Institution: University of Chester		
Unit of Assessment: 11 Computer Science and Informatics		
Title of case study: Digital Control and Simulation of Complex Energy Systems (CES)		
Period when the underpinning research was undertaken: 2014 – 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 Counsell	Research Professor	2016 – ongoing
Yousaf Khalid	Dr, Lecturer	2017 – ongoing
Matt Stewart	Dr, Senior Researcher	2016 – 2018
Period when the claimed impact occurred: 2014 – 2019		
Is this case study continued from a case study submitted in 2014? N		

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

The Department of Computer Science, Electrical and Electronic Engineering has researched the underpinning science and algorithm development for the design of digital control systems and high speed computational simulations of nonlinear dynamic multivariable models of Complex Energy Systems (CES). This research has, in collaboration with global industrial and academic partners, developed copyrighted high speed simulation software tools and patented appliance/system controllers on a global scale. Fundamental scientific research in digital nonlinear control theory for the design and modelling of complex nonlinear multi-input and multi-output control systems has been published and disseminated in learned society journals and conferences, and the department's research group iDEAS's series of one day workshops for industry and academics in Artificial Intelligent Multi-vector Energy Systems (AIMES). The resulting software tools have been applied to real industrial and local authority case studies in partnership with BRE, Arup, Leep Utilities, URENCO, Eastbourne Homes, EDF Energy, Fujitsu/Kawasaki City, Advanced Control Partnerships, M&I Materials and ISIM International. The results from the software tools and controller algorithm designs have to date had a commercial impact in excess of £100Million, sustained 200+ jobs in the UK and reduced the UK's carbon emissions by 50,000 tonnes of CO_2 *pa* within this REF period.

2. Underpinning research (indicative maximum 500 words)

In 1997, Professor John M. Counsell, as a Director of Lancaster University's EPSRC funded Engineering Design Centre for Computer Aided Conceptual Design, led the development of what is now known as an object-oriented Meta Modelling approach to the modelling, simulation and design of complex energetic systems and their controllers. The method was named Schemebuilder. In 2007, Counsell, as Director of BRE's Centre of Excellence in Energy Utilisation, led the application of Schemebuilder Meta modelling methods and Nonlinear Inverse Dynamics controller design to building energy systems. This resulted in the approach being applied in feasibility studies to develop a fully integrated Combined Heat & Power with Photovoltaic generation system controller [1] which led to the InnovateUK project CHPV with Arup, BRE and University of Liverpool. This substantial period of research into Meta and object-oriented modelling, computer simulation and the use of intelligent model based nonlinear control of complex energy systems identified the need to: 1) calibrate energy models with best practice and building regulation methods; 2) speed up the run-time of computer simulations and increase the complexity of multi-vector energy system models dealing with heat, power, carbon emissions, and thermal comfort; and 3) optimise many other metrics for building regulation compliance.

One very complex emerging technology in need of modelling and control was that of Demand Side Response (DSR) solutions for scheduling electrical appliances in the presence of intermittent supply of low carbon energy. The underpinning scientific breakthrough was made at the University of Chester in 2016/17 to combine all these technical and functional components resulting from the underpinning research in a highly structured modelling environment where digital nonlinear multi-input multi-output controllers for complex energy systems (CES) could be designed and simulated at high speed – typically 10 times faster than the current best practice. This aggregation of scientific methods primarily used nonlinear inverse dynamics algorithms, which could be simultaneously used to greatly assist the numerical solving efficiency of the dynamic equations. This approach was applied in partnership with Arup NW, Leep Utilities, Eastbourne Homes, BRE and Fujitsu [2], and [3].

The main breakthrough in underpinning research was made at University of Chester by successfully designing nonlinear inverse dynamic control laws for the high speed and accurate control of multi-input multi-output control systems for multi-vector local energy systems [4]. This research output proved that CES and their intelligent optimising controls could be designed using deterministic nonlinear inverse dynamic modelling approaches and provide algorithms to allow rapid computer simulation of these systems' performances. The high-speed simulation allows the novel energy system controller design methods and simulations to be incorporated into the design processes of industry for urban environmental design and planning, new local energy systems and in the detailing of energy generating products/systems and their controls. Typically, a CES's dynamics consisting of five or more buildings would take hours to simulate a one-year period when assessing annual energy costs, carbon emissions etc. This new integrated approach of controller design and simulation allowed quick and optimum controller design and to simulate annual multi-vector results in less than 5 minutes. The success of the feasibility studies of this method in 2017/18 has led on to the design and build of software tools at the University of Chester, with Advanced Control Partnerships Ltd and ISIM International, to be used in real world urban design collaborative R&D projects to develop CES and heating products for the UK and Global needs.

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

1. Counsell JM, Murphy GB, Allison J. Control of micro-CHP and thermal energy storage for minimising electrical grid utilisation. International Journal of Low-Carbon Technologies Advance Access Published, August 21, 2014
2. J M Counsell, Al-Khaykan Ameer, M J Stewart. "Advanced Control of a fully integrated Renewable and CHP Heated, Cooled and Powered Building ". The 5th IET International Conference on Renewable Power Generation (RPG) London, UK. 2016, page 10. http://digitallibrary.theiet.org/content/conferences/10.1049/cp.2016.0531.
3. Counsell, J. M., Ameer, A. K., & Stewart, M. J. (2016). Advance control of a fully integrated energy system for a building. International Journal of Smart Grid and Clean Energy, vol 5, no. 4, October 2016, pp229-236
4. Stewart, M. and Counsell, J. (2017). Assessment of Multi-Domain Energy Systems Modelling Methods. International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering, 11(7), 793 - 799
5. J. M. Counsell, Y. Khalid, M. J. Stewart, Hybrid Heat Pump for Micro Heat Network, World Academy of Science, Engineering and Technology International Journal of Energy and Power Engineering Vol:11, No:7, 2017
6. J. Counsell, Y. Khalid and M. Stewart, "Comparative performance modelling of heat pump based heating systems using dynamic carbon intensity," The 11th IET International Conference on Advances in Power System Control, Operation and Management (APSCOM 2018), Hong Kong, China, 2018, pp. 1-6, doi: 10.1049/cp.2018.1768.

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

Initially, the nonlinear inverse dynamics controller algorithm design approach delivered high speed simulation and high performance controller design utilisedin two very important initial uses: 1/ At the University of Liverpool in 2014 and continued at Chester 2016+ with the InnovateUK Local Energy Systems programme project CHPV in collaboration with Arup NW, Leep Utilities and BRE. 2/ At the University of Chester in partnership with the University of Newcastle, and later Durham University, through the EPSRC programme Heat Storage's project Heat STRESS [2], [3], [4]. This project also had industrial participants in an industrial advice panel consisting of representatives of Glen Dimplex, Arup, Fujitsu, Kawasaki City, Eastbourne Homes and BRE. These initial projects helped perfect the software tools developed using both Matlab and ESL in partnership with ISIM International Ltd and Advanced Control Partnerships Ltd. These projects also facilitated the start of the Internet enabled Digital Energy and Autonomous Systems (iDEAS) research group in the Computer Science, Electronics & Electrical Engineering Department. This group established the Artificial Intelligent Multi-vector Energy Systems (AIMES) workshops that runs annually and is now scheduling its 5th workshop in 2021. Previous workshops have been organised in partnership with University of Manchester and BRE between 2017 and 2020.

The underpinning research [5] and the new copyrighted software tools Poweriver led to the development of the domestic energy systems models being used as part of the EPSRC Heat STRESS project. In this project, studies were used to assist Glen Dimplex to improve the controller design of its high retention storage heaters Quantum Heaters to enable improved SAP2012[11] ratings. Later in 2019-20 they were used again to potentially obtain further improvements in SAP10 ratings for compliance in Part L building regulation compliance. The improved rating in SAP2012 hugely improved the sales potential of these new heaters, bringing about Quantum Heater sales of over 500,000 heaters in the winters of 2016-21, a business turnover of c.£100 million and delivering an annual carbon saving of c.50,000 tonnes CO_2 as well as safeguarding 200+ manufacturing jobs at Glenn Dimplex's factory in Seagoe, Northern Ireland [Evidence Letter Alan McDonald]. The modelling has also been used to investigate other novel storage type heating solutions in partnership with Glen Dimplex, which is expected to bring further business growth in 2021 onwards with the release of SAP10.

The success of the Quantum heater and home energy modelling tools led to a more ambitious R&D partnership in the use of the modelling tools and controller design methods [1] to invent the RISE hybrid heating system by Counsell, Perry (BRE) and Khalid [5]. Its R&D was funded as part of an InnovateUK Energy Catalyst programme, total funding c.£950K, in partnership with Glen Dimplex, EDF Energy, and Eastbourne Homes. This development is now seeking further investment in partnership with Glen Dimplex, but an immediate impact came from the BRE Prince's Trust house prototype system, which was used to investigate the feasibility of dynamic carbon emission modelling [6]. The resulting dynamic simulation models [6] are now being used in discussion with BRE and BEAMA for the possible use in SAP version 11 for future compliance of England & Wales Part L building regulations.

The initial projects of CHPV and Heat STRESS have underpinned the development of sophisticated high speed modelling tools of complex energy systems and are now receiving private company R&D investment from Fujitsu, URENCO and EA Technology. This has provided the iDEAS research group with a further £55K of funding in the REF period. The resulting models are being used to carry out feasibility studies into large local infrastructure projects accounting for potentially £10s millions investment for URENCO in Cheshire and Kawasaki City in Japan. Further projects are now being established with Eastbourne Homes as part of the EPSRC's recently awarded grant of c.£360K project "Solar" in partnership with the University of Durham, which is expanding the use of the tools for use in rebuilding and delivering more sustainable built environment infrastructure in Iraq with Al-Hussain University College.

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

Letters stating:

A. BRE statement on contribution to SAP on High Retention Storage Heating Modelling
B. Commercial Value of Quantum Heater's modelled in SAP and controller design and innovation of RISE Heating System, Glen Dimplex & ACP
C. CHPV system research impact for Arup & Axsym & Leep
D. Local Energy System Modelling for Eastbourne Borough Council
E. Kawasaki City Energy Modelling and Impact of Climate Change Fujitsu & ACP
F. LED modelling in Iraq
G. Modelling of Heat Recovery and Heat usage in Ellesmere Port, URENCO
H. Modelling of Heat Recovery from Power Grid Transformers, M&I Materials