Institution:	Imperial College London
Unit of Assessment:	12 Engineering
Title of case study:	Technology Development and Applications for Low Emissions Road Vehicles
Period when the underpinning research was undertaken:	2000 to 2020

Details of staff conducting the underpinning research from the submitting unit

Name(s):	Role(s) (e.g. job title):	Period(s) employed:
Prof Jianguo Lin	Professor in Mechanics of Materials	2008 – present
Prof Ricardo Martinez-Botas	Professor of Turbomachinery	1994 – present
Prof Nigel Brandon	Professor of Sustainable Development in Energy & Dean, Faculty of Engineering	1998 – present

Period when the claimed impact occurred:	2014 – 31 December 2020
Is this case study continued from a case study submitted in 2014?	No

1. Summary of the impact

In 2018, the transport sector was the largest (27%) emitter of greenhouse gasses in the UK, with 86% of transport emissions coming from road vehicles. To meet the government's "net zero by 2050" goal, the transport sector will need to be revolutionised. Research being conducted at Imperial College London ("Imperial") has already had the following impact:

I1. Replacing steel in car panels with lighter aluminium using the Hot Form Quench (HFQ®) Technology that is being commercialised via Imperial spinout company **Impression Technologies Limited** founded in 2013, producing over 100,000 units from a UK supplier in 2019.

I2. Improving turbochargers, enabling engine downsizing, leading to improved fuel economy and hence CO2 reduction. Imperial designs are in production at **Mitsubishi Heavy Industries**, with 2,200,000 units produced in the current REF period and a demonstrated fuel economy benefit of 2.2%. Furthermore, our research is now being used by Caterpillar and Daimler AG.

I3. Imperial spinout **Ceres Power Ltd**. (founded in 2001) has developed a high efficiency (50%, compared to 30% of a typical automotive engine), fuel flexible system, currently being deployed as an electric bus range extender in collaboration with Chinese company Weichai Power. Ceres has doubled its revenue in the previous four consecutive years, a market capitalisation of over GBP2,000,000,000, and opened a new factory in the UK, creating 60 skilled jobs in 2020.

2. Underpinning research

Coordinated by Imperial's Energy Future Lab, founded by **Prof. Brandon** in 2005, the following underpinning research activities were undertaken, which are testament to Imperial's leadership in the area of emissions reduction for road vehicles:

1. Automotive body panels and chassis structures have conventionally been made from steel, despite the fact that using high strength aluminium alloys could significantly reduce

their weight and thus reduce the emissions of the vehicles they support. This is because aluminium is difficult to form/stamp into the complex shapes required. A novel technology, Hot Form Quench (HFQ®), has been developed and patented by Imperial's **Prof. Lin** and his team (WO2011/058332A1). HFQ enables high strength aluminium alloys to be stamped to form similar shaped components to those that have previously been produced using steel. New theories and experimental techniques have been created for the modelling and characterisation of materials at hot stamping conditions [R1, R2], significantly advancing the state-of-the-art. For example, a continuum damage mechanics theory for modelling "forming limit diagrams" has been established [R1] for the first-time. This theory has been implemented in the commercial simulation software Pamstamp by ESI (A world leading software developer headquartered in France), making it available to the global hot stamping industry for process optimisation. A unique test rig has been developed and patented (U.S. Patent 15/751,605), which enables, for the first time, forming limit diagrams to be generated for sheet metals at hot stamping conditions [R2].

2. Development of turbochargers that harness the unsteady energy emerging from engines is essential to achieve high energy efficiency. The state of the art in design and engine air management only makes use of the steady components, thus forcing the design along lines of quasi-steady operation. Critically, such an approach does not harness the full energy potential contained in an unsteady flow and implies sub-optimal component choices (leading to higher emission impact). **Prof. Martinez-Botas** was first to incorporate unsteady effects into turbocharger models, which has since become industry standard. The recognition of volume effects in the turbine [R3] is now common on all simulation methods for turbocharger matching. His group undertook the first unsteady 3D simulation of a turbocharger under pulsating conditions, bringing the device to real engine conditions [R3]. The recognition of unsteady conditions on the compressor [R4] has led to an improvement in the stability margin that it is being incorporated in engine design programs.

3. Research into materials processing methods suitable for intermediate temperature solid oxide fuel cells (SOFCs) was pursued by Imperial's **Prof. Brandon** and colleagues since 2000. In particular, their work on ceria-based electrolytes [R5] enabled the design of cells with lower operating temperature. Conventional SOFC technologies need to be held at around 800 °C to operated efficiently, which adds significant cost to the housing as it requires special materials. However, Brandon et al. showed that by changing the electrolyte material, it is possible to operate efficiently at less than 600 °C. Furthermore, the use of composite electrode materials to improve rate performance at low temperatures [R6] was demonstrated. This concept combined the properties of two ceramic materials synergistically, resulting in electrodes that facilitate the chemistry at the surfaces, as well as showing sufficient mechanical strength and low-cost. These patented processing innovations enabled the use of porous steel as the cell's support, which unlocked the path to the low-cost technology sold by Ceres Power today. Based on these patents, Brandon and colleagues ultimately set up Ceres Power Ltd. in 2001.

3. References to the research

R1. **Lin, J.**, Mohamed, M., Balint, D. and Dean, T.A., 2014. The development of continuum damage mechanics-based theories for predicting forming limit diagrams for hot stamping applications. International Journal of Damage Mechanics, 23(5), pp.684-701. DOI: 10.1177/1056789513507731

R2. Shao, Z., Li, N., **Lin, J.** and Dean, T., 2017. Formability evaluation for sheet metals under hot stamping conditions by a novel biaxial testing system and a new materials

model. International Journal of Mechanical Sciences, 120, pp.149-158. DOI: 10.1016/j.ijmecsci.2016.11.022

R3. Palfreyman, D and **Martinez-Botas, R.F.**, The Pulsating Flow Field in a Mixed Flow Turbocharger Turbine: An Experimental and Computational Study. Trans. ASME Journal of Turbomachinery, 127, (2005), 144-155. DOI: 10.1115/1.1812322

R4. Barrera-Medrano, M.E., Newton, P., **Martinez-Botas, R.,** Rajoo, S., Tomita, I. and Ibaraki, S., 2017. Effect of exit pressure pulsation on the performance and stability limit of a turbocharger centrifugal compressor. Journal of Engineering for Gas Turbines and Power, 139(5), p.052601. DOI: 10.1115/1.4034689

R5. Brandon, N.P., Blake, A., Corcoran, D., Cumming, D., Duckett, A., El-Koury, K., Haigh, D., Kidd, C., Leah, R., Lewis, G. and Matthews, C., 2004. Development of metal supported solid oxide fuel cells for operation at 500–600 C. Journal of Electrochemical Energy Conversion and Storage, 1(1), pp.61-65. DOI: 10.1115/1.1794709

R6. Esquirol, A., Kilner, J. and **Brandon, N.,** 2004. Oxygen transport in La0. 6Sr0. 4Co0. 2Fe0. 8O3− δ/Ce0. 8Ge0. 2O2− x composite cathode for IT-SOFCs. Solid State Ionics, 175(1-4), pp.63-67. DOI: 10.1016/j.ssi.2004.09.013

4. Details of the impact

All of the impact described in this section is based on the underpinning research in Section 2, which focuses on the reduction of emissions in the transport sector. The establishment of companies and key partnerships has resulted in the deployment of manufacturing capacity and job creation in the low emissions vehicle sector.

I1. Manufacturing aluminium panels using Hot Form Quench (HFQ®) Technology [R1, R2]

I1.1. Replacing current steel parts with HFQ® processed parts for car body and chassis structures achieves a weight reduction up to 40-55%, resulting in overall, 20-25% fuel saving and 28-35% CO2 emissions reduction. Similarly, travel ranges of electric vehicles can be extended by 30-35% [E1].

Aston Martin DB11 with HFQ Technology

I1.2. Spin-off company, Impression Technologies Ltd (ITL), established in 2013 with private investment. Based on seven key patents and over 80 research papers including [R1, R2], it built the world's first HFQ® production facility in 2016 in Coventry [E2], to exploit a market valued at potentially GBP10,000,000,000 per year for passenger cars alone [E1]. Over the past 5 years, ITL has expanded to over 35 people, 2 of them are our former PhDs.

I1.3. First commercial license granted to PAB Coventry (UK) in 2014, which is a Tier-1 SME providing components for automotive and aerospace OEMs. From 2014 to the end of 2017, PAB has produced over 30,000 high value components for Aston Martin and Lotus Cars [E3], which results in PAB tripling in size over a 3-year period, employing 105 people in 2017 (35 people in 2014). This success was published by the Government on its website as a case study on impact of academic research on UK industry [E3]. HFQ

has enable PAB Coventry to increase its income from GBP3,000,000 per annum in 2014 to over GBP9,000,000 per annum by 2020. The growth in impact of our technology continues to increase: orders for more than 100,000 components in 2019 is worth over GBP7,000,000 in total [E4].

I1.4. ITL established collaboration with Gestamp (Spain) to scale the HFQ technology in mass market vehicle applications to beyond 1,000,000 vehicles per annum, and to establish 4 mass production lines in the UK with the direct investment from Gestamp (Spain) in collaboration with ender users, such as Jaguar Land Rover (JLR) [E1].

I2. Engine Downsizing and waste heat recovery via turbochargers [R3, R4]

New turbocharger by Mitsubishi Heavy Industries

I2.1. Mitsubishi Heavy Industries (MHI): New turbine concept resulting in an improvement of approximately 2% in engine level fuel economy. A joint patent between Imperial and MHI was filed and published in 2013 [E5a] and it received the "The Best Innovation 2016, special award for best new technology" of whole MHI group. This new concept volute entered large scale production in 2016 with an estimated production volume of over 2,200,000 units during the REF period [E5b]. Bespoke design of a compressor rig facility that for the first time recognises pulsating flow based on engine conditions. Two new compressor concepts for enhanced stability margin have been designed by Imperial's Turbo Group and they are currently being patented [E5b].

I2.2. Caterpillar: Concept for aerodynamically-optimized turbine interstage duct, which has gone into volume production on the Caterpillar C4.4 engine, manufactured in tens of thousands per annum at Caterpillar's Peterborough UK plant, leading to approximately 20,000 tonnes of CO2 annual reduction from 2019 [E6]. The group demonstrated for the first time how electrically assisted turbochargers can be designed to optimize boost assist and energy recovery [E6].

I3. Intermediate temperature solid oxide fuel cells at Imperial spin-out Ceres Power [R5, R6]

Ceres Power technology used in a hybrid bus in China

I3.1. Ceres Power's SteelCell® exceeds key milestone of 50% electrical efficiency, around 70% better than that of a conventional gas engine and similar to that of a centralised megawatt-scale gas turbine [E7], using intermediate temperature design developed at Imperial.

I3.2. GBP8,000,000 investment by Ceres in new blueprint manufacturing facility (CP2) in Redhill, UK and began production in January 2020, creating 60 new skilled jobs [E7].

I3.3. Ceres completed joint development with Weichai Power (China) of a prototype 30 kW range extender system for electric buses in 2018 [E8].

I3.4. Our research helped Ceres Power to win GBP14,000,000 worth of orders by the close of 2020, to grow the company since 2014 to one with a market capitalisation of over

GBP2,000,000,000 [E9], and to secure long term licensing agreements with Doosan (South Korea) and Bosch (Germany) [E7].

5. Sources to corroborate the impact

E1. Email from CEO of Impression Technologies Ltd regarding the market and the use of HFQ®-technology.

E2. Video from ITL showing the market and applications of the HFQ®-Technology: https://www.youtube.com/watch?v=KKVW1Dn3xXY Link archived here.

E3. Case Study "New Aston Martin DB11 features UK firm's low-carbon innovation", Government website. https://www.gov.uk/government/case-studies/new-aston-martin-db11-features-uk-firms-low-carbon-innovation PDF available here.

E4. Email from CEO and President of PAB Coventry, 2005-present, regarding the effect of the use of HFQ® on their company; and (http://www.pabgroup.co.uk/what-is-hfq/) shows the details of their applications.

E5. a) Joint patent between Imperial and Mitsubishi EP3088700B1 based on which production started in 2016. PDF available here.

b) Email from General Manager, Mitsubishi Heavy Industries Ltd., Japan stating the impact of Imperial-MHI partnership on the design of their new turbine.

E6. Email from Director of Innovation & Emerging Technology, Caterpillar Inc., USA on impact of our research to Caterpillar's business.

E7. Ceres Power - Interim results for the year ended 30 June 2020 - https://wp-ceres-2020.s3.eu-west-2.amazonaws.com/media/2020/09/28064454/Ceres-Power-Holdings-plc_Interim-Results-for-the-12mths_FINAL.pdf PDF available here.

E8. Ceres Power and Weichai Finalise Strategic Collaboration and JV Agreement - https://www.businesswire.com/news/home/20181203006106/en/Ceres-Power-and-Weichai-Finalise-Strategic-Collaboration-and-JV-Agreement Link archived here.

E9. Market capitalisation of Ceres Power on 29 Jan 2021 showing the value of the Company reached GBP2,300,000,000 on that day. PDF available here.