Institution: University of Leeds

Unit of Assessment: UoA 8 Chemistry

Title of case study: C-Capture: a University spin-out for the commercial application of novel CO_2 capture technology

Period when the underpinning research was undertaken: 2000-date

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Professor Christopher Rayner	Professor of Organic Chemistry	1/10/1989-date

Period when the claimed impact occurred: 2014-date

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact (indicative maximum 100 words)

C-Capture is a University of Leeds spin-out company established to develop novel low-energy CO_2 capture technology. The company has secured major investment from BP Ventures, Drax and IP group (ca. GBP3,500,000 in most recent funding round), and competitive funding of >GBP6,000,000 from BEIS. The company's technology has two major applications: CO_2 capture from large-scale point source emitters (e.g. power stations), and gas upgrading (natural and biogas) by CO_2 removal. C-Capture are partnering with Drax on the first pilot Bioenergy Carbon Capture Storage Project in Europe, and the first in the World using 100% biomass fuel.

2. Underpinning research (indicative maximum 500 words)

Carbon capture and storage (CCS) technology typically relies on amine-containing solvents, which were first introduced in the 1930's for CO_2 removal as part of natural gas sweetening. Amine solvents act as bases to initiate reaction of CO_2 (an acid gas) to form chemical species that are held within the chemical solvent, whilst all other gases pass through, thus leading to separation. However, the amine/CO_2 adducts are relatively stable and thus significant energy is required to subsequently liberate the captured CO_2 for storage. This high-energy input is a significant barrier to the economics of commercial CCS; many amines are also highly corrosive leading to very expensive plant construction on scale. Additionally, there are environmental concerns over the emissions from degradation of some amine-based capture agents.

Professor Chris Rayner at Leeds has longstanding experience in the organic chemistry of carbon dioxide, spanning the use of (mainly supercritical) CO_2 as a solvent for extraction of natural materials and as a medium for organic chemical reactions. As part of this programme he has made fundamental studies of the reactivity and simple solvent properties of CO_2, **[1]** as well as studying intermolecular interactions with common organic functional groups **[2]** and complex molecules such as proteins. **[3]** Building on this expertise, Rayner initiated a search for more suitable amine-free methods for CO_2 capture which could lead to major advantages in performance and environmental impact. Using his expert knowledge of CO_2/organic molecule interactions, Rayner devised a range of novel CO_2 capture media based upon the use of phenoxides, which show comparable Bronsted basicity to amine-based CCS agents. **[4, P1]** These agents were shown to capture CO_2 effectively alone, and when used as blends with amine-based reagents showed comparable capture rate/capacity and energy use compared to leading commercial blends based solely on amines. **[4]** C-Capture was established in 2009 as a spin-out of the University of Leeds (through investment by IP Group) to further develop and exploit the use of these novel CO_2 capture media. **[P1]** More recently, C-Capture technology has evolved from utilising phenoxide salts as capture agents to employing carboxylic acid salts with a proprietary blend of modifying agents. This approach requires less expensive materials of construction, has reduced environmental impact,

and most importantly releases the captured CO_2 with a significantly lower energy input. This technology was filed for patent protection in December 2013. **[P2,P3]**

Rayner and his research team continue to work closely with C-Capture to improve fundamental understanding of the chemistry of their carbon capture media, and to develop new technologies in support of their business, for example in developing new tomographic sensor technology with the potential to enable quantitation of CO_2 capture *in situ*. **[5]** In order to support C-Capture through a period of rapid growth, Rayner was seconded to the company (0.5 FTE) from Sept 2017 to Aug 2018 to drive technical and commercial development in the company, funded by the University of Leeds EPSRC Impact Acceleration Account; he remains a Director of C-Capture.

3. References to the research (indicative maximum of six references)

The quality of the underpinning research is evidenced by (a) outputs [1]-[5] being published in international peer-reviewed journals and (b) the citations (Web of Science, 10/2/21) of each output that support their influence and scientific impact within the community.

[1] "The potential of carbon dioxide in synthetic organic chemistry" C. M. Rayner, *Org. Proc. Res. Dev.*, **2007**, 11, 121-132. DOI: 10.1021/op060165d. (110 citations)
Invited review containing, inter alia, 10 published references (2001-2006) and previously unpublished work from Rayner.

[2] "An in situ high pressure FTIR study on molecular interactions of ketones, esters, and amides with dense phase carbon dioxide" Y. Akiyama, S. Fujita, H. Senboku, C. M. Rayner, S. A. Brough, M. Arai, *J. Supercritical Fluids*, **2008**, *46*, 197-205. DOI: 10.1016/j.supflu.2008.03.009. (30 citations)
Physicochemical study of interactions of CO_2 with common organic functional groups.

[3] "Stabilisation of carbon dioxide-in-water emulsions by proteins" B. S. Murray, E. Dickinson, D. A. Clarke, C. M. Rayner, *Chem. Commun.*, **2006**, 1410-1412. DOI: 10.1039/b515700e. (7 citations)
Physicochemical study of stabilisation of carbon dioxide emulsions in water.

[4] "CO_2 capture using phenoxide salts; alternatives to amine-based capture agents, and comparative speciation studies as components in solvent blends" J. E. Wheatley, S. Bala, D. C. Barnes, C. Schoolderman, G. Jakab, G. Raynel, C. M. Rayner, *Int. J. Greenhouse Gas Control*, **2019**, *88*, 353-360. DOI: 10.1016/j.ijggc.2019.06.012. (1 citation)
Joint paper from University of Leeds and C-Capture outlining the performance of phenoxide salts, alone and as blends with amines, as superior to conventional amine-based CO_2 capture agents.

[5] "A feasible process tomography and spectroscopy measurement system to determine carbon dioxide absorption" M. Wang, N. P. Ramskill, S. Barns, G. Raynel, C. H. Qiu, C. M. Rayner, *Flow Measurement and Instrumentation,* **2013**, *31*, 77-85. DOI: 10.1016/j.flowmeasinst.2012.09.005. (4 citations)
Joint paper from University of Leeds and C-Capture describing advances for the quantitation of CO_2 absorption at scale.

Patents:

[P1] "Process for the capture of carbon dioxide", C. M. Rayner, G. R. J.-F. Raynel; WO 2011/135378 A1
University of Leeds patent submission covering use of phenoxide-based carbon-capture systems.

[P2] "Methods for the capture and release of acid gases", C. M. Rayner, D. C. Barnes, G. Jakab, C. Schoolderman; WO2015/092427 A2, PCT/GB2014/053786. Currently granted in 22 territories, including USA, China, Japan, India and various EU. Other territories pending (S. Korea, Canada). Divisional patent also filed in EU.

[P3] "Aqueous system for the capture and release of acid gases", C. M. Rayner, D. C. Barnes, G. J. Jakab, C. Schoolderman; PCT/GB2018/052209.
[P2] and [P3] are patents on carboxylic acid-based CO_2 capture media, the main technology now used by C-Capture.

4. Details of the impact (indicative maximum 750 words)

The International Energy Agency has stated that if the world is to meet the Paris Agreement for levels of CO_2 then approximately 2,000 carbon capture and storage (CCS) facilities need to be operating by 2040, contributing a 7% reduction in cumulative emissions. This underscores the global need for development and deployment of CCS technologies. Based directly on IP generated at the University of Leeds, **[4, P1]** C-Capture was established as a spin-out in 2009 with an initial investment from IP Group and additional support from the University. **[A, B]** Impact has been demonstrated in the review period through the growth of the business (including creation of jobs); the design and delivery of new processes; and engagement with C-Capture technology by other companies.

Growth of C-Capture

C-Capture has grown significantly in the impact period. In 2013, turnover was *ca.* GBP250,000 with 3 employees, and was still based within University laboratories, where the current carboxylate-based technologies were developed. **[A, P2, P3]** It has since attracted significant and ongoing investment, including a 2019 injection of GBP3,500,000 from a consortium comprising BP Ventures, Drax and IP Group. **[A, B, C]** The company moved to their own premises in 2014 and has grown to 20 employees, with a cost base in 2020 of ca. £3.2M (including grant and investment income). **[A]** Significant competitive funding has been won to underpin its development including, in 2017, >GBP1,000,000 from the Department of Business, Energy and Industrial Strategy (BEIS) Energy Entrepreneurs Fund and the CO_2 Capture Programme (an industry-based consortium of BP, Chevron and Petrobras) to develop and scale up initial solvent chemistry for use in CCS and biogas upgrading, and develop a further generation of solvent technology. **[D]** C-Capture is accredited by BP as a partner through their Advancing Low Carbon programme; to achieve accreditation, partners must meet criteria independently assured by Deloitte LLP. **[E]**

Application to CCS from biomass powerstations: the Drax partnership

A key part of the commercial development of C-Capture's technology towards CCS from power stations has been carried out in partnership with Drax, the UK's largest power station and the second largest in Europe. Drax has moved from coal to biomass fuel in recent years, and are now combining this with CCS towards negative emissions technology. Following their withdrawal from the use of oxyfuel technologies in 2015, Drax have since partnered with C-Capture to develop and apply their propietary post-combustion technology. **[A]** Drax provided GBP400,000 in 2018 for a pilot project in which CO_2 generated in the combustion of 100% biomass is captured – the first such venture in the world. **[A]** By 2019, capture of up to 1 tonne of CO_2 per day had been demonstrated. This work is the subject of a new grant by BEIS under their CCUS Innovation programme, led by C-Capture (grant value ca. GBP4,900,000). **[F]** This includes large-scale trials with international partners at SINTEF (capture of 1 tonne CO_2 per day at their highly instrumented Tiller facility) and potentially at Technology Centre Mongstat (up to 100 tonnes CO_2 per day capture, 100th scale of proposed Drax unit). Then Minister for Energy and Clean Growth, Chris Skidmore said at the launch "*This innovative project from C-Capture and Drax represents a major milestone in efforts to rollout carbon capture at scale by the 2030s*." **[F]** The context of the significant investment by Drax is that it underpins major strategic business decisions: deployment

of CCS technology at Drax has the potential to capture 15 million tonnes of CO_2 pa, most of which can be considered as negative emissions, and would represent an investment of GBP1-2 billion depending on scale. The C-Capture/Drax project is highlighted in the Government's response to the Committee on Climate Change's 2019 progress report to parliament ("Leading on Clean Growth"), **[G]** and was awarded the Breakthrough Of The Year Award in the 2019 Business Green Awards. **[H]** The company was also recently listed in the prestigious Global Cleantech 100 report, produced by Cleantech Group, which lists the top 100 international companies best positioned to contribute to a more digitized, de-carbonized and resource-efficient future. **[A]**

Diversification of applications

C-Capture has diversified its technology interests into biogas sweetening (removal of CO_2 from gas streams generated from anaerobic digesters to improve fuel properties). This technology won first prize (GBP150,000) in the national 2016 Shell Springboard competition for low-carbon technologies. **[A, I]** Further funding to develop biogas upgrading platforms has been obtained from Innovate UK (GBP103,938, Nov 2018).

C-Capture and Pilkington UK Limited have recently secured funding through Innovate UK's Sustainable Innovation Fund for a feasibility study into deployment of C-Capture's technology on Pilkington's site as a step towards decarbonising glass manufacture, which has a particularly challenging flue gas, and has the potential to derisk other industrial CCS applications. **[J]**

Professor Rayner remains a Director of C-Capture. As Founder Director, he played a key role in the growth of the company and was seconded to C-Capture (0.5FTE) 2017-2018 to oversee the expansion of the company prior to the appointment of a full time CEO. He continues to impact on the performance of C-Capture through provision of scientific advice (until August 2020 he consulted for C-Capture one day per week; he continues to consult one day per month), in addition to board roles. He has been a named inventor on all C-Capture patents in the review period. **[A]**

5. Sources to corroborate the impact (indicative maximum of 10 references)

[A] Letter of corroboration from CEO of C-Capture (22nd December 2020)
[B] Letter of corroboration from IP Group (4th December 2020)
[C] https://www.drax.com/press_release/c-capture-raises-3-5m-funding-round-led-bp-drax-ip-group/
[D] https://www.c-capture.co.uk/c-capture-wins-energy-entrepreneurs-5-funding-for-ccs-scale-up/
[E] https://www.bp.com/en/global/corporate/news-and-insights/bp-magazine/advancing-low-carbon-programme-update.html
[F] https://www.drax.com/press_release/5m-boost-scale-ground-breaking-carbon-capture-pilot-drax-uks-largest-power-station/
[G] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/839555/CCS0819884374-001_Government_Response_to_the_CCC_Progress_Report_2019_Web_Accessible.pdf (page 64)
[H] https://www.businessgreen.com/news/3084522/businessgreen-technology-awards-all-the-winners
[I] https://www.shell.co.uk/about-us/latest-news-and-features/2016-news-and-features/innovators-receive-shell-funding-to-tackle-waste.html
[J] https://www.c-capture.co.uk/c-capture-to-demonstrate-carbon-capture-capabilities-for-glass-manufacturing-with-pilkington-united-kingdom-limited/