Institution: University of Chester		
Unit of Assessment: B8 Chemistry		
Title of case study: Development of a novel hydrogen fuel cell with associated water treatment spin-off technologies		
Period when the underpinning research was undertaken: November 2015 – present		
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:**
David Ward	Dr, Leading Research Fellow	2015 – ongoing
Robert Smith	Dr, Researcher	2016 – ongoing
Trevor Davies	Dr, Senior Lecturer	2014 – 2018
Ahmed Al-Saadi	VL Chemical Engineering	2018 – 2020
Period when the claimed impact occurred: 2017 – present		
Is this case study continued from a case study submitted in 2014? No		

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

Ongoing research concerns the development of a novel *Redox Regenerative Proton Exchange Membrane (PEM) hydrogen fuel c*ell. Work in this area has supported *Acal Energy Ltd* in its efforts to seek investment to commercialise and further develop this technology. Fuel cell intellectual property arising from the process need to efficiently generate, react and coalesce microbubbles, has led to the investigation and application of spin-off water treatment technologies. Research in this area has resulted in the development of key knowhow which has enabled the investigation and advancement of other commercial water treatment products with potential financial and environmental impacts beyond fuel cells and generation of carbon free energy. The principle beneficiaries of these spin-off technologies are expected to be the water treatment and process industries and through them, wider society.

2. Underpinning research (indicative maximum 500 words)

Research has been led by a small but dedicated team with a strong combined background in the field. Both the team and the Fuel Cell Research Laboratory was founded by Senior Lecturer and electrochemist, Dr Trevor Davis, during his time at the University between 2014 and 2018.
Dr David Ward is a Leading Research Fellow who joined the University in 2015. Formally a Senior Research Engineer for Acal Energy Ltd, David played a key role in the conception and development of much of the fuel cell technology under investigation and as such, is more than familiar with its workings. His career spans three decades, in which he has enjoyed roles working within and between both industry and academia. During this time, his work in research and product development has covered waste water, gas and solids processing.

Dr Bob Smith is an electrochemist who began his PhD working with Acal Energy Ltd. Bob joined the team in 2018 as a Senior Researcher and has since played a key role in the reservation, modification, installation and recommissioning of a pilot scale Redox Regenerative Fuel cell demonstration unit on campus.

Dr Ahmed Alsaadi joined the team between 2019-20 as a Research Assistant with materials and modelling expertise.

Hydrogen PEM fuel cells have the potential to become a major future energy technology, capable of generating electricity that is clean and carbon free at source. However, their widespread acceptance is currently hindered by several long-standing limitations: cost, durability and heat management. Research at the University of Chester is investigating a *Redox Regenerative PEM hydrogen fuel cell*. This novel approach avoids the aforementioned limitations and thus has the potential to become a game changing technology.

The technology differs from conventional hydrogen PEM systems in that, rather than directly supplying air to the cathode, it circulates a phosphomolybdovanadate polyoxoanion electrolyte solution (or catholyte). Advantages are: i) reduced platinum requirement (~70% reduction), ii) increased durability (demonstrated to maintain performance for at least twice as long as the conventional approach, and iii) simplified heat management (avoiding the need for complex cooling channels and coolant). During operation, the liquid catholyte undergoes reduction as it passes through the cathode but is subsequently re-oxidised by air bubbling within a gas-liquid contact reactor called the *Regenerator* before recirculation. Further development is required, however, due to rigorous scientific investigations ongoing at the University of Chester, a detailed and evidence-based understanding of the technology has emerged with respect to optimisation of catholyte formulation and operating conditions. Techniques for evaluation of system performance have also been established. Such work has led to three journal and two conference publications [1 – 5].

Research in this area has also led to the development of 'spin-off' technologies with potential applications beyond fuel cells. The development of a compact and energy efficient regenerator, capable of high rates of oxygen mass transfer, has led to innovations with potential uses within the water and wastewater treatment sector. This includes devices for the generation, reaction and separation of microbubbles within liquids. Within the context of the Redox Regenerative system, the Regenerator is required to ensure the supply of re-oxidised catholyte to the fuel cell. As the most effective way of achieving this is by air bubble infusion, the regenerator has been developed to create, contact and separate microbubbles from the liquid catholyte. As such, novel technologies were developed to achieve this in a manner which was both volumetrically and energetically efficient. These include: i) a laminated gas bubble diffuser, ii) an in-line static bubble coalescer, and iii) a planar shear reactor. All three of these devices were the subject of an Innovate UK funded project to investigate their effectiveness with regards to the hot gas stripping of ammonia from waste and aquaculture waters [14]. This also led to the development of a laser surface enhancement technique which greatly improved the separation efficiency and, in turn, led to a further funding award from the HEIF 2018-19 KT Funding Scheme [28]. This included funds to patent the laser surface enhancement – filing is ongoing. Funding has also been awarded via the HEIF 2019-20 KT Funding Scheme in order to investigate the development of a microbubble disk diffuser nozzle, based on the patented laminate technology – i.e. a design compatible with existing commercial water treatment plants [29].

Furthermore, the HEIF KT Funding Scheme has also supported the recovery, repair, recommissioning and evaluation of a 2 kW Redox Regenerative fuel cell demonstration pilot system [26]. The unit was originally constructed by Acal Energy Ltd and installed at the local Solvay plant in Warrington. Although operated for a short period, the unit was then abandoned by Acal. The reconditioned demonstrator is now installed at a new location at the University of Chester's Thornton Science Park, where it will serve to both showcase and investigate this exciting new technology

Current research is directed and performed by Leading Research Fellow, Dr David Ward and Senior Associate Researcher, Dr Bob Smith. Both have worked for the University since 2015 but were previously employed by *Acal Energy Ltd* and hence, are more than familiar with the technology. Three areas of investigation have so far been pursued to the point of academic publication.

During their time at the University, both researchers have successfully attracted a combined total of over £400k of grant and commercial funding in order to advance this research.

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

Journal Papers

1. Ward D. B., Davies T. J. (2018). Effect of Temperature and Catholyte Concentration on the performance of a Regenerative Fuel Cell. Johnson Matthey Technology Review, Vol. 62, 189-203.

2. Ward D. B., Gunn N. L. O., Uwigena N., Davis T. J. (2018). Performance comparison of protonic and sodium phosphomolybdovanadate polyoxoanion catholytes within a chemically regenerative cathode polymer electrolyte fuel cell. Journal of Power Sources, Vol. 375, 68-76.
3. Gunn N. L. O., Ward D. B., Menelaou C., Herbert M. A and Davies T. J. (2017). Investigation of a chemically regenerative redox cathode PEM fuel cell using a phosphomolybdovanadate polyoxoanion liquid catalyst. Journal of Power Sources, Vol. 348, 107-117.

Conference Papers

4. Ward D. B., Gunn N. L. O. and Davies T. J. (2016). Investigation of a Second Generation PEM Fuel Cell System. FCH2 Technical Conference, Millennium Point, Birmingham, UK. May.
5. Ward D. B., R. Smith, Davis T. J. (2018). Impact of varying temperature and catholyte concentration within a chemically regenerative redox cathode polymer electrolyte fuel cell system using phosphomolybdovanadate polyoxoanion catholyte. FCH2 Technical Conference, NEC, Birmingham, UK. March.

Patents

R. Smith and Davis T. J. (2017 Priority Date). Electrode support and electrode assembly GB2564862 (A)

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

The technology described above is still in the relatively early stages of development and hence, has yet to realise its full potential. However, collaboration with Acal Energy Ltd was of significant benefit to the company in that it provided it with access to the research facilities necessary to: a) continue advancing the technology, b) produce requested technical results for potential investors, and c) provide technical consultation for when dealing with potential investors. Ownership of the IP was transferred to the University, allowing the work not only to continue but to develop beyond fuel cells by including water treatment. As alluded to above, this led to the development of technologies for the generation, enhanced reaction and rapid removal of microbubbles in water. Again, although nascent, efforts have been made to commercialise this technology. Direct impacts have yet to manifest, however, vital knowhow led to productive research engagements with commercial water treatment companies. This has involved: a) the development of a solar powered electrochemical water purification process [11], b) the development of a commercial ion exchange material for the treatment of road surface run-off [7-9], and c) the performance evaluation of a self-cleaning vortex media filter [10].

The establishment of expertise in the dual research fields of electrochemistry and water treatment led to a collaborative partnership with Arvia Technology Ltd and a Masters by Research (MRes) project to develop a solar powered electrochemical device for the adsorption and oxidation of organic pollutants and microbes in water, co-funded through an ERDF Eco-Innovation project. The aim is to develop an inexpensive off-grid solution for the purification of water in remote locations - communities in developing countries being key target end users. To date, the work has led to the establishment of a pilot scale system in the Murcia region of Spain, where the technology is currently being used to treat drinking water for approximately 100 consumers. The process is very energy efficient and consumes only 4.37 kWh/day. This would normally translate into a CO_2 release of approx. 2.2 kg/day, however, the use of solar cells avoids even this meagre contribution. Although difficult to calculate, treatment by other means would result in much higher energy consumption and, therefore, much greater carbon emission. [11].

The University of Chester was commissioned by SDS Ltd to evaluate a series of ion exchange media blends in an attempt to determine the most effective. Of the materials examined, the media identified as performing the best is now on sale as a branded product from SDS Ltd: Aqua-Xchange™. Details of the material are given on the company website [7-9]. Performance figures quoted on the product datasheet are those reported to SDS Ltd [8]. These not only include the capture and retention of zinc and copper ions but also applicable flows rates and recommended bed depth. Aqua-Xchange™ has been successfully installed along a 1.3km stretch of the M56 by SDS Ltd during the winter of 2018/19. The issued report was used to convince Highways England of the material's efficacy. This installation will remove soluble pollutants and protect the local aquatic environments. Two further highway installations are in the planning stage in England and a third is suggested for a sizeable car park in Wales. Sales have so far totalled £85,000, with projected sales for 2020 totalling £150,000. SDS Ltd are confident that sales will increase significantly over the next 5 years [9].

Regarding the vortex filter, a detailed and rigorous scientific investigation was carried out by the University. This produced a hitherto unavailable insight into both the performance and operation of the device. As such, Amiad Water Systems UK Ltd were provided with an evidence-based understanding of their filter's behaviour. This information continues to be used by company designers, engineers and technical sales staff to inform decision-making with regards the specification, design and operation of DVF (Double Vortex Filter) installations. This includes determining: i) the number, arrangement and size of units to meet customer requirements, ii) the most effective and efficient flow rates, iii) expected output water, iv) the expected pressure drop and energy usage, v) expected filter sand loss rates, vi) expected/required cleaning frequency and duration, and vii) expected wastewater generation rates. As such, Amiad have been able to improve the quality, efficiency and cost effectiveness of vortex filter installations and services. This has also enabled them to more effectively manage customer expectation and satisfaction. Furthermore, the reported results have also been used to inform and validate marketing claims made by the company when promoting the product range [10].

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

6. Scientist, Inovyn Chlorvinyls Ltd
7. http://www.sdslimited.com/what-we-do/stormwater/treatment/filtration/#aqua-xchange
8. http://www.sdslimited.com/wp-content/uploads/2018/04/SDS-Aqua-X-change-Datasheet.pdf
9. Company contact: Business Development Manager, SDS Ltd
10. Company contact: General Manager UK & Ireland, Amiad Water Systems UK Ltd
11. Company contact: Director, Arvia Technology Ltd