Smart Local Energy Systems Towards Net Zero: Practice and Implications from the UK

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***Abstract*—In transition towards net-zero carbon emissions, a high penetration of renewable power generation and electrification of heat and transport at the grid edge will increase total and peak power consumption significantly with greater uncertainties, thus posing serious challenges to electric power systems. Smart local energy systems, which manage distributed energy resources locally with various smart technologies and commercial arrangements, are one of the promising solutions to this problem. This paper provides a comprehensive review and analysis of the practice of local energy systems in the UK in the context of net-zero transition. At the macro level, local conditions, local businesses, profitability, investment and whole electricity system impacts of local energy systems are reviewed. Then, a practical case in North Wales, UK, is analyzed for demonstrating technical, commercial and regulatory arrangements available and needed for setting up a local energy system practice. Implications are summarized for providing a useful reference for developing smart local energy systems within and beyond the UK.**

***Index Terms*—Distributed energy resource, microgrid, net zero, smart local energy system, smart grid.**

I. INTRODUCTION

THE Paris Agreement has been adopted by about 200 nations across the world, and its long-term goal is to keep the increase in global average temperature to well below 2°C above pre-industrial levels, and to pursue efforts to limit the increase to 1.5°C, recognizing this would substantially reduce the risks and impacts of climate change [1]. In this context, there have been an increasing number of both developed and developing countries in the world, as many as 137 countries by September 2022, who have committed to carbon neutrality [2].

The energy sector is the source of more than 75% of greenhouse gas emissions across the world, where electricity is expected to account for almost 50% of total energy consumption in 2050, thus being vital to averting the worst effects of climate change [2].

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Renewables and electrification are two important pillars of decarbonization, which are transforming modern energy systems significantly. Specifically for the electricity sector, the supply and demand patterns at the edge of power systems are changing dramatically, with rapidly increasing connection of distributed energy resources (DERs) such as distributed renewable power generation, distributed energy storage, electric vehicles, heat pumps and power-to-gas units [3].

Large amounts of DERs pose great challenges for power systems, led by intermittent renewable power generation and multiple times total and peak electricity demand to be accommodated at the grid edge (i.e., the demand side of power grid). On the other hand, the flexibility contained in DERs, i.e., the capability of DERs to change their normal power generation, storage and consumption patterns according to external requests, also has great potential to address these challenges [4]. As a result, a number of concepts and solutions have been proposed to coordinate and manage DERs, such as microgrids [5], virtual power plants [6] and peer-to-peer energy trading [7]. In the UK [8] and from some literature [9], the concept "smart local energy systems (SLESs)" has been proposed to describe the organization of DERs locally facilitated by "smart" technologies such as advanced sensing, measuring, communication and control technologies. Nevertheless, it is worth noting that SLES is a broad concept with vague boundaries and is interpreted from different perspectives by different people in different cases [10].

This paper provides an overview and analysis of the practice of SLESs in the UK in the context of net-zero transition. The uniqueness of this paper lies in that it is based on practice, in contrast to solely theoretical, methodological or technological studies in the same area. The experience of the UK is considered interesting, because the UK is the first major economy in the world passing laws to achieve net zero greenhouse emissions with high-level development of SLESs. Implications from the practice in the UK are able to provide value for other places in the world in their journey of decarbonization.

The contents of this paper are organized from the macro landscape to the micro case study. Historical development of SLESs to date is first described in Section II, followed by analysis from different perspectives presented in Section III. Section IV then presents a practical case in North Wales, Wales, the UK, demonstrating and analyzing technical, commercial and regulatory arrangements in developing a real SLES and suggesting potential solutions. Finally, Section V concludes the paper with the implications of further development of SLES.

II. Development of Local Energy Systems in the UK

Policies and outcomes of SLESs in the UK are summarized in this section, featuring three stages to date [11], i.e., community energy, local energy and smart local energy systems. Fig. 1 depicts the evolution of local energy systems in the UK.

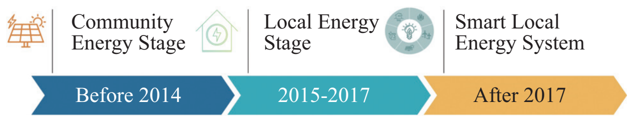

Fig. 1. Timeline of the evolution of local energy systems in the UK [11].

A. Community Energy Stage (Before 2014)

Before 2014, development of local energy systems in the UK was led by the government's "Community Energy Strategy". Community Energy projects are characterized by grassroots, bottom-up energy initiatives with strong citizen participation, local ownership and collective benefit sharing [11]. The UK government hoped that "every community across the country could initiate an energy project, regardless of background or location" [12].

As a result, from 2008 to 2014, there were around 5,000 unique community groups that had been involved or interested in undertaking Community Energy projects, as surveyed by the UK Energy Research Center [13]. Fig. 2 illustrates the estimated number of established community groups which were involved or interested in community energy projects prior to 2014 [13], demonstrating that community groups were growing at a rapid pace. Community Energy projects were located across the whole of Britain and Northern Ireland. The types of projects included awareness raising, energy efficiency, renewable energy, local sustainability plan, or combinations of these.

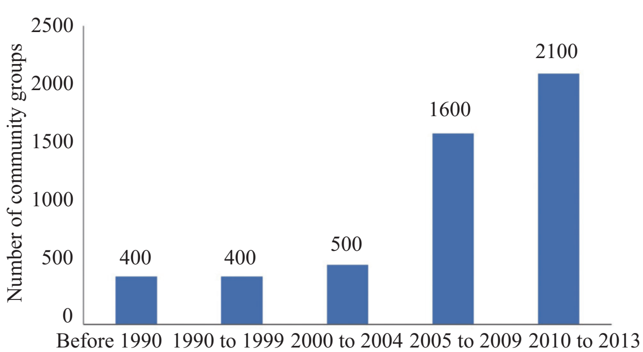

Fig. 2. The estimated number of established community groups which were involved or interested in community energy projects [13].

B. Local Energy Stage (After 2015)

Since 2015, the UK government has changed the policy focus from Community Energy Strategy to Local Energy Strategy [11]. Compared to "bottom-top" Community Energy projects, Local Energy projects also adopt a more "top-down" manner and are usually led by a partnership between local authorities and local enterprises. Local Energy projects focus more on economic growth, job creation, skill development and infrastructure improvement [11].

According to the statistics from the UK Energy Research Center in 2017, 72% (i.e., 311) of local authorities in the UK had energy plans, and 48% (i.e., 208) of them had mobilized finances for a total of 458 Local Energy projects [14]. The main technologies involved in these Local Energy projects included combined heat and power, building energy efficiency improvements, heat networks, solar photovoltaic technologies, biomass boilers, etc. [14].

C. Smart Local Energy Systems (After 2017)

In 2017, the UK government published its new Industrial Strategy, identifying four "Grand Challenges", i.e., artificial intelligence and data, ageing society, clean growth and future of mobility [15]. Accordingly, the Industrial Strategy Challenge Fund was set up and further divided the four Grand Challenges into more detailed ones. To address one of the detailed challenges, i.e. the "Prospering from the energy revolution challenge", the government has been investing around £102.5 million in industry and research to accelerate innovation in SLESs, matched by project participants, creating a total investment of £200 million [16].

SLES development in the UK is set in the history of the UK to reach net zero carbon emissions by 2050. Although conventional centralised energy systems in the UK work well, they have evolved to take advantage of cheap fossil fuel energy, being inefficient and emitting huge amounts of carbon. Therefore, the UK decided to develop SLESs supported by smart digital technologies, which are able to enable more flexibility at the demand side, two-way energy flows and better connectivity across power, heat and mobility provision. As part of the solution towards net zero, SLESs have the potential to bring cleaner, cheaper and more efficient energy to local communities, to attract investment and to build local jobs and prosperity [16]. Building SLESs involves new business models, advanced data management, bold investment, supportive policy environment, a shift in thinking and public acceptance in the development of local energy systems [8].

Specifically, supported by UK Research and Innovation (UKRI), three large demonstrators and 11 small future designs, projects have been set up to practice and design various aspects of SLESs [8], several of which are illustrated in Table I with key characteristics presented.

An interdisciplinary academic program "EnergyREV" [17] and an independent entity "Energy Revolution Integration Service" [18] have also been created to accelerate research and promote social and economic benefits of SLESs.

In previous community and local energy stages, projects were usually about single energy technology, such as combined heat and power (CHP), solar photovoltaic (PV), biomass boilers, etc. [19]. By contrast, SLESs, as the name indicates, are energy systems typically involving multiple energy supply, transmission, storage and demand technologies, as well as different value streams with both energy markets and flexibility

TABLE I
SOME SMART LOCAL ENERGY SYSTEMS PROJECTS IN THE UK [8]

Projects	Aims	Features	UKRI funding
Local Energy Oxfordshire	Unlocking flexibilities for renewable generation and demand response	Electricity system	£15.2 m
Energy Superhub Oxford	Showcasing integrated approach to accelerate net zero for urban areas	Urban energy system	£10.3 m
ReFLEX Orkney	Addressing the challenge of decarbonizing Orkney's full energy system	Integrated energy system	£8 m
GreenSCIES and GreenSCIES 2	Devising a smart grid to integrate heat, power and transport sources	Integrated energy system	£3.31 m
Greater Manchester Local Energy Market	Altering current market mechanism by cultivating a peer-to-peer trading	Integrated energy system	£3.11 m
Girona	Trialing the use of PV panels with batteries across homes and businesses	Microgrid	£2.11 m
Zero Carbon Rugeley	Producing an innovative design for a town-wide smart local energy system	Urban energy system	£1.4 m

services included. For SLESs in the UK, the most widely applied technologies are solar PV and battery storage, followed by CHP, heat pumps, electric vehicle charging and wind turbines, with a few applications of hydrogen, tidal and hydro energy [20].

For coordinating the large amounts of interconnected equipment in an SLES, a lot of advanced measurement, information and communication technologies are needed and applied in SLESs. Smart scheduling and control strategies are also needed for managing SLESs across multiple time horizons (from real-time, hourly, daily, monthly up to yearly) for multiple purposes including cost minimization, carbon emission reduction, multi-energy optimization, infrastructure expansion, as well as flexibility service provision. We have published a comprehensive review paper in this regard [20].

III. Analysis of Local Energy Systems in the UK

A series of analysis of local energy systems in the UK is reviewed in this section, from various perspectives including development conditions, businesses, profitability, investment and whole electricity system impacts.

A. Local Conditions for Development

Whether or not, and to what extent, local energy systems will develop in an area are related to a series of local conditions such as energy infrastructure, socio-economic factors and housing conditions. Understanding these conditions will provide guidance for enterprises to make investment decisions on SLESs, or for governments to make policies to encourage development of SLESs. A survey of 146 local energy systems during the period 2010–2020 was conducted [21], and information on these local energy systems is summarized in Table II. Analysis of the survey results (for detailed data refer to [21]) further revealed the key positively and negatively correlated conditions for developing SLESs in the UK. The positively correlated conditions include the number of renewable energy projects, electric vehicle charging infrastructure and relevant technical businesses, as well as coverage of universities and home energy audits. The negatively correlated conditions include coverage of new building stock, efficiency improvement in fuel poor households and gas grid, as well as average household income.

TABLE II
CATEGORIES AND STATISTICS OF LOCAL ENERGY SYSTEMS IN THE UK [19]

Categories	Number of Projects	Main Players	Median Budget
Supply-side focused	24	Private firms	£2.4 m
Network-focused	47	Distribution network operators	£1.8 m
Demand-side focused	41	Public sector organizations	£3.3 m
Supply, network and demand integrated	34	Private firms	£4.0 m

B. Local Energy Businesses

For companies developing local energy in the UK, ownership is diverse, including municipally-owned, community-owned, trust/foundation owned, university-owned and private companies. As illustrated in Fig. 3, the vast majority of local energy businesses in the UK are run by private companies, accounting for 77%, followed by 14% of trust/foundation-owned companies, with very minor percentages for other types of ownership [22].

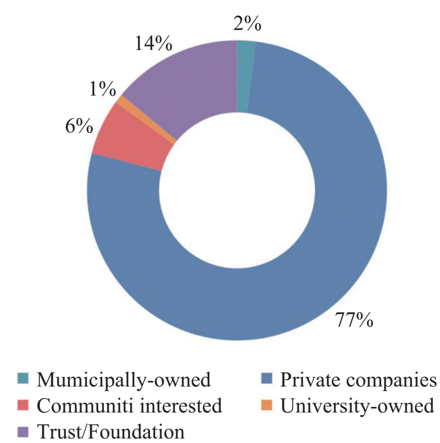

Fig. 3. Ownership structure of local energy businesses in the UK [20].

From the perspective of company size, almost half of local energy businesses in the UK are medium-sized, while large and ultra-large companies also account for considerable proportions [22].

From the perspective of technology, onshore wind and solar PV are two dominant technologies applied in local energy systems, both in terms of the number of companies involved (around 200 companies for each technology) and installed capacity (over 2 GW and 1 GW, respectively). For offshore wind and pumped storage for local energy systems, the number of relevant companies is very small (both below 10), but installed capacities are high, i.e. around 2 GW for both technologies in local energy projects [22]. There are also other technologies applied in local energy businesses with small to medium numbers of companies (from around 10 to 100 companies) involved and moderate installed capacity (below 1 GW for each technology), including waste to energy, energy storage, biomass, combined heat and power, hydropower, and biogas.

C. Profitability and Investment

Profitability of local energy systems is of great importance, indicating whether or not local energy systems can be scaled up, because only with good profitability will capital flow into the sector, boosting development of local energy systems.

A relevant survey shows that over 90% of local energy projects investigated make a financial surplus [23]. However, the severe issue is, if the price guarantee mechanisms (Renewable Obligation, Feed-in Tariff or Renewable Heat Incentive) from the government are removed, only 20% of local energy projects will be profitable [23], indicating that most local energy projects in the UK still rely on subsidies from the government and are not commercially scalable. Within the 20% of projects which are profitable even without government's subsidies, one prominent business mode is installing rooftop solar PV panels in buildings, where most electricity generated is sold to onsite consumers [23].

Various factors affect the profitability of local energy systems. It is revealed the more a local energy system is "local", the less profitable it would generally be [24], which remains a great challenge for developing local energy systems. Profitability of local energy systems also varies with ownership – it is found that private projects usually have higher levels of profitability, while some municipal projects perform badly financially [24]. One potential reason is that municipal projects may have other objectives, such as helping people with energy poverty, besides financial profitability.

From the macro perspective on social investment in local energy systems, it is found that current investment across housing, public and commercial buildings, etc., is failing to capture major cost-effective carbon savings [25]. There is also a shortage of about £4 billion in developing local heat networks for decarbonization of heat [25]. Moreover, it is found that investing in people, skills and expertise can bring forward local net zero carbon programs, supported by statistics that £1 million technical assistance funding to every UK local authority could lead to over £15 billion in local energy investment [25].

D. Whole Electricity System Impacts

Besides benefits delivered to local residents and businesses, it is vital to understand how and to what extent development of SLESs could contribute to the whole electricity system in its transition to net zero.

In this regard, a study has been conducted to analyze whole system impacts of SLESs which were considered to be able to facilitate uptake of very small-scale demand side response and distributed battery storage (at kilowatt scale) [25]. Four cases with different levels of SLES uptake, i.e. 0%, 10%, 25% and 50%, were assessed in two future scenarios with different levels of grid carbon intensity, that is, 2030 and 2040 with grid carbon intensity assumed to be 100 and 25 $gCO_2/kW\cdot h$ respectively [26].

Simulation results show the average electricity cost (in £/MW·h) will decrease with increasing uptake of SLESs, especially for a future grid with low carbon intensity. At most, average electricity cost could be reduced by 19.1% at 50% SLES update compared to no SLES in 2040 [26].

One prominent source of cost saving comes from the fact that SLESs can facilitate powering consumers by local power generation through local flexibility, so peak demand and thus reinforcement cost of electricity distribution networks can be reduced. Simulation results show that peak demand and the associated reinforcement cost of distribution networks decrease with increasing uptake of SLESs. As the most significant case (50% SLES update in 2040), reinforcement cost can be reduced by as much as £1.6 billion across the UK [26].

IV. Developing a Practical Local Energy System: A Case in North Wales, UK

In contrast to the macro analysis conducted in Section III, this section starts from a specific case to describe and analyze considerations, challenges and potential solutions for developing a practical local energy system in the UK.

A. Case Description

The case is located in one County in North Wales of the UK. There are multiple sites having the potential to build local PV power plants. Local government and the Welsh Government, would like to link potential PV power plants to the surrounding public buildings to form SLESs to power the buildings with green energy at reduced cost and reduce payback periods of building PV power plants.

Geographical information of the four sites is illustrated in Fig. 4, with the high-level generation and demand data presented in Table III.

TABLE III
ELECTRICITY GENERATION AND DEMAND OF THE POTENTIAL SITES IN A PARTICULAR COUNTY, NORTH WALES, UK

Sites	Potential PV Generation Capacity (kW)	Total Annual Demand of the Surrounding Public Buildings (kW·h)
A	500	507,712
B	16,500	692,030
C	2,000	1,723, 742
D	1,500	746,150

B. Connection Options

For all four sites shown in Fig. 4, potential PV power plants have two connection options, that is, (a) directly connected to surrounding public buildings through private wires, and (b) connected to public electricity distribution networks, as illustrated in Fig. 5.

The two connection options have their respective strengths and drawbacks. In the private wire option, the PV power plants and buildings they supply will be behind the same meter, so that simultaneous generation and demand can be directly net offset with each other, without paying any network

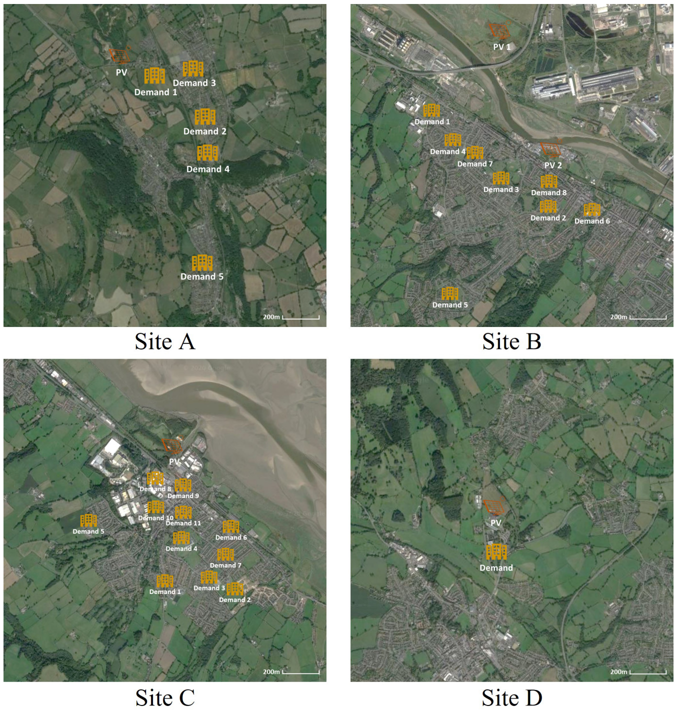

Fig. 4. Potential sites of PV power plants and the surrounding public demands in the County in North Wales, UK.

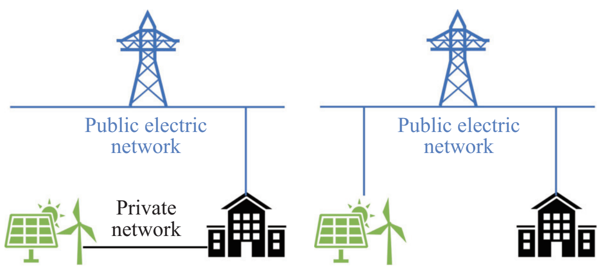

Fig. 5. Connection options for the potential PV power plants.

usage charges, levies and taxes, thus being able to save a considerable amount of costs (network charges, levies and taxes account for over 60% of an electricity bill). Nevertheless, private wires are subject to high upfront investment and high management costs. Calculation has been conducted, weighing the operational benefits and costs, and results show that payback periods of building PV power plants with private wires are 18 years on average, which is too long for investors to accept. Private wires are also faced with complex contractual and license exemption issues, and long-term uncertainties on investment recovery, supply security and regulatory changes [27].

Besides the financial issue, the private wire option also has other issues. From the perspective of distribution network operators (DNO), private wires may lead to unnecessary duplication of network assets and investment, and their operations are invisible to the DNO, increasing difficulty for the DNO to optimally plan and operate public distribution networks. Furthermore, investment in the public distribution networks will be recovered by charging the customers connected. Increasing installation of private wires will decrease the number of customers relying on public distribution networks, and thus network charges imposed on the remaining customers will be increased. Increased network charges may further encourage more customers to build private wires, resulting in a vicious cycle (referred to as the 'Death Spiral' for power network companies [28]).

Based on the above analysis, local government has decided not to proceed with the private wire option and turned to using public distribution networks. Thereafter, technical, commercial and regulatory arrangements need to be made to create an SLES for managing and operating the PV power plants and the surrounding public buildings, which are connected through public distribution networks.

C. Technical Arrangements

Compared to being separately connected and managed, distributed generation and demand in an SLES can create more value because they are coordinated. One essential prerequisite of coordination is that there needs to be "flexibility" in the supply side, or demand side, or both sides of the SLES. The "flexibility" can come from a wide variety of technologies – for the case in North Wales, technologies can be battery energy storage to be installed at the PV power plants, EV chargers at public buildings, or other retrofits that enable demand side response from public buildings. With flexibility, communication links need to be established between PV power plants and the buildings and also with central controllers or cloud platforms. Intelligent coordination can then be conducted, in a centralized, decentralized or hybrid way to utilize flexibility within the SLES. Flexibility, communications and intelligent control technologies are largely commercially available, and thus the key question would be how many benefits they could create, depending on the commercial arrangements that will be analyzed in the next sub-section.

D. Commercial Arrangements

Among various options for commercially linking PV power plants and the surrounding buildings in the County, the "sleeving contract" [29], which is a special type of Power Purchase Agreement (PPA) [30], is a suitable arrangement, where PV power plants can supply buildings in a way of peer-to-peer (P2P) energy trading. Simultaneous generation and demand are virtually netted off each other, with the remaining electricity surplus or deficit topped up by an energy supplier. SLES containing PV power plants and buildings itself can become a registered energy supplier as well [30], but customer bases in the four sites in the County are still too small to make the supplier business profitable. It is also noted that PV power plants and buildings will still have to pay all network charges, taxes and levies as if they are separately traded with an energy supplier, because electricity is transmitted through public distribution networks.

Quantitative analysis has been conducted for the four sites in the County, comparing annual electricity costs of adopting the "sleeving contract" with those of PV power plants and buildings separately trading with an energy supplier. It is assumed there is enough flexibility to be utilized for making the demand of buildings supplied by PV power plants as much as

TABLE IV
COMPARISON OF THE ELECTRICITY COSTS WITH AND WITHOUT THE SLEEVING CONTRACTS IN THE COUNTY, WALES, UK

Sites	Annual Electricity Costs (£, Only including energy costs, excluding network charges, taxes, levies, etc.)			
	Separate Trading	Sleeving Contract	Saving	
			Absolute Value	Percentage
A	−906	−1,231	325	35.9%
B	−703,517	−703,960	443	0.06%
C	−22,689	−23,792	1103	4.9%
D	−35,495	−35,972	477	1.35%

possible, with an incentive provided by the sleeving contract. Numerical results are presented in Table IV. An electricity bill includes multiple components, but only the components regarding energy are presented and compared in Table IV, considering sleeving contracts cannot be exempted from other costing components such as network charges, taxes and levies. Negative numbers represent that SLESs actually earn money from selling surplus PV power generation. Absolute values of saving because of the sleeving contract adopted as the commercial arrangement are close for the four sites, ranging from £325 to £1103 per year, which are not significant, although it might be high when translated to percentages, because absolute value of the earnings might be low (such as that of Site A). Saving comes from reduced energy imbalance because of increasing level of balance between local generation and demand, incentivized by sleeving contracts. This results in reduced energy imbalance costs in the electricity bill, but this reduction is not significant, because imbalance costs only account for a small percentage in an electricity bill (usually less than 1%). It is also noted the order of absolute saving, in descending order, is C > D > B > A, and this is consistent with the order of total annual demand of the sites as shown in Table III. The reason is that, for all four sites, total annual PV generation is much higher than total annual demand (this can be seen from the fact that costs of all the four sites are negative, representing income from selling surplus PV generation), and therefore, sites with higher annual demand can consume more electricity generated by local PV generation with lower energy price, resulting in more saving.

E. Regulatory Arrangements

As described in the previous sub-section, electricity trading between the PV power plants and the buildings in the SLESs cannot be exempted from distribution network charges (called "Distribution Use of System (DUoS)" charges in the UK), which account for around 15% of a typical electricity bill. The current DUoS arrangement in the UK does not reflect the actual use of the networks in the SLESs and does not provide the right incentives for SLESs from the network perspective, as well.

The actual use of distribution networks by PV power plants and surrounding buildings in the four sites of the County has been quantified. The electrical connection of the four sites is simplified and illustrated as single line diagrams shown in Fig. 6. There is no way to actually trace real-time movement of electrons at the speed of light in power networks, and thus, it is reasonably assumed that generation and demand below the same transformer can be balanced without using the upper-level networks. Accordingly, it is assumed that generation /demand that cannot be balanced below the same transformer has to be supplied from other external generators through the upper-level networks. Network losses are omitted.

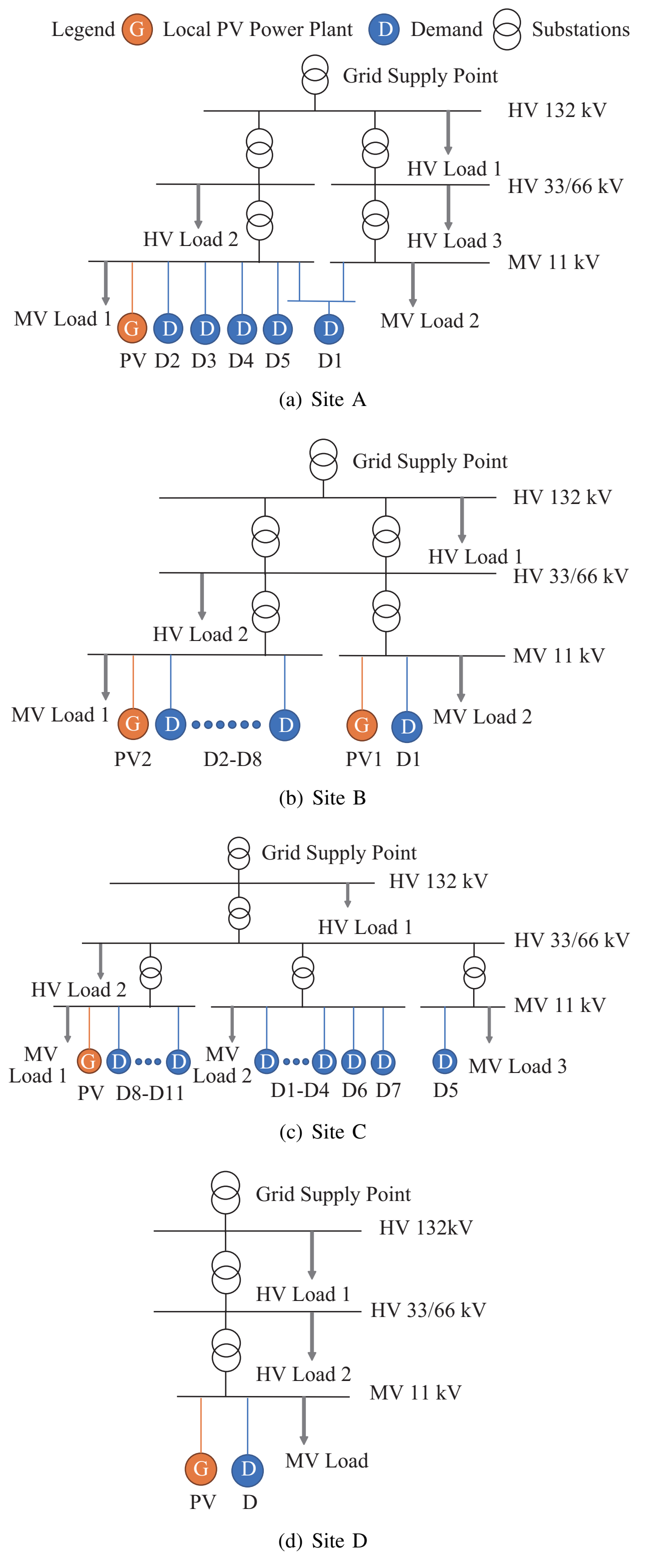

Fig. 6. Electrical connection of the four sites in North Wales, UK.

Numerical results are presented in Table V. The estimated

TABLE V
ESTIMATED ACTUAL USE OF DISTRIBUTION NETWORKS OF THE FOUR SITES IN NORTH WALES, UK

Sites	Entities	Use of LV/MV Networks	Use of HV Networks
A	Generation	46.98%	53.02%
	Demand	49.73%	50.27%
B	Generation	2.33%	97.67%
	Demand	59.47%	40.53%
C	Generation	16.48%	83.52%
	Demand	85.60%	14.40%
D	Generation	26.24%	73.76%
	Demand	56.75%	43.25%

actual use of distribution networks depends on a number of factors, including the specific electrical connection topology and matching between half-hourly generation and demand profiles. In spite of this, in sites A-D, 2.33%–46.98% of local PV generation only uses low voltage (LV) and medium voltage (MV) networks to supply local demands, and 49.73%–85.60% of demand is supplied by local PV generation only through LV/MV networks. However, these parts of local PV generation/demand will have to pay network charges of the upper-level high voltage (HV) networks in current network charging regulations, which may not be completely fair. Nevertheless, it is also worth noting that distribution networks were designed based on worst-case scenario (i.e. peak power periods), so accumulating network usage throughout the year may not accurately reflect actual investment in distribution networks.

Furthermore, the current regulatory scheme provides little incentive for facilitating power and energy balancing in local distribution networks, because DUoS charges will not change no matter that PV power plants and buildings are coordinated with each other or not. Local power and energy balancing is important for enhancing the utilization rate of network assets and reducing peak power, thus deferring reinforcement investment of local distribution networks. Failing to do so poses increasing physical and financial burden on DNOs, especially with increasing distributed renewable power generation and rapid electrification of heat and transport during net-zero transition.

V. IMPLICATIONS FOR FUTURE DEVELOPMENT OF SMART LOCAL ENERGY SYSTEMS

Based on analysis of SLES history and practice in the UK as presented in Sections II-IV, a number of implications have been drawn for informing future development of SLESs, which are general and applicable to both within and beyond the UK. The implications are grouped at macro- (i.e., sector/country-wide) and micro- (i.e., for one single specific SLES project) levels.

A. Macro-level Implications

Macro-level implications are summarized as follows:

1) System Integration: SLESs will need to achieve integration of generation, demand, storage and network, integration of multiple energy carriers such as electricity, gas and heat, integration of multiple sectors such as energy and transport, and integration of physical systems with multiple smart technologies such as those in measurement, communications and intelligent control.

2) Business Model: Example business models need to be developed for rolling out SLESs quickly enough for matching the decarbonization agenda.

3) Locality: Developing SLESs needs to consider specific local conditions in energy infrastructure, socio-economic features and housing conditions.

4) Local Business: Medium-sized companies are key practitioners for rolling out SLESs.

5) Technology: Onshore wind and solar PV are two dominant technologies being used in SLESs, so far.

6) Profitability: The key to wide deployment of SLESs is to improve profitability of SLESs. Profitability of most existing SLESs in the UK has problems without supporting policies/subsides from governments. Having buildings with rooftop PV panels is one major configuration that has relatively good profitability even without public subsidies, when most electricity generated by PV panels is sold to onsite consumers.

7) Investment: Investing in people, skills and expertise can bring multiple times returns for developing SLESs towards net zero.

B. Micro-level Implications

Micro-level implications for developing an SLES in practice are summarized as follows:

1) Electrical Connection: Connection to public power networks is the most common and proper option except special cases (e.g., islands or remote areas), considering the financial risk and high complexity, as well as other negative effects of private wires.

2) Technical Arrangements: Flexibility is vital for an SLES. Flexibility sources (generation, network, storage or demand which can change its normal operating status responding to external price or direct control signals) and associated enabling smart technologies (e.g., measuring, communications and intelligent control technologies) are commercially available in the market and need to be decided.

3) Commercial Arrangements: For an SLES based on public power networks, a special type of PPA (i.e., sleeving contracts) can be used for achieving P2P electricity trading to a certain extent between sources and loads in the SLES, resulting in higher overall economic benefits.

4) Regulatory Arrangements: For an SLES based on public power networks, regulatory innovation regarding distribution network usage charges is needed for reflecting actual use of the network and providing proper incentives for facilitating local power and energy balancing within the SLES, which will be beneficial for both the SLES and the network.

Macro-level implications are applicable for general SLESs and can therefore inform both high-level governmental policy making and specific-level SLES development, thus being able to link to micro-level implications, as well. For example, when building a specific SLES at the micro-level, implications regarding system integration and technology at the macro-level can be considered when designing technical arrangements. Moreover, implications regarding business model, locality, local business, profitability and investment at the macro-level are useful for making commercial arrangements. Further, all macro-level implications will support the forming and innovation of regulatory arrangements for developing a specific SLES.

C. Concluding Remarks

SLESs play an important role in managing a large amount of renewable energy and electrified heat and transport connecting to the edge of future net-zero power systems. Various innovative technical, commercial and regulatory arrangements need to be made for developing an SLES. Rolling out of SLESs for achieving net-zero transition needs thorough consideration, assessment and improvement on various aspects including local conditions, business models, profitability, investment and whole electricity system impacts.

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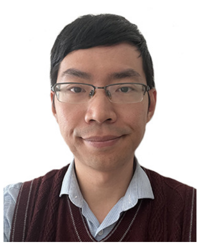

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