Institution: University of Sheffield		
Unit of Assessment: B-09 Physics		
Title of case study: The role of PV Live, Great Britain's solar photovoltaic monitoring service, in the net-zero carbon energy transition		
Period when the underpinning research was undertaken: 2010–2018		
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:**
Alastair Buckley	Senior Lecturer	2009–present
Lisa Hall	Knowledge Transfer Fellow	2011–2015
Giuseppe Colantuono	Research Associate	2011–2014
Jamie Taylor	Senior Data Scientist	2014–present
Julian Briggs	IT Manager	2014–present
Aldous Everard	Business Development Manager	2012–2020
Period when the claimed impact occurred: 2016–2020		
Is this case study continued from a case study submitted in 2014? N		

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

PV Live is Great Britain's national-level solar photovoltaic (PV) electricity monitoring service. It is a 'cornerstone' of our electricity system, used half hourly by National Grid Electricity System Operator, as well as by commercial energy forecasters, distribution grid control room operators, energy services companies, energy traders, policy makers, and as a public information source in the recent, rapid, decarbonisation of electricity.

It is underpinned by PV systems research undertaken between 2010 and 2015 and was then implemented as a web-based data service between 2015 and 2020, all by the Sheffield Solar research group at the University of Sheffield.

Upon its inauguration in April 2016, PV Live led to a reduction in National Grid ESO's daytime electricity demand forecast error and, as a result, has since saved consumers a total of approximately [Text removed for publication].

www.solar.sheffield.ac.uk/pvlive

2. Underpinning research (indicative maximum 500 words)

Between 2010 and 2019, approximately one million individual solar photovoltaic (PV) systems, with a total rated capacity of ~13 GW, were installed across Great Britain. They are able to produce up to ~10 GW of electrical power or up to ~30% of the total national electricity demand. This power is either consumed near the installation site or exported into the national electricity network. The overall impact of the embedded solar PV is to reduce the demand for centrally supplied electricity (displacing gas and coal) and reducing carbon emissions.

Prior to 2010, the state of the art research relating to the field performance of solar PV systems in the UK was the 2006 Department of Trade and Industry funded BRE Domestic Photovoltaic Field Trial. In this study, around 400 systems were installed across the UK and best practice in

terms of installation and operation was learned. The impact resulting from these field trials and the associated work was submitted by the University of Northumbria as a REF2014 impact case study. One key conclusion of these field trials, that will be referred to later, was that a typical domestic UK PV installation could generate 770 (+/- 100) kWh / kWp per year.

Beginning in 2010, **Buckley** founded the Sheffield Solar research group, spurred by recent investments in PV technology by the UK government. In 2010 **Hall** and **Buckley** developed a citizen-science database [R1] for UK PV system owners to log their own PV electricity generation. The goal was to build public and market confidence in PV systems through a public dissemination tool. These public sourced measurements enabled a step change in research on the performance of the UK fleet of systems and a platform from which to research the integration of PV into the wider national energy system. From 2011 to 2016, **Buckley** led £1.3m EPSRC funded "Solar Energy in Future Societies" to explore the socio-technical future of PV and between 2013 and 2017 **Buckley** collaborated with colleagues at Manchester and Loughborough in £1.1m EPSRC funded "Whole System Impacts and Socio-Technical Integration of Wide Scale PV". These projects mapped in much more detail the actor-networks of data, organisations and people involved in the UK PV supply chains [R2, R3, R4] and the citizen science database grew by extending data donation to commercial system and equipment operators such as E.ON, Passiv Systems, Energence and Enphase. By 2017 it included historical and live data for over 20,000 systems. As a result, a much more detailed statistical analysis of PV performance was possible, but also, much of the basis of the information system that was needed to build a real time PV monitoring service (i.e. PV Live) was developed.

Specifically, system performance research performed by **Colantuono**, **Everard**, **Buckley** and **Hall** revealed in much greater detail than the existing state-of-the-art how compass orientation, tilt angle, system size, mounting systems and local micro-climate associated with PV systems contribute to the overall accuracy of models that predict the electricity generation of the system [R5]. Critically for PV Live, **Taylor**, **Buckley** et al [R6] reported how modules degrade year on year once in the field, and also how the initial performance of systems improve year on year relative to their specified efficiency. These numerical findings are used in PV Live to adjust the as-calculated national yield by the age and installation date of individual systems. By 2015 **Buckley**, **Taylor** et al [R6] found that the yield of the average UK PV system had improved by ~15% from the 2006 trials and could now generate 900 (+/- 70) kWh / kWp.

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

R1. The Micro Generation Database. https://microgen-database.sheffield.ac.uk/

R2. Hall, L. M. H., & **Buckley, A. R.** (2016). A review of energy systems models in the UK: Prevalent usage and categorisation. *Applied Energy, 169,* 607–628. https://doi.org/10.1016/j.apenergy.2016.02.044 (114 citations)

R3. Krzywoszynska, A., **Buckley, A.,** Birch, H., Watson, M., Chiles, P., Mawyin, J., Holmes, H., & Gregson, N. (2016). Co-producing energy futures: impacts of participatory modelling. *Building Research & Information, 44*(7), 804–815. https://doi.org/10.1080/09613218.2016.1211838 (8 citations)

R4. Krzywoszynska, A., Watson, M., **Buckley, A.,** Chiles, P., Gregson, N., Holmes, H., & Mawyin, J. (2018). Opening Up the Participation Laboratory. *Science, Technology, & Human Values, 43*(5), 785–809. https://doi.org/10.1177/0162243917752865 (11 citations)

R5. Colantuono, G., Everard, A., Hall, L. M. H., & **Buckley, A. R.** (2014). Monitoring nationwide ensembles of PV generators: Limitations and uncertainties. The case of the

UK. *Solar Energy, 108*, 252–263. https://doi.org/10.1016/j.solener.2014.06.030 (10 citations)

R6. Taylor, J., Leloux, J., Everard, A., Briggs, J. Hall, L. M. H. & **Buckley, A.** (2015). Performance of distributed PV in the UK: A statistical analysis of over 7000 systems. *Proceedings of the 31st European Solar Energy Conference, Hamburg.* https://doi.org/10.13140/RG.2.1.2019.6568

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

PV Live was developed between 2015 and 2020 with funding from National Grid ESO. It comprises three key processes. The first is tracking the location and capacity of all the PV systems in Great Britain by synthesising and cleansing multiple government and commercial datasets such as the Feed in Tariff register and the Renewable Energy Planning Database. The capacity is scaled using outputs from [R5] and [R6] to adjust for system degradation and installation date. The second process is to stream a sample of real time PV generation data and calculate a geospatially resolved normalised PV yield that can be used in the third process to scale up the national capacity to compute national and regional outputs. All three processes have been operated by Sheffield Solar since 2016 as part of the PV Live service delivery.

PV Live has had economic and societal impact in three ways.

1. Impact of PV monitoring on National Grid ESO energy forecasting and grid balancing

National Grid ESO is the electricity system operator for Great Britain. They ensure that customer demand for electricity is met with a continuous supply, operating within specific frequency and voltage boundaries. This balance is achieved by operating several electricity markets. The rise in renewable energy has introduced a free but uncontrollable electricity generation element (i.e., wind and solar PV systems) that reduces the amount of generation that needs to be purchased, but also, critically, reduces the accuracy of electricity forecasting used to manage the markets. To forecast solar PV output accurately, National Grid ESO needs to be able to measure it precisely. This requirement led to the development of PV Live.

In April 2016, National Grid ESO started using PV Live. The immediate impact was a 130 MW reduction in the average demand forecast error [S1a, S2] that was significant enough to be reported as a case study in the 2018 Electricity Network Innovation Strategy [S1b]. PV Live has since been evaluated by the National Grid ESO demand forecasting team to have made a 'critical' [S2] service contribution to the management of the electricity system with multi-million pound per-year savings [S2]. The combination of demand forecast saving [S1b] and reserve holding costs [S3] lead to a consumer saving [Text removed for publication] between 2016 and 2020.

Of additional significance is the role of solar PV in the recent decarbonisation of the electricity sector. In 2015, 443 gCO_2/kWh of carbon emissions was produced by electricity generation, but in 2018, this amount had reduced to only 248 gCO_2/kWh, as coal-fired generation was displaced by wind and solar PV systems. PV Live not only indirectly contributed to reduced carbon emissions by supporting PV deployment through the provision of a trusted information source that reports yearly solar PV generation, but also had a direct impact by reducing the demand forecast error and consequently mitigating reserve capacity holding. Without PV Live, an additional ~130 MW reserve capacity (normally diesel generators) would have been needed between 2016 and 2019, adding approximately 10% (or 14,000 tCO_2e per year) to the carbon output [S4].

2. Impact of PV Live as a public information service

PV Live is a key source for public data relating to PV electricity generation in Great Britain. Via National Grid ESO it becomes part of the public record of the electricity market through the 'Balancing Mechanism Reports', managed by Elexon Ltd. [S5]. In addition, PV Live feeds directly into a series of public-facing websites and energy tracking tools that include 'MyGridGB' (14,400 Twitter followers), 'Gridwatch', National Grid's 'CarbonIntensity', Drax's 'ElectricInsights' [S5] and media reports of solar-related energy events such as new records for maximum PV generation and periods without coal [S6] (such as The Guardian on 26/5/17, inews on 3/1/19 and BBC on 17/5/17). Since 2017 PV Live has been used by Energy Sparks [S7] to provide virtual monitoring of PV systems in hundreds of schools, in order to embed sustainability education in the curriculum. The societal impact of PV Live as a result of these information sources is complex but helps public understanding and supports market confidence in the transition to net-zero CO_2 emissions. For example, solar PV has the highest public perception rating of any electricity generating technology, and PV Live has made a strong positive contribution to the provision of reliable and timely information during the energy transition [S8a, S8b, S5, S7].

PV Live is also used by The Department for Business, Energy, and Industrial Strategy (BEIS) to fulfil statutory requirements for energy monitoring (for example to the International Energy Agency [S9]) and also to improve on existing approaches to monitoring and tracking. BEIS also [S9] report the use of PV Live data in 2020 improvements to renewable capacity tracking and, during the early stages of the COVID-19 pandemic, when very sunny days and low demand required swift action by OFGEM to balance the system through the development of a new electricity market, the Sheffield team were consulted to reduce sources of uncertainty in PV output [S9].

3. Impact of PV Live on energy services companies

Since 2016 PV Live has grown a commercial user base of hundreds of organisations. [S10a] is a list of 59 specific use case requests and [S10b] Google Analytics data showing 3,000 unique PV Live web site visitors each month. Industrial users take both real-time and historical data for various operational functions in network balancing, forecasting and energy trading as described by the information requests in [S10b]. [Text removed for publication].

One of many new businesses that are supporting the net-zero-carbon energy transition by providing a range of services that assist in balancing electricity supply and demand in light of the growing contribution of renewables. They use PV Live data on an hourly basis to plan how they operate electricity generation, consumption and storage assets at the premises of their customers and see PV Live as a "cornerstone" of the emerging net-zero electricity system [S8a].

PV Live is also widely used to train energy forecasting models that are used to make real-time decisions in terms of balancing services. [Text removed for publication].

A European weather and energy forecast service provider, uses PV Live to train PV power forecast models that they then sell to companies [Text removed for publication]. Through the use of PV Live, they have been able to reduce the error on their forecasts by 25% between 2018 and 2020 [S8b]. Being an international company, [Text removed for publication] was able to report the ubiquity of PV Live across not only the UK but also in Europe, stating that "almost every energy trading company" currently uses it.

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

S1. (a) National Grid ESO's analysis of demand forecasting during the period when PV Live was first introduced in April 2016. On p.21, the report cites a "15% improvement" in demand forecast error which equates to 130 MW. (b) National Grid's Electricity Network Innovation Strategy from 2018 uses PV Live as a case study. On p.25 it cites "to date a 100 MW saving" as an estimate of the value of PV Live.

S2. Testimonial from National Grid ESO describes the relationship between Sheffield Solar and National Grid and the value that PV Live has brought the organisation. P.1 introduces the role of the System Operator in National electricity supply, p.2 describes how PV Live delivers multi-million pound savings each year and p.3 summarises the "critical" service that PV Live provides to the electricity system.

S3. The 2019-2021 National Grid ESO Forward Plan (page 109) shows the cost of demand forecast errors. This information has been used to estimate the overall economic impact of PV Live over the 4 years of operation that lie within the impact census period (https://www.nationalgrideso.com/document/140736/download).

S4. A National Grid ESO report that documents the carbon intensity of short-term operating reserve (https://www.nationalgrideso.com/document/85801/download).

S5. The five key public information services that include PV Live data via programmatic integration: http://www.mygridgb.co.uk/about/ is a privately curated record of the GB electricity mix that is widely used with 14400 twitter followers; https://electricinsights.co.uk/ is operated by Drax and provides live and historical electricity system data; https://www.bmreports.com/bmrs/ is the official GB electricity market information repository operated by Elexon and includes PV out turn data that originates from PV Live; https://carbonintensity.org.uk/ was developed by National Grid ESO and provide real time and forecast carbon intensity. It trains on PV Live data. Finally, https://gridwatch.co.uk/ is another widely used privately curated grid monitoring service that interfaces directly to PV Live over API.

S6. A sample of 48 media reports using PV Live data. These include general press releases from the BBC, inews, Guardian, Independent, Telegraph as well as trade specific online articles from Solar Power Portal.

S7. Is a letter from the CEO of charity Energy Sparks about their use of PV Live for the virtual monitoring of PV generation in schools as part of energy education programmes.

S8. [Text removed for publication].

S9. Letter from a statistician in the Energy team at the Department for Business Energy and Industrial Strategy. It describes three uses of PV Live by the department – for statutory reporting of energy to the International Energy Agency, to improve the accuracy of PV capacity reporting and in consultation during the first months of the COVID-19 pandemic.

S10. [Text removed for publication]