Institution: Imperial College London

Unit of Assessment: 8 – Chemistry

Title of case study: B8-2 Green chemistry research and innovation policy driving a world-class cleantech cluster in London

Period when the underpinning research was undertaken: 2006-2020

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 Richard Templer	Hofmann Professor of Chemistry	RT: Oct 1990–present
Prof Tom Welton	Professor of Sustainable Chemistry	TW: Oct 1993-present
Prof Jason Hallett	Professor of Sustainable Chemical Technology	JH: Oct 2007 - present
Prof Anthony Kucernak	Professor of Physical Chemistry	AK: July 1995-present
Dr Daniel Malko	Research Associate	DM: Nov 2016-May 2018
Prof Nigel Brandon	Dean of Faculty of Engineering	NB: Sep 1998 - present
Prof Tom Ellis	Professor of Synthetic Genome Engineering	TE: Jan 2010 - present
Prof Paul Freemont	Professor of Protein Crystallography	PF: Jan 2000 - present
Prof Richard Kitney	Professor of BioMedical Systems Engineering	RK: Oct 1979 - present

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

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

1. Summary of the impact

Green chemistry research and innovation policy originating at Imperial College (IC) has propelled technologies that are now helping to achieve a thriving ‘net zero’ economy in London. Research commencing in 2006, co-led by Professor Richard Templer, conceptualised the design of a near net zero industrial ecosystem which provided the framework for an EU-funded accelerator programme for new clean technology start-ups. Since 2011, the IC-based accelerator has supported 64 start-ups in securing $300 million of investment – a 25-fold return on public funding. Building on this success, the Mayor of London sought Professor Templer’s advice in 2017 to create a cleantech roadmap that has now become part of official Mayoral policy.

2. Underpinning research

A number of countries, including the UK, have made commitments to move to a net zero emissions economy. In 2006, **a UK-US chemistry group co-led by Professor Richard Templer**, published the conceptual design of a near net zero industrial economy, underpinned by sustainable biopower and biomaterials **[1]**. It considered micro-technologies, for example, gene engineering approaches to increase the efficiency of the carbon fixing photosynthetic reaction of the enzyme RuBisCO, as well macro- interventions such as designing biomaterials for recycling as part of a circular system.

Since then, the fundamental underpinning chemistry and many of the research themes and technologies outlined in the 2006 paper have been further explored and developed at IC, partly through the support of a Climate-KIC Accelerator Programme (see section 4).

An **IC team led by Professors Jason Hallett (co-author of [1]) and Tom Welton plus Dr Agnieszka Brandt-Talbot** investigated the use of lignocellulosic biomass as a source of liquid biofuels, bio-based materials and bio-derived chemicals. This requires a pre-treatment step before the sugars contained in the biomass can be processed biologically or chemically. In 2017, the group demonstrated the feasibility of using low-cost (ca. $1 kg^{-1}) ionic liquids, including triethylammonium hydrogen sulfate, for fractionation into a cellulose rich pulp, a lignin and a distillate. They found that up to 85% of the lignin and up to 100% of the hemicellulose were solubilized into the ionic liquid solution. The ionic liquid was successfully recovered and recycled four times **[2]**. This work effectively represented the first demonstration of an efficient and repeated lignocellulose fractionation and ultimately led to the creation of the successful **startup Lixea**.

An **IC team led by Professor Anthony Kucernak and Dr Daniel Malko** have investigated the use of non-precious elements, including nitrogen carbon composites, as catalysts for the oxygen reduction reaction. For example, in 2015 they found that the polymerisation of 1,5-diaminonaphthalene provides self-assembled nanospheres, which form a catalytically active high surface area. Crucially the reaction is tolerant to a wide range of substances that normally poison precious metal-based catalysts, thus lending itself to applications in complex and challenging mixtures, including in fuel cells using low quality fuels; oxygen sensing in different biological media; and in wastewater treatment **[3]**. Indeed, this work led to the creation of **startup SweetGen**, offering solutions for the treatment of industrial wastewater streams (with concurrent generation of electricity).

For over a decade, **an IC group including Professors Nigel Brandon and Anthony Kucernak** has been developing stable, cost-effective hybrid redox flow cells (HRFC) and regenerative fuel cells (RFC) for potential use in renewable energy grids. In a recent collaboration with the University of Warwick, the IC team showed enhanced durability and performance of HRFCs with hybrid electrodes consisting of electrophoretically deposited nitrogen-doped graphene on carbon paper and economically sourced electrolytes (including manganese or sulfur) **[4]**. In parallel to this work, Brandon, Kucernak and others have commercialised the technology through the spinout **RFC Power**.

Bacterial cellulose has potential use in novel biomaterials for tissue engineering, medicine, electronics and fabrics. In 2016, an **IC team including Professors Tom Ellis, Paul Freemont, and Richard Kitney** reported the development of a modular genetic toolkit that enables biosynthesis of patterned cellulose; functionalization of the cellulose surface with proteins; and tuneable control over cellulose production. This work laid the foundations for using genetic engineering to produce cellulose-based materials, with numerous applications including novel high-specificity water filters **[5]**. Indeed, the work inspired the creation of **startup Puraffinity** which is developing a range of adsorbent media materials targeted to selectively capture and remove polyfluoroalkyl substances (PFAS) - a global environmental challenge.

3. References to the research

[1] Ragauskas, A.J., Williams C.K., Davison, B.H., Britovsek, G.; Cairney, J., Eckert, C.A., Frederick Jr., W.J., Hallett, J.P., Leak, D.J., Liotta, C.L., Mielenz, J.R., Murphy, R., Templer, R., Tschaplinski, T., The path forward for biofuels and biomaterials, Science, 2006, 311, 484. https://science.sciencemag.org/content/311/5760/484

[2] Brandt-Talbot, A., Gschwend, F.J.V., Fennell, PS., Lammens, T.J., Tan, B., Weale, J., Hallett, J., An economically viable ionic liquid for the fractionation of lignocellulosic biomass. Green Chemistry, 2017, 19, 3078-3102. https://pubs.rsc.org/en/content/articlelanding/2017/GC/C7GC00705A#!divAbstract

[3] Malko, D., Lopes, T., Symianakis, E. & Kucernak, A. R. The intriguing poison tolerance of non-precious metal oxygen reduction reaction (ORR) catalysts. J. Mater. Chem. A 4, 142–152 (2015). https://pubs.rsc.org/en/content/articlelanding/2016/ta/c5ta05794a#!divAbstract

[4] Chakrabarti, B.K., Feng, J., Kalamaras, E., Rubio-Garcia, J., George, C., Luo, H., Xia, Y., Yufit, V., Titirici, M.M., Low, C.T.J., Kucernak, A., Brandon, N.P. Hybrid Redox Flow Cells with

Enhanced Electrochemical Performance via Binderless and Electrophoretically Deposited Nitrogen-Doped Graphene on Carbon Paper Electrodes. ACS Appl. Mater. Interfaces 12, 48, 53869–53878. 2020. https://pubs.acs.org/doi/10.1021/acsami.0c17616

[5] Florea, M., Hagemann, H., Santosa, G., Abbott, J., Micklem, C.N., Spencer-Milnes, X., de Arroyo Garcia, L., Paschou, D., Lazenbatt, C., Kong, D., Chughtai, H,. Jensen, K., Freemont, P.S., Kitney, R., Reeve, B., Ellis, T., Engineering control of bacterial cellulose production using a genetic toolkit and a new cellulose-producing strain. PNAS. 2016; 113(24): E3431-40. https://www.pnas.org/content/113/24/E3431/

4. Details of the impact

Transitioning to a net zero emissions economy was one of the focuses of the AtlantIC Alliance between IC, Georgia Tech and Oak Ridge National Labs **[A]**. In 2006, members of the group, co-led by Professor Richard Templer, published the conceptual design of a near net zero industrial economy, underpinned by sustainable biopower and biomaterials (see section 2). To help bring this net zero vision to reality the team sought to create a climate-change innovation organisation. In 2009, scientists at IC and ETH Zurich wrote a successful bid to fund an EU innovation partnership, the Climate Knowledge and Innovation Community KIC (Climate-KIC). Professor Templer led and wrote the components on the creation of an Accelerator Programme and an allied education programme in the art of the efficient commercialising of innovation.

The IC-based Climate-KIC Accelerator, has been one of the most prolific programmes of its kind in this area. It ran from 2011 until 2020, with a total of €9.4 million of funding from the EU (renewed yearly) and has recently been awarded £5.9 million from HSBC and the European Regional Development Fund to run from 2021-2025.

Propelling clean tech solutions

Successful applicants received up to €40k each in seed funding from the Accelerator. Out of the 95 entrants to the programme, 64 have gone on to 'graduate' by raising over €200k investment each and/or achieving significant sales within 18 months. Collectively these startups have raised a total of $300 Million, creating upwards of 1000 jobs **[B]**. This represents a 67% success rate in raising significant funds and a 25-fold return on initial public funding. Successful graduate companies include Lixea (lixea.co), Puraffinity (puraffinity.com) RFC Power (rfcpower.com) and SweetGen (sweetgen.co.uk) (see section 2).

Lixea was awarded €2.3 million (£2m) from the European Innovation Council in December 2019 in order to build a pilot plant to scale its innovative biomass fractionation process for the production of biochemicals, bioplastics, and biofuels from wood waste **[C]**.

Puraffinity received $3.55 million (£2.8m) from leading sustainability investors in 2019. This has allowed them to focus their PFAS water contamination solution on industries facing the most severe problems, such as airports, military bases and chemical manufacturing. Lead investor Kindred Capital commented: "*We see their new product as a pioneering development which leverages chemistry principles in an advanced way to provide a solution to a key environmental issue*." **[D]**

RFC Power has secured [redacted] from investors including IP Group, who noted that "*the market opportunity for long duration battery storage is already large and it is likely to grow rapidly over the next 10 years*," adding that "*RFC can achieve a sustainable competitive advantage thanks to its two highly distinctive patent-protected systems with lower levelised cost than current offerings*." **[E]**

After winning the Royal Society of Chemistry's Emerging Technologies Competition 2016, SweetGen has now completed a trials and demonstration period and focusing its abiotic wastewater fuel technology on the water treatment industry before expanding to different sectors including brewing, chemical and food and agriculture industries. **[F]**

Building a legacy in policy
Following seminal green chemistry research at IC and the success of the Climate-KIC Accelerator, Templer was asked by the London Sustainable Development Commission (LSDC) to lead a team advising the Mayor of London on how to strengthen the growth of new clean technology (cleantech) businesses in London. This led to the 'Better Future' (2016) roadmap for the development of a cleantech innovation cluster **[G]**.

Better Future's central conclusion was that both greater visibility and accelerated growth rate of the cleantech sector would be supported by the establishment of an innovation cluster.

To test some of the ideas within Better Future, IC chemists collaborated with partners including the Greater London Authority (GLA) and West London Business, through a European Regional Development Fund funded project – Better Futures **[H]**. This examined the effect of geographical clustering of a community of 56 cleantech businesses and the impact of technical assistance from IC's researchers and postgraduate internships.

The influence of Better Future can now be seen in four major aspects of Mayoral strategy and policy – notably in the London Plan (2017); the Mayor's Environment Strategy (2018); the Mayor's Economic Development Strategy (2018); and Cleantech London (2020).

The London Plan is the key document defining binding policy and regulation for development in London **[I]**. In Policy E8, part F, it is written that "Clusters such as Tech City and MedCity should be promoted and the development of new clusters should be supported where opportunities exist, such as CleanTech innovation clusters". This policy and recommendation follow directly from Better Future's recommendations. Notably, the London Plan was approved by the UK Secretary of State for Housing, Communities and Local Government in January 2021 **[I]**.

The impact of Better Future in both the Environment Strategy and Economic Development Strategy is corroborated by a letter from the Assistant Director, Energy and Environment Team, Greater London Authority **[J]**.

The Assistant Director, Energy and Environment Team, writes:

'The Mayor recognises that for London to remain an influential global city it must be at the forefront of developing the solutions to address the challenges of climate change. Prof. Templer's contributions have been timely and important in helping us to determine how we turn these challenges into important opportunities.'

'We have taken the ideas presented in Better Future and embedded them in Mayoral policy; they will continue to be influential policy until at least 2040; they form the basis for a significant part of London's approach to addressing the climate emergency, and will be important in developing green and sustainable jobs for Londoners hit by the Covid-19 pandemic.'

Mayoral support for Better Future's vision led to Templer working with the GLA to undertake a further study of how a cleantech cluster might be formed. This led to the development of the collaborative Cleantech London initiative **[K]** launched in March 2020. Its stated mission is to help London become a world-leading cleantech innovation hotspot and Professor Templer now sits on the Board.

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

[A] Scientists set sights on biomass to reduce fossil fuel dependence. Phys Org https://phys.org/news/2006-01-scientists-sights-biomass-fossil-fuel.html (Archived here)
[B] Letter from the Innovation Lead, EIT Climate-KIC.

[C] Using wood waste to produce biochemicals: Green chemistry for a green future. The Chemical Engineer. https://www.thechemicalengineer.com/features/using-wood-waste-to-produce-biochemicals-green-chemistry-for-a-green-future/ (Archived here)
[D] CustoMem changes name to Puraffinity, secures new funds. WWT Online. https://wwtonline.co.uk/news/customem-changes-name-to-puraffinity-secures-new-funds (Archived here)
[E] RFC Power secures seed investment to develop the world's lowest cost flow battery. IP Group. https://www.ipgroupplc.com/media/portfolio-news/2020/2020-01-21 (Archived here)
[F] SweetGen: abiotic wastewater fuel cell. Royal Society of Chemistry. Emerging Technologies. https://www.rsc.org/competitions/emerging-technologies/case-studies/sweetgen/ (Archived here)
[G] Better Future. A Route Map to Creating a Cleantech Cluster in London. London Sustainable Development Commission (LSDC) (co-author Richard Templer). https://www.london.gov.uk/sites/default/files/lsdc_-_better_future_report_2016.pdf (Archived here)
[H] Mayor of London, About Better Futures. https://www.london.gov.uk/what-we-do/environment/better-futures/about-better-futures (Archived here)
[I] Collated evidence around The London Plan.

- The London Plan. Mayor of London. Draft 2017 https://www.london.gov.uk/sites/default/files/new_london_plan_december_2017.pdf (Archived here)
- Letter from Secretary of State approving the London Plan https://www.london.gov.uk/sites/default/files/letter_from_sos_mhclg_london_plan_29_jan_21.pdf (Archived here)

[J] Letter from Assistant Director, Energy and Environment Team, Greater London Authority
[K] CleanTech London. https://cleantech.london/cleantech (Archived here)