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Short communication

The role of 'living laboratories' in accelerating the energy system decarbonization

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A B S T R A C T

To decarbonize the energy system by the year 2050, it is crucial that innovations are trialled in a 'real world' setting for the purpose of increasing public adoption and support, and for providing insights to decision-makers to ensure their decisions are effective and influential. Together, renewable energy systems, distributed and digitized 'smart' energy networks (SEN) provide opportunities to maximize energy efficiency, reduce transmission losses and drive down greenhouse gas emissions. Yet, such integrated Smart Local Energy Systems (SLES) are in the early stages of development and the technologies that underpin them lack testbeds where they can be developed and tested in a real-world environment. Here we demonstrate the potential role of one of Europe's largest 'at scale' multi-vector Smart Energy Network Demonstrator—SEND, developed within a 'living laboratory' setting that provides the 'blueprint' for the development and testing of low-carbon energy technologies on the UK's journey to net zero. Based on the SEND platform and data, we have developed and demonstrated several novel AI based smart algorithms for intelligent SLES control and management. We are also working with industry partners to develop a digital twin of the smart energy system on our campus.

1. Introduction

Decarbonization of the energy system is key to achieving a net-zero (NZ) greenhouse gas future. Globally, the energy system (electricity, heat and transport) is responsible for about 73.2% of greenhouse gas emissions (Zhang et al., 2021). The 2018 Intergovernmental Panel on Climate Change (IPCC) report highlights the climate emergency and criticalness of achieving a NZ greenhouse gas future to limit future temperature rise to 1.5 °C (IPCC, 2018). UK is among the countries in the world that have announced significant and necessary targets to meet the NZ future for their economies by 2050 with decarbonization of the energy system as one of the priority areas (Janda et al., 2021). In a bid to meet this statutory obligation, the UK government aims to power UK entirely by renewable energy sources by 2035 (Janda et al., 2021), end the sale of new petrol and diesel cars by 2030 (Matteo et al., 2021) and accelerate the deployment of low carbon heating systems like heat pumps (Heat Pump Association, 2019). UK is expected to have more than 14 million electric vehicles (EV) (Earl and Fell, 2019; Anon, 2021) and 1.2 million electric heat pumps by 2030 (Heat Pump Association, 2019).

Together, these trends are changing the conventional way in which the UK energy system (and energy systems in other countries) is operated and managed by increasing the coupling between the multi-energy systems (electricity, heat, gas, transport). Energy systems are no longer passive and uni-directional but active and bi-directional with end-users taking active roles in the operation and management of the energy system (Samende et al., 2022). This energy transition paradigm introduces new benefits to end-users like security of energy supply and affordability while grid operators benefit from deferred grid reinforcement plans and increased diversity of energy supply. At the same time, the paradigm introduces new technical, economic, and social challenges for grid operators, end-users and regulators particularly due to the unreliability, intermittency and non-dispatchability of most RESs. The International Energy Agency predicts that by 2050, around 7% of wind and solar output worldwide would be above and beyond what can be integrated if the current electricity market design remains unchanged (Bouckaert et al., 2021).

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Abbreviations

AI	Artificial Intelligence
BEIS	Department for Business, Energy and Industrial Strategy
BEMS	Building Energy Management System
DEMS	Decentralized Energy Management System
DEOP	Decentralized Energy Optimization
DR	Demand Response
DSM	Demand Side Management
FLISR	Fault Location Isolation and Service Restoration
IoT	Internet of Things
LCEG	Low Carbon Energy Generation
PLC	Programmable Logic Controllers
RES	Renewable Energy Sources
SCADA	Supervisory Control and Data Acquisition
SEND	Smart Energy Network Demonstrator
SLES	Smart Local Energy Systems

To overcome these challenges, innovations have emerged across four key dimensions of the energy system: (i) enabling technologies (e.g., through energy storage systems like behind-the-meter batteries (Fitzgerald et al., 2015), electrification of end-user sectors like vehicle to everything (V2X) (Zhou et al., 2020), digital technologies like internet of things/artificial intelligence (Fuller et al., 2020), and new-grids like renewable energy-based micro-grids (Hatziargyriou et al., 2007)), (ii) business models (e.g., empowering customers through energy aggregation (Ma et al., 2017), peer-to-peer energy trading (Samende et al., 2022), energy-as-a service (Altamimi et al., 2012) and enabling renewable energy supply through community-ownership (Clausen and Rudolph, 2020) and pay-as-you-go models (Ulsrud et al., 2018)), (iii) market design (e.g., by re-designing capacity markets (Trum, 2021) and market integration of distributed energy resources in the retail market (Olivella-Rosell et al., 2018)) and (iv) system operation (e.g., by redefining future roles of distribution network operators (Anisie et al., 2019) and by accommodating uncertainty related to energy prices, renewable energy production and consumption through advanced forecasting techniques and the use of machine learning (Akhter et al., 2019)).

However, most of the four key dimensions of innovations in the energy system outlined above are in their early stages of development and are based on simulation or emulated energy system environments which do not fully capture the stochastic and dynamic nature of a real-world setting (Gupta and Zahiri, 2020). Without evidence that the low-carbon energy technologies being deployed have been tested and evaluated using a real-world environment, it is unlikely that the public and other stakeholders will risk adopting and supporting them (Cherry et al., 2014).

To overcome the adoption challenges and provide for testing before wider deployment for present research and innovation systems described above, living labs present a real-world environment where smart energy strategies, technologies and interventions can be flexibly researched, developed and trialled prior to deployment. The power in the living lab approach lies in the potential to maximize the impact across both the education and research missions of a university, as well as in the benefits of working with businesses and wider community with multiple stakeholders represented in discussions from the outset (Robinson et al., 2022a). Examples of successful living labs are reported in Clarke and Searle (2021), Christensen et al. (2020), Bliek et al. (2010), Andersson and Rahe (2017). However, these labs either consider a single building as a testing environment (Clarke and Searle, 2021), a single topic (e.g., demand-side management) (Christensen et al., 2020) or do not consider other energy sources like wind turbines and hydrogen in their generation and energy storage portfolio (Bliek et al., 2010; Andersson and Rahe, 2017).

In this paper, we demonstrate the potential role of Keele University's Smart Energy Network Demonstrator—SEND, developed within a 'living laboratory' setting to provide the 'blueprint' for research, development and testing of low-carbon energy technologies on the UK's journey to net zero. Compared to the existing living labs (Clarke and Searle, 2021; Christensen et al., 2020; Bliek et al., 2010; Andersson and Rahe, 2017) and energy demonstrators (Gupta and Zahiri, 2020), Keele University's living lab is unique in the following ways:

- It is the first at scale living laboratory in Europe to consider all the energy vectors (electricity, gas, heat and transport) and to include solar, wind, battery and hydrogen energy storage systems
- The digital twin allows renewable energy generation, distribution, storage, forecasting and energy balancing to be intelligently carried out across the different energy vectors
- The living lab has access to a 650-acre site with 341 buildings (academic, student residential, staff flats & houses, Science Park) and 20 EV chargers, making it suitable for transdisciplinary research and engaging experts across research, small-to-medium enterprises, and policymakers
- Keele University owns and operates all of the utilities on the campus, thus creating a single owner/operator environment across power, gas, heat, telecoms, water and drainage, and making it a suitable place for learning and researching low-carbon interventions and innovations

The rest of the paper is organized as follows. Detailed description of the SEND as a living lab is described in Section 2. In Section 3, key features of the living lab are presented. Key roles of the living lab for accelerating the decarbonization of the energy systems are discussed in Section 4, with conclusions presented in Section 5.

2. Overview of the SEND

Funded by the European Regional Development Fund and Department for Business, Energy and Industrial Strategy (BEIS), the Keele University's SEND was established to create Europe's largest 'at scale' multi-vector smart energy demonstrator on the Keele campus. The demonstrator provides a platform that allows energy generation, distribution, storage, forecasting and energy balancing to be intelligently carried out across different energy sources using the Keele University campus as a genuine 'living laboratory' as shown in Fig. 1.

Set in the grounds of the Sneyd Family Estate, Keele University owns and operates all of the utilities on the campus, thus creating a single owner/operator environment across power, gas, heat, telecoms, water and drainage. The campus operates at the scale of a small town with 5,000 residents and more than 12,000 staff and students on campus per day. Annual energy demand across the campus is circa 63 GWh.

Being a private network, SEND is able to integrate existing gas, water, and electricity networks to form a digitally managed, flexible and extensible smart system. Keele University has been working with Siemens and Engie to install the following infrastructure on the SEND network: 1500 smart meters (electric, heat and gas), 5.5MW Solar farm, 1.9 MW wind turbines, 1 MW battery storage, upgrade of 25 substations, Spectrum distribution

Fig. 1. Overview of the SEND Living Laboratory at Keele University (copyright: Keele University).

management system, decentralized energy management system (DEMS), Mindsphere (IoT cloud platform), SEND digital twin, IoT smart appliance control, over 20 EV charging points, and many residential, commercial and industrial controllers.

The SEND system is an ideal testbed to explore how intelligent generation and distribution of electrical energy can be managed in a SLES environment. SEND enables the campus system operators to control how the generation from the renewable energy sources is self-consumed in the Keele distribution network, feed-in of the excess generation to the grid and optimize the energy use on campus by measuring the grid carbon intensity. This is an innovative scheme in the way that the researchers and system operators can test novel leading-edge algorithms, methodologies and resolutions for energy distribution in a closed environment with energy-conscious consumers. Hence, it is also crucial from a social science perspective as researchers find this as the area where social science meets the science, and this is one of the essential aspects of the living laboratory at Keele.

3. The SEND system architecture

Fig. 2 shows the whole SEND system architecture, including Infrastructure, Control and Management, and Dataset. Central to the SEND is the control centre and digital twin, which facilitates distribution system management, power system simulation, distributed energy optimization and augmented reality as described below:

Advanced Distribution Management System: The advanced distribution management system is facilitated by the Siemens Spectrum software. It controls Keele's medium voltage (11 kV) network, conveying real-time substation data, predicting possible demand constraints and is capable of intelligent healing the network in the event of outages. It enables the SEND network to establish the supervisory control and data acquisition (SCADA), thus assisting system controllers. Further, it allows reconfiguring, tweaking, and testing the impact of planned and possible network modifications before they are committed.

Power System Model and Simulation: The SEND system utilizes the software tool PSS Sincal to model, simulate, plan and analyse Keele's power network using live or offline data. Technical information coupled with geographic information from the Spectrum and SCADA can be fed to PSS Sincal to examine the variabilities in the power networks according to various scenarios and explore the technical issues such as power flow analysis, optimal routing, short circuit analysis, etc. A broad range of multi-vector energy systems comprising of renewable energy resources, storage, the conventional resources such as gas turbines, combined heat and power, hot water and loads are studied by the PSS simulator.

Distributed Energy Optimizer Platform: The whole dataset of SEND is managed by a Distributed Energy Optimizer Platform (DEOP), a cloud-based open and flexible platform that uses sophisticated algorithms to control various campus assets. DEOP can include third-party algorithms developed in a compatible programming language, e.g., Python. DEOP can manage controllable assets according to an optimization logic configured by the user. The first goal for optimization in SEND is to minimize the CO_2 in the grid, which can be pursued by taking into account all the emission factors of generation assets and consumption assets.

Microgrid Control/Distribution Automation (DA) Unit—The purpose of the DA unit is to provide an interface of the existing electrical network to the Spectrum Power 5 subsystem in near real time. Keele has 27 substations and 9 of these have DA Units. A DA Unit also provides an interface to controllable assets which allows Spectrum Power 5 to perform various control functions, such as sending signals to retrofit actuators which allow remote substation switching operations. The DA units can operate in balance mode, for example the DA unit located at the Low Carbon Energy Generation Park's substation models a microgrid

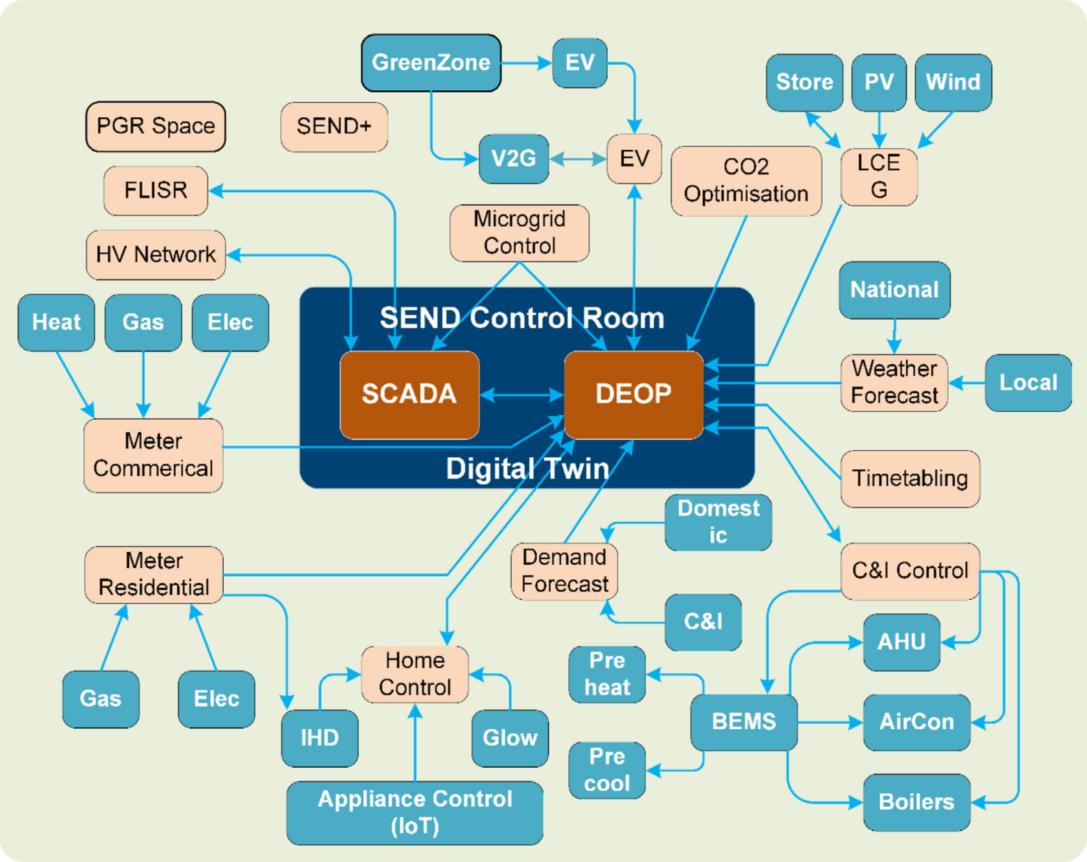


Fig. 2. SEND system architecture, including the main functions (1) Digital Twin with SCADA (Supervisory Control and Data Acquisition) and DEOP (Decentralized Energy Optimization); (2) Microgrid Control for distribution grid automation; (3) FLISR (Fault Location Isolation and Service Restoration); (4) CO2 optimization to reduce the carbon emission based on demand response: (5) LCEG (Low Carbon Energy Generation) with 5.5MW Solar farm, 1.9 MW wind turbines, 1 MW battery storage; (6) Weather, demand forecasting: (7) BEMS (Building Energy Management Systems) with flexible demand; (8) C&I and PLC Asset Control, (Commercial & industrial (C&I) Controllers and Programmable Logic Controllers PLC); (9) Home controller; (10) Smart meters for heating, electricity and gas.

consisting of renewable generation (from the wind turbines and photovoltaics), battery storage and campus load.

Fault Location Isolation and Service Restoration (FLISR) – The 8 substations that form the 'Automated Ring' have Fault Passage Indicators (FPI) along with DA Units. The LCEG substation has a DA Unit but it is not within this ring. FPI's assist in the rapid location and isolation of faults on high and medium voltage networks. It has a current sensor fixed around the three phases of a cable and can detect a current imbalance due to an earth fault. An earth fault trip is indicated by an LED indicator on the unit. The FPI also sends a signal to the DA Unit which triggers an alarm and an icon to appear within SP5. SP5 will use the information provided by the DA unit to identify and localize the fault area. The SP5 subsystem will create a schedule of switching procedures that will isolate the faulty area of the network and restore power to the de-energized area by moving the normally open point. Options exist within SP5 to configure the extent of autonomy. Keele Estates abide to an industry rule where switching schedules are reviewed by two High Voltage Senior Authorized Persons (HVSAP) before switching operations are performed.

C&I and PLC Asset Control—Commercial & industrial (C&I) Controllers and Programmable Logic Controllers (PLC's) have been installed to enable SEND to control assets that can reduce or increase their energy demand based on either DEOP's carbon saving optimization logic or grid constraints identified by SP5 (aka DR or Demand Response). Typically, SEND's PLC and C&I controllers' interface with the BEMS systems which monitors room temperature etc, so an asset's change in energy use does not decrease the building occupier's comfort levels beyond set points implemented in the BEMS. Some examples of flexible assets are air handling units (AHU's), pumps, car chargers and air conditioning units. Keele also has 3 electric boilers on campus (total 1.5MW) which can be used for Demand Response.

Artificial Intelligence Application: Based on the dataset located in DEOP, the SEND researchers are studying the application of Artificial Intelligence (AI) into the SEND local energy systems. The research includes energy arbitrage using battery storage with detailed battery degradation model based on rainbow deep reinforcement learning (Jun et al., 2020; Harrold et al., 2022) and multi-agent deep reinforcement learning (Dan et al., 2022). The other research investigates privacy preserving smart energy data analytics using federated learning (Briggs et al., 2022). The AI algorithms developed by SEND researchers will be deployed into DEOP in the future.

Data Visualization and Analysis: DEOP can activate the Demand Side Management (DSM) facility of the load flexible campus buildings, which can either increase the building load, balance the on-site renewable generation or reduce the load in response to one of the two options, day-ahead or ad hoc. Day-ahead: based on a day-ahead grid constraint identification and/or CO$_2$ Optimization, the DEOP algorithms initiate a load reduction command to the appropriate PLC. Ad hoc: triggered when DEOP is notified of potential network constraints or violations by SP5. This will

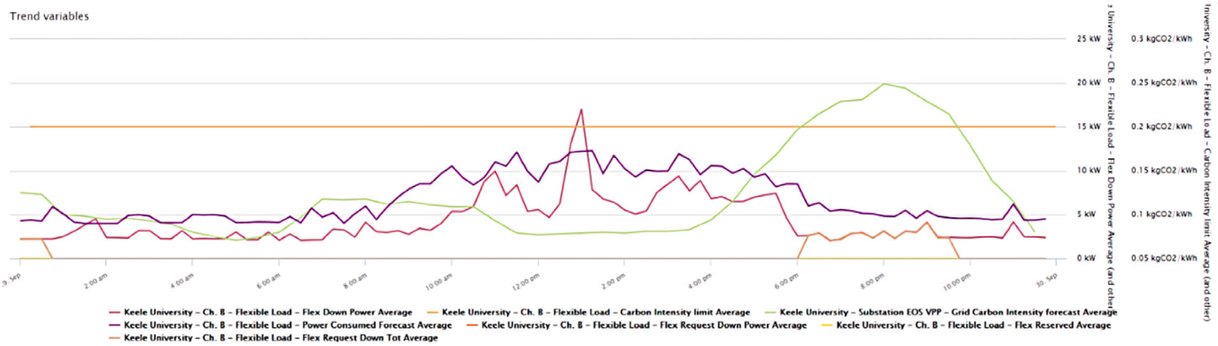


Fig. 3. Example of DSM mechanism occurring for CO_2 minimization in a flexible building.

result in DEOP initiating a Demand Response (DR) command to be sent to each PLC within the appropriate group or a Commercial and Industrial (C&I) controlled asset. C&I controllers are used to control a single asset such as an electric boiler. The systems control assets based on either a VPP (Virtual Power Plant) or DR event. DEOP monitors the grid CO_2 intensity forecast. This forecast, along with data from the controllable assets is fed into the Energy Optimal Scheduling (EOS) algorithm in DEOP. This algorithm considers different inputs from each type of asset involved and creates a schedule for the controllable ones. When the grid carbon intensity breaches the CO_2 limit of a building, the output from the EOS algorithm will control the VPP assets to minimize the CO_2 emissions by reducing the consumption of electricity.

Fig. 3 showcases an example of DSM mechanism for CO_2 minimization in a flexible building at Keele on September 29, 2021. The nominal AC power capacity from the PV systems is 4.4 MW. Zooming into high-resolution data, weekly and daily data can be read from Fig. 4 (Sept. 21–27, 2021). During this week, the total energy demand was 202.11 MWh. The amount supplied by the PV system was 86.260 MWh, from where the consumers directly consumed 65.893 MWh, and the rest amount of 20.374 MWh was fed into the grid (Fig. 4a). These account for 32.599% of self-sufficiency (SS) and 76.388% of self-consumption (SC) from PV systems.

Augmented Reality: The augmented reality disseminates system data in all possible ways a user wants, including the heatmap to show system efficiency, in-depth system statistics, network, renewable energy feed using a graphical dashboard, etc. as shown in Fig. 5.

4. Potential roles of the keele university's living laboratory

The energy sector's decarbonization, decentralization, and digitization require balancing environmental, economic, and social concerns. This is quite challenging as there is a risk in passive trade-offs between equally critical priorities. The living laboratory welcomes the challenges to explore and demonstrate the efficacy it holds. With structures ranging from late Victorian to ultra-modern, the opportunity to adopt sustainable measures at the campus and examine the system efficiency and the resulting carbon emissions in detail inside this controlled environment provides a remarkable opportunity.

The digital twin within SEND is based on models of the physical components and takes input from demands that are fed into the system, other exogenous data (such as weather forecast or actual weather data, various IoT sensor data) to investigate different "what-if" scenarios. We are also investigating the combination of physics-based energy network models and advanced explainable AI techniques (e.g., deep neural networks and reinforcement learning) (Jun et al., 2020) to facilitate the data-driven optimal design and real-time operation of future net-zero energy systems, by harnessing the power of live data from the SEND platform.

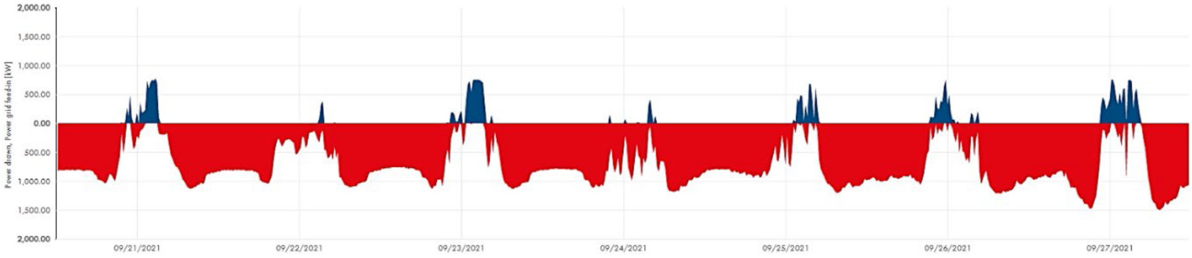
The living laboratory's capabilities allow the engineering community to design a roadmap for Grid 2.0 in the UK, where grid digitalization and decentralization demonstrate the possibilities for energy supply chain decarbonization and ensure supply security. The UK government has set aggressive ambitions to reach net-zero emissions, and in this regard, the Grid 2.0 supported SLES can assist in meeting these objectives. For instance, as a typical SLES system, SEND showcases the critical path to net-zero while also creating significant commercial potential and opportunities for the development of cutting-edge energy technologies. Working with industry partners, we have been researching and trialling the novel concept of peer-to-peer (P2P) energy trading on this testbed (Samende et al., 2022). Electricity trading on a P2P basis empowers prosumers and consumers, resulting in increased renewable energy development and system flexibility.

The living laboratory allows for innovation and infrastructure development for regional and national testing and pilot programmes for government projects. It provides space and opportunities for large to small, multinational and multisectoral companies to test and demonstrate how sustainable cities and communities should look. Towns, organizations and companies can help decarbonize their operations and supply chains by learning from the pilot projects and real-life demonstrations using the living lab. By extending the hand of partnership and cooperation, the living laboratory at Keele can strengthen the means of implementation and revitalize the global partnership for sustainable development.

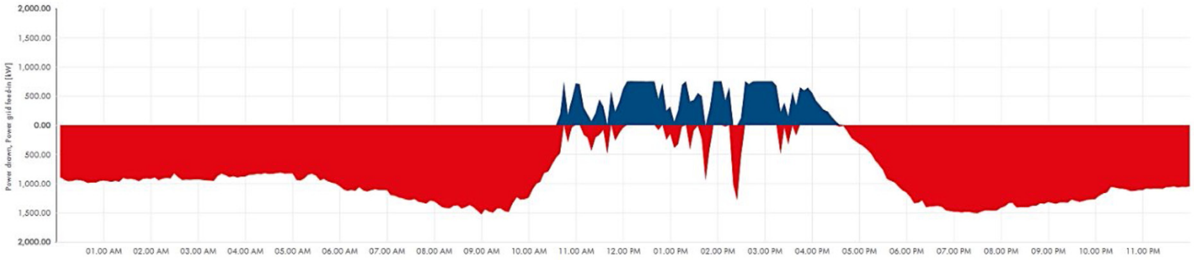
Finally, we recognize the distinctive social benefits of the SEND living lab and the opportunities for converting scientific knowledge into the practice of society. In particular, the lessons learned from SEND are embedded into novel educational opportunities offered by the university—both through a vast array of interdisciplinary degree programmes, but also in wider public engagement and knowledge dissemination. The latter is particularly powerful because it has been shown that demonstrator projects can help increase the public's confidence in novel or unfamiliar energy technologies (Robinson et al., 2022b), in turn overcoming often difficult barriers regarding social acceptance and behavioural change (Groves et al., 2021). Keele University's living lab is thus a crucial tool in increasing public trust in novel energy systems, for testing novel engagement and knowledge dissemination practices, and for involving the public more concretely at the forefront of smart energy system transition pathways.

5. Conclusion

The living laboratory's takeaways allow initiatives to be implemented all around the world, not only in the UK. The technologies



(a) 09/21/2021 - 09/27/2021



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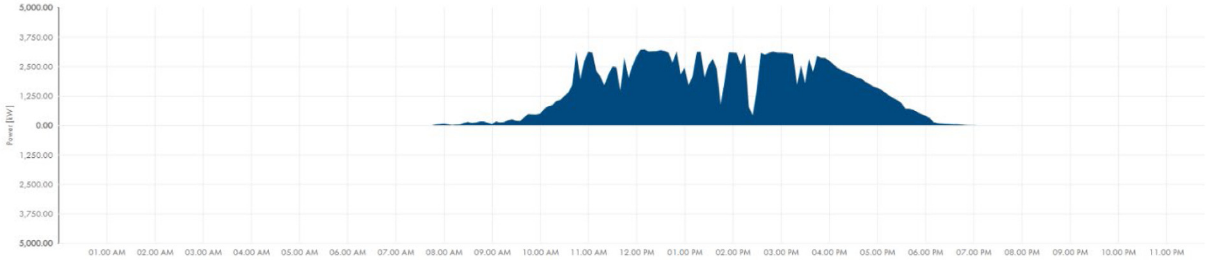
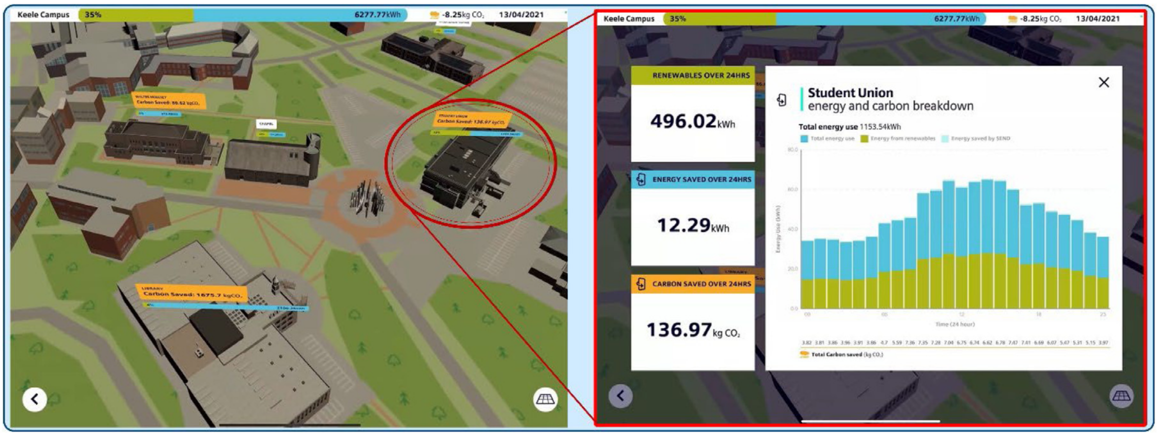


(c) on 09/27/2021

Fig. 4. Weekly and daily distribution of grid feed-in and consumption (red colour—power drawn from the grid, blue colour—feed-into the grid from excess generation in the campus). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)


Keele Campus 35% 6277.77kWh -8.25kg CO₂ 13/04/2021

RENEWABLES OVER 24HRS
496.02kWh

ENERGY SAVED OVER 24HRS
12.29kWh

CARBON SAVED OVER 24HRS
136.97kg CO₂

Student Union
energy and carbon breakdown

Total energy use 1153.54kWh

Fig. 5. Augmented reality showing the amount of renewables used, energy and carbon saved over 24 h at different facilities across Keele campus on 13/04/2021. For example, 496.02 kWh of renewables was used, 12.29 kWh of energy was saved and 136.97 kg CO_2 of carbon was saved at the Student Union building.

developed can also be scaled up to other big demonstrators and SLES systems. This will pave the way for knowledge sharing on how communities can benefit from the low-carbon energy future. Ongoing research activities on the living lab include using SEND data on applying advanced artificial intelligence and blockchain technology to SLES, study of consumer behaviour and perception of novel SLES technologies, user-centred design of SLES, as well as new materials for smart energy. Leveraging the SEND platform, we have been partnering with many institutions in UKRI funded projects such as EnergyREV,[1] Hydex,[2] and Zero Carbon Rugeley,[3]

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[1] https://www.energyrev.org.uk/

[2] https://www.era.ac.uk/hydex

[3] http://www.rugeleypower.com/zero-carbon-rugeley-project/

to play a major role in researching and developing low-carbon energy technologies on the UK's journey to net-zero.

CRediT authorship contribution statement

Zhong Fan: Conceptualization, Investigation, Methodology, Project administration, Resources, Supervision, Roles/Writing – original draft, Writing – review & editing. **Jun Cao:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Roles/Writing – original draft, Writing – review & editing. **Taskin Jamal:** Conceptualization, Investigation, Roles/Writing – original draft. **Chris Fogwill:** Conceptualization, Project administration, Supervision. **Cephas Samende:** Conceptualization, Investigation, Methodology, Roles/Writing – original draft, Writing – review & editing. **Zoe Robinson:** Project administration, Resources. **Fiona Polack:** Project administration, Resources. **Mark Ormerod:** Project administration, Resources. **Sharon George:** Project administration, Resources. **Adam Peacock:** Project administration, Resources, Writing – review & editing. **David Healey:** Project administration, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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