ORIGEN

Phase 1 Final Report
Passive Lime Carbonation Project
Non-confidential Version

31 December 2021

Executive Summary

Phase 1 of the Passive Lime Carbonation project has explored the potential of using the lime cycle to remove carbon dioxide from the air. Independent of the Phase 1 project we have developed a technology to produce lime (CaO) in a way that allows the carbon dioxide generated in the lime-production process to be captured and stored. This results in a 'zero-carbon lime' which can then be allowed to react with CO_2 from ambient air in a range of settings. Overall, combining the production of zero-carbon lime and the subsequent removal of CO_2 from the air results in a process that is carbon-negative – it results in net removal of CO_2 from the atmosphere.

The Phase 1 project explored four different options for recarbonating lime with CO_2 from ambient air, through chemical and physical modelling and through experimentation.

As a result of this work we have decided to refine our focus for a Phase 2 project onto two of those approaches:

- One approach involves the creation of a range of 'zero-carbon lime' products and services. These are products (such as lime-based building materials) or services (such as use of lime in water treatment) which already employ conventionally-produced lime and which react with CO_2 from the air as part of their function. During a Phase 2 project we would demonstrate the use of our zero-carbon lime in such products and services at a scale sufficient to achieve the goal of removing CO_2 from the air at a rate of at least 1000 tonnes per year.
- The other approach involves entraining highly reactive lime in a flow of ambient air so as to directly remove CO_2 from the air. We have designed a module which will capture 25 tonnes of CO_2 from the air per year. During a Phase 2 project we would continue to develop this module through a test and design cycle, and by the end of the project will have deployed sufficient modules to achieve the goal of removing CO_2 from the air at a rate of at least 1000 tonnes per year.

The first of these approaches is expected to deliver a very low-cost approach to removing CO_2 from the air. By creating two value streams – the products and services themselves and the removal of CO_2 from the air – the costs ascribed to removing CO_2 from the air can be significantly reduced. This approach will be scalable to the extent that there exists a market for the products and services that use lime.

The second approach does not benefit from the ability to share its costs with other value streams and so will be more expensive. It will however be scalable without any practical limit.

We have a clear plan for developing these approaches in a Phase 2 project. As previously stated, independent of the Phase 1 project, we have developed a process for production of zero-carbon lime. We are constructing a pilot plant which will have the capacity to produce sufficient zero-carbon lime to enable the removal of 2400 tonnes of CO_2 from the air per year. The pilot plant will be commissioned in April 2022. We have already undertaken a FEED study of the design at 120,000 tonne per year scale, so, provided that appropriate incentives, physical infrastructure and regulations are in place we are in a strong position to be able to deploy at a scale of 50,000 tonnes per year well before 2030.

The biggest barrier to developing this approach in the UK is the current lack of regulatory frameworks that incentivise removals, the lack of development of measuring, reporting and verification (MRV) standards that would apply to removals, and uncertainty relating to the timing and costing of transport and storage solutions for CO_2. Currently existing incentives, regulatory standards and storage solutions in the US indicate that our approach is already commercially viable there.

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Introduction and Structure of this report

This document is the non-confidential version of the Phase 1 Final Report for the Passive Lime Carbonation Project. A confidential version of this report has also been prepared for the funder.

This report follows the structure as laid out in Annex 2 of the Competition Rules and Guidance Document addressing each of the headings and sub-headings laid out in the guidance.

This report includes a conclusion which draws together the preceding information and details the challenges of developing GGR techniques in the UK in absence of the required regulatory and physical infrastructure.

A detailed description of the science and engineering underpinning the proposed GGR solution

(i) All chemical and physical processes used, materials and substances required, how they will be sourced and consumed or disposed of

Origen's process involves two steps

1. The production of a 'zero-carbon lime', and
2. The use/treatment of that lime in a manner that allows it to capture CO_2 from the air

The overall process for removing CO_2 from the air requires both of these steps. The first step (production of zero-carbon lime) has been explored in activity undertaken by Origen independent of this Phase 1 project, while the second step (use of lime to remove CO_2 from the air) is the focus of the work of this Phase 1 project.

The combination of these two steps results in net removal of CO_2 from the air.

The proposal for a Phase 2 project will integrate both of these steps together to demonstrate this end-to-end solution.

1. Production of zero-carbon lime

The raw materials for this process are limestone ($CaCO_3$) and natural gas (required to generate the heat required to thermally decompose the limestone into lime and pure carbon dioxide: $CaCO_3 \rightarrow CaO + CO_2$). The limestone is first milled to a particle size less than 100 microns in diameter, then heated to ~1000°C in a specially-designed kiln (a flash calciner) which is fired with natural gas and oxygen. The flue gas comprises CO_2 (from both the combustion of the natural gas and the thermal decomposition of the limestone) and water vapour. Nitrogen is not present in the flue gases as no air has been introduced into the system. Once the water vapour is removed the resulting gas mixture is ~97% pure CO_2, requiring minimal clean-up to achieve pipeline-quality standards.

Independent of this Phase 1 project, Origen is constructing a new design of lime kiln that will generate lime in a way that allows the capture of the CO_2 from the lime-production process. The pilot plant (with capacity to produce 3000 tonnes per year of zero-carbon lime – sufficient to remove 2400 tonnes of CO_2 from the air per year) will be commissioned in April 2022. We anticipate using a proportion of the output from this pilot plant in a Phase 2 project if we are selected.

In addition, Origen has completed a FEED Study for a 50,000 tonne per year lime kiln of the same design and will complete a FEED Study for a 150,000 tonne per year lime kiln in Q1 2022.

2. Use of zero-carbon lime in a manner that allows it to capture CO_2 from the air

Modelling and experimental work undertaken during the Phase 1 project

The results of this section are confidential and have been excluded from the publicly-available report.

Creation of lime-base products and services that remove CO_2 from the air

During the course of the Phase 1 project we undertook detailed exploration of the creation of three-dimensional structures that incorporated lime in them. The initial focus of this line of work was to explore how we could increase the surface area of material that was exposed to the air with the intention of increasing the amount of CO_2 that could be removed per unit area. We engaged with several companies that already used lime in the creation of products and quickly realised that we could simultaneously make valuable products and at the same time remove CO_2 from the air. This was a key beneficial finding of the project.

By incorporating our zero-carbon lime in products that already use conventionally-produced lime in the creation of certain building products we can make those products and at the same time remove CO_2 from the air. For example, transparent limewash (a solution/suspension of calcium hydroxide) is clear when applied, but turns white as CO_2 from the air reacts with the $Ca(OH)_2$ to form $CaCO_3$. And hempcrete – a material made from mixing together hydrated lime, water and hemp shiv sets as CO_2 from the air reacts with the hydrated lime to form calcium carbonate. Such building materials – if made from a zero-carbon lime – are carbon-negative – there is less CO_2 in the air as a result of the creation of these products. From a commercial perspective, the fact that this approach creates two benefits – the removal of CO_2 from the air and the creation of marketable products - allows the costs to be shared, thereby reducing the cost of removing CO_2 from the air.

This is more of a business model innovation rather than a process innovation. It is anticipated that the zero-carbon lime we will produce will behave in the same way as conventionally-produced lime in existing products that use lime.

We also undertook research on services that used lime that results in its carbonation with CO_2 from ambient air. A detailed study[1] indicates that, depending on what the lime is used for, a significant proportion (up to 100% in some instances) of the lime will recarbonate in a way that removes CO_2 from the air.

We anticipate that this approach will result in a very low-cost way of removing CO_2 from the atmosphere. We anticipate that the zero-carbon lime that we produce will cost roughly 30-50% more than conventionally-produced lime (this is due to the fact that the zero-carbon lime process involves additional steps (milling of the material, production of oxygen, compression of CO_2 and charges for transporting and storing the CO_2, etc). Thus we could sell our zero-carbon lime at existing market prices for conventionally-produced lime as long as we can recover the incremental cost by being adequately recompensed for removing CO_2 from the air.

In a Phase 2 project we would undertake work to determine:

(i) The substitutability of our zero-carbon lime in place of conventionally produced lime. We anticipate that our zero-carbon lime will be purer and more reactive than conventionally-produced lime and we need to check that it will be suitable for the range of applications for which it could be used

(ii) The scale of the markets for each of the products and services that use lime. While the cost-sharing nature of this approach can significantly reduce the costs attributed to removing CO_2 from the atmosphere, it can only do so while the markets for the products and services remains unsaturated. We must not assume that the market size is static – the very ability of this process to remove CO_2 from the air may put products that use lime at an advantage over competing materials for cost reasons (for example a sandlime brick that absorbs CO_2 will have a lower (indeed negative) carbon footprint and may be able to take market share from conventional clay bricks which have a significant carbon footprint. As carbon prices rise, the relative costs of these products will shift in favour of sandlime bricks). In addition, there may be marketing advantages of having carbon-negative building products – we anticipate significant consumer demand for materials that would enable the construction of carbon-negative houses.

(iii) The full lifecycle analysis of CO_2 removal using such products. In order to obtain credit for CO_2 removal detailed LCA and MRV for the use of zero-carbon lime in products will need to be

[1] Campo, Francesco Pietro, et al. "Natural and enhanced carbonation of lime in its different applications: a review." *Environmental Technology Reviews* 10.1 (2021): 224-237.

undertaken. This will require detailed involvement of academic researchers in this space and engagement with policymakers who are developing the relevant standards.

(ii) All energy and fuel requirements for each stage or process, how they will be sourced, and the reasons for their selection

Lime production

The production of a zero-carbon lime requires the kiln to be heated to ~1000°C. This will be achieved by the combustion of natural gas in a stream of oxygen and recycled flue gases (a mixture of CO_2 and water vapour).

Natural gas has been selected as the energy source because:

i. the firing of kilns with natural gas is existing industrial practice
ii. the CO_2 generated by its combustion is captured as an integral part of this process and so does not contribute to climate change
iii. other energy sources are not appropriate – coal would introduce contaminants to the process, while electricity and hydrogen would be prohibitively expensive

A tonne of zero-carbon lime requires xGJ of natural gas (to provide thermal energy) and xGJ of electricity (to provide energy for processing and compression of CO_2). As stated above, the CO_2 generated from the combustion of the natural gas is captured as an integral part of the process and so will not contribute to climate change. It is anticipated that electricity will be sourced from the grid, with the expectation that it will become increasingly low-carbon in the years ahead.

(iii) A description of its environmental impacts

Apart from the major beneficial aspect of this process – the removal of CO_2 from the air, which counters climate change – the approach we are adopting is environmentally neutral with no other significant benefits or harms.

At the outset of the Phase 1, we explored a range of proposed approaches to enable lime to react with CO_2 from the air, including ones that exposed the external environment to lime (for example, the liming of soils with lime[2]). However, awareness of the potential environmental harms of such approaches – namely the risk of creating a spike in pH levels, and wind-blown lime causing air pollution (both through lime's caustic nature and the creation of PM10 particles) resulted in us discarding these as potential routes.

Instead we have focused on those approaches that can be undertaken in a controlled setting. The two approaches that we would explore in a Phase 2 project involve construction of air capture modules and the use of zero-carbon lime in existing products and services that already use conventionally-produced lime.

While the use of any resources results in environmental impacts, the fact that in the first instance, the components used are already licensed and in the second instance, the products created are already in use, would indicate that neither approach would create countervailing negative impacts.

[2] Farmers routinely lime their soils to increase pH. Somewhat confusingly, liming uses limestone (calcium carbonate) rather than lime (calcium oxide). Lime can also be used to increase pH, which is one of the avenues that we explored in Phase 1 of this project.

A detailed engineering design for a pilot project

(i) Sufficient detail that the credibility of the design and its costs can be assessed by independent experts

The key components of the Phase 2 project are:

Work Package 1: Project management

Work package 2: Operation of flash calciner

Operation of the oxy-fuel flash calciner pilot plant which will generate a zero-carbon lime. Please note that Origen has already committed the funds to the construction of this pilot plant which will be commissioned in April 2022. As such we are not seeking capex funding for this pilot plant, but we will be seeking opex funding to cover raw materials, energy, labour, maintenance and depreciation costs.

Work Package 3: Lime slaker

The capex associated with the construction and operation of a lime slaker. The lime (CaO) needs to be slaked (hydrated) with water to form calcium hydroxide ($Ca(OH)_2$). We intend to use a batch slaker, which will enable us to produce hydrated lime with the required properties.

Work package 4: Air capture modules

Construction of the reaction of CO_2 in ambient air with hydrated lime to capture in the resulting $CaCO_3$. As detailed above we will construct a module capable of removing 25 tonnes of CO_2 from the air per year. We have spec-ed this module assuming worst case reactivity of material, so anticipate that we could achieve considerably more throughput, but will only know this for certain once we are able to test the reactivity of the zero-carbon lime. On the basis of the performance of the initial module we will build more, larger modules to demonstrate the removal of CO_2 from the air at a rate of 1000 tonnes per year.

Work package 5: Zero-carbon lime building products

Demonstration of the use of our zero-carbon lime in the creation of building products that remove CO_2 from the air as they cure. This will involve us hiring sub-contractors who have the expertise to create such products. We will provide them with hydrated lime required to make our products at no cost, pay them for their time and the other materials required and then take possession of the products that they make. In accordance with the requirements of SBRI funding we will not sell these products, but instead will use them to analyse the performance of the products both for their intended purposes and for their ability to remove CO_2 from the air.

Work package 6: CO_2 purification

Demonstration of the purification of CO_2 from the oxy-fuel flash calciner (~97% purity) up to the pipeline quality standards required for CO_2 transport and storage. As the purification of CO_2 is already routinely practised (TRL9), it is not necessary (or indeed a sensible use of public money) to demonstrate this step. Instead we would obtain detailed quotes for such a purification system during the course of a Phase 2 project, so as to arrive at a full costing for the end-to-end process.

Work package 7: Analysis of zero-carbon lime products

Analysis of materials produced by reaction of zero-carbon lime with CO_2 that originated from the air. To establish MRV standards and a comprehensive LCA, it will be necessary to show the extent of carbonation (a small proportion of the lime may remain uncarbonated due to occlusion of the material by the build-up of a passivating layer of calcium carbonate) and also that the CO_2 that reacts with the lime originated from the atmosphere. This will require detailed analysis in a laboratory setting (thermogravimetric analysis, electron microscopy, isotopic analysis, etc) and we intend to work with academics who have particular expertise in this space.

Work package 8: Detailed social and environmental impact studies

Detailed social and environmental impact assessment of the overall process. We are aware that the deployability of GGR techniques is contingent on not only their technical feasibility, but also their social acceptability. We would propose including costings for not only standard impact assessments, but also funding for public engagement research.

Work package 9: FEED Study for 500k tonnes per year

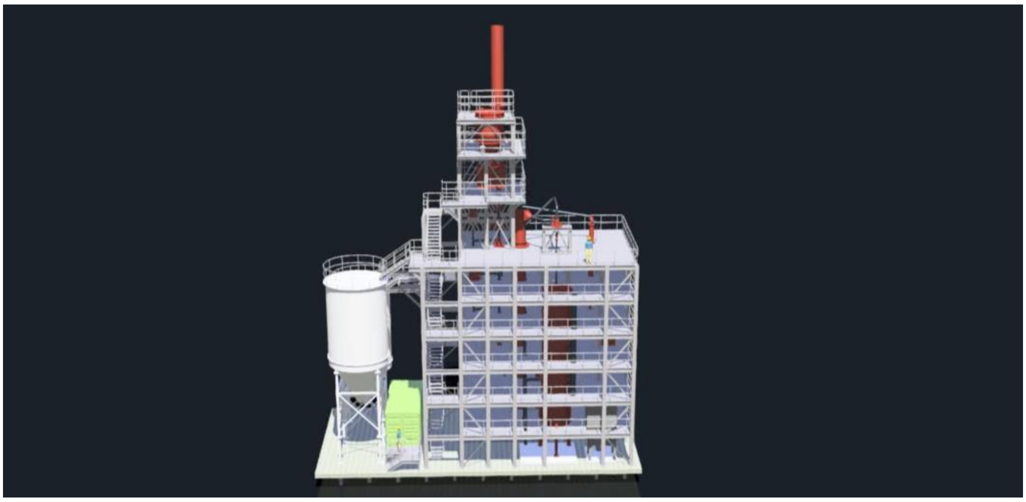
Undertake detailed techno-economic analysis and market assessment at larger scales. While Phase 2 projects are intended to demonstrate removal of CO_2 from the air at a rate of 1000 tonnes per year, we anticipate that much larger scales will be required and that within the budget envelope of a Phase 2 project we can make a detailed cost estimate at a scale of 500,000 tonnes per year.

Work Package 10: Commercialisation

Undertake detailed analysis of the costs of production in a range of locations within the UK and internationally and market demand for removals. We anticipate that the precise engineering solution will vary not only with location, but also with respect to incentive structures for removal which will affect the cost of capital and hence the design.

(ii) Technical drawings of the pilot plant proposed

(a) The CAD model below is of the oxy-fuel flash calciner that is already under construction at Singleton Birch's site (Step (a) in the description in the preceding section). The structure will be 35m tall. More detail will be provided in the Phase 2 project application.



(b) Lime slaker. We would intend to purchase a batch slaker that would allow us to control the reaction conditions for the production of hydrated lime. This would allow us to tailor the performance of the hydrated lime (particularly the size of particle) as required. We would purchase a plant similar to the one shown below.

(c) Air capture module. Confidential – not shared.

(d)-(i) These sections do not require technical drawings

(iii) Cost savings compared with exclusive development contracts

We will undertake the work on this project at cost and will not charge at rates that include a profit element. We will, where possible, seek competing bids for sub-contracted work that is required for this project.

Where the GGR solution will be piloted if selected for funding

(i) The site (give address) & the reasons for choosing it, its benefits & risks

Singleton Birch's site in North Lincolnshire - Singleton Birch Limited, Melton Ross Quarries, Barnetby. North Lincolnshire, DN38 6AE. Existing lime production (expertise, access to limestone, industrial site with access to natural gas, electricity, anaerobic digester). Site of oxy-fuel flash calciner pilot plant under construction. We also intend to build the air capture modules at this site.

(ii) How the GGR solution interacts with current or proposed use of the site or activities undertaken at it

Singleton Birch is the UK's largest independent lime producer. And is a partner in the Net Zero Humber initiative with access to the planned CO_2 transport and storage pipeline for the East Coast Cluster. Singleton Birch also operates an anaerobic digester on their site which could be used to supply biogas for that element of the pilot project.

A programme and business plan detailing how the GGR solution could continue to be developed beyond the end of the pilot phase, should the pilot phase be funded, including:

(i) What the next stage in the development of the GGR would be, including its scale and likely location

We anticipate the construction of a 50,000 tonne per year plant as the next stage of the development of the process. We have already completed a FEED Study for the oxy-fuel flash calciner at this scale and would seek to complete studies for the scaling up of the other elements of the end-to-end process to this scale during the course of the Phase 2 project. We would also undertake commercial development of CO_2-negative building products with a view to supplying such products to the market in the UK and internationally during the course of the Phase 2 project.

We anticipate that there will be a ready export market for our approach. The precise location of international development of our process will depend on:

(i) Regulatory mechanisms that provide sufficient incentives

(ii) Access to pipelines for CO_2 storage

(iii) Comprehensive MRV regulations that give clarity of what qualifies for incentives

(iv) Clarity as to length of contracts/incentives (as this will directly inform the cost of capital for projects, which is reflective of the risk of a project)

(v) Possibility of a Regulated Asset Base model (as has been envisaged for future nuclear power projects) as this would reduce cost of capital.

It should be noted that the UK is currently not the favoured market due to lack of incentives and lack of infrastructure in comparison with other markets.

A single unit can be scaled to 500,000 tonnes per year. The physical resources needed for this approach are:

- Limestone (~10% of the surface mineral on the planet)
- Natural gas (there are many locations around the world that have large unexploited natural gas reserves due to the gas being geographically stranded – that is that it costs more to convey the gas to a market than the gas is worth in that market. The fact that it does not matter where CO_2 is removed from the atmosphere – the atmosphere is well-mixed – suggests that large amounts of stranded gas could be employed to remove CO_2 from the atmosphere)
- Storage space for the CO_2 (the storage resource in disused oil and gas fields, saline aquifers and basalts is far more than is required to return CO_2 concentrations back to pre-Industrial levels if it were desired to deploy GGR on such a scale)

As such, we do not anticipate that the scale of this GGR approach is restricted – it could be scaled to whatever level is required without impinging on physical limits. The scalability is also unlikely to be restricted due to social constraints – the quarrying of limestone and the production of lime are already undertaken at significant scale without creating particular countervailing issues. The scalability due to political constraints is a function of society's willingness to pay adequately for action required to avoid the impacts of climate change.

Recognition that notwithstanding the development of regulations that incentivise removals, the UK may still not be the favoured location for large-scale development of this GGR technique as higher costs in the UK (land, planning constraints and cost of energy) suggest other locations which are less densely populated and have lower energy costs (for example parts of North America, the Middle East and Australia) are likely to be preferable. Origen, as a UK-based company, could generate export earnings and contribute tax revenues on the sale of IP to develop its process in other countries.

(ii) How this development would be informed by information gained during Phase 2

A Phase 2 project will provide essential information relating to the costing of our approach at climatically-relevant scale, the regulatory issues that need to be addressed and to demonstrate our approach to the satisfaction of regulators, investors and potential customers. The current lack of MRV standards for GGR techniques currently hampers development significantly. Until a technique is demonstrated end-to-end in physical form (even if the component parts of a system have already been deployed in other industries) it will not be considered and understood by policymakers – and in the absence of policy it will not be possible to generate the investment to deploy such techniques.

(iii) Dependencies – describe what your plan depends upon and any assumptions made

The key assumptions are:

(i) The oxy-fuel flash calciner works – flash calcination understood and routinely practised in the cement and alumina industries; oxy-fuel combustion understood and routinely practised in a range of industries; use of waste heat to drive oxygen separation well understood but not yet practised.

(ii) Lime recarbonates with CO_2 from ambient air – understood and documented in peer-reviewed journals.

(iii) CO_2 captured from the air by lime used in products is eligible for credit for carbon removal – when lime carbonates with CO_2 from the air, logic dictates that this would be eligible for removal credits as it results in permanent storage of CO_2 from the air. However, as this has yet to be demonstrated it will require regulators to get comfortable with this as an approach.

(iv) Societal willingness to create regulatory mechanisms that incentivise the removal of CO_2 from the air. This is a broader issue relating to the acceptability of incentives for all GGR techniques. As yet, the UK has not incentivised the deployment of GGR techniques and so this cannot yet be confirmed.

(v) To be deployable in the UK will require the development of a sufficiently scaled transport and storage infrastructure. Confirmed in policy, but not yet implemented.

Conclusion

Origen is confident that this approach can remove CO_2 from the air at scale in a way that is safe, socially acceptable, permanent, scalable – and at a reasonable economic cost. The key question is whether there is the appetite for policy to support the deployment of this and other GGR techniques in the UK.

Doing this in the UK will require rapid development of regulatory and physical infrastructure

- Regulatory infrastructure: MRV standards, incentive mechanisms, financing architecture (length of contracts, fixed or floating fees, cost of capital – for example, Regulated Asset Base model)
- Physical infrastructure: CO_2 pipelines, pipeline specifications, costing, capacity, location, timing

Other countries are further developed in this regard. For example, in the US, both regulatory and physical infrastructure are already in place. There are incentives there of $85 per tonne for sequestering CO_2 and $180 per tonne for removing CO_2 from the air, which make it a highly attractive target market.

We want to develop our technology here in the UK and believe that provided that we could achieve CO_2 removal here at £100 per tonne by 2030 (contingent on reasonable regulations and long-term contracts). And we can do this without a limitation of scale – provided the infrastructure and incentives are in place our approach could be scaled to the UK Government's target of 10 million tonnes per year by 2030 and the entirety of the forecast demand for removals in the UK in 2050.