Institution: University of Strathclyde		
Unit of Assessment: C13 Architecture, Built Environment and Planning		
Title of case study: Built environment modelling and monitoring to support the clean energy transition		
Period when the underpinning research was undertaken: 2000 – 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:**
Joseph Clarke	Professor	01/07/1977 – 31/12/2019
Nicolas Kelly	Reader	01/01/1999 – present
Paul Strachan	Senior Lecturer	21/09/1987 – 30/09/2016
Daniel Costola	Senior Lecturer	14/09/2015 – present
Jon Hand	Senior Research Fellow	27/02/1989 – present
Aizaz Samuel	Research Fellow	01/10/2005 – 31/01/2020
Period when the claimed impact occurred: 1st August 2013 – 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Research conducted in the Energy Systems Research Unit (ESRU) at Strathclyde evolved the state-of-the-art in software tools for the planning, design and monitoring of low carbon urban environments. These tools are made available under an open source licence and have been applied by ESRU staff and construction industry practitioners worldwide to adapt to the changing energy landscape, inform performance improvements and energy demand reduction in urban contexts, and expand construction business offerings. The models have also informed energy-related policy and standards intended to drive societal change, including at the city scale, and the identification of new business opportunities for technology deployments.

2. Underpinning research

A core challenge in improving the energy resilience of cities is the provision of decision-support tools that represent the operational complexity of real energy systems. These systems evolve dynamically, are systemically interlinked and are influenced by uncertain events related to weather, human behaviour and equipment reliability. Further, such tools must provide performance information in a form that is meaningful to a range of stakeholders, from designers to policy makers and from citizens to service providers. This has been the focus of a sustained research effort, since the establishment of ESRU in 1988, to investigate cross-discipline approaches to energy demand and supply in the built environment, resulting in the development and evolution of energy systems planning, design and monitoring tools – principally GOMap, ESP-r, HUE and EnTrak (evolved since 2015, 1990, 2007 and 2010 respectively). These tools, which are at the vanguard of design tools based on reality emulation, are complementary in use: GOMap identifies urban sites that can be readily developed; ESP-r provides detailed insight into the performance of new materials, technologies and energy utilisation approaches; HUE rapidly quantifies the impact at scale of proposed upgrades in any combination; while EnTrak provides high frequency operational information to those who manage facilities or seek to establish new policy directives.

Examples of research insights that have enhanced these tools include:

- Research into network representations of mechanical/ natural ventilation and Computational Fluid Dynamics approaches to zone air/ contaminant movement led to **a modelling capability for ventilation efficiency and indoor air quality** [R1].
- Research into low carbon technologies (e.g. photovoltaic components, heat pumps, biomass boilers, embedded energy storage and demand management/ response) evolved an **integrated modelling capability for the performance appraisal of urban energy systems** [R2].

- Research integrating electrical network modelling and building simulation led to a new capability for the **appraisal of smart grid features**, such as load manipulation and distributed energy storage for wind power curtailment avoidance [**R3**].
- Research into program validation, automated model calibration and parameter uncertainty estimation has imparted new capability for **program self-checking and the highlighting of operational risk** at the design stage and post occupancy [**R4**].
- Research into stochastic occupant presence and behaviour evolved the simulation state-of-the-art in a manner that **closes the gap between design intent and performance** as widely observed [**R5**].
- Research into wireless pervasive sensing resulted in new capability to deliver **reports on building energy use, indoor conditions and equipment status** to estate managers and occupants in a timely manner that may be acted upon to alleviate environmental problems and unacceptable energy use [**R6**].
- Research into city planning constraints and energy system infrastructure needs resulted in new capability to **identify intra-city sites that are policy enabled and technically unconstrained** in relation to urban renewable energy technology deployment [**R7**].

Using these and other developments, ESP-r was configured in 2019-2020 as the 'engine' for automated performance assessments featuring, for the first time, life cycle resilience testing as part of the building performance assessment procedure. The project was funded by the Construction Scotland Innovation Centre with the participation of 5 industry partners along with the Chartered Institute for Building Services Engineers, the Royal Incorporation of Architects in Scotland and the Building Research Establishment to disseminate the outcome to the wider industry and encourage uptake by UK Government as a future approach to building standards compliance.

3. References to the research (Strathclyde affiliated researchers in **bold**)

R1 **J. Clarke** (2013) Moisture flow modelling within the ESP-r integrated building performance simulation system, *Building Performance Simulation*, 6(5): 385-399 https://doi.org/10.1080/19401493.2013.777117

R2 **J. Clarke** and J. Hensen (2015) Integrated building performance simulation: Progress, prospects and requirements, *Building and Environment*, 91: 294-306 https://doi.org/10.1016/j.buildenv.2015.04.002

R3 **J. Clarke**, **J. Hand**, **J. Kim**, **A. Samuel** and **K. Svehla** (2014) Performance of actively controlled domestic heat storage devices in a smart grid, *Journal of Power and Energy*, 229(1): 99-110 https://doi.org/10.1177%2F0957650914554726

R4 **F. Monari** and **P. Strachan** (2017) CALIBRO: An R package for the automatic calibration of building energy simulation models, *Proc. Building Simulation '17*, San Francisco, Aug. 7-9. [available at https://strathprints.strath.ac.uk/62081/ or from HEI]

R5 **G. Flett** and **N. Kelly** (2017) A disaggregated, probabilistic, high resolution method for assessment of domestic occupancy and electrical demand, *Energy and Buildings*, 140: 171-187 https://doi.org/10.1016/j.enbuild.2017.01.069 [REF2]

R6 **J. Clarke**, **D. Costola**, **N. Kelly** and **F. Monari** (2017) A 'big data' approach to the application of building performance simulation to improve the operational performance of large estates, *Proc. Building Simulation '17*, San Francisco [available at https://bit.ly/3vWCIEN or from HEI]

R7 **J. Clarke**, **R. McGhee** and **K. Svehla** (2020) Opportunity mapping for urban scale renewable energy generation, *Renewable Energy*, 162: 779-787 https://doi.org/10.1016/j.renene.2020.08.060

Notes on the quality of research: All referenced research outputs were peer-reviewed ahead of publication. The underpinning body of research has been supported by GBP22,000,000 in external, competitively awarded funding since 2000 (e.g. Kelly (PI), Bell, Clarke, Strachan, Tuohy (CIs), FITS-LCD: Fabric Integrated Thermal Storage for Low-Carbon Dwellings, EPSRC, 01/04/2016-31/03/2019, GBP998,879). The national standing of the research is indicated by its BRE Trust Centre of Excellence award.

4. Details of the impact

The software tools developed by ESRU are freely available under the GNU General Public License. The President of the International Building Performance Simulation Association (IBPSA; 4,700 members) confirms that these tools are '*internationally renowned and widely applied, including for the identification of urban sites for energy technology deployment, for the prediction of building performance at the design stage, for the appraisal of upgrade options for large building stocks and for the monitoring of performance in use*' [**S1**]. In addition, ESRU researchers have supported companies in their endeavours to embed the simulation-assisted design approach within their businesses and apply it in practice [**S1**,**S2**]. The President of the Chartered Institution of Building Services Engineers (CIBSE; 21,000 members) highlighted that: *'ESRU has, over several decades, delivered innovative knowledge exchange to the construction industry through advanced consultancy and training support…ESRU's freely available software tools and willingness to support their application has contributed to a significant increase in simulation-assisted designs in the construction industry'* [**S2**].

This open availability and international dissemination has resulted in significant subsequent impacts by government, industry and research groups within and outwith the UK. A previous independent evaluation for 2002-2008 confirmed an annual average of 360 practitioners given innovation assistance, 10 major deployments of tools within companies and a GBP700,000 increase in revenue for assisted companies. While no repeat study has been undertaken, it is expected that the impact statistics are no less for the current period. Case studies below provide examples of the way that, since August 2013, ESRU's research and expertise on built environment modelling and monitoring has:

- Informed policy and standards in the context of a changing energy landscape;
- Enabled companies to extend their business capability; and
- Facilitated realistic assessment of the quality of proposals before deployment.

Informing policy and standards in the context of a changing energy landscape

ESP-r was used to quantify the impact of alternative approaches to building energy efficiency, directly informing the 2017 ISO Standard 52016-1:2017 Energy Performance of Buildings, which is used in all calculations for building space heating and cooling carried out within the EU [**S3**], and ASHRAE Standard 90.1 Energy Standard for Buildings in 2019, which is a benchmark for commercial building codes in the United States [**S3**]. ESRU's modelling tools have been adopted by BuroHappold, an international, integrated consultancy of engineers, consultants and advisers operating in 26 locations worldwide with over 1,900 employees, to assess low carbon solutions within UK cities on behalf of their clients [**S4a**]. From 2016-2017, ESP-r was utilised to assess the potential for connecting different commercial building types to heat pump district heating networks throughout the city of London. The outcomes of this informed Greater London Authority's Plan in relation to their strategy for delivering Policies 5.2 (Minimising carbon dioxide emissions) and 5.5 (Decentralised energy networks) [**S4a**]. According to the Assistant Director of Environment for Greater London Authority: '*District heating networks form an integral part of the Mayor's strategy for how London will meet its zero-carbon by 2050 target*' [**S4b**]. Similarly, BuroHappold used the HUE software tool in 2019 to assess the potential for electrification of domestic heating systems when applied to different dwelling types [**S4**]. The findings from this analysis are informing ongoing work via Zero Waste Scotland for the Scottish Government's initiative on Local Heat and Energy Efficiency Strategies [**S4**].

Enabling companies to extend their business capability

Arbnco, a building performance technology company, which supplies solutions for human-centric sensing, smart energy and climate change resilience, currently offers solutions relating to indoor environment quality and energy optimisation, informed by research developed at the University of Strathclyde [**S5**]. In particular, the *arbn well* platform, used to assess and enhance health and wellbeing in buildings, was developed and further evolved through two Knowledge Transfer Partnerships (2016-2018, 2018-2020) with ESRU. The resulting platform helps facilities managers to optimise the operational performance of building systems and reduce energy costs and CO_2 emissions through improved utilisation of heating, cooling, ventilation and lighting. It also advises on how to reduce indoor pollutants and encourage activity and social interaction, leading to enhanced health, wellbeing and comfort for building occupants. Launched in 2019, the platform has been applied by 15 companies to date, including, since May 2020, being used to inform COVID-19 'return to work' preparations [**S5**]. The platform was awarded the CIBSE Building Performance Award for 'Wellbeing Product of the Year 2020', with the announcement crediting '*the breadth of arbnco's collaboration with industry and academic partners*' and the '*continuous evolution and improvement of the product*' [**S5**]. In addition to the *arbn well* platform, ESRU research and expertise has informed the development of the *arbn insight* (launched 2020 – circa 2000 users), *arbn consult* (launched 2017 – 25 large corporate users), *arbn estates* (launched 2017 – 25 large corporate users) and *arbn renew* (launched 2019 – 20 users) platforms [**S5**]. As a result, arbnco have been able to significantly expand their offer to customers, leading to 40 new jobs and GBP600,000 increased turnover [**S5**].

Similarly, ESRU's research has informed several aspects of the BEMServer platform, the key outcome of the Horizon 2020 HIT2GAP project (2015-2019) to develop new tools and methods to reduce the gap between predicted and actual energy performance of large estates [**S6**]. The BEMServer platform is a highly innovative system for managing and controlling building energy and environmental performance. It delivers a variety of performance modelling, monitoring and management modules, with ESRU's research informing pervasive data collection via wireless sensors, the construction of high-resolution building models, automated model calibration using estate data, and automated performance assessments in support of energy action planning [**S6**]. These contributions underpin several of the innovative services delivered by BEMServer: ESRU's ESP-r application, for example, provides simulation-based thermal/ visual comfort and air quality assessments for each user workstation within a commercial building, with outcomes indicating locations and times when standards are not being met [**S6**]. This allows facilities managers to make early interventions where problems are indicated. Since its launch in late 2019, the platform has been successfully applied by 2 clients, is currently being deployed to a further 3 clients' buildings, with numbers expected to rise significantly in the near term [**S6**].

The ESRU modelling tools have enabled the Building Research Establishment (BRE) Innovation Parks to demonstrate the efficacy of innovative builds, thereby addressing BRE's aim to inform sustainable development at a global level by stimulating local innovation through Parks located in the UK (Glasgow, Garston), China (Beijing), Brazil (Brasilia) and Canada (Toronto) [**S7**]. Since 2014, ESRU tools have been applied to 11 buildings within the Innovation Parks [**S7**]. According to the Group Director for BRE:

> *'Your low cost, wireless technology solution enabled us to track energy use and indoor conditions at high frequency, display these data in near real-time via the in-built Web connectivity, and apply data analytics in a manner not previously possible…The research and expertise of the ESRU group has allowed us to both expand and deepen the assessments we are able to undertake on behalf of our Innovation Park clients and thereby encourage a greater range of potential innovations applicable to the built environment'* [**S7**].

Facilitating realistic assessment of proposals before deployment or investment

Energy Network companies, including Scottish Power Energy Networks (SPEN) and Scottish and Southern Electricity Networks (SSEN), have applied ESRU modelling tools to inform their clean energy investments. Between 2014-2016 and funded by Ofgem, SPEN modelled future low carbon energy scenarios within urban centres, resulting in a greater understanding of the levels of base and peak load reduction that can be realised through demand response interventions in public, retail and office buildings [**S8**]. According to the Lead Engineer for SPEN, the tools *'contributed significantly to our understanding of how the electrification of heating in non-domestic buildings will change energy demand and consumption and what adaptations to the low voltage electricity network would be required on our part to accommodate this change*' [**S8**]. This knowledge informed SPEN's RIIO-T2 Business Plan for 2021-2026, which details their ambitions for the transmission network and evidences their ability to meet the challenge of increased electrification [**S8**]. ESRU supported SSEN's NINES project (2011-2016) to demonstrate an electricity distribution system on the Shetland islands, using a high proportion of local renewable generators; since 2014, ESRU has deployed monitoring and modelling tools to model various smart control and energy storage scenarios, optimise renewable integration, enhance user comfort and help to avoid unintended consequences for SSEN customers [**S9**]. This has allowed

SSEN to understand and rectify numerous issues and improve the flexibility and delivery of the project [**S9**]. Confirming the benefits of this collaboration for SSEN, the Innovation Strategy Manager stated:

> *'ESRU's inputs to the NINES project were considerable and had a major impact on SSEN's network planning for Shetland and smart grid activities elsewhere in the UK…The learning from NINES has undoubtedly helped shape not only SSEN's thinking on the use of flexibility but also that of the wider industry. The use of flexibility will be a major contributor to ensuring that the UK achieves its Net Zero objectives in a cost efficient manner'* [**S9**].

Since 2015, Hurley Palmer Flatt, a leading, independent multidisciplinary engineering consultancy, has utilised ESRU's software tools to inform design decisions by reducing the uncertainty associated with low and zero carbon technologies [**S10**]. This, in turn, allows clients to introduce emerging technologies for energy generation and storage and meet increasingly stringent carbon emissions targets. For example, ESRU tools were applied in the development of the Energy Centre at the Aberdeen Exhibition and Conference Centre to inform the energy strategy, which was a key issue for the development due to significant fluctuations in energy demand, the required carbon emission reductions for the site, and Aberdeen City Council's aspiration for the Exhibition Centre to be the most sustainable venue of its type in the UK [**S10**]. The final design successfully combined a low carbon heating, cooling and power network with decarbonised transport fuel. In 2019, the Exhibition and Conference Centre was shortlisted twice for Scottish Green Energy Awards, with Scottish Renewables crediting *'its innovative energy solutions'* [**S10**].

Finally, ESRU has worked closely with Glasgow City Council to assess innovative proposals for housing upgrades, low carbon technology deployment and electric vehicle charging from renewable energy sources [**S11**]. Within the Innovate UK Glasgow Future Cities Demonstrator project (2014-2015), ESRU deployed innovative wireless monitoring procedures in 65 hard-to-heat dwellings to demonstrate the benefit of automated procedures for the quality-assurance of planned housing upgrades throughout the city [**S11**]. For the EC Horizon 2020 RUGGEDISED project, modelling studies were undertaken to aid the design of several low carbon energy system demonstrators, including the installation of solar photovoltaic canopies on city car park roofs as a means to contribute to the charging of electric vehicles; the introduction of load control and energy storage in new housing as a means to better utilise energy and effect a match with renewable energy sources; and an assessment of the benefit of multi-organisation connection to district heating infrastructure [**S11**]. In all cases, this analysis informed existing or proposed plans and implementation is underway [**S11**]. As a result, ESRU research has significantly contributed to Glasgow City Council's smart technology deployment plans and furthered its aim of a sustainable and low carbon city [**S11**].

5. Sources to corroborate the impact

S1 Factual statement from President, IBPSA, dated 30 September 2020.
S2 Factual statement from President, CIBSE, dated 29 September 2020.
S3 Collated standards informed by ESRU tools: ISO Standard 52016-1:2017 *Energy Performance of Buildings*; and ASHRAE Standard 90.1 *Energy Standard for Buildings*.
S4 Collated sources relating to influencing policy for Greater London Authority and Scottish Government:
- **a.** Factual statement from Director, BuroHappold, dated 21 November 2020;
- **b.** Major of London, ADD2293 Delivering District Heating Networks, Assistant Director's decision, signed 26 November 2018.

S5 Factual statement from CEO, Arbnco, dated 28 September 2020.
S6 Factual statement from HIT2GAP Project Coordinator, Nobatek/INEF4, dated 1 October 2020.
S7 Factual statement from Group Director, Building Research Establishment, dated 30 June 2020.
S8 Factual statement from Lead Engineer, Scottish Power Energy Networks, dated 19 October 2020.
S9 Factual statement from Innovation Strategy Manager, Scottish and Southern Electricity Networks, dated 20 November 2020.
S10 Factual statement from Associate Director, Hurley Palmer Flatt, dated 23 October 2020.
S11 Factual statement from Head of Sustainability, Glasgow City Council, dated 5 October 2020.