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REVIEW

Information and communications technology (ICT) infrastructure supporting smart local energy systems: A review

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Abstract
Smart local energy systems (SLES) have been reported in the past decade, which are associated with diverse energy carriers, components and objectives. This paper provides a comprehensive review of information and communications technology (ICT) infrastructure of SLES. A systematic survey of existing research work and industrial projects was provided to highlight, categorise and analyse the ICT infrastructure, which lays the foundation for the successful functioning of SLES. First of all, various SLES measurements are described and categorised based on the energy carriers and technologies. Then, communications infrastructure for SLES is described with communications technologies summarised. Moreover, the ICT infrastructures for SLES are categorised and summarised based on their objectives and technologies. Finally, the challenges and recommendations are presented. The findings from this paper are intended to serve as a convenient reference for developing future SLES.

KEYWORDS
distributed power generation, energy management systems, information and communications infrastructure (ICT), multi-vector energy systems, smart local energy systems

1 | INTRODUCTION

The power industry is the major source of carbon emissions in the world, contributing to about 31% of total emissions [1]. In order to reduce excessive greenhouse gas emissions from fossil-fuel-based centralised energy systems, various efforts are being made to utilise resources more efficiently and generate electricity with minimal or even without carbon emissions [2, 3]. In consideration of serious environmental issues caused thereby, new targets and milestones are being laid out in different countries [4–7], for encouraging localised renewable energy systems and achieving the zero-carbon transition.

However, a local energy system is challenging to handle as it usually relies heavily on intermittent renewable power generation. Additionally, the demand side of power systems would become more complex, with the increasing integration of heating and transport sectors with the electricity sector [8]. To address these challenges, smart local energy systems (SLES) are generally accepted as an important part of the future energy systems, owing to their diverse benefits [9–11]. The benefits of SLES include modernising established networks, improving operational performance, promoting improvements in customer behaviours and experience, delivering innovative technologies and facilitating the shift to competitive low-carbon energy systems.

To date, the governments of various countries have laid various plans [12–18] for promoting SLES and have made a substantial investment in various SLES demonstration projects. These programmes were implemented with various supporting measures, such as financial support, and tried out new products and tools for SLES. They range greatly in size, from a community system to a large high-voltage distribution network. In conjunction with the governmental plans [4–7] and project initiatives [12–18], the roadmaps for the future low carbon transition were also put forward by various academic institutions, such as those in Denmark [19], Ireland [20] and Portugal [21]. Similar studies have also been conducted in many countries, for example, the U.S. [22], China [23] and Croatia [24]. These efforts integrate multiple energy carriers (such as electricity, gas and heat) and transport networks, in order to achieve a higher level of renewable energy integration and utilisation and highlight the importance of information and communications technology (ICT) infrastructure in the success of SLES.

This paper provides a systematic survey of existing research work and industrial projects to categorise and analyse the ICT infrastructure supporting SLES, specifically in the following aspects: (i) various measurements associated with multiple energy carriers in SLES, (ii) communications infrastructure in SLES, and (iii) ICT infrastructure regarding scheduling and management of SLES with various objectives. These aspects form the foundation for building a zero-carbon energy system, and therefore, they are considered as an important part of developing a carbon-free society. The findings from this work will thus provide valuable guidelines for developing the ICT infrastructure in future SLES.

Compared to existing relevant work, the novelty of this review paper is summarised as follows:

- The ICT infrastructure of SLES has been comprehensively identified, categorised and analysed from the perspectives of measurements, communications, objectives and technologies.
- The ICT infrastructure has been revealed for multiple energy vectors in SLES including electricity, gas and heat.
- Key challenges and recommendations of the ICT infrastructure of SLES have been identified and made.

2 | THE SMART LOCAL ENERGY SYSTEMS CONCEPT

In the majority of literature, the terms 'decentralised energy', 'community energy', and 'localised energy' were often used interchangeably with local energy systems. Smart local energy systems is a new concept that incorporates the elements of the definitions of 'smart energy' and 'local energy', for which there has not been a unified description. This paper adapts the definition of SLES as, '*a locally and collectively organised system, which includes distributed energy conversion equipment supplying energy demand through local electrical network, gas network, heat network and transportation network, and controlled by local authorities, including municipalities, or enterprises, based on voluntary and open participation, whose primary objective is to provide environmental, economic, financial, and social community benefits*' (adapted from [25]).

The energy conversion equipment comprises various types of electrical technologies (like solar and wind power generation), heating technologies (like combined heat and power units [CHP]) and gas technologies, along with energy storage systems. The day-to-day operation of multiple energy conversion equipment in SLES is crucial for achieving various benefits [26]. A highly efficient SLES development involves integrated multi-energy carriers [27]. This integrated approach optimises the flow of energy among different energy carriers and satisfies the multi-energy demand of community users while facilitating energy trading with and ancillary service provision to the neighbourhood energy systems and the bulk energy networks [25, 26].

Some of the studies concentrated on the infrastructure and physical elements with certain features, such as efficiency and accessibility [28], while others concentrated on the intents of the programs, such as emissions mitigation, network and service stability, and profitability [29]. Essentially, SLES are expected to render a cost-effective [29], more productive [30], more stable [28] and more sustainable system [29]. The specific meanings of terms 'smart', 'local' and 'energy systems' in SLES are summarised in the report [31].

3 | REVIEW OF MEASUREMENTS IN SMART LOCAL ENERGY SYSTEMS

This section highlights the key measurements of different energy carriers in SLES, which include electricity, heat and gas. A schematic of interaction between electrical, heat and gas energy carriers is shown in Figure 1. Note that the gas networks in this paper refer to those carrying natural gas and also those carrying hydrogen and other alternative green gases. As indicated by the practice and plan in the UK, most existing gas networks currently carry natural gas, but to allow bio-methane and hydrogen injection to natural gas and conversion of the gas networks to deliver hydrogen are important options for decarbonisation for the future.

Each of these energy carriers is equipped with specific measurements corresponding to their components. Besides, there are measurements of the coupling components, which act as an interface for the exchange of energy between different energy networks. The measurements associated with all these components are further categorised into the measurements for operation and management of SLES. As the names suggest, the 'operation-oriented' measurements are short-term (hourly or shorter) measurements, which mainly include performance indicators and the energy imports/outputs of the components. By contrast, the 'management-oriented' measurements mainly include long-term measurements such as energy supply/consumption for billing purposes and energy efficiencies. Besides, there are measurements supporting flexibility markets, for example, those for dynamic pricing and demand response solutions [32–34]. All these measurements are categorised and reported in this section. Figure 2 depicts the key measurements in the integrated energy networks in SLES, where the 'operation-oriented' measurements are depicted in red text, flexible market supporting measurements in black text, and the 'management-oriented' measurements in purple text.

3.1 | Measurements associated with electric energy carrier

The components of the electrical network in SLES include, (i) electricity supply such as solar photo-voltaic (PV) farms, wind farms, hydro-energy generators, tidal-energy generators and supply from the bulk power grid; (ii) electric energy storage (EES) units, which include batteries, super capacitors, flywheels

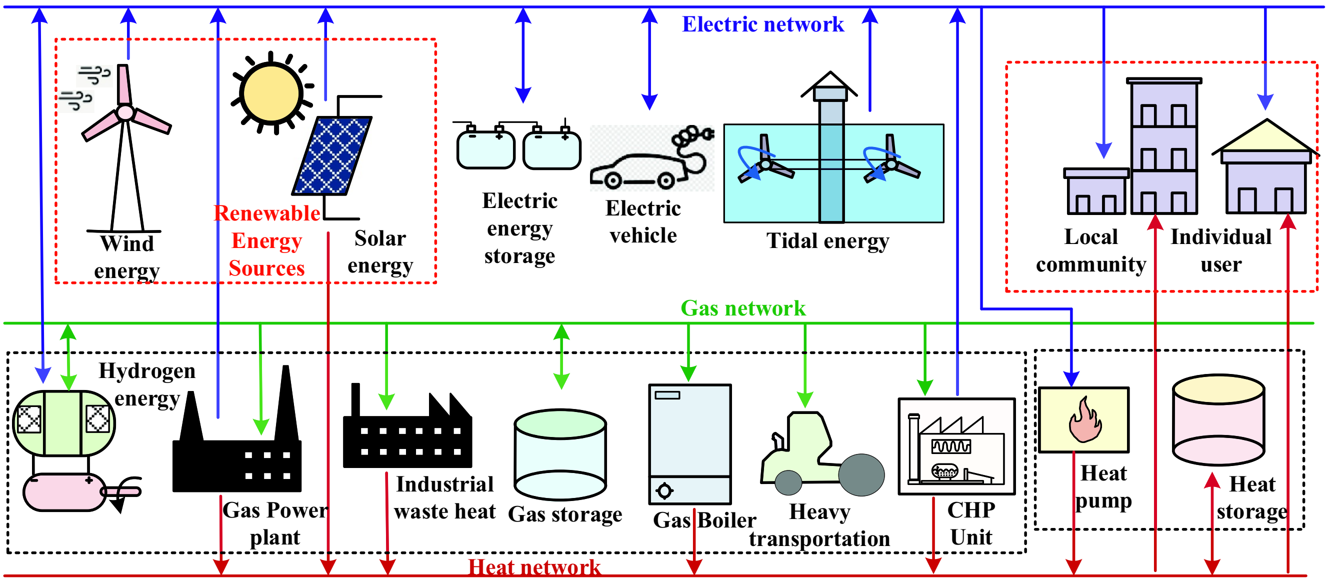


FIGURE 1 Schematic of interaction between electric network, heat network and gas network

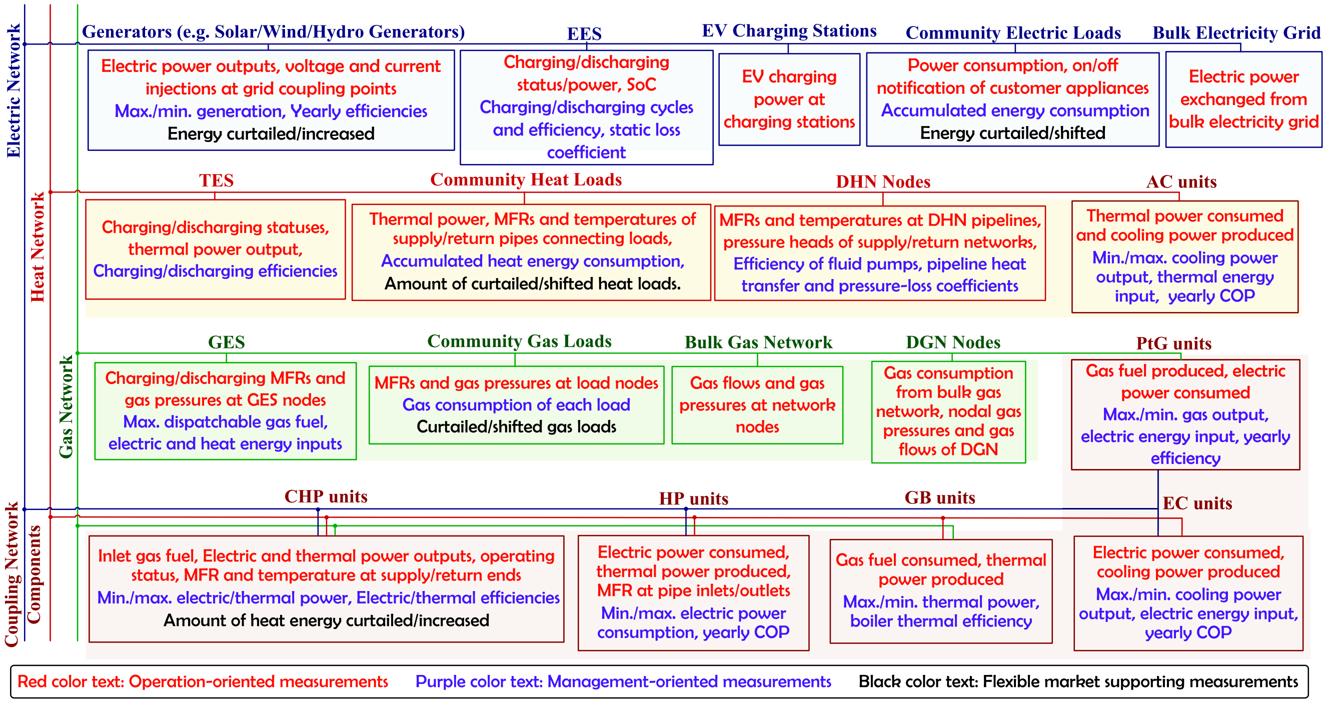


FIGURE 2 Key measurements associated with multi-carrier local energy networks

etc.; and (iii) electric loads with the charging of electric vehicles included. All these measurements are reported as follows.

3.1.1 | Generators

The operation-oriented measurements include electric power outputs from the generators (e.g. solar/wind/hydro generators) and voltage and current injections at the grid coupling points [35, 36]. The management-oriented measurements include the accumulated energy output, average efficiencies, maximum and minimum power generated from these generators etc. [37, 38]. The measurements associated with flexibility markets include the amount of power/energy changed (e.g. curtailed/increased) and the corresponding time duration for providing flexibility services [39].

3.1.2 | Electric energy storage systems

The operation-oriented measurements include operating (charging/discharging) statuses of the EES, the amount of electric power charged/discharged by/from the EES, energy stored in the EES, and the associated state of charge [35, 38, 40]. While the EES plays a vital role in the commercial sector, it also plays an important role in energy harvesting and management in the local energy systems [41, 42]. The management-oriented measurements include the number of charging/discharging cycles of the EES, charging and discharging efficiencies of the EES, and the static loss co-efficient [37, 38].

3.1.3 | Electric loads

The operation-oriented measurements include the power consumption, voltage and current injections at various load buses and on/off notification of customer appliances [35, 36, 43], and EV charging power and energy consumption at charging stations [36, 44–47]. EV charging load is separately emphasised here considering its special importance due to that it will greatly increase both the total and peak electricity consumption of SLES and at the same time act as an important source of flexibility to support SLES. The flexibility markets related measurements include the amount/duration of power curtailed/shifted [36, 39]. The management-oriented measurements include energy consumption for billing purposes and energy efficiencies [37, 38].

3.1.4 | The bulk electricity grid

The measurements include electric power exchanged from the bulk electricity grid, and maximum and minimum power exchanged with the grid [35, 36, 38].

In the context of capturing the SLES electric network measurements, advanced metering infrastructure (AMI) [48] is regarded as an important support for SLES, which facilitates demand information availability and load control with two-way communications in real time. Smart electric meters collect information from end users' devices and appliances while also having some capability to control the devices [49]. Specifically, smart meters enable the following functions [49, 50]: (1) two-way end-to-end communication, (2) automatic metering and billing; (3) appliance monitoring and control, (4) detection and diagnosis of system faults, and (5) data storage and management.

There are also other measuring devices associated with the electricity grid including phasor measurement units and remote terminal units, but they are usually installed at higher voltage levels than those of SLES, generally above 11 kV, thus not described in detail in this paper.

3.2 | Measurements associated with heat energy carrier

The heat networks in SLES attract many interests from the researchers in the past decades [51, 52]. Like electrical networks, heat networks also consist of heat generation units, storage units and heating load. The heat generation units such as CHP and electric Heat pumps (HPs) are considered as coupling components in this report, which will be introduced in Section 3.4. The measurements corresponding to various heat network components are reported as follows.

3.2.1 | Thermal energy storage systems

The operation-oriented measurements include operating (charging/discharging) statuses of thermal energy storage systems (TES), thermal power charged/discharged, and energy stored in TES [53–55]. The management-oriented measurements include charging and discharging efficiencies of TES [56, 57].

3.2.2 | Heating loads

The operation-oriented measurements include heat power of loads, mass flow rates (MFRs) and temperatures of supply and return pipes connecting the loads [58–61]. The management-oriented measurements include the accumulated amount of heat energy consumed by each load [56, 57]. The flexibility markets related measurements include the amount and duration of loads curtailed/shifted [53, 62].

3.2.3 | District heating network

The operation-oriented measurements include mass flow temperature at the inlet and outlet of pipelines in supply/return District heating network (DHN), MFRs of heat stations in DHN, pressure heads of the supply/return DHN, mixed temperature at a node in supply/return DHN, minimum/maximum temperature at different nodes in supply/return DHN, and water flow at different nodes in DHN [53, 54, 62, 63] The management-oriented measurements include total rate of heat energy available at the central source for district heating need, available heat energy at central energy source, efficiency of water pumps in heat stations, heat transfer coefficient of pipelines, and coefficients of pressure loss in water pipelines [56, 57].

In the context of capturing the heat network measurements, authors in [64] briefly discussed heat meter production, but smart heat meters have not been addressed. In comparison with smart electric meters, there are far fewer studies on smart heat meters. Over recent decades, however, DHN firms have developed intelligent metrology and technologies, which borrows experiences of electric power systems, to gather useful knowledge of DHNs [64, 65], paving the path towards smart heat meters. As the European countries have a number of approximately 6000 DHNs with the estimated revenue of EUR 25–30 billion [66], Europe has become the region with the largest potential for smart heat metering, especially in the Scandinavian countries.

3.3 | Measurements associated with gas energy carrier

The gas system in SLES usually includes community gas consumption (gas loads) and gas energy storage (GES) units [67, 68]. The operator of SLES governs the exchange of gas with these components in a community gas system, along with the exchange of energy with the bulk gas network. The measurements associated with gas energy carrier are summarised as follows.

3.3.1 | Gas energy storage systems

The operation-oriented measurements include pressure and charging/discharging MFRs of gas at GES nodes [69–71]. The management-oriented measurements include maximum dispatchable gas fuel, the accumulated gas output and electric and heat energy inputs of GES [70, 71].

3.3.2 | Gas consumption

The operation-oriented measurements include gas flow rates and gas pressure in the pipelines at the gas load nodes [69, 72, 73]. The management-oriented measurements include gas consumption of each load [74, 75]. Flexibility markets related measurements include the amount and duration of gas loads curtailed/shifted [68, 69].

3.3.3 | The bulk gas network and district gas networks

The measurements include gas flow and pressure at branches of a gas network, the gas flow rate from the bulk gas network to district gas networks (DGN), nodal gas pressures at different nodes of DGN and the maximum and minimum gas exchanges [69, 72–74].

In the context of capturing the gas network measurements, the production of domestic gas meters has been examined in [76], with the emphasis on versatile and realistic methods for calculating MFRs in gas networks. Around 400 million mechanical gas meters are in service in the world, slowly replaced by smart gas meters. For instance, in the UK, the government planned to replace 53 million gas and electricity meters across the UK with smart meters, and in Italy, 16 million gas meters were prepared to be installed [77, 78]. Also in China, the current prepaid meters are gradually replaced by smart gas meters equipped with single- or double-way communication modules.

3.4 | Coupling components in integrated energy networks

Besides the various components associated with the electric, heat and gas networks, respectively, there are coupling components, which exchange energy with multiple energy carriers simultaneously, mainly including CHPs, HPs, adsorption chillers, Electric chillers (ECs), Gas boilers (GBs) and power to gas units. The measurements corresponding to these units are highlighted as follows.

3.4.1 | Combined heat and power units plants

The operation-oriented measurements include thermal power output, MFR and temperature of the supply and return fluid, electric power output, and inlet gas fuel consumption of the plants [53, 58, 59, 69–72]. The management-oriented measurements include the accumulated energy output of each CHP unit, annual average electric and thermal efficiencies, minimum and maximum electric and thermal power of each unit [56, 57]. The measurements regarding flexibility markets include the amount/duration of power/heat generation changed (e.g. curtailed/increased) [62, 68].

3.4.2 | Heat pumps

The operation-oriented measurements include electric power consumed and heat power produced by HPs [53, 58, 73]. The management-oriented measurements include accumulated electric energy consumption and thermal energy output of HPs and the annual average coefficient of performance of HPs [56, 57].

3.4.3 | Gas boilers

The operation-oriented measurements include the gas power consumed by boilers and thermal power output of the boiler units [54, 56, 79] while the management-oriented measurements include accumulated gas consumption and thermal generation and annual average boiler thermal efficiency [57, 75].

3.4.4 | Power-to-gas (PtG) units

The operation-oriented measurements include the gas fuel produced and electric power input to the PtG units while the management-oriented measurements include accumulated electrical energy consumption and average efficiency [70, 71, 80].

3.4.5 | Electric chillers and absorption chillers

The operation-oriented measurements with ECs include electric power consumed and cooling power produced by ECs while the management-oriented measurements include accumulated electrical energy consumption and cooling energy output and annual average coefficients of performance of ECs [61, 81]. The operation-oriented measurements with Absorption chillers (ACs) include the amount of thermal power input and cooling power output while the management-oriented measurements include the accumulated amount of thermal and cooling energy output and its average coefficient of performance [79, 80].

4 | COMMUNICATIONS INFRASTRUCTURE IN SMART LOCAL ENERGY SYSTEMS

The communications infrastructure plays a crucial role to accomplish the various objectives of SLES (e.g. cost saving, carbon minimisation, demand side management (DSM)). This section introduces the communications infrastructure in SLES, which will support the transmission of measurements, data and control signals between various measuring devices (e.g. smart electric/gas/water/heat meters), data concentrators and control centres, to facilitate the process of monitoring, scheduling and planning associated with SLES.

4.1 | Communications technologies for Smart local energy systems

The potential communications technologies in SLES are broadly classified into wired and wireless technologies.

4.1.1 | Wired communications technologies

The wired communications technologies include the well-known fibre-optic communications [82], which are immune to electromagnetic and radio interference, and power line communication (PLC) technology, which carry data by using existing power lines [82, 83]. They can provide communication services for several scenarios relevant to SLES including automatic meter reading, AMI and home area networks (HAN) [83, 84].

Fibre optical network architectures such as the synchronous optical networking and synchronous digital hierarchy (SDH) (SONET/SDH) are capable of delivering varying data levels at the link, convergence, and core stages. They include frameworks for multi-service provisioning applications [85]. Because of the flexibility and cost-effectiveness of Ethernet, implementing Internet Protocol with Multi-Protocol Label Switching to accomplish Ethernet transportation over SONET/SDH on the current packet switching networks would improve stability, quality of service, and protection in SLES. These can provide rates of 40 Gbps in 100 Gigabit Ethernet [86]. Similarly, Ethernet and Gigabit passive optical networks (GPON) (EPON/GPON) [87, 88] employ multiple optical-electrical solutions to have adequate power for large-scale data processing as well as high-speed data transfer of network connectivity. They deploy fibre optics to the end-user in SLES to support premises networks of local communities, by offering broad versatility in the distribution and synchronisation of optical signals at the same time.

On the other hand, PLC utilises the power lines to provide a communication network to support conventional power distribution services like load control and remote measurement. It employs low-frequency (several kHz) narrowband (NB) and high-frequency (several kHz) broadband (BB) technologies and inherits the advantages of (i) cheap cable building through the use of existing cable systems, and (ii) power supplies in premises network. The recently developed E-Line system is capable of accommodating a substantially improved data rate of over 1 Gbps and works between 100 MHz and 10 GHz [88]. However, PLC often faces concerns of attenuation, vibration and interference that are present in radio frequency communications. The specifications of Home Plug^{TM} Powerline Alliance include IEEE P1775, P1901, POWERNET, and ETSI PLT [89, 90].

4.1.2 | Wireless communications technologies

Wireless technologies such as cellular networks and LAN WiFi networks are well-equipped today and can be quickly implemented. The Long-Term Evolution enhanced 4G and 5G networks for SLES potentially have the most compelling benefit of being able to reduce updating expense of the current networks for the incumbents and equipment companies. The critical importance of 5G networks, along with its traffic requirements in smart energy systems, is identified in [90].

The Wi-Fi technology is based on the Wi-Fi protocol IEEE 802.11. IEEE 802.11a/b/g/n is specified and is used in frequency bands between 2.4 and 5 GHz [91]. This offers net data speeds for IEEE 802.11a/b/g running on a 20 MHz channel between 1 and 54 Mbps [91]. The IEEE 802.11n extension, which allows higher net data speeds up to 600 Mbps provided by 20- or 40-MHz channels [92], includes multiple input and multiple output in the range of 26 Mbps.

Unfortunately, WiFi is vulnerable to the challenges and selection of functionality absent from roaming and authentication. Therefore, new and evolving WiMAX IEEE 802.16 and P802.16 m/n 5G systems, all of which enable fixed and mobile internet wired networking, are most likely to incorporate WiFi and offer better security and efficiency. The two main backers of WiMAX construction technologies are Sprint and its staff, Grid Net Inc.

Besides, wireless mesh networks could be used for SLES [93]. Wireless mesh networks depend primarily on IEEE 802.11 for secure and inexpensive mesh networking and simple deployment. Wireless mesh networks, which was initially built for group or neighbourhood interactions, is perceived to be one of the reliable methods to support SLES.

In terms of broader range coverage and a greater number of devices integrated throughout its network, ZigBee [94] is a reliable and streamlined solution for many applications regarding SLES.

Finally, the satellite communication emerged as a good solution for remote control and monitoring data in smart systems [95]. Authors in [95] pointed out its advantages as a cost-effective communications system for renewable generation deployments, such as PV energy/wind energy.

4.2 | Communication time intervals and scheduling horizons associated with smart local energy systems

In SLES, smart meters usually routinely send the metering data while the data collection period from other sources can still be changed for various purposes according to a specific need.

The communication time intervals of data in SLES (i.e. how frequently the data are sent/received) may also be relevant with the time resolution of the scheduling conducted in SLES, for example, the day-ahead generation or load scheduling with an hourly update, as those in [36, 43, 44, 63, 73, 74]. Besides this, the flexibility markets in SLES usually involve frequent updates of prices (e.g. in dynamic pricing) and the corresponding change in energy consumption/generation of various devices or energy exchange with the external power grid [32–34, 53, 68]. Essentially, the data exchange and the frequency need to be sorted through the various communication paths/routes.

4.3 | Integrated communications infrastructure in Smart local energy systems

Heterogeneous communications networks and technologies need to be integrated for achieving effective communication in SLES. It comprises (*i*) HAN, Building Area Networks and Industrial Area Networks for the automation of homes, buildings and industrial sites; (*ii*) Field Area Networks and Neighbourhood Area Networks for linking various homes, buildings, industrial sites, local generators etc. in SLES; (*iii*) Wide Area Network for linking entities in SLES with faraway flexibility service providers, utilities etc. Smart local energy systems could take advantage of established communications networks to reduce the expense. On the other hand, SLES could also create new communications networks if existing ones cannot fit for purpose or the rental charges are too high.

An example of communications infrastructure in SLES is presented in Figure 3. The communication environments in SLES mainly include *premises area network* and *field area network*. The *premises area network* is responsible for the communication of data from smart meters to data aggregators [96, 97]. There are a number of wired/wireless communication technologies available for this purpose, which could ensure broadband speed [96, 98]. The *premises area network* also includes HAN, using IEEE 802.15.4 and IEEE 802.11 specifications for example, with which the home energy management system controls various components such as a smart thermostat, EV and rooftop solar panels [86, 96, 98]. The *field area network* links the data aggregators in the AMI and some other devices to the control centres of electricity distribution network operators and smart local energy system operators [96, 97, 99]. The network needs to be simple, cost-effective and versatile and is usually supported by the modern cellular technologies [96, 97]. Wired technologies are sometimes preferred for this network to handle huge loads of data with good connectivity.

5 | INFORMATION AND COMMUNICATIONS TECHNOLOGY INFRASTRUCTURE FOR SMART LOCAL ENERGY SYSTEMS WITH VARIOUS OBJECTIVES

The form of the ICT infrastructure is decided by the objectives to be accomplished in particular SLES, such as cost minimisation, DSM and carbon savings. These objectives are mainly accomplished through solving various optimisation problems with integrated energy network models involved. Some examples include those in MODEST [100], Perseus-RES [101], ICS-EM [102] and IRES [103]. The data from smart meters (electricity, heat and gas) provide an important basis for the SLES operators to conduct scheduling and achieve various objectives. The objectives, energy carriers involved, key components, key measurements, communication frequencies and scheduling horizons associated with various SLES are summarised in Table 1.

The various objectives with the ICT infrastructure are consistent with the sustainable development goals identified in [104]. It has been pointed out in [104, 105] that the ICTs are capable of providing powerful environmental and economic benefits while economic benefits for the global energy consumption of the ICT sector are systematically analysed in [106] along with the future predictions until 2030. Moreover, to enhance the operation of the ICT sector with different objectives, an energy internet architecture is introduced in [107], for a scalable ICT infrastructure for the future renewable energy delivery. The relations between the trend of big data era and that of the various objectives with the ICT infrastructure are reported in [108, 109] through a comprehensive literature survey.

A brief review of various SLES projects in the UK [110, 111] is also conducted. These projects are classified in terms of energy carriers involved and the objectives of the projects. The details are listed in Table 2, where each project is represented with a particular letter in the alphabetical sequence, along with a

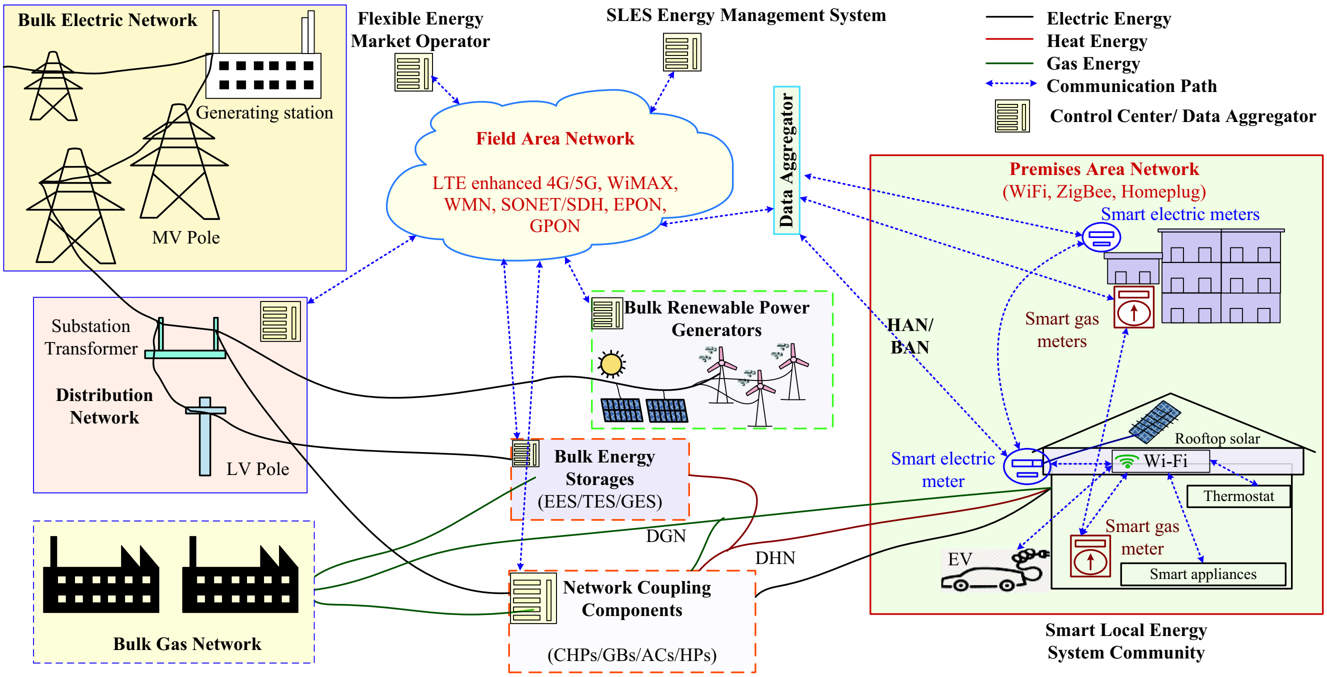


FIGURE 3 An example of communications infrastructure in smart local energy systems (SLES)

particular colour code. It can be observed that there are three sets of colour codes and these sets are classified as per the location of the project: the green colour corresponds to 'England', the sky-blue colour for 'Scotland' and yellow colour for the 'Wales'. The alphabets in the ellipses depict various projects map with various energy carriers and objectives. For example, project 'V' has its only objective as cost-minimisation and involves three energy networks (Electricity, Heat and Gas) while the project 'F' shares both objectives (i.e. cost minimisation and carbon saving), but it is associated with only two networks (Electricity and Heat). The projects that share all the three objectives are separately indicated in the last row.

Figure 4a,b depict the overall share of objectives and components of these projects. As shown in Figure 4a a majority (80.7%) of the SLES projects in the UK are concerned with carbon emission reduction, and a good share (53.8%) of them involve optimisation across multiple energy carriers. Similarly, Figure 4b represents the overall share of various technologies involved in the SLES projects.

6 | CHALLENGES AND RECOMMENDATIONS

The primary challenges being faced with SLES are more of an integration issue than the technical ones, with the technological components in various energy vectors becoming increasingly commercially viable. A successful business plan needs to combine all the aspects of SLES so that all the parties involved can benefit. This requires innovatively optimising the technological framework with modern business models in the dynamic market environment.

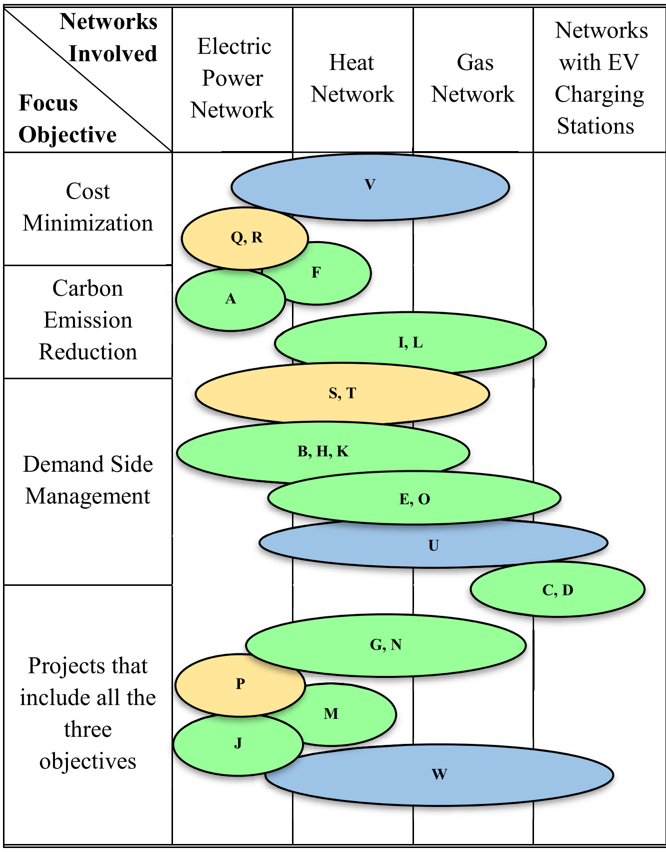
The main findings and recommendations from this work are summarised as follows:

a. ICT infrastructure of SLES includes (*i*) measurements at generation, demand, storage devices and energy network nodes, (*ii*) communications technologies and (*iii*) communications networks that transmit measurements, data and control signals between devices, data concentrators and control centres.
b. There is no 'silver bullet' ICT solution that fits all. The configuration and requirements of the ICT infrastructure of SLES, vary with four key features of SLES, namely, (*i*) energy vectors, (*ii*) technology mix, (*iii*) objectives and (*iv*) time horizons and resolutions of management.
c. Mapping the type of the ICT infrastructure that will be needed for certain types of SLES is essential. This review enables to identify the types and features of the ICT infrastructure for effective design, analysis and operation of SLES.
d. Most existing ICT solutions are dedicated to specific devices, system configurations or objectives. Future ICT infrastructure of SLES needs to be designed and operated from a 'whole system' perspective, to be more efficient and economical, and from a 'forward-looking' perspective to be more flexible and open to changes.
e. Cyber security of the ICT infrastructure in SLES is still understudied and rarely focussed on in practical projects, and more investments are needed in this area foreseeing the wide deployment of SLES in the future.

TABLE 1 Summary of various smart local energy systems (SLES) attributes based on the survey of academic studies

Ref.	Objective	Scheduling horizons	Time resolution of data	Energy carriers and components	Key measurements: Generation side	Key measurements: Demand side	Key measurements: Storage
[35, 38]	Cost minimisation	Day-ahead	Hourly	Electric energy: • Renewable (solar/wind) energy systems • Electric vehicle • Electrical energy storage • Electric loads	• Output power and energy from local generators • Power and energy exchange with the bulk power grid	• Electricity consumed • Electricity demand changed for DSM • EV charging power and energy	• Output electric energy • SoC
[36, 37]	Cost minimisation, DSM	Yearly/day-ahead	Hourly/daily				
[39]	Cost minimisation, DSM	Day-ahead	Hourly				
[43, 44]	Cost minimisation, DSM	Yearly/day-ahead	Daily/hourly				
[48, 52]	Cost minimisation, DSM	Yearly/day-ahead	Daily/hourly	Electric and heat energies: • Renewable (solar/wind) energy systems • Electric vehicle • Electrical energy storage • Electric loads • Chillers • Heat pump • Thermal energy storage • Heating loads	• Heat energy output of CHP, AC, EC and HP • Electric energy input of EC and HP • Output power and energy from local electric generators • Power and energy exchange with the bulk power grid	• Electricity and heat consumed • Electricity and heat demand changed for DSM • EV charging power and energy	• Output and stored electric/heat energy, • Charging/discharging status of TES
[49]	Cost minimisation	Yearly/day-ahead	Hourly				
[50]	Cost minimisation, DSM	Day-ahead	Hourly				
[53–56]	Cost minimisation	Yearly/day-ahead	Hourly				
[57]	Cost minimisation DSM, carbon savings	Yearly/monthly	Daily/hourly				
[58, 59]	Cost minimisation	Yearly/day-ahead	Hourly				
[60, 62]	Cost minimisation, DSM	Yearly/day-ahead	Daily/hourly				
[61]	Cost minimisation, carbon savings	Yearly/day-ahead	Hourly				
[67]	Cost minimisation, carbon savings	Yearly/day-ahead	Monthly/daily	Electric, heat and gas energies: • Renewable (solar/wind) energy systems • Electric vehicle • Electrical energy storage • Electric loads • Chillers • Heat pump • Thermal energy storage, • Heating loads • CHP • Gas boilers • PtG • Gas loads	• Heat energy output of CHP, AC, EC and HP • Electric energy output of CHP and GB • Electric energy input of PtG, EC and HP • Gas input of CHP and GB	• Electricity, heat and gas consumed • Electricity, heat and gas demand changed for DSM • EV charging power and energy • Pipeline pressures and temperatures at gas load nodes	• Output and stored electric/heat energy, • Charging/discharging status of TES • Gas input/output of GES
[68–70]	Cost minimisation	Yearly/day-ahead	Daily/hourly				
[71]	Cost minimisation, DSM, carbon savings	Yearly/day-ahead	Hourly				
[72, 79]	Cost minimisation, carbon savings	Yearly/Monthly	Daily/Hourly,				
[73, 74]	Cost minimisation	Yearly/Day-ahead	Daily/Hourly				
[75]	Cost minimisation, DSM	Yearly/Day-ahead	Daily/Hourly				

TABLE 2 Summary of local energy systems projects—with the corresponding objectives and energy-networks addressed



SLES Projects in the UK [110]-[111]			
A	ADEPT (Address Energy in Parallel Technologies)	**M**	Green Smart community Energy System
B	BankEnergi, London	**N**	SmartHub SLES
C	Lemdex - Local Energy Market	**O**	Greater Manchester Local Energy Market
D	Energy Autonomous Community	**P**	Canna Renewable Energy Electrification
E	Bristol Energy	**Q**	Isle Of Muck Project
F	E-Port Energy	**R**	Eigg Electric
G	Energy Superhub	**S**	Whole Energy System
H	Helix, Newcastle University	**T**	Reflex Orkney
I	InTeGReL Newcastle University	**U**	Distributed Ledger Technology (DLT)
J	Low Carbon Hub	**V**	Energy Revolution
K	Project LEO	**W**	Bridgend Energy Design
L	Ashton Hayes Project		

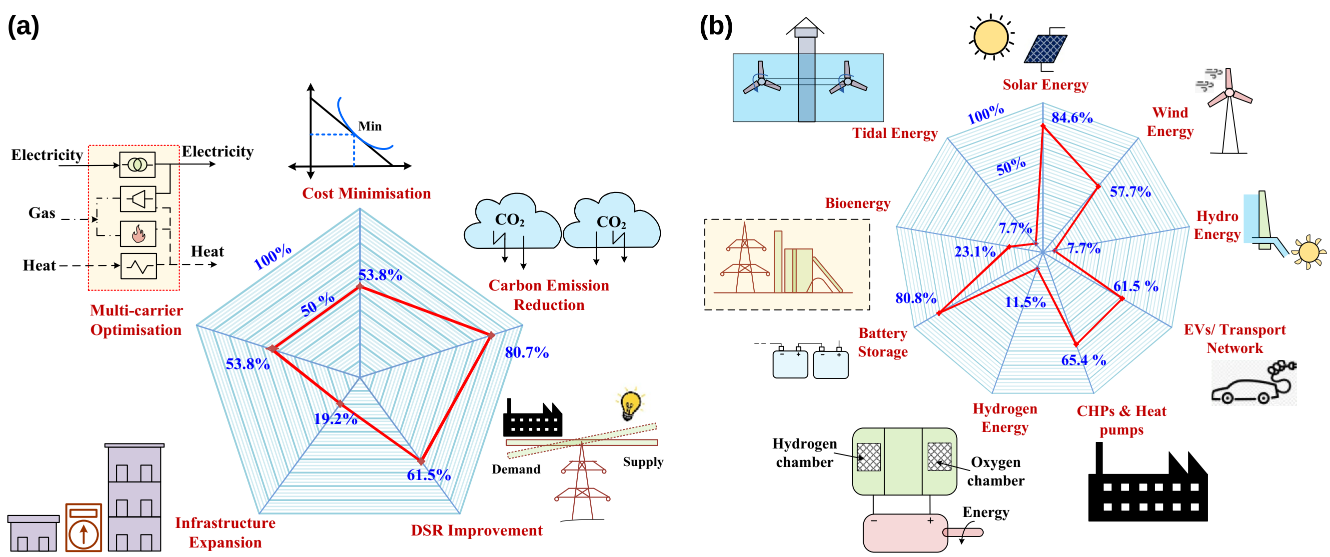


FIGURE 4 Selected Smart local energy systems (SLES) projects in the UK (a) Share in objectives (b) Share in technologies employed

7 | CONCLUSIONS

A review of the ICT infrastructure of SLES has been conducted, through a systematic survey of existing research work and industrial projects. First, the measurements in SLES have been categorised based on the energy carriers and systematically summarised. Then both wired and wireless communications technology candidates have been summarised in the context of SLES. The relationship between the communication time intervals and the time resolution of the scheduling in SLES has been discussed. The integrated communications infrastructure of SLES is also discussed. Moreover, the ICT infrastructures for SLES have been categorised and summarised based on the objectives and technologies in SLES.

Finally, the major challenges and recommendations are presented for the ICT infrastructures for SLES. While the major challenges faced are more about integration than just the technical, recommendations have been made for developing ICT infrastructures for SLES, including the major components summarised, the importance of developing ICT infrastructures according to specific key features and needs of SLES, developing flexible and open ICT infrastructures from 'whole system' and 'forward-looking' perspectives and more study and investment needed for addressing cyber security issues.

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CONFLICT OF INTEREST

The author declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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