the total CAPEX of installing the decarbonization technology and in cases involving CO_2 capture, the CAPEX of a CO_2 compressor in addition. The calculation of energy savings is done by the simplifying assumption that the status quo/baseline fuel used to fulfill the energy requirements of the kiln is natural gas. Thus, to estimate energy savings, we first take the energy savings from a technology's use and find the equivalent savings in terms of less MMBtus of natural gas combusted. (Since the actual mix of energy sources used in California cement plants is not publicly available, we are using natural gas for our model.[8]) Then, we multiply this amount with an historic, average industrial price for natural gas in California of $8/MMBtu[9] [10].

Energy-related CO_2 emissions were computed using the carbon intensity of natural gas combustion and accounting for the efficiency of gas burners. To calculate the total CO_2 abatement and simplify our model, we took natural gas as the only status-quo fuel. However, the actual fuel mix of cement plants varies and is not generally publicly disclosed. It can be made up of more carbon intensive fossil fuels like coal or petroleum coke. Thus, our model may underestimate total CO_2 avoided and may underestimates the energy cost when LEILAC and Rondo displace more CO_2 intense and less expensive fossil fuels because we assume the emissions and costs of natural gas[11].

The energy costs are approximated based on the additional energy requirement of a technology. For LEILAC this additional requirement was represented by the energy (in kWh) needed to operate its pre-calciner for direct CO_2 separation during calcination and a CO_2 compressor for supercritical compression. For Rondo, we approximate the energy costs based on the heat it supplies either to LEILAC's pre-calciner or a conventional cyclone pre-calciner. The $10/ton cost of CO_2 transport is based on a pipeline carrying 1MT of CO_2 to a storage site 50 miles from the cement facility[12]. The CO_2 storage cost ($/ton) is derived from US Department of Energy estimates for geological storage of CO_2[13].

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[7] Friedmann, S.J., Fan, Z., Byrum, Z., Ochu, E., Bhardwaj, A. and Sheerazi, H., 2020. Levelized cost of carbon abatement: An improved cost-assessment methodology for a net-zero emissions world. Columbia University SIPA Center on Global Energy Policy: New York, NY, USA.

[8] Nhuchhen, D.R., Sit, S.P. and Layzell, D.B., 2021. Alternative fuels co-fired with natural gas in the pre-calciner of a cement plant: Energy and material flows. Fuel, 295, p.120544

[9] https://www.eia.gov/dnav/ng/hist/n3035ca3m.htm

[10] Average Industrial Natural Gas Price for CA from January 2019 to December 2021 was approximately $8/MMBtu

[11] https://www.climateworks.org/wp-content/uploads/2019/02/CA-Cement-benchmarking-report-Rev-Final.pdf

[12] Friedmann, J., friedmann2@gmail.com, 2022. CO2 transport costs. [email] Message to B. Epstein (bobepstein@gmail.com). Sent Saturday, 26 November, 2022: 17:45 PST.

[13] National Petroleum Council, 2019. Meeting the Dual Challenge–A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage.

Assumptions, Conversions & Calculations

We calculated the CO_2 abatement cost for LEILAC's module with following figures, assumptions, and conversions.

Scenario 1: LEILAC Pre-Calciner Only

The total 2019 CO_2e emissions for the two representative cement plants were obtained from a California Air Resources Board (CARB) dataset from 2019. From the cumulative CO_2 emissions data, the process and energy-related emissions figures were extrapolated by their percentage contributions of 62% and 38% to total emissions respectively. The total CAPEX includes the upfront expense of LEILAC's pre-calciner module to capture all the process emissions and a compressor to convert the CO_2 into supercritical state for transport. We model LEILAC using renewable electricity for heat. The CAPEX figures were obtained from Calix, the parent company behind the LEILAC technology[14]. The CAPEX number was multiplied with the CRF of 8% to obtain the capital recovery amount.

To estimate the energy savings of LEILAC's technology, we first estimated the energy required in LEILAC's pre-calciner for the calcination process. To do this, we assumed the total energy requirement of the kiln and the calciner to be 3.8GJ/ton clinker[15]. Since 60% of this energy is consumed by the pre-calciner, the energy requirement of LEILAC's pre-calciner is approximately 2.28 GJ/ton clinker. Here we assume that LEILAC's pre-calciner has no energy penalty for CO_2 separation due to reasons discussed earlier in the paper. Using a clinker/cement ratio of 0.9, and conversion factor of 1GJ = 0.947 MMBtu, we obtained 1.9499 MMBtu/ton cement produced as the heating requirement for the pre-calciner[16], On multiplying this heat requirement for the pre-calciner with total cement production for plant A and B, we estimated how many MMBtus of heat will be saved when LEILAC's technology eliminates the need for natural gas combustion to provide heat to its pre-calciner. We also divided the pre-calciner MMBtu heating requirements we found for both plant A and B amount by 0.88 to adjust for the 88% efficiency that is typical of natural gas combustion. Finally, we multiplied the pre-calciner MMBtu heating requirements, adjusted for the efficiency of combustion, with the industrial price for natural gas to calculate the energy savings (in $) from avoided combustion of natural gas.

To calculate the energy-related CO_2 emissions abated when LEILAC eliminated the need for natural gas combustion to heat the pre-calciner, we first converted the pre-calciner MMBtu heating requirements for plant A and B (adjusted for 88% efficiency) into Therms. Then, we multiplied this amount with the CO_2 (tons) released per Therm of natural gas combusted to obtain the energy-related CO_2 emissions abated at both facilities. To calculate the total CO_2 emissions abated, we summed up the energy-related CO_2 emissions abated with the process emissions separated by LEILAC's facilities at both facilities.

The energy costs for LEILAC were calculated by summing up the electrification needs for LEILAC's pre-calciner and energy requirements of running a CO_2 compressor to deliver super-critical CO_2 into the pipeline for transport to the sequestration site. To estimate the electrification requirements of LEILAC's pre-calciner, we converted the MMBtu heating requirement for LEILAC's pre-calciner at both plants into kWh. The energy requirement for running a CO_2 compressor was assumed to be 140kWh/tCO_2 and multiplying this figure with the total process emissions captured and compressed at

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[14] Rennie, D., drennie@calix.global, 2022. costs for calix. [email] Message to B. Epstein (bobepstein@gmail.com). Sent Tuesday, 16 August, 2022: 08:05 PDT.

[15] https://www.climateworks.org/wp-content/uploads/2019/02/CA-Cement-benchmarking-report-Rev-Final.pdf

[16] https://www.climateworks.org/wp-content/uploads/2019/02/CA-Cement-benchmarking-report-Rev-Final.pdf

plant A and B gave us the total energy required for CO_2 compression. We added LEILAC's pre-calciner's energy requirements (in kWh) to the energy requirements for the CO_2 compressor (in kWh) to obtain the total energy required for LEILAC's CO_2 separation and compression. Finally, we multiplied this figure for LEILAC's total energy requirement with the cost of renewable electricity. We examine three different prices for renewable electricity. The first two models assume a dedicated, adjacent renewable energy source priced at $0.05/kWh or $0.02/kWh. These prices reflect current pricing impacted by supply chain issues and the expected longer-term pricing. Our third model assumes purchasing grid power at $.18/kWh and also purchasing Renewable Energy Credits at $0.02/kWh, leading to a total price of $0.20/kWh. In scenarios where there are local renewables to power the CO_2 compressor, we assume electric power comes 25% from local renewables and 75% from the grid. The energy requirement figures for CO_2 separation and compression were also obtained from Calix[17]. Since several of the cement facilities are located where there are excellent solar and wind resources, we demonstrate that the economics strongly encourages the use of local renewables.

Scenario 2: Rondo's Heat Battery Provides Heat for LEILAC's Pre-Calciner

To model a situation where Rondo's heat battery provides the energy required by LEILAC's pre-calciner, we performed the same calculations as above. The key difference was the addition of the capital expense of installing Rondo's heat battery capacity and charging it with a dedicated renewable electricity to meet the energy requirements for LEILAC's pre-calciner (in kWh). This change is reflected simply by changing the electricity price in our energy cost calculations for LEILAC's pre-calciner from scenario 1. We computed the capital expense for Rondo's heat battery, using the following information and calculations. We converted the energy required for LEILAC's pre-calciner from MMBtus to MWh using a MMBtu to MWh conversion factor of 0.293. Given that an ideal cement plant operates 8,700 hours a year, we then divided LEILAC's energy requirement in MWh with 8,700 to obtain the total MW of continuous heat required to operate LEILAC's pre-calciner at both plants. A single RHB300 Rondo heat battery can provide 20MW of continuous heat. For both facility A and B, we divided LEILAC's continuous heat requirement in MW with the continuous heat output of a single Rondo heat battery to calculate how many heat batteries would be required. Finally, we multiplied the $25,000,000 CAPEX of a single RHB300 heat battery with the number of heat batteries required at each facility to obtain the CAPEX for Rondo.

Scenario 3: Rondo's Heat Battery Only Provides Heat for a Conventional Cyclone Pre-Calciner

Here we modeled a situation where Rondo only provides heat for a conventional cyclone pre-calciner and not a LEILAC. This scenario borrows the same assumptions, conversions and calculations from scenario 1 with a few key exceptions. The energy requirement for conventional pre-calciner is equal to the LEILAC one estimated in Scenario 1 in GJ/ton clinker, MMBtu/ ton cement, and kWh. The calculation for energy savings is similar to Scenario 1 and 2. In calculating the energy costs, we only deviate from scenario 1 and 2 by removing the energy costs for CO_2 compression. For CAPEX and Capital Recovery calculations, we used the CAPEX calculations for Rondo's heat battery for both facilities from section 2 and removed the CAPEX for LEILAC's pre-calciner and a CO_2 compressor. The final change is total abated emissions. Since there are no process CO_2 emissions being captured, the total abated emissions only include the energy-related CO_2 emissions abated when Rondo displaces natural gas combustion to provide heat for the conventional pre-calciner.

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[17] Email exchange between Project 2030 and Calix

Effective Benefit, Net Marginal Cost of Abatement & The Business Case

To compute the effective benefit, we first calculated the financial gain from CO_2 captured and sequestered by LEILAC with the 45Q federal tax credit amount of \$85/ton. To obtain the financial gain from 45Q federal tax credit, we multiplied the \$85/tCO_2 amount with the total process CO_2 separated at both plants in cases where LEILAC was implemented. Then, we computed the financial gain from avoided cap-and-trade fees. To do this, we multiplied the latest California cap-and-trade GHG allowance price of \$27/tCO_2 with the total CO_2 emissions abated (process emissions captured by LEILAC + energy-related emissions abated). The effective benefit in \$/ton from CO_2 abatement was obtained using the following equation:

$$EffectiveBenefit = \frac{(85)(ProcessCO2capturedstored) + (27)(TotalCO2Abated)}{TotalCO2Abated}$$

Annex 1

Cement Facility	Production (tons/year)	CO_2 Emissions
A	627,000	342,207
B	1,600,000	1,069,304

Annex 2

Fixed Costs (provided by Calix and Rondo)	Plant A	Plant B
CAPEX for LEILAC's Module	\$40,000,000	\$120,000,000
CAPEX for Dense Phase Conveying CO_2Compressor	\$4,400,000	\$16,800,000
CAPEX for Rondo's Heat Battery	\$50,000,000	\$25,000,000

Annex 3

CO_2 Logistics	\$/tCO_2
Transport	10
Storage	13
Distance to Sequestration Site	50 miles