Institution: EaStCHEM School of Chemistry

Unit of Assessment: UoA 8: Chemistry

Title of case study: Expertise in solid-state materials and techno-economic analysis leads to Scottish policy implementation and demonstrator projects to accelerate the use of hydrogen fuel for public transport.

Period when the underpinning research was undertaken: 2003 – 2019

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:
John Irvine	Professor	01 September 1994 – present
Martin Smith	Research Fellow	01 January 2009 – present

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

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

1. Summary of the impact

Drawing on two decades of world-leading research on advanced materials for fuel cells and electrolytes, EaStCHEM Professor John Irvine and colleague Dr. Martin Smith have advised industry and policy makers on solving the technical and economic challenges impeding the use of hydrogen as a fuel for public transport in Scotland. The following have resulted directly from this research and their techno-economic expertise.

- The *Scottish Government Hydrogen Assessment* (12-2020) marks a culmination in policy change towards the adoption of green hydrogen as an integral solution for decarbonization of public transport.
- *Aberdeen City Council* has assembled a fleet of 21 hydrogen-powered buses, which have carried over 1,600,000 people (passengers) and travelled approximately 1,000,000 miles, achieving a significant reduction in CO_2 and NO_x emissions.
- The *HySeas* program is delivering the world's first hydrogen-powered zero-emission ferry, including EUR12,000,000 investment for vessel development.
- Led by Professor Irvine, The *Hydrogen Accelerator*, with GBP300,000 per year in funding, provides expert advice and support to transport initiatives across Scotland, including building the showpiece hydrogen train, with GBP3,500,000 from the Scottish Government, for the *UN Climate Change Conference* (COP26, Glasgow 2021).
- *Low Emissions Resources Global Ltd.* (*LERG*) has opened a R&D centre at the *Michelin Scotland and Innovation Parc* (*MSIP*) in Dundee creating jobs, to exploit materials developed by Irvine for green hydrogen production.

2. Underpinning research

The Challenge: technological barriers preventing the use of hydrogen as a fuel for transport

Whilst batteries are emerging as a viable and scalable technology to power cars for the domestic market, hydrogen fuel cells are envisaged as a more appropriate technology for clean-emission public transportation, including for buses, trains and ferries. This is due to the combination of the high energy value of hydrogen that can translate to a greater range for these modes of transport coupled with sufficient on-board storage of the fuel. In addition, an infrastructure of centralized refuelling depots can be rolled out, using hydrogen generated via electrolysers from electricity derived from renewable sources. Key to delivering this low carbon vision is the technological expertise in the use of fuel cells and electrolysers at scale.

Key Research Findings

Since 2003, EaStCHEM Professor Irvine has optimised electrochemically active materials for use in high temperature fuel cells and electrolysers, improving their durability and stability, as well as reducing the cost of manufacture. His landmark early report concerned the development

of new fuel flexible solid oxide anode formulations, such as the perovskite composition LSCM, $(La,Sr)Mn_{0.5}Cr_{0.5}O_3$, which enable efficient utilisation of fuels **[R1]**, including hydrogen **[R2]**, for electricity generation. Separately, proton-conducting **[R3]** oxides and hydride-conducting oxides **[R5]** applicable to hydrogen production were developed, led to the discovery of a highly effective route to fabricate electrolytes for electrolysers **[R3]**, materials that have ultimately been patented (**US7906006**, **EP1730327**, **CA2561852**, **US8262896**) and adopted by industrial collaborators *LERG* (see section 4.3).

Irvine's research on solid state materials led to him being PI on large interdisciplinary grants, such as the EPSRC-funded Supergen project *Delivery of Sustainable Hydrogen* (*DOSH*, EPG01244X/1 2008-2012). This project broadened his research interests into techno-economic and policy aspects of using hydrogen to power public transportation, in collaboration with EaStCHEM colleague Dr Martin Smith. They pioneered new technologies and became agents **[R6]** in policy development for hydrogen rollout. One direct result from this project was the discovery of redox exsolution, which in turn led to the switching phenomenon discovered for steam electrolysis and fuel cells **[R4]** – a more efficient technology for producing and using hydrogen.

3. References to the research The underpinning research listed was supported by peer-reviewed grants (e.g., EPG01244X/1). All publications are peer-reviewed and published by well-regarded academic journals.

R1. S. Tao and **J.T.S. Irvine**, "A Redox-Stable, Efficient Anode for Solid-Oxide Fuel Cells", *Nat. Mater.,* **2003**, *2*, 320-323. DOI: 10.1038/nmat871.

R2. X. Yang, **J.T.S. Irvine**, "(La0.75Sr0.25)0.95Mn0.5Cr0.5O3 as the cathode of solid oxide electrolysis cells for high temperature hydrogen production from steam", *J. Mater. Chem.*, **2008**, *18*, 2349-2354. DOI: 10.1039/B800163D.

R3. **J.T.S. Irvine**, S. Tao, A. "A Stable, Easily Sintered Proton-Conducting Oxide Electrolyte for Moderate-Temperature Fuel Cells and Electrolyzers", *Adv. Mater.,* **2006**, *18*, 1581-1584. DOI: 10.1002/adma.200502098.

R4. J-H. Myung, D. Neagu, D.N. Miller & **J.T.S. Irvine**. "Switching on electrocatalytic activity in solid oxide cells", *Nature*, **2016**. *537*, 528-531. DOI: 10.1038/nature19090.

R5. M.C. Verbraeken, C. Cheung, E. Suard, **J.T.S. Irvine**. "High hydride ionic conductivity in barium hydride", *Nat. Mater.*, **2015**, *14*, 95-100. DOI: 10.1038/nmat4136.

R6. K. Turner, O. Alabi, **M.J. Smith**, **J.T.S. Irvine**, P.E. Dodds, "Framing policy on low emissions vehicles in terms of economic gains: might the most straightforward gain be delivered by supply chain activity to support refuelling?" *Energy Policy,* **2018**, *119*, 528-534. DOI: 10.1016/j.enpol.2018.05.011.

4. Details of the impact

4.1. Input to and implementation of transport policy in Scotland

EaStCHEM Professor Irvine's world-leading research in fuel cells and electrolysers, as exemplified by **[R1-R5]**, together with his and Dr. Martin Smith's techno-economic expertise **[R6]**, led to both becoming leading technical advisors on the use of hydrogen for public transport in Scotland. Between 2006 and 2013, Irvine co-founded and led the *Scottish Hydrogen and Fuel Cell Association* (*SHFCA*) bringing together industry, academia and government, to promote the use of renewably generated (green) hydrogen and to create significant new industrial activity/jobs. Smith is presently on *SHFCA*'s board of directors. This "*extensive research experience and expertise…underpin many of the technological and policy activities that have arisen since the inception of SHFCA*" **[S1]**. In 2005, Irvine was appointed to the Scottish Government's *Hydrogen Energy Group* (*HEG*), which formulated the initial hydrogen energy policy for Scotland as part of the 2009 *Climate Change Bill and Renewables Action Plan for Scotland*. This activity, together with input from major demonstrator projects, some driven by the technical expertise of and coordinated by Irvine and/or Smith (Section 4.2), has culminated in the publication of the Scottish Government's *Scottish "Hydrogen Policy Statement"* (12-2020) **[S2]**, which is an update of the 2015 document *"2020 Routemap for Renewable Energy in*

Scotland", on which Irvine consulted **[S3]**. This commits Scotland to the future decarbonisation of public transport using hydrogen, for which the *Hydrogen Accelerator* programme, led by Irvine, is one of the key drivers (Section 4.2c). The Scottish government, now committed to a Hydrogen economy, has already coordinated the investment of "*over GBP40,000,000*", which "*has been successfully invested or earmarked for ground-breaking hydrogen transport projects*" over the past 5 years **[S2, p39]**. Based on its assessment, the Scottish Government estimates that the scale of the economic opportunity from the production and use of hydrogen transport will be "*over 300,000 jobs supported and Gross Value Added (GVA) impacts of GBP25,000,000,000 by 2045*" **[S2, p4]**.

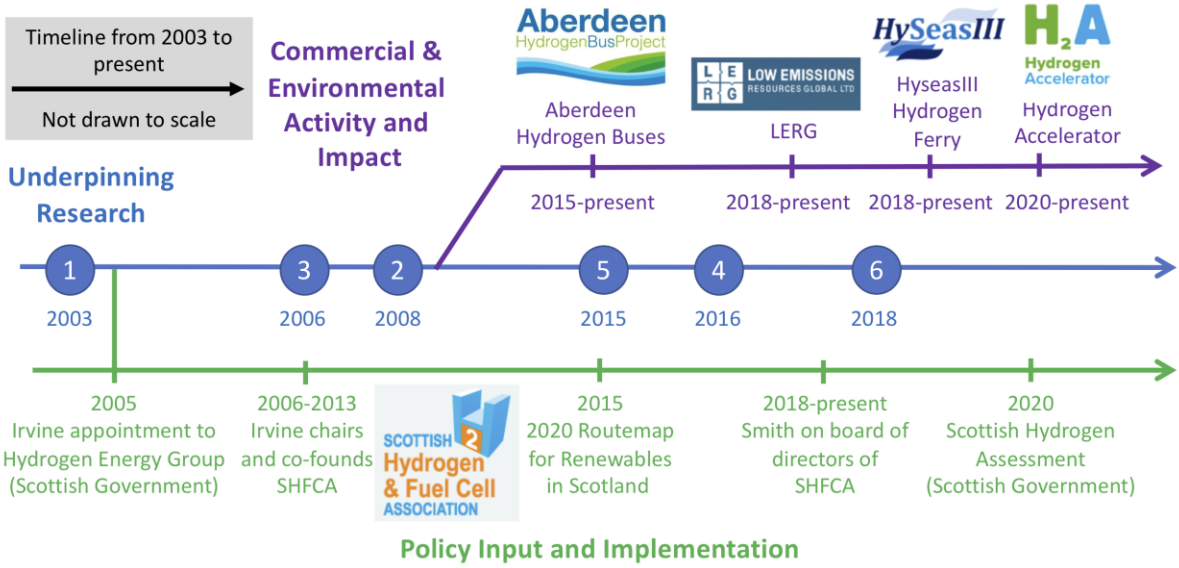

Figure 1. *Timeline showing the development of impact from the primary underpinning research described in Section 2 (blue line and blue circles refer to publications referenced in Section 3).*

4.2. Demonstrations of the use of hydrogen for public transportation in Scotland

Irvine and Smith have both been actively involved in the implementation of the following projects, demonstrating the potential of hydrogen to power clean-emission public transport in Scotland (Figure 1).

(a) Aberdeen hydrogen buses. As a result of the hydrogen energy policy for Scotland set out by the *HEG*, *Aberdeen City Council* assembled Europe's largest hydrogen-powered fleet of buses, supported by two hydrogen fuelling stations, funded as part of a 2015 green transport demonstration project (Figure 2a). This is one of the world's largest, fully integrated, green transport demonstration projects **[S4]**. Relying on his techno-economic analysis, Smith built the original project consortium, which led to the project's GBP19,000,000 EU funding **[S4, S5]** across a range of public and private sector partners.

In the first year (2015-2016), the fleet of 21 buses, operated by companies *First* and *Stagecoach*, had travelled 250,000 miles carrying more than 440,000 people (passengers). Using green electricity generation, there is now a significant 156t CO_2 emission reduction per H_2-bus per year **[S5, p32]**. Studies also showed a 40% reduction in NOx emissions within Aberdeen, which contributes to improved air quality **[S5, p33]**. As of 2018, Aberdeen's hydrogen buses have carried over 1,600,000 people (passengers) and travelled approximately 1,000,000 miles.

Jo Bamford, owner and Executive Chairman of UK-based bus manufacturing company *Wrightbus*, remarked on 19-10-2020: *"these buses represent much more than Aberdeen striving to reach a clean air, zero-carbon future. They represent the start of what could be a world-leading hydrogen economy here in Scotland which will bring with it multi-million-pound investments and tens of thousands of jobs."* **[S4]**

Recognizing the success of this program, an additional GBP4,500,000 has been awarded by the Scottish Government, as part of its *Scottish Hydrogen Assessment* commitment to decarbonise public transport, in order to procure 10 hydrogen double decker buses to add to the existing Aberdeen hydrogen bus fleet. Overall, approximately GBP40,000,000 has, or is being, invested in hydrogen mobility projects across Scotland, including refuelling infrastructure for Aberdeen, Dundee and Glasgow as of December 2020 (Section 4.2c) **[S2, p41]**.

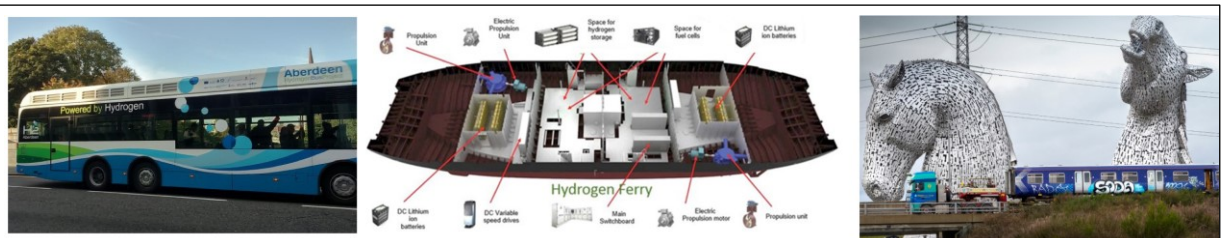

Figure 2. *a) Hydrogen-powered bus in Aberdeen; b) plan of the H_2 ferry in construction via HySeasIII; c) ScotRail Class 314 electric set on its way to be converted into an H_2 train.*

(b) Hydrogen Ferries. The *HySeas* program, initiated in 2011 by Smith and *Caledonian Maritime Assets Ltd*, aims to deliver the world's first hydrogen-powered zero-emission ferry (Figure 2b). Its current phase, *HySeasIII*, coordinated by Smith **[S6]**, began in 2018 and targets vessel delivery. *HySeasIII* is funded by the EU (EUR12,000,000) in partnership with a consortium including *Ferguson Marine Engineering Ltd* (UK); *Ballard Power Systems Europe* (Denmark); *Kongsberg Maritime AS* (Norway); *Interferry* (Belgium); *DLR Energy Systems Institute* (Germany) and *Orkney Islands Council* as the operator. The first ferry is presently under construction in Glasgow. The ferry will be powered by renewable hydrogen generated from the *SHFCA*-initiated projects *Surf'n'Turf* and *BIG HIT*, both of which are also based in Orkney with combined investment of GBP13,000,000. These projects represent a substantial economic investment in Scotland and beyond, with accompanying jobs creation. The *HySeasIII* consortium won the 2019 award for *The Innovation of the Year* at *The Green Awards*.

(c) The *Hydrogen Accelerator* (H_2A). Based on Irvine's expertise in hydrogen technology and its implementation and his successful leadership of past and present demonstration projects, *Transport Scotland* engaged him to deliver the *Hydrogen Accelerator* (H_2A) programme with an initial investment of GBP300,000. Based at the University of St. Andrews, H_2A links academic, public and commercial interests towards the development and deployment of hydrogen technologies and provides expertise and support to the design, development and implementation of transport initiatives across Scotland. As such it plays a central role in defining and delivering decarbonisation in Scotland, supporting the Scottish government's commitment to its net-zero target of 2045, including support its ambition to phase out petrol and diesel cars and vans by 2032.

Although only launched in 07-2020, the H_2A has successfully achieved the following.
i) Arranged and awarded a GBP3,500,000 contract to *Arcola Energy*, a leading specialist in hydrogen and fuel cell technologies, to build a showpiece hydrogen train (Figure 2c) using a Scottish supply chain for the *UN Climate Change Conference* (COP26, Glasgow 2021). This has led to the initial creation of 20 jobs to date at *Arcola Energy* located at the *Michelin Scotland Innovation Parc* (*MSIP*) in Dundee **[S7]**.
ii) Following from the successes of the Aberdeen H_2-bus roll out, the H_2A has delivered a techno-economic assessment of and provided the technical specification for the contract negotiations to purchase a fleet of 12 hydrogen buses and the associated hydrogen refuelling infrastructure (contract tendered: 12-2020) that have been ordered by *Dundee City Council* through the Scottish Cities Alliance (with each bus costed at just over GBP500,000, as part of the EUR25,000,000 *Joint Initiative for hydrogen Vehicles across Europe – JIVE2* – project).

iii) In collaboration with *Strathclyde Power Engineers*, enabled the specification of a large scale GBP3,000,000 hydrogen and battery testing facility (LOCATE) at the *MSIP*.

The Cabinet Secretary for Transport, Infrastructure and Connectivity in the Scottish government said: "*I'm pleased that we can establish a new Hydrogen Accelerator for Scotland at the University of St Andrews. With their renowned specialism in hydrogen technologies and innovation – this is a perfect match at a time when there is really exciting work in the sector taking place across Scotland… I wish Professor John Irvine and his team at St Andrews every success in supporting our flourishing hydrogen sector*." **[S8]**.

Of the *H_2A* and the COP26 hydrogen train project, the Scottish Enterprise Managing Director noted that "*… this creates quality jobs and supports our national ambitions for a net zero carbon economy*" **[S9**].

4.3. Direct commercialisation of EaStCHEM research for the production of green hydrogen for transportation

Since 2017, The *Low Emissions Resources Global Ltd.* (*LERG*) has been associated with Irvine and has created 15 research positions (headcount: 15) involving the fabrication of electrolysers for H_2 production based on Irvine's solid-state electrolytes **[R3]**. They have recently relocated to a R&D facility at the *MSIP* in Dundee **[S10]**.

5. Sources to corroborate the impact

S1. Letter from CEO of SHFCA. Confirms Irvine's central role in leading SHFCA, the importance that Irvine's research and expertise brought to project creation and management.

S2. Scottish Government Hydrogen Policy Statement 2020. Supports the claim that the H2A is central to the Scottish Government's implementation of their H2 policy and the importance that H2 use has for the overall Scottish Energy policy.

S3. 2020 Routemap For Renewable Energy In Scotland – Update (2015). Supports the claim that hydrogen/fuel cells remain central to Scottish policy during this REF period, and gives an overview of the progress of the projects listed in part 4 of the impact statement

S4. "The world's first hydrogen-powered double decker bus arrives in Aberdeen". Aberdeen City Council press release, 19-10-2020. Supports the claim that significant investment from the Scottish Government has been and continues to be put in place to increase the size of the Aberdeen hydrogen-powered bus fleet and the positive impact the fleet has had on the economy and the environment. https://news.aberdeencity.gov.uk/the-worlds-first-hydrogen-powered-double-decker-bus-arrives-in-aberdeen/

S5. UK Renewable Hydrogen Hub Techno-economic and environmental assessment report. Supports the claims of positive environmental impact that the H2 buses have had.

S6. "Consortium to develop World-first Renewables-Powered Hydrogen Ferry – HySeas III". HyseasIII Website, 18-05-2018. Confirms that Smith is the coordinator of the HySeasIII project. https://www.hyseas3.eu/news-media/consortium-to-develop-world-first-renewables-powered-hydrogen-ferry-hyseas-iii/

S7. Letter of support from CEO of Arcola Energy. Confirms the employment data at Arcola Energy, the importance of Irvine's research to the expansion of the company and the link to H2A.

S8. "Scotland establishes hydrogen accelerator at University of St Andrews". Rail Engineer article, 29-07-2020. Supports the intimate link between H2A and Irvine. https://www.railengineer.co.uk/scotland-establishes-hydrogen-accelerator-at-university-of-st-andrews/

S9. "Scotland's first hydrogen-powered train showcased at COP26 summit". Scotsman article, 12-09-2020. Supports the claim of the economic importance of the H2A program and the associated hydrogen train tender. https://www.scotsman.com/news/transport/scotlands-first-hydrogen-powered-train-showcased-cop26-summit-2969509

S10. Letter of support from CEO of LERG. Confirms the links between Irvine and his research, and LERG, their location at MSIP in Dundee and the number of jobs created.