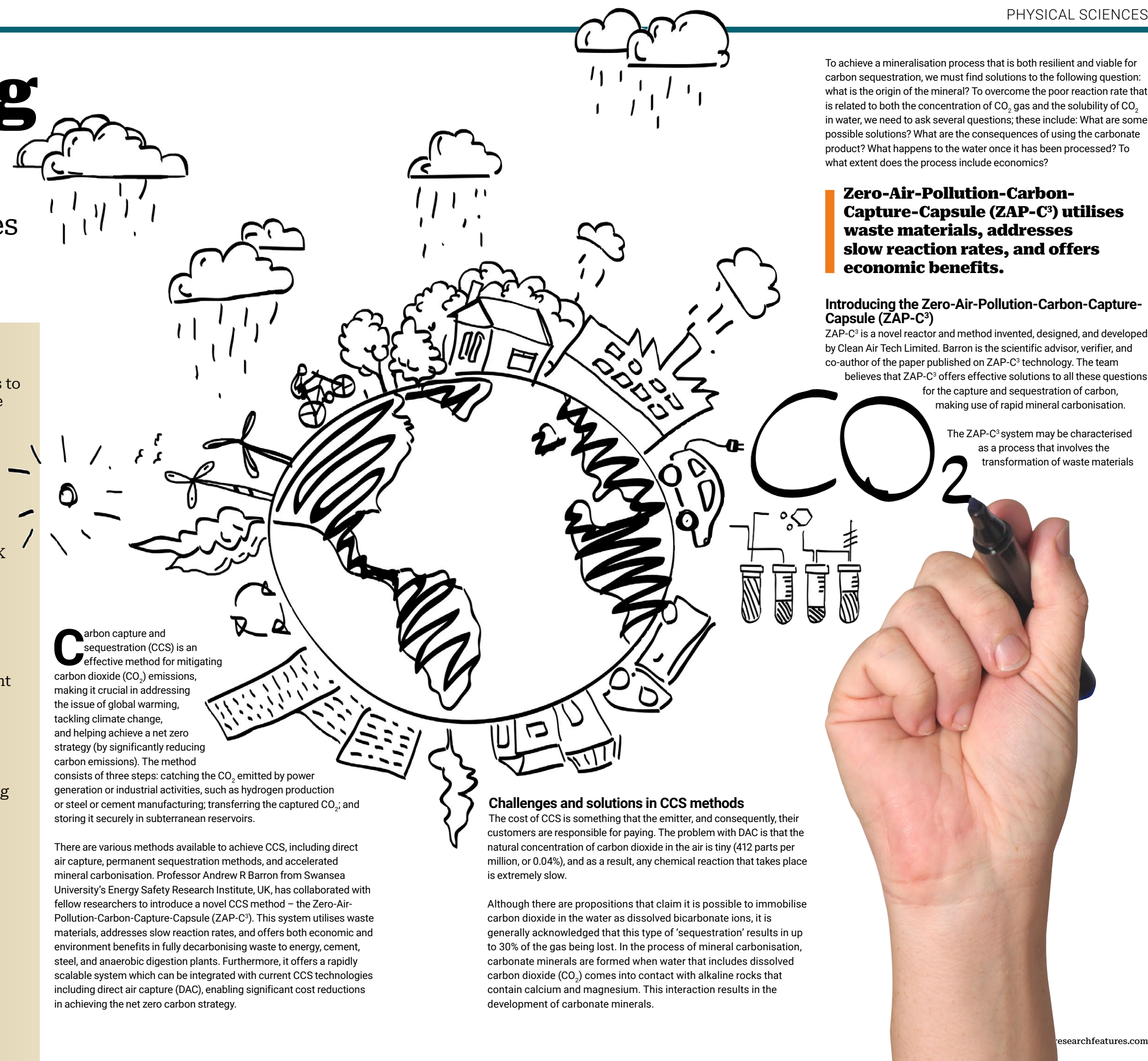


Breaking ground

ZAP-C³ revolutionises carbon capture and sequestration

- Climate change spurs urgency for reducing carbon emissions; carbon capture and sequestration (CCS) aims to capture and sequester CO₂ to mitigate its impact.
- High costs, technological limitations, and environmental concerns hinder widespread adoption of CCS.
- Professor Andrew R Barron from the Energy Safety Research Institute, Swansea University, and the team from Clean Air Tech Limited in the UK introduce a novel CCS method – the Zero-Air-Pollution-Carbon-Capture-Capsule (ZAP-C³).
- ZAP-C³ converts waste materials like recycled concrete or basic oxygen steelmaking (BOS) slag and CO₂ into valuable products, facilitating efficient carbon capture and sequestration.
- ZAP-C³ tackles carbon capture challenges by efficiently using waste, utilising water sustainably, rapid mineral carbonisation, generating valuable end products, and addressing technical and economic barriers.



To achieve a mineralisation process that is both resilient and viable for carbon sequestration, we must find solutions to the following question: what is the origin of the mineral? To overcome the poor reaction rate that is related to both the concentration of CO₂ gas and the solubility of CO₂ in water, we need to ask several questions; these include: What are some possible solutions? What are the consequences of using the carbonate product? What happens to the water once it has been processed? To what extent does the process include economics?

Zero-Air-Pollution-Carbon-Capture-Capsule (ZAP-C³) utilises waste materials, addresses slow reaction rates, and offers economic benefits.

Introducing the Zero-Air-Pollution-Carbon-Capture-Capsule (ZAP-C³)

ZAP-C³ is a novel reactor and method invented, designed, and developed by Clean Air Tech Limited. Barron is the scientific advisor, verifier, and co-author of the paper published on ZAP-C³ technology. The team believes that ZAP-C³ offers effective solutions to all these questions for the capture and sequestration of carbon, making use of rapid mineral carbonisation.

The ZAP-C³ system may be characterised as a process that involves the transformation of waste materials

Carbon capture and sequestration (CCS) is an effective method for mitigating carbon dioxide (CO₂) emissions, making it crucial in addressing the issue of global warming, tackling climate change, and helping achieve a net zero strategy (by significantly reducing carbon emissions). The method consists of three steps: catching the CO₂ emitted by power generation or industrial activities, such as hydrogen production or steel or cement manufacturing; transferring the captured CO₂; and storing it securely in subterranean reservoirs.

There are various methods available to achieve CCS, including direct air capture, permanent sequestration methods, and accelerated mineral carbonisation. Professor Andrew R Barron from Swansea University's Energy Safety Research Institute, UK, has collaborated with fellow researchers to introduce a novel CCS method – the Zero-Air-Pollution-Carbon-Capture-Capsule (ZAP-C³). This system utilises waste materials, addresses slow reaction rates, and offers both economic and environment benefits in fully decarbonising waste to energy, cement, steel, and anaerobic digestion plants. Furthermore, it offers a rapidly scalable system which can be integrated with current CCS technologies including direct air capture (DAC), enabling significant cost reductions in achieving the net zero carbon strategy.

Challenges and solutions in CCS methods

The cost of CCS is something that the emitter, and consequently, their customers are responsible for paying. The problem with DAC is that the natural concentration of carbon dioxide in the air is tiny (412 parts per million, or 0.04%), and as a result, any chemical reaction that takes place is extremely slow.

Although there are propositions that claim it is possible to immobilise carbon dioxide in the water as dissolved bicarbonate ions, it is generally acknowledged that this type of 'sequestration' results in up to 30% of the gas being lost. In the process of mineral carbonisation, carbonate minerals are formed when water that includes dissolved carbon dioxide (CO₂) comes into contact with alkaline rocks that contain calcium and magnesium. This interaction results in the development of carbonate minerals.



Images of the carbon capture, usage and storage (CCUS) unit on site in Belgium.

such as basic oxygen steelmaking (BOS) slag, recycled concrete aggregate (RCA), fly ash, bottom ash, and carbon dioxide. They are transformed into two useful products, calcium carbonate (CaCO_3) and a volumetrically stable aggregate (which maintains its volume without significant changes under specific conditions), which are synonymous with the permanent sequestration of carbon dioxide.

Utilising waste minerals for sustainable carbon sequestration

It is crucial to understand the origin of the calcium or magnesium mineral. For instance, even though magnesium hydroxide ($\text{Mg}(\text{OH})_2$ or brucite) is a naturally occurring mineral, its use requires mining and processing, which results in significant carbon emissions. Before being deployed, it is intrinsically a carbon emitter.

Thus, minerals that are neither mined nor create heat are the ideal choice for mineral selection in sequestration. Furthermore, the ability to react with these minerals directly is crucial for evaluating their storage capacity over an extended period. BOS slag, fly ash, bottom ash waste, or recycled concrete aggregate are all examples of waste mineral sources that may be utilised in the ZAP-C³ process. This method is designed to utilise a waste mineral source that requires minimum processing.

Following the adsorption of water vapour onto the hydrophilic surface, the utilisation of steel BOS slag as the mineral source results in the

The ZAP-C³ system converts waste materials like RCA or BOS slag and CO₂ into valuable products like calcium carbonate and volumetrically stable aggregate, allowing for permanent sequestration of CO₂.

production of appropriate alkalinity. One example is the addition of BOS slag to water with a pH of 3.8, which causes the pH of the water to shift to 11. Not only does this make it easier for carbon dioxide to dissolve and activate through the creation of carbonate, but it also leads to the solubilisation of the cations through the process.

Innovative techniques in carbonation and mineralisation

There is no product in and of itself when it comes to in-situ mineralisation processes, and the majority of previous ex-situ CCS

methods recommend returning CO₂ minerals to the environment, for instance, by depositing them in the seas. When it comes to the creation of valuable goods through the mineralisation of waste, the ZAP-C³ process is a novel strategy.

In phase 2 of the ZAP-C³ process, a portion of the cooled exhaust from the ZAP-C³ reactor in phase 1 is passed through the cooled leachate solution using a micro-bubbler system. This system enhances the reaction between carbon dioxide and the dissolved calcium ions, which ultimately results in the precipitation of calcium carbonate which is then recovered.

Environmental and economic benefits of ZAP-C³

The mining of a mineral reagent does not result in any energy costs, emissions, or negative effects on the environment because it is accomplished by the utilisation of a waste mineral. The ZAP-C³ process employs a closed-loop system where all water is recycled and returned to the reactor system. Additionally, since the ZAP-C³ process makes use of hot flue gas, there is no considerable extra heat energy that is required, which results in a reduction in the overall energy expenditure.

Crucially, the ZAP-C³ method generates a product that offers substantial economic value. The carbonated hydrophobic aggregate that is used for anti-slip road paving has a value of 50 USD per tonne, which is significantly more than the value of the ground and sized BOS slag, which is only 5 USD per tonne. The CaCO_3 that is created during the second step of the process has a value of 95 USD per tonne, which is an additional benefit.

The fine carbonated recycled concrete aggregate (RCA) replaces clinker valued at 75 USD, while the coarser carbonated RCA replaces virgin mined aggregate valued at 40 USD. Currently, RCA is sold as sub-base material for less than 5 USD per tonne. Additionally, toxic fly ash and bottom ash from waste-to-energy incineration are converted into non-toxic, carbonaceous material for use in cement manufacturing, fetching a decent sale value. Furthermore, the process saves landfill costs exceeding 100 USD per tonne.

The path forward: End products and applications

The ZAP-C³ system converts waste materials like BOS slag and CO₂ into valuable products like calcium carbonate and volumetrically stable aggregate, allowing for permanent sequestration of CO₂. This process allows for direct verification of CO₂ sequestration and 100% water recycling. This process is useful for road construction and carbon sequestration, making it ideal for anti-slip road surfaces.

Personal response

What measures are taken to ensure 100% water recycling within the ZAP-C³ process, and what are the environmental implications of this approach?

The two possible water loss pathways involve evaporation and residual water retained in the final aggregate. In order to minimise evaporation, we plan to condense water vapour at the gas outlets through the implementation of our own super-hydrophilic water capture technology. This is already being used under a UK FCDO-funded project for water harvesting in agriculture. The use of a surface treatment allows the water to be collected and recycled. The loss of water in the aggregate product can be partially overcome by using the heat from the flue gas to dry the aggregate product, while simultaneously cooling flue gas, straight from a hot combustion source to below 90°C as required for the ZAP-C³ process. The water evaporated from the drying aggregate can be collected using the same super-hydrophilic water harvesting technology.

How does the ZAP-C³ process compare to other carbon capture and sequestration methods in terms of efficiency, cost-effectiveness, and sustainability?

ZAP-C³ should be compared to other mineralisation technology as well as other CCUS processes. Because ZAP-C³ is designed to work with a waste material such as BOS slag, recycled concrete aggregate, and fly/bottom ash, there are no emissions associated with mining of the material that is required in the majority of mineralisation processes. Most importantly, unlike many mineralisation processes,

the ZAP-C³ process of measurement, reporting, and verification (MRV) is a simple process because the CO₂ sequestered is measured directly on the product from the process rather than estimated over time. The low power consumption of ZAP-C³ (40 kWh) ensures that irrespective of the electricity source used, any CO₂ emissions associated with its operation is minimal, in contrast to mineralisation technologies requiring electrolysis. Finally, the formation

of a valuable mineral product along with precipitated calcium carbonate means that it is a carbon capture, usage and storage (CCUS) process that does not rely on carbon credits.

Are there any potential challenges or limitations associated with the implementation of the ZAP-C³ system, and how are they addressed?

The ZAP-C³ system requires a waste mineral source such as RCA or BOS slag or fly/bottom ash. The biggest challenge will be minimising transportation costs and associate emissions of bringing this mineral waste to the site. Situating the ZAP-C³ system adjacent to both CO₂ emission sources and waste material sites will obviate this challenge.

Can you explain the mechanism by which BOS slag enhances alkalinity and facilitates carbon dioxide activation in the process?

Calcium containing materials, such as RCA, BOS slag, and fly ash, react with acid water (formed by the dissolution of CO₂ from a flue gas source) by two processes. First, soluble calcium is extracted into a leachate that is alkaline due to the formation of carbonate (CO_3^{2-}). Second insoluble calcium reacts with CO₂ to form stable carbonate minerals within the RCA/BOS slag. Both of these processes occur within the ZAP-C³ system where water is sprayed through the flue gas atmosphere onto the mineral. The alkaline leachate is then treated with additional CO₂ rich flue gas in a micro-bubbler to precipitate out CaCO_3 .

Where do you envisage research in this novel strategy could proceed to?

At the highest level, our success in showing a CCUS process that has an economic benefit beyond carbon credits, should encourage other researchers and industry to see CCUS as a business and not a cost, which will drive the adoption of CCUS globally as well as merge it into the wider arena of the circular economy. Most importantly, this strategy can be extended by integration with other processes to create a net zero ecosystem. For example, the ZAP-C³ process can be linked to an algae bioreactor which would consume the CO₂ depleted flue gas, converting it to protein, and high value chemicals, where the growth media required is formed from food-waste. Furthermore, the alkaline leachate has been shown to be able to be used for green hydrogen electrolysis. All these processes can be brought together to operate in concert.

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Bio

Andrew R Barron has previously served as Professor at Harvard, RICE, and Swansea Universities. Barron is the founder of Energy Safety Research Institute. An author of over 550 scientific papers, he is a serial entrepreneur focusing on decarbonisation. Barron is also the recipient of the World Technology Award, Star of Asia Award, and Hydrogen Award.

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- Clean Air Tech
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Competing interest statement

Professor Barron is an advisor to Clean Air Tech.

Further reading

Narasimhamurthy, P, Prakashkumar, Y, Prakashkumar, S, et al, (2024) [A high efficiency approach to carbon capture and permanent sequestration through mineralisation](#). [preprint] *ChemRxiv*.

