Institution: Imperial College London

Unit of Assessment: 8 – Chemistry

Title of case study: B8-5 ECONIC – Catalysis to Deliver Polymers from Carbon Dioxide

Period when the underpinning research was undertaken: 2008-2015

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:
Prof Charlotte Williams	Professor of Catalysis and Polymer Chemistry	2004-2016

Period when the claimed impact occurred: 1 August 2013 – 31 December 2020

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

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

A major global industrial priority is to reduce emissions of CO_2 and move towards a circular economy, designing waste out of systems. IC research now underpins the plastic industry in achieving this major goal. From 2004-2016, Professor Charlotte Williams' group developed and validated novel catalysts which incorporate CO_2 into polymer polyols, used to manufacture polyurethanes, which are found in a whole range of everyday items from the fabrication of building insulation, to furniture, and clothing. The process has been scaled-up by the IC spinout company Econic Technologies, which has since August 2013 secured £24M of investment, employs 30 people and aims to achieve substantial market adoption by 2030. Market adoption at 30% will reduce global CO_2 emissions by 3.5M tons annually.

2. Underpinning research (indicative maximum 500 words)

The global polyurethane market is worth $95 billion a year (2019) and is expected to grow at 12% annually to reach $149.91 billion by 2023, according to Business Wire. Traditionally, polyurethane plastic products are manufactured from fossil-based feedstocks, epoxide derived polyether polyols, in alkoxylation reactions with isocyanates. Polyurethanes are used in the production of flexible and rigid foams, elastomers, adhesives, sealants and coatings. These polyurethane based products are used in the manufacture of many everyday products including automobiles, footwear & clothing, furniture, household appliances and construction materials.

From a cost and environmental perspective, it would be highly beneficial to replace a portion of the fossil-based feedstock with carbon dioxide (CO_2), a non-toxic, highly abundant, and relatively inexpensive waste product of many processes.

In 2004, Professor Charlotte Williams' group investigated the catalytic copolymerisation reactions of CO_2 and epoxides. Noting that efficient polymer production from CO_2 is critically dependent on the activity and selectivity of the catalyst, they began exploring different metal-ligand catalysts.

In 2009, the group reported a novel dizinc macrocyclic ligand complex that showed remarkable activity in facilitating the copolymerisation of CO_2 and cyclohexene oxide with a diol or polyol initiator to produce poly(cyclohexanediol carbonate) – with high selectivity for desirable hydroxyl groups **[1]**. These polycarbonate polyols have molecular weights of 600-9000 g/mol which matches the range for commercial polyols. The reaction displayed encouraging turnover numbers of 585 and a turnover frequency of 25 h^{-1}, at a pressure of one atmosphere of CO_2. The polymerisation also showed high uptake of CO_2 (>99%) and, with an optimally designed ligand, did not require any co-catalyst. Previous investigations have reported the necessity of additive salts, which are relatively expensive and can be corrosive towards steel reactors, in such copolymerization reactions.

From 2010 to 2019, the team was able to markedly improve copolymerisation efficiencies by several orders of magnitude. For example, using a highly active dimagnesium catalyst, with water as a chain transfer reagent, they reported a turnover number of up to 6000 and turnover frequency of up to 750 h^{-1} **[2]**.

The group also explored the use of an inexpensive bimetallic iron and bi- and trimetallic cobalt catalysts for copolymerisation of epoxides and CO_2, which performed well and gave crucial insights on polymerisation optimisation **[3,4]**.

Ultimately, research showed that the copolymerisation of CO_2 and epoxides could produce commercially suitable polycarbonate polyols with the potential to replace polyether and polyester polyols (which are entirely derived from fossil-based epoxides) for the manufacture of polyurethanes. The low-pressure conditions in particular demonstrated the potential of the process to be used in existing polyol production plants – utilising on-site waste CO_2 streams as feedstock. Thus, in 2011 Econic Technologies was spun-out from Imperial, based on intellectual property from the Williams' group.

In parallel, the group continued research on the validation of the process and demonstrated that it was scalable. They performed experiments using their dinuclear zinc and magnesium catalysts but with CO_2 captured from a demonstrator plant at Ferry Bridge Power Station **[5]**. Remarkably, the catalysts display nearly equivalent turnover numbers and turnover frequencies using captured CO_2 as with high purify CO_2. Critically, the system also continued to perform well with the addition of contaminants such as water, nitrogen, sulfur dioxide, amines and thiols without compromising catalyst activity **[5]**.

The group also demonstrated the possibility of controlling polymer constitutions from mixtures of different monomers (including a lactone, epoxide and CO_2) by adapting the metal chain end group of the zinc catalyst **[6]**.

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

[1] Kember, M.R.; Knight, P.D.; Reung, P.T.R.; Williams, C.K., Highly Active Dizinc Catalyst for the Copolymerization of Carbon Dioxide and Cyclohexene Oxide at One Atmosphere Pressure, *Angew. Chem. Internat. Edn.*, **2009**, *48*, 931-933. DOI: 10.1002/anie.200803896
[2] Kember, M.R.; Williams, C.K., Efficient Magnesium Catalysts for the Copolymerization of Epoxides and CO_2; Using Water to Synthesize Polycarbonate Polyols, *J. Am. Chem. Soc.* **2012**, *134*, 15676-15679. dx.doi.org/10.1021/ja307096m
[3] Buchard, A.; Kember, M.R.; Sandeman, K.G.; Williams, C.K., A bimetallic iron(III) catalyst for CO_2/epoxide coupling, *Chem. Commun.* **2011**, *47*, 212-214. doi.org/10.1039/C0CC02205E
[4] Kember, M.R.; Jutz, F.; Buchard, A.; White, A.J.P.; Williams, C.K., Di-cobalt(III) catalysts for the copolymerisation of CO_2 and cyclohexene oxide: support for a dinuclear mechanism? *Chem. Sci.* **2012**, *3*, 1245-1255. doi.org/10.1039/C2SC00802E
[5] Chapman, A.M.; Keyworth, C.; Kember, M.R.; Lennox, A.J.J.; Williams, C.K., Adding Value to Power Station Captured CO_2: Tolerant Zn and Mg Homogeneous Catalysts for Polycarbonate Polyol Production, *ACS Catalysis* **2015**, *5*, 1581-1588. DOI: 10.1021/cs501798s
[6] Zhu, Y.; Romain, C.; Williams, C.K., Selective Polymerization Catalysis: Controlling the Metal Chain End Group to Prepare Block Copolyesters. *J. Am. Chem. Soc.* **2015**, *137*, 12179-12182. DOI: 10.1021/jacs.5b04541

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

Formation of Econic and Job Creation
Research at Imperial led by Professor Charlotte Williams identified and validated a system to use carbon dioxide at low pressure as a feedstock to produce polycarbonate diols, which are 30-50 mol% derived from CO_2. This work led to the formation of Econic Technologies in 2011 **[A]**, which has since attracted £24 million in external investment in 4 funding rounds **[A]**. Much of this investment has occurred since August 2013, with Econic attracting £17 million in equity investment primarily from venture capital sources, with an additional £2.5 M in public funding including a H2020 SME award **[B].** Private backers include OGCI Climate Investments, IP Group and

Jetstream Capital, while public funders include EU Horizon 2020, European Institute of Innovation and Technology (EIT), UK Climate-KIC and EPSRC (early research). The company employs 30 people at several UK sites with CEO Dr Rowena Sellens and co-founder Professor Williams as CSO **[B]**.

Building Industrial Partnerships

Econic's initial focus is on manufacturers of polyols, which typically have numerous internal sources of CO_2 on site, many of which are already captured and others that will soon have to be depending on country jurisdiction. Econic's technology unlocks the potential of CO_2 as a carbon feedstock with no additional energy requirement. This creates an economic benefit, where producers can achieve 30% cost savings on raw material feedstock as well as a substantial CO_2 reduction. Indeed, for every 1 tonne CO_2 used, a further 2 tonnes are abated through reduced fossil-based feedstock demand. As well as the economic benefit there is the environmental benefit of using captured waste CO_2 in the production of plastics.

Econic is closely working with many of the major global petrochemical producers of polyols, in 2021 these consortia will carry out large-scale trials in the existing commercial plants of those producers in Europe and China **[B]**.

In October 2017 the UK government launched its Clean Growth Strategy, reaffirming that carbon capture, usage and storage (CCUS) has the potential to decarbonise the economy and maximise economic opportunities for the UK. Following this in 2018, Econic opened the UK's first carbon capture utilisation (CCU) polymerisation demonstration facility in Runcorn **[B, C]**. It incorporates a fully integrated polycarbonate polyols production process producing multi-kg samples at industrially relevant temperatures and pressures for customer testing. Bespoke amounts of CO_2 can be used from low levels up to the maximum 50%, depending on the application of the polycarbonate polyol **[D]**. The opening of the CCU demonstration facility combined with Econic's move from London in 2017 created 12 jobs across the two Econic sites in Cheshire **[B, C]**.

In January 2020, Econic Technologies started a major partnership with the electrical power generation company, Drax Group, to utilise the waste CO_2 captured from Drax's biomass power generation as a feedstock in polycarbonate polyols production thereby reducing the amount of oil required **[B, E]**. The partnership represented a major step which allows other sectors, including automotive, consumer, and construction sectors, to produce more sustainable polyurethane products, by making use of the waste CO_2 in the process **[B, E]**. Will Gardiner, Drax Group CEO said: "*By working with innovative tech companies like Econic* […], *we are exploring new opportunities for clean growth, which could be critical not only for beating the climate crisis, but also in enabling a just transition, protecting jobs across the North – delivering for the economy and the environment.*" **[E]**

While the polyurethane market was the initial focus for Econic and where it has gained significant traction, the underpinning catalysts systems are also now being applied and adapted to other plastic sectors, to produce glycerol carbonates, polyalkylene carbonates or aromatic polycarbonates. Indeed, in 2017 Econic Technologies partnered with Asian petrochemical group SCG Chemicals to develop the production of high molecular weight polymers using Econic's catalyst technologies **[F]**.

Long term projections indicate that using Econic's catalyst systems to make plastics for the widest viable applications could eliminate over 500 million tonnes of CO_2 per year by 2070.

Outreach and Engagement

The Williams group has undertaken outreach, specifically around using waste CO_2 to make plastics, which has resonated with the public. In 2014 with the assistance of Lord Robert Winston, a CPD module titled "'Changing Materials". This was distributed to UK primary schools and teachers as part of Reach Out CPD materials designed to help Primary school teachers create engaging science lessons. Since its launch in October 2014 the course page and video has been viewed by 4,403 users with 1,086 viewings of the video **[G]**.

In 2015, Econic Technologies won the Shell UK Chairman Special Award at the Shell Springboard awards, along with a €64,000 prize. In 2019 the company was named in the prestigious Global Cleantech 100 of leading companies in sustainable innovation **[H]**.

Both the work of the Williams group and Econic Technologies itself have received significant and highly complementary coverage in high profile national UK media outlets, including the BBC News Online, BBC Radio 4, The Times, Daily Express and The Telegraph as well as in specialist journals and trade publications including Chemistry World, The New Scientist, Carbon Capture Journal, Polyestertime, Industry Europe, Energy Live News and the British Plastics and Rubber Magazine. Representative media coverage is given in Econic Media Coverage **[I]** and is underscored in the quote below by Harry de Quetteville and Hannah Boland (Telegraph Special Correspondents for Technology):

"*Perhaps the most eye-catching British start-up hoping to make a fortune from CO_2, however, is Econic Technologies, a British company spun out from Imperial College London. It has developed catalysts and processes it claims can incorporate CO_2 into polymers, which it mixes with oil-based raw materials to create anything from mattresses and car seats to bendy phones.*" – Telegraph, 2019 **[I]**.

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

[A] Confidential Letter from IP group.

[B] Confidential Letter from CEO of Econic.

[C] 'Econic opens UK's first carbon capture utilisation demonstration plant', British Plastics and Rubber Magazine: https://www.britishplastics.co.uk/materials/econic-opens-uks-first-carbon-capture-utilisation-demonstra/ (Archived here)

[D] Environmental Potential, Econic Technologies: http://econic-technologies.com/environmental-potential/ (Archived here)

[E] Drax and Econic partner to produce plastic using waste CO_2, The Chemical Engineer: https://www.thechemicalengineer.com/news/drax-and-econic-partner-to-produce-plastic-using-waste-co2/ (Archived here) and https://www.drax.com/press_release/negative-emissions-pioneer-drax-announces-new-ccus-projects-during-energy-ministers-visit/ (Archived here)

[F] Econic Technologies joins Asian petrochemical group SCG Chemicals to develop high molecular weight polymers. British Plastics and Rubber Magazine: https://www.britishplastics.co.uk/News/econic-technologies-joins-asian-petrochemical-group-scg-chem/ (Archived here)

[G] Document showing ReachOut CPD (reachoutcpd.com) Course usage stats and https://www.youtube.com/watch?v=kBHe36EFTkc&ab_channel=TwigEducation

[H] Econic prizes: https://econic-technologies.com/news/econic-wins-shell-uk-chairman-special-award-shell-springboard-2015/ (Archived here and here)

[I] Coverage by the BBC (October 7, 2017), The Telegraph (June 25, 2019), The Times (August 19, 2017) and New Scientist (March 14, 2018) attached PDF: Econic Media Coverage. (Archived here)